Manufacturing Cost Analysis of 1, 5, 10 and 25 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications

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Collaborators

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Executive Summary

Fuel cell power systems may be beneficially used to offset all or a portion of grid-purchased electrical power and supplement on-site heating requirements. For this application, the fuel of choice will usually be pipeline natural gas or on-site propane storage. These fuel sources generally have much higher reliability than utility electric power, being less subject to damage-related outages, and can therefore provide for some continued operation in the event of grid outage, performing both primary power and back-up power functions. Battelle evaluated low-temperature polymer electrolyte membrane (LTPEM) and solid oxide fuel cell (SOFC) systems for use as a continuous power supplement (primary power) and to provide auxiliary heating in combined heat and power (CHP) configurations. The power levels considered were 1, 5, 10, and 25 kilowatts (kW). A primary-power/CHP commercial market has not yet developed in the 1-kW to 25-kW range; however, our analysis suggests an attractive business opportunity under the right conditions.

In the absence of a developed market and commercially available systems for analysis, Battelle defined and evaluated representative systems that could serve a hypothetical market. The representative system concepts were subjected to 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. (BDI) 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.

The evaluation showed that the highest cost category for these systems was the balance of plant (BOP) hardware. Within the overall BOP, the hardware directly related to connecting to the grid and providing heat to an on-site process (e.g., water heating) represents a major portion of the cost for both PEM and SOFC systems. This hardware includes the power electronics (direct current/direct current [DC/DC] converter and direct current/alternating current [DC/AC] inverter), energy storage to enable grid-outage operation, and the appropriate hardware for continuous connection to a utility electric grid. For PEM systems, the fuel processing costs were comparable to the grid/CHP hardware costs. For SOFC systems, the fuel processing costs were significantly lower due to the ability of the SOFC stack to accept partially reformed fuel and to benefit from internal reforming rather than requiring high-hydrogen reformate. Stack costs were less than 30% of the overall system cost for all technologies and system sizes once production volumes reached 1,000 units/year—and less than 10% in several cases. PEM stack costs were lower than SOFC stack costs for all sizes and production volumes, though the difference becomes negligible at larger sizes and higher production volumes.

A life cycle cost analysis was performed for restaurants in two U.S. locations: San Diego, California, and Honolulu, Hawaii. Both locations showed attractive return on investment through operational savings without taking any credit for avoided losses that would occur in the case of a grid outage without back-up power. Both sites had high electricity costs which helped to offset the initial cost of the CHP system. Payback was estimated as under 3 years for all cases analyzed at these two locations, and internal rate of return was on the order of 28% or greater for the projected 5-year life of a system. Future cost reduction opportunities identified in the report can make the systems attractive in a wider range of locations, and improvements in reliability will extend the projected life, resulting in higher rates of return. Site-specific assessment of grid outage impact (loss of refrigerated food, loss of ongoing business, loss of data) without back-up power will provide additional incentive to install these systems. Key assumptions to enable this value proposition include electrical and system efficiencies of the systems and the lifetime (durability) of the systems in the field.

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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 5-year cooperative agreement with the U.S. Department of Energy's (DOE's) Fuel Cell Program, will provide an independent assessment of fuel cell manufacturing costs at various volumes and appropriate system designs for the market analyzed. This report provides cost estimates for the manufacture of 1-, 5-, 10-, and 25-kilowatt (kW) fuel cell systems for combined heat and power (CHP) and primary power applications. Both polymer electrolyte membrane (PEM) fuel cell stacks and solid oxide fuel cell (SOFC) 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 system design and manufacturing approaches were defined based on Battelle's fuel cell system integration expertise and were refined through discussion with industry partners. The report presents our representative designs for both SOFC and PEM systems, including the basic sizing and configuration design assumptions. Key components of the example designs were evaluated using manufacturing processes modeled with the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA®) software. Costs of the system, subsystem, and specific components were calculated 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 and of those components whose included cost is less certain. A discussion of possible opportunities for cost reduction is included.

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2. Approach

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

Step 1—Market Assessment

Step 2—System Design

Step 3—Cost Modeling

Step 4—Sensitivity Analysis/Life Cycle Cost Analysis

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

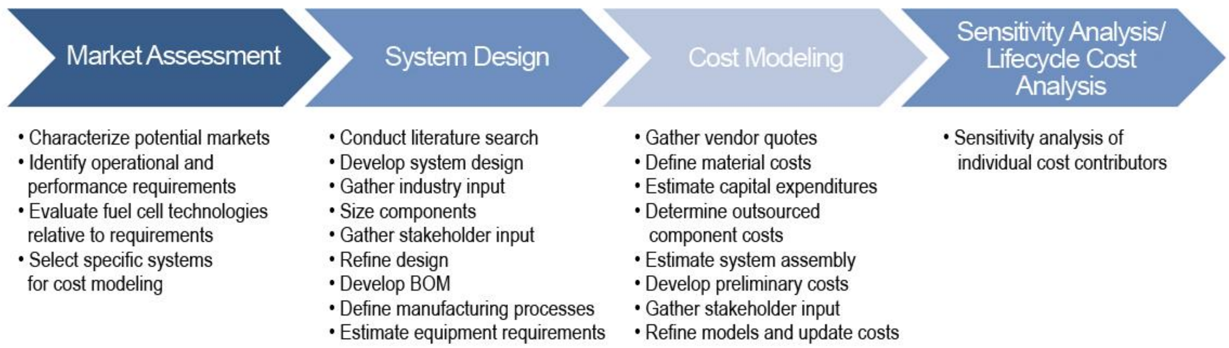

Figure 2-1. Battelle's cost analysis approach

The first step in our methodology, ***Market Assessment***, ensures that we have selected the right fuel cell type and appropriate production volumes to meet market requirements. In this step, Battelle identified the operational and performance requirements (e.g., hours of operation, frequency, expected lifetime) of the target application and market. Using this information, we assessed the user requirements for a fuel cell product. For this phase, Battelle, working with industry professionals, completed a quick survey of the market to estimate the number of units in the market and the expected market growth for fuel cells in CHP and primary power applications in the 1- to 25-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 CHP and primary power applications, including component design and manufacturing processes. Possible improvements in system design and manufacturing were identified and incorporated into the example systems. From these results, the basic construction and operational parameters for a fuel cell stack and system were defined, along with potential improvements. A ChemCad® model of each system was generated to assist with sizing of components and ensure that both mass and energy balances were closed. The fuel cell system design did not focus on an individual manufacturer's designs, but instead was representative of typical design based on literature and Battelle's engineering expertise. The stack and system designs were vetted with industry stakeholders to ensure their feasibility, identify possible improvements, and determine

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[1] Battelle. 2011. The High Volume Manufacture Cost Analysis of 5 kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Backup Power Applications. DOE Contract No. DE-FC36GO13110.

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

current and alternate manufacturing approaches. The finalized design and projected improvements were consolidated to form the basis for developing the bill of materials (BOM). Decisions were then made, based on machine utilization rates, about which components would be manufactured internally and which would be outsourced. For 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 reflective of annual production volumes 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 and of energy and labor requirements for individual steps that comprise the custom process. The sequence of actions required to assemble the components and test the final fuel cell system was developed and analyzed for cost reduction opportunities through component consolidation and process optimization. Manufacturing quality control requirements were based on input from equipment vendors and Battelle’s experience with product manufacturing. Outsourced components costs were estimated through vendor quotes. Mathematic functions for scaling factors were developed to estimate the changes to outsourced components and material costs with production volumes when vendor quotes for higher volumes were not available. These estimates were derived using engineering rules of thumb and estimates from other manufacturing processes and considered impacts on system design.

Using the DFMA® software, component costs calculated from both custom and library manufacturing processes and the outsourced components were incorporated into the assembly and test sequence models to determine the final cost of producing the fuel cell systems. The output of the DFMA® models was also used to calculate production station utilization. The calculated value determined the number of individual process lines required to support various product demand levels. The manufacturing capital cost model is 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 stack 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-26.

The ***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 analysis was 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.

3. Market Analysis

The small- and micro-scale CHP markets in the United States have grown in the past 10 years. Nationally, over 54% of all CHP installations (including those powered by both fuel cells and traditional hydrocarbon fuels) are under 1 megawatt (MW) (Figure 3-1).[3] Fuel cell installations make up approximately 3% of all CHP installations and less than 0.1% of all energy (megawatts) provided by CHP systems (Figure 3-2 and Figure 3-3).[3] Over 90% of existing fuel cell CHP systems are installed in three states: California (62% of total installations and 67% of the total installed megawattage), Connecticut (17% of total installations and 15% of the total installed megawattage), and New York (14% of total installations and 12.0% of the total installed megawattage).

According to Grandview Research, small- and micro-scale systems accounted for over 15% of all CHP installations in 2014 and are expected to witness significant growth rates of over 8% from 2015 to 2022. Reciprocating engines accounted for 54% of the total installations, followed by turbine and microturbine with 26% and 9% of total installations, respectively.[3] The micro-scale CHP market is very young, especially for 30-kW systems and smaller. Only 126 units had been installed between 2000 and 2015. Since 2004, a total of 26 fuel cell CHP units had been installed.

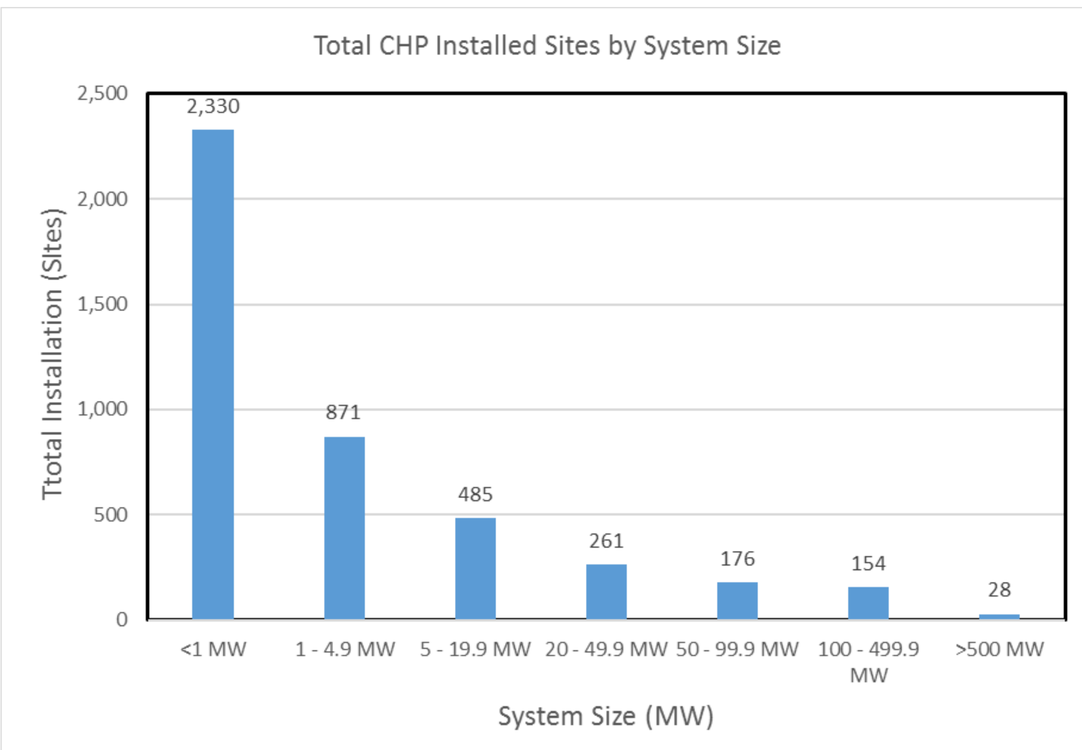

Figure 3-1. Total CHP installed sites by system size

[3] U.S. DOE Combined Heat and Power Database. Accessed December 2016. https://doe.icfwebservices.com/chpdb/about

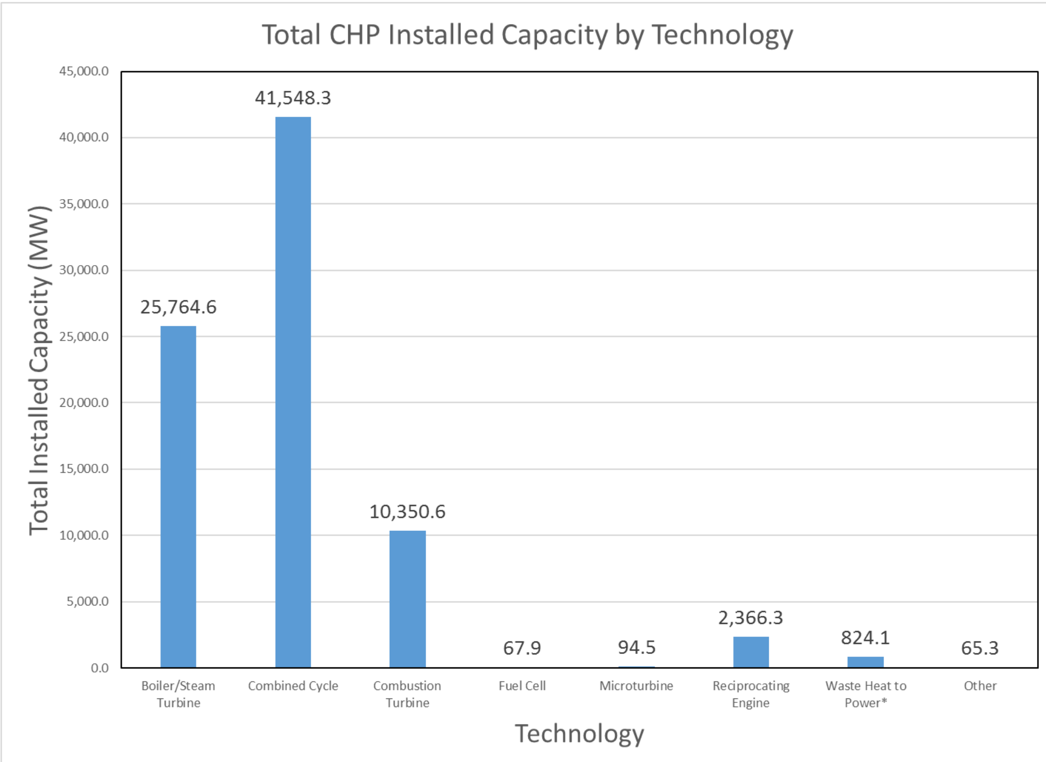

Figure 3-2. Total CHP installed capacity by technology

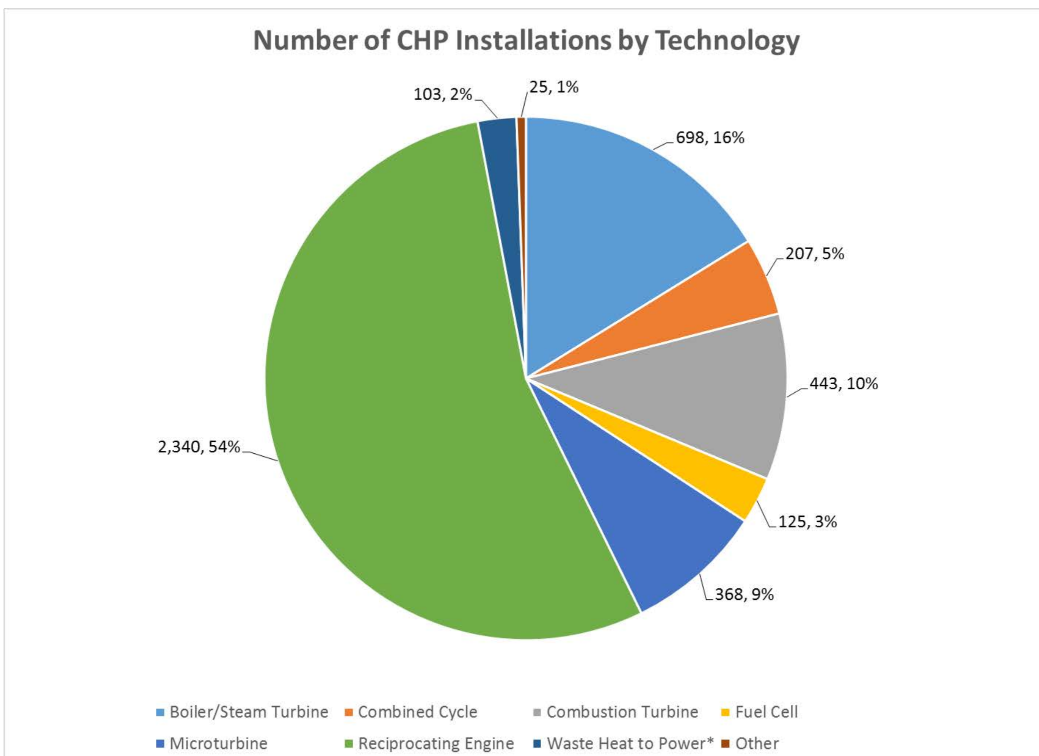

Figure 3-3. Current number of CHP installations by technology

3.1 Market Requirements and Desired Features

Conditions advantageous for CHP systems:

- Significant electrical demand, especially during peak hours.
- Constant heating load.
- Desire for back-up power during grid outage.

Given the nascent fuel cell primary power or CHP market, we drew on our experience providing services to market sectors that could potentially benefit from a high-efficiency CHP system. Although we considered primary power as an option, the economics are more attractive if the rejected heat from the fuel cell system can offset other energy use on site; hence, the focus was primarily on CHP applications. A notable exception for primary power is remote telecom support.

Primary power and CHP applications will use readily available gaseous fuel—primarily pipeline natural gas with some potential use of propane, though the cost benefits are typically less for propane than natural gas. This can be deduced through Figure 3-4, which shows that most fuel cell installations are fueled with natural gas as opposed to biomass or other fuel sources, including propane.[4] To be attractive, particularly for an emerging technology like fuel cells, the savings compared to grid electricity must be significant: anecdotally, equal to or less than a 2-year payback, based on personal communications with the president of a national restaurant chain.

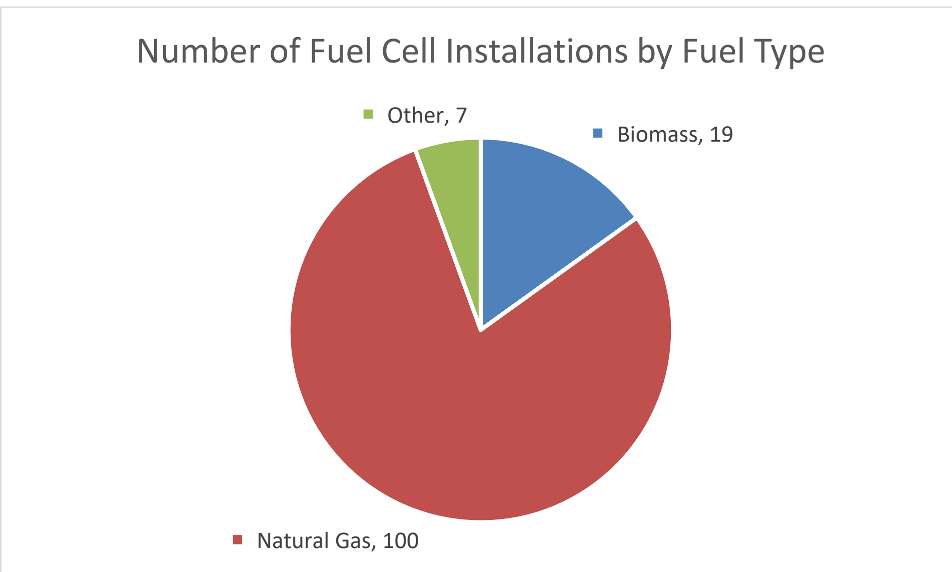

Figure 3-4. Number of fuel cell installations by fuel type

Many of the early installations will likely be at locations with significant heat load that can be served by the heat rejected by the fuel cell system. For example, restaurants and hotels have significant water heating loads with desired water temperatures near 135°F (57°C) for washing applications (hands, dishes, linens, showers). Restaurants are also subject to significant electric demand charges, so offsetting the peaks which naturally occur at meal times can have notable economic benefits. Both PEM and SOFC systems can support the hot water demand at either restaurants or hotels. Typical water heating applications

[4] U.S. DOE Combined Heat and Power Database. Accessed December 2016. https://doe.icfwebservices.com/chpdb/about

include gas-fired storage-type water heaters. For sterilization, a booster heater is typically used to heat water from 135°F (57°C) to 180°F (82°C). An SOFC system could support the higher-temperature water, while a PEM system would provide only the 135°F water. Battelle has access to an extensive database of restaurant utility usage data (natural gas, electricity, water) through past commercial projects and personal contacts. These data allowed Battelle to imagine an attractive product for restaurant applications which would potentially translate to hotel and other applications. Fuel cell-based CHP systems may also be attractive in regions which have strict emission standards. Discussions with a combustion-based CHP company indicate that emission standards may prevent combustion-based CHP systems from being installed in regions with strict emission standards such as California. Fuel cell-based systems are expected to offer advantages over combustion-based CHP systems in these applications.

A significant consideration for CHP and primary power systems is the nature of the utility grid connection. Some CHP installations are connected to the grid to primarily provide heat and partially offset base power but depend on the grid for transient management and starting. If the grid goes down, so do these systems. In discussions with some potential end users, we found that back-up operation during grid outage is considered to be a significant benefit. This seems to be a basis for at least some Bloom Energy installations. We believe this benefit is particularly relevant for restaurants and grocery stores (refrigeration), hotels (emergency egress/elevators, restaurant refrigeration), light commercial/industrial (critical process continuation), and residential (refrigeration, sump pump, space heating, medical equipment), even if all business/normal operations cannot be continued during the outage. Grid connection and operation during grid outage asserts significant influence on system design. With the grid available, the fuel cell system can be operated at steady-state power appropriate for the application. When the grid is not available, a back-up power system must effectively follow applied load and respond to transients (for example, refrigeration compressor operation), thus requiring appropriate electrical energy storage (typically batteries).

3.2 Technology Selection

Three fuel cell technology operations were considered: low-temperature PEM (LTPEM), high-temperature PEM (HTPEM), and SOFC. In discussions with several knowledgeable stakeholders, it became clear that HTPEM was unlikely to achieve reasonable lifetimes and certainly not the necessary 40,000-hour life. Although a few companies remain committed to HTPEM, BASF has discontinued commercial production of the polybenzimidazole (PBI) membrane material, and future commercial deployment in the CHP market is unlikely. Therefore, this otherwise attractive technology was not actively considered for this project.

SOFC and PEM systems have different operating characteristics and may therefore serve different segments of the CHP/primary power market. SOFC systems will be less expensive than PEM because PEM systems require reformate clean-up hardware and somewhat higher use of precious metals. However, where off-grid operation is expected to occur with some frequency, the relatively slow load-following capability of SOFC may result in a higher cost for energy storage to allow transient management. LTPEM stack technology is relatively mature and will benefit from future cost reductions achieved by the automotive industry, though the durability requirements are much higher for CHP, so automotive cost targets are not relevant to CHP. LTPEM is well suited to load management in off-grid conditions; however, transients are not as fast for a reformer-based system as for a stored hydrogen system, so additional energy storage in the form of lead acid batteries is required. The demonstrated durability of PEM systems is approaching 40,000 hours. SOFC durability lags but may eventually reach the same level.

LTPEM stacks will typically be operated at 60°C to 70°C for long life and are appropriate only for low-temperature CHP. However, in a reformer-based system, some heat is recovered from intermediate cooling within the fuel processor and from the reformer exhaust enabling delivered temperatures to exceed 70°C. In SOFC CHP systems, delivered temperatures may be higher since the stack operates at over 650°C. Recuperative heat exchangers are typically employed to improve electrical efficiency by reducing uncontrolled heat loss, but temperatures in excess of 200°C should be achievable with SOFC systems.

3.3 Market Analysis Conclusion

Both SOFC and PEM systems have potential applications in the CHP market. Demonstrated durability for PEM stacks is considerably higher than for SOFC, and load following for applications that experience significant load swings is superior. The greater flexibility of PEM will be beneficial for residential, restaurant, and some other applications at the smaller scales where a greater exposure to uncontrolled operating conditions exists. SOFC will ultimately be less expensive, have higher efficiency, and be capable of serving higher-temperature thermal loads. At this point in the development of the CHP/primary power market, there is no reason to down-select to a single technology.

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4. System Specifications

This section provides a general description of the systems selected for analysis. Initial expectations were for three different systems to be considered—one for each fuel cell technology. However, as noted in Section 3, HTPEM technology was determined to be poorly matched to the long-life expectations for CHP. Therefore, only SOFC and LTPEM systems were considered. The systems analyzed represent 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.

4.1 General Description

This report concerns primary power and CHP applications—that is, stationary systems that provide electrical power and may or may not use waste energy to export thermal energy to some form of process or space heating. The systems may be sized to match a specific heat load or a specific electrical load. With few exceptions, either one or both of the loads will be variable, and the variations may or may not be in phase. That is, the heat load may be high when the electrical load is low or vice-versa.

For most applications, there will be some form of "hard-start" electrical hardware such as refrigeration or air conditioning compressors. These devices have very high power demand for a short period as the system is coming up to speed. Inrush current can be 6 to 10 times the normal run current. The duration may only be a few cycles (alternating current [AC] power assumed) to a few seconds, but the power must be available. If the voltage decreases due to the heavy current draw, the high-load period may be extended due to slower motor spin-up. For a grid-connected system, these transients are not applied to the fuel cell but are handled by the grid. An opposite condition arises if a heavy load is turned off: the sudden drop in current may cause a sharp increase in voltage. With the grid available, the voltage is largely absorbed by the grid.

A key assumption for the systems evaluated in this study is that the utility grid is available; therefore, the fuel cell system is offsetting grid power and, in some cases, excess power generated may be exported onto the grid. This allows the fuel cell system to be operated to meet a specific heat demand or to be operated at an optimum condition for offsetting grid power at the owner's discretion. However, a key benefit to a fuel cell CHP system is continued operation of at least critical loads during periods of grid outage. This benefit may be particularly important for some industries; in fact, for industries such as grocery stores, food and health service locations, and critical industrial operations, it may be the primary reason for the purchase of a CHP system. Therefore, the designs considered include features to enable off-grid operation—most importantly, battery support for transient loads and load management.

During a grid outage, the primary objective is to meet the critical load (heat and/or power); efficiency is somewhat less important. Since grid outages in the United States occur infrequently and typically have durations less than 1 week, our system designs favor lower first cost over high efficiency during outages. We did not include capability for black start—that is, off-grid starting from a cold condition—as the CHP systems are intended for near continuous operation. CHP systems would therefore be expected to be in operation when a grid outage occurs. Transient loads which change more quickly than the fuel cell system can respond are handled by the electrical grid during normal operation, and by batteries when the grid is unavailable. Non-critical loads are shed when the grid is unavailable, with the fuel cell covering only the most critical circuits.

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, and Table 4-3 provides details on the fuel cell stack design for the SOFC systems. Table 4-1, Table 4-2, and Table 4-3 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. Nominal Design Basis

Metric/Feature	Objective
Input, Fuel	Utility Natural Gas or Propane
	(>30 psig preferred)
Input, Air	Ambient air (-20° to 50°C)
Input, Other	N/A
Output	120/240 VAC
	480 VAC 3-phase optional
Net Power Output (AC)	1, 5, 10, 25 kW
System Efficiency, LHV (electrical)	
LTPEM	30%
SOFC	40%
System Efficiency Overall	
LTPEM	80%
SOFC	90%
System Life	50,000 hrs
System Maintenance Interval (filter change: sulfur trap, air filter, fuel filter)	1 yr
Grid Connection	Yes, local and/or utility
Operate off-grid	Yes, critical load back-up
Start off-grid	No

Table 4-2. PEM System Design Parameters

Parameter	1 kW	5 kW	10 kW	25 kW
Power Density (W/cm^2)	0.27			
Current Density (A/cm^2)	0.4			
Cell Voltage (VDC)	0.68			
Active Area Per Cell (cm^2)	200		400	
Net Power (kW)	1	5	10	25
Gross Power (kW)	1.2	6	12	30
Number of Cells (#)	22	110	110	276
Full Load Stack Voltage (VDC)	15	75	75	188
Membrane Base Material	PFSA, 0.2 mm thick, PTFE reinforced			
Catalyst Loading	0.4 mg Pt/cm^2 (total) Cathode is 2:1 relative to Anode			
Catalyst Application	Catalyst ink prepared, slot die coating deposition, heat dried, decal transfer			
Gas Diffusion Layer (GDL) Base Material	Carbon paper 0.2 mm thick			
GDL Construction	Carbon paper dip-coated with PTFE for water management			
Membrane Electrode Assembly (MEA) Construction	Hot press and die cut			
Seals	1 mm silicone, infection molded			
Stack Assembly	Hand assembled, tie rods			
Bipolar Plates	Graphite composite, compression molded			
End Plates	Die cast and machined A356 aluminum			

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

Table 4-3. SOFC System Design Parameters

Parameter	1 kW	5 kW	10 kW	25 kW
Cell Power Density (W/cm^2)	0.32			
Cell Current Density (A/cm^2)	0.4			
Cell Voltage (VDC)	0.7			
Active Area Per Cell (cm^2)	200	200	400	400
Rated Net Power (kW, continuous)	1	5	10	25
Rated Gross Power (kW, continuous)	1.2	6	12	30
Number of Cells (#)	21	107	107	268
Open Circuit Voltage (VDC)	24	118	118	295
Full Load Stack Voltage (VDC)	15	75	75	188
Cell Design	Planar, Anode supported			
Anode Material	Ni-8YSZ, 250 µm thick			
Anode Application	Tape cast, kiln fire			
Anode Active Layer Material	NI-YSZ, 15 µm thick			
Anode Active Layer Application	Screen Print, kiln fire			
Anode Contact Layer Material	NI-YSZ, 10 µm thick			
Anode Contact Layer Application	Screen Print, kiln fire			
Electrolyte Material	8YSZ, 8 µm thick			
Electrolyte Application	Screen print, kiln fire			
Cathode Active Layer Material	YSZ/LSM, 5µm thick			
Cathode Active Layer Application	Screen Print, kiln fire			
Cathode Material	LSCF, 30 µm thick			
Cathode Application	Screen Print, kiln fire			
Cathode Contact Layer Material	LSM/YSZ, 10 µm thick			
Cathode Contact Layer Application	Screen Print, kiln fire			
Seals	Wet application bonded glass/ceramic			
Stack Assembly	Hand Assembled, tie rods, furnace brazed			
Interconnects	Ferritic Stainless Steel (SS-441) with Perovskite coating, 2-3 µm thick			
End Plates	Die Cast and Machined A560 Steel			

4.3 System Sizing and Operation

Grid outage conditions apply some constraints on system size and design. For our analysis, we assumed that the CHP system has a 2:1 turndown ratio for both heat and power. If the grid does not provide additional power or accept excess power, the fuel cell system must be sized to cover critical loads but not over-power the on-site electrical system when power usage drops.

Figure 4-1 shows a notional load curve (red) along with horizontal lines representing the peak, minimum, and critical loads. Critical loads are safety- or process-critical loads (e.g., elevator power and stairwell/exit lighting for commercial, sump-pump and refrigerator power for residential) that should be available at all times, though they may not be continuous.

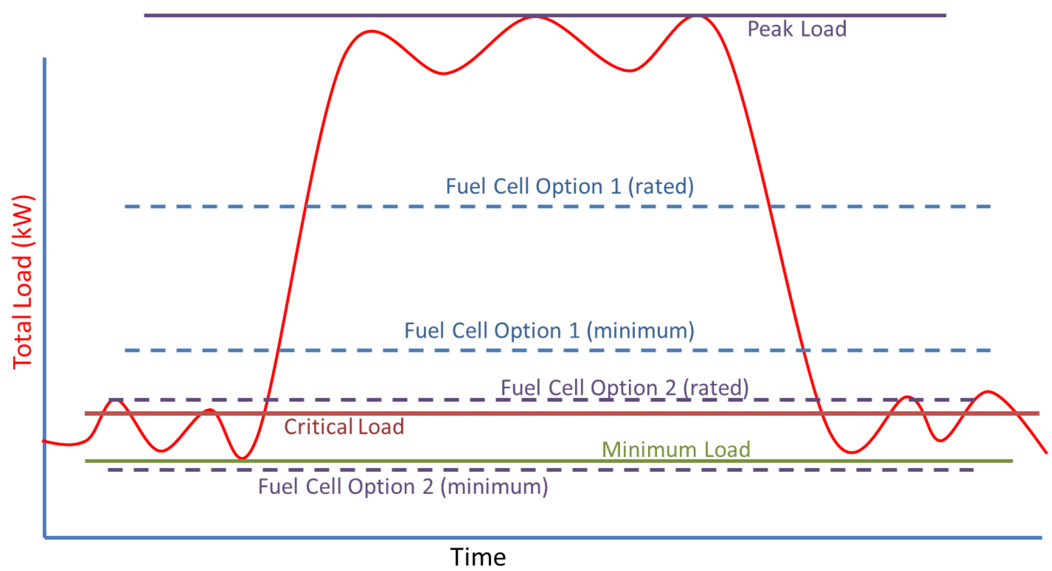


Figure 4-1. Notional load curve for illustration

As shown in Figure 4-1, the critical load is shown above the red load curve for a significant portion of the time, representing loads such as refrigeration which operate intermittently but which must be available when needed. The illustrated load curve does not include transient (surge) power required for compressor starting or voltage spikes caused by switch opening to turn off high-power loads. Those issues are addressed separately.

With the grid available and power export allowed, the fuel cell system may be sized to meet either the heat load or some selected fraction of the total electrical load. So long as the grid is available, the fuel cell is assumed to be operated continuously and at steady load, with the grid providing any load power beyond the fuel cell rating and absorbing any excess power generated. Two options for fuel cell sizing are illustrated in Figure 4-1. Both options are shown at rated power and at minimum power (approximately 50% turndown):

- Option 1 is sized to cover a significant portion of the total load during the high-load portion of the day.
- Option 2 is sized so that the power at fuel cell minimum is less than the minimum load expected for the system.

In Figure 4-1, purchased power is represented by the area under the load curve and above the fuel cell rated power. Any demand charge would be based on the maximum difference between load curve and fuel cell power. Option 1 would clearly make a significant change in both purchased power and demand charges. When the fuel cell power is above the load curve, power is assumed to be exported to the grid. The fuel cell power might be reduced to minimum during low-load conditions unless an attractive power purchase arrangement is in place with the utility for those times. If the grid is not available (during a grid outage or if power exporting is not allowed), the difference between the minimum fuel cell output power and load must be rejected to ambient in some way (e.g., an air-cooled resistor bank). As illustrated in Figure 4-1, under Option 1, significant power must be rejected or returned to the grid during a significant portion of the day even at minimum power. For occasional grid outages, the excess power wasted might represent an acceptable cost of maintaining operation and reducing demand/power charges over the remainder of the year. When grid export is disallowed by regulation or when no utility agreement is in place, the “wasted” energy represents a significant and likely unacceptable cost.

Option 2 offsets significantly less of the overall load for the profile in Figure 4-1 but still maintains sufficient power to handle the critical loads continuously. In fact, as shown it may be larger than needed to cover the critical loads since some of the intermittent load might be addressed with energy storage (e.g., batteries, which are required to manage start/stop transients for off-grid operation). As illustrated, the minimum fuel cell power level is below the overall minimum load power—an intentional design choice. Thus, it should not be necessary to export or dump power at any time under this configuration, and the cost of power export hardware or power dump hardware can be avoided. For applications in which the difference between peak load and minimum load is much less significant than illustrated, Option 2 may be very attractive because it will offset a greater portion of the average load without requiring power export or dump while still maintaining the ability to operate critical loads during grid outage. Applications with near-constant heat or power load are well suited to the Option 2 approach.

Since the sizing is typically specific to the load profile of the application, we assume that a nominal resistor bank will be provided (and included in the cost of installation) for most applications to allow sizing based on normal, grid-available operation.

4.4 System Configuration

Figure 4-2 is a high-level schematic of a CHP fuel cell system. The fuel of choice for CHP applications is natural gas. For residential units (1 kW and 5 kW), gas supply pressure is assumed to be 2 pounds per square inch gauge (psig) at the meter. For commercial units, available natural gas pressure is assumed to be 30 psig or greater. An auxiliary natural gas compressor is required if the supply pressure is less than 10 psig for the PEM system and less than 30 psig for the SOFC system. Propane is an acceptable fuel, although some modifications to the system may be required to accommodate propane. Generally, propane will be available at 30 psig or greater from the tank.

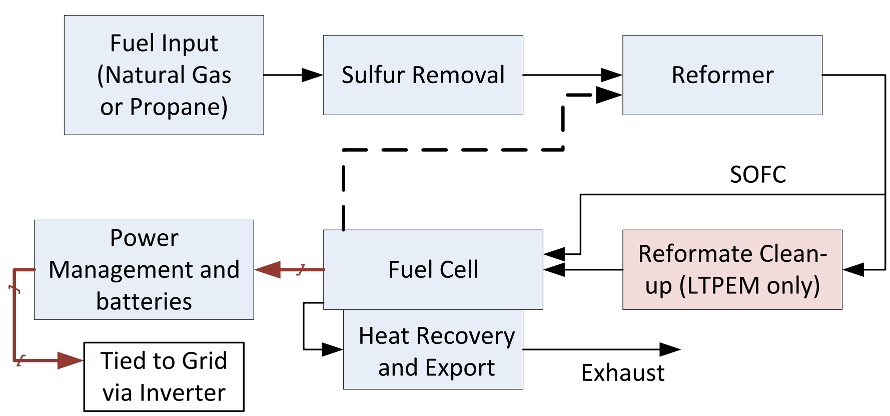


Figure 4-2. High-level fuel cell system schematic

Both propane and natural gas will contain generally low levels of mercaptan odorant, a sulfur-bearing compound. However, even low levels of sulfur are damaging to catalyst in the reformer and/or fuel cell, so sulfur removal is included in all systems considered.

The SOFC and LTPEM systems share significant hardware, particularly in the BOP. The key differentiating factor is the composition of the anode inlet stream. LTPEM systems prefer pure hydrogen. However, some LTPEM stacks can be designed to operate on reformate so long as the carbon monoxide (CO) content of the gas is low (less than 50 parts per million). We have based our systems on reformate-capable LTPEM stacks in order to avoid the high cost of hydrogen purification. SOFC stacks can accommodate percentage levels of CO and methane (CH_4) in the reformate, so they require minimal reformate clean-up and tolerate less effective reforming so long as the higher hydrocarbons that may be present in natural gas are reformed to methane. Excess methane and/or percent levels of higher hydrocarbons in the reformate reaching the stack can lead to carbon deposition on the stack anode, capacity loss, and eventual failure.

As indicated by the dashed line in Figure 4-2, the anode and/or cathode exhaust from the fuel cell (SOFC or PEM system) may be routed to the reformer for energy and water recovery. While both systems use steam reforming in order to achieve high efficiency, the details of how the fuel cell exhaust energy is recovered differ significantly. Water produced appears primarily on the cathode side for the LTPEM system and on the anode side for the SOFC system. For the SOFC system, some of the anode exhaust is directed to the reformer, where the water content (as steam) directly interacts with the input fuel to achieve steam reforming. For efficient operation of PEM systems, particularly open anode (once-through anode) systems, the residual heating value in the anode effluent is recovered by combusting the gas in a separate burner to heat the reformer. Water is condensed from the combustion and cathode exhausts and revaporized for use in the reformer. The energy required to vaporize the water for LTPEM systems is a factor in their lower overall efficiency compared to SOFC systems.

Other features of the overall system configuration that differentiate SOFC systems from LTPEM systems are discussed in Sections 4.4.1 and 4.4.2.

4.4.1 LTPEM System

A schematic of the LTPEM system configuration used for this costing study is shown in Figure 4-3. The major subassemblies are:

- Fuel supply: a natural gas compressor, fuel filter, and sulfur sorption reactor.
- Fuel processor: steam generator, reformer, and reformate CO removal reactors along with several heat exchangers. All these components are typically hot, albeit at different temperatures; integrating them reduces heat loss and improves system efficiency.
- Air supply: filter, three blowers (combustion, preferential oxidation [PrOx], and cathode), and recuperative cathode humidifier.
- Cooling and heat export system: several heat exchangers operating on low-electrical-conductivity water/glycol coolant and a CHP load heat exchanger that couples the fuel cell coolant system to the external thermal (heat) load. The heating load is assumed to be independent of the fuel cell system—that is, the fuel cell system cannot adjust the external heat load, it can only respond to it. A radiator is included in the system design to shed excess heat should a heat load not be available.
- Electrical system: batteries, overall controls, and voltage/current management. The electrical system also includes the grid connection electronics (inverter and any required physical disconnects). Additional detail, including a schematic of the electrical subsystem, is provided in Section 4.5. The electrical system is essentially identical for both LTPEM and SOFC systems.

As shown in Figure 4-3, fuel enters the system through a compressor (if required) and passes immediately through a sulfur sorption trap to remove mercaptan odorant and any other sulfur compounds present. The sulfur sorbent is considered disposable and, if space permits, would typically be designed for a 1- or 2-year replacement cycle based on local conditions of sulfur in the gas. For start-up, desulfurized fuel is routed directly to the reformer burner and combusted to preheat the reformer and steam generator (vaporizer) directly. Once combustion gas temperature at the vaporizer is adequate (~150°C), water is started and the system is preheated by flowing steam through the downstream reactors. Once the system is adequately preheated, fuel is diverted from the start-up burner and mixed with hot steam before being routed to the reformer. Leaving the reformer, the reformate is cooled by steam from the vaporizer to approximately 350°C before entering the shift reactor. A water-cooled heat exchanger reduces the reformate temperature before the PrOx reactor to less than 200°C (typical, depending on PrOx catalyst requirements). The shift and PrOx reactors are packaged with the reformer to minimize heat loss. Reformate leaving the PrOx reactor is cooled to stack operating temperature, typically ~60°C.

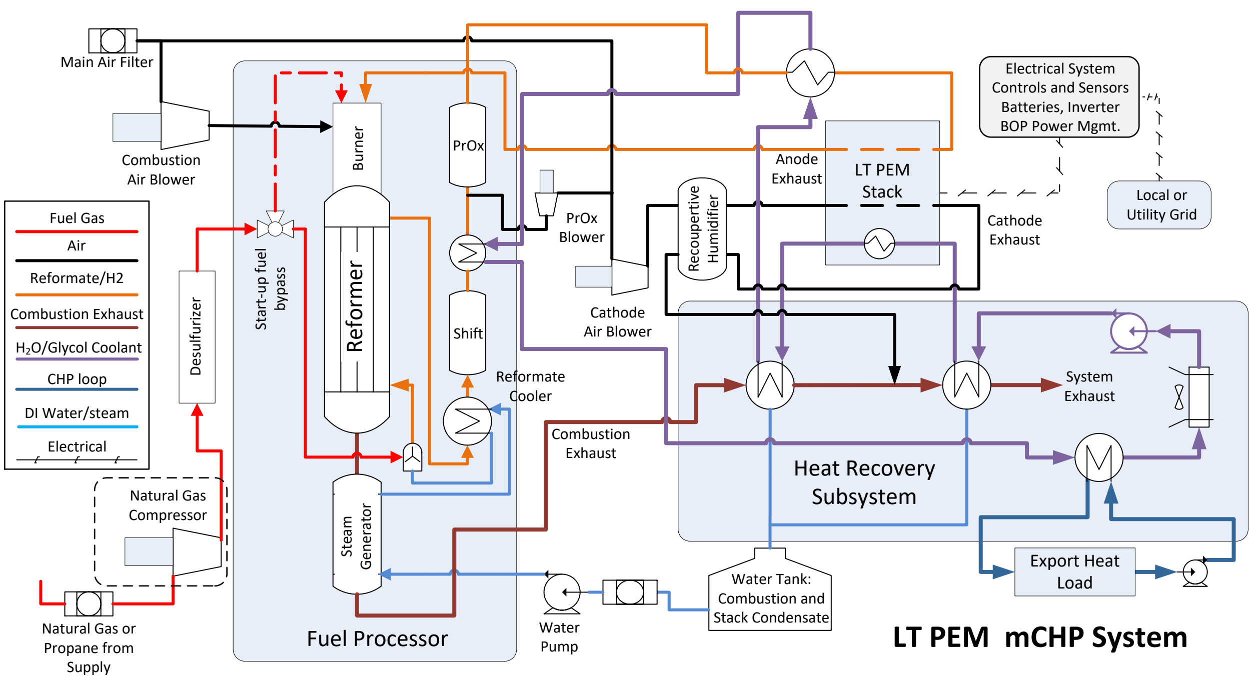


Figure 4-3. Representative LTPEM CHP system

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. Anode exhaust is routed to the reformer burner. Stack fuel utilization is adjusted to balance the system so that the anode exhaust has sufficient energy content to support reforming.

A low-electrical-conductivity glycol/water mixture is used to cool the PEM stack. Coolant should enter the stack at about 50°C. As shown in Figure 4-3, coolant leaving the circulating pump is preheated slightly by the final combustion exhaust. This preheating serves to condense some residual water out of the combustion exhaust for reuse in the system. After the stack, the glycol coolant is directed to the initial combustion gas condenser, where the coolant temperature is increased above the stack operating temperature by combustion gases and the initial condensation of water from the combustion exhaust occurs. Following the initial condenser, the coolant is routed to the pre-stack reformate cooler, then to a heat exchanger between the shift and PrOx reactors. This somewhat arbitrary heat exchanger sequence was developed based on a simplified ChemCad® model of the PEM system that allowed several heating and cooling scenarios to be considered. Of the systems evaluated, this configuration provided the highest temperature coolant to the CHP system. The PEM system is equipped with a radiator on the stack coolant loop to reject any heat not absorbed by the CHP system. Since the coolant loop is required to maintain system temperatures, especially the stack temperature, the radiator must be sized to reject all heat from the system if a CHP thermal load is not present. A smaller radiator might be specified for systems with known continuous CHP load. Because the coolant to the export heat exchanger is projected to be less than 90°C, it is not necessary to bypass the export heat exchanger if little or no CHP load is present. All heat exchangers are assumed to be counter-flow heat exchangers (typically either tube-in-tube or plate-frame type) with the exception of the radiator, which is automotive-style cross-flow.

4.4.2 SOFC System

A schematic of the SOFC system used in our cost analysis is shown in Figure 4-4. The major subassemblies are:

- Fuel supply: a natural gas compressor, fuel filter, and sulfur sorption reactor. Because the SOFC system uses an eductor for anode gas recirculation, natural gas pressure must be 30 psig or greater for all systems.
- Fuel processor: natural gas/anode recirculation eductor/mixer, preheater/reformer, and tail gas combustor.
- Air supply: filter and two blowers (start-up and cathode) and recuperative cathode preheater.
- Heat export system: an exhaust gas to CHP heat exchanger and a bypass valve combination to manage the heat delivered to the CHP system. The heating load is assumed to be independent of the fuel cell system—that is, the fuel cell system cannot adjust the external heat load, it can only respond to it. Therefore, the valve system allows high-temperature exhaust gas to be diverted away from the CHP system if required.
- Electrical system: batteries, overall controls, and voltage/current management. The electrical system also includes the grid connection electronics (inverter and any required physical disconnects.) Additional detail, including a schematic of the electrical subsystem, is included in Section 4.5. The electrical system is essentially identical for both LTPEM and SOFC systems.

The schematic of Figure 4-4 is notably simpler than Figure 4-3:

- No shift or PrOx reactors are required, and no PrOx blower or PrOx heat exchanger is needed.
- No recuperative humidifier is required.
- No steam generator is required.
- No special glycol cooling loop is required.
- Several heat exchangers are not needed.
- No water supply subsystem is required.

The relative simplicity of an SOFC system is attractive from a cost perspective. The higher-quality heat also facilitates SOFC system use in a broader range of applications.

As shown in Figure 4-4, the fuel is first passed through an absorber identical to the one used for the LTPEM system to remove sulfur; however, due to the higher efficiency of the SOFC system (10% over PEM) the absorber will have an extended service life. Fuel may be routed directly to the tail combustor for start-up, where it is burned with cathode air to preheat the cathode indirectly via the cathode recuperative heat exchanger. As the stack warms above 100°C, the fuel is shifted to the preheater/reformer, where it is burned in catalytic partial oxidation (CPOx) mode to continue heating from both the anode and cathode sides of the stack. Combustion is completed in the tail gas burner for indirect preheating on the cathode. Careful control of flow rates and burner temperatures is necessary to heat the stack uniformly. When fuel is initially routed to the preheater/reformer, anode exit gas begins recirculating to mix with the fuel. Initial recirculation will be limited because the fuel flow for start-up will be significantly lower than for final operation, causing the aspirator used to operate significantly off-design.

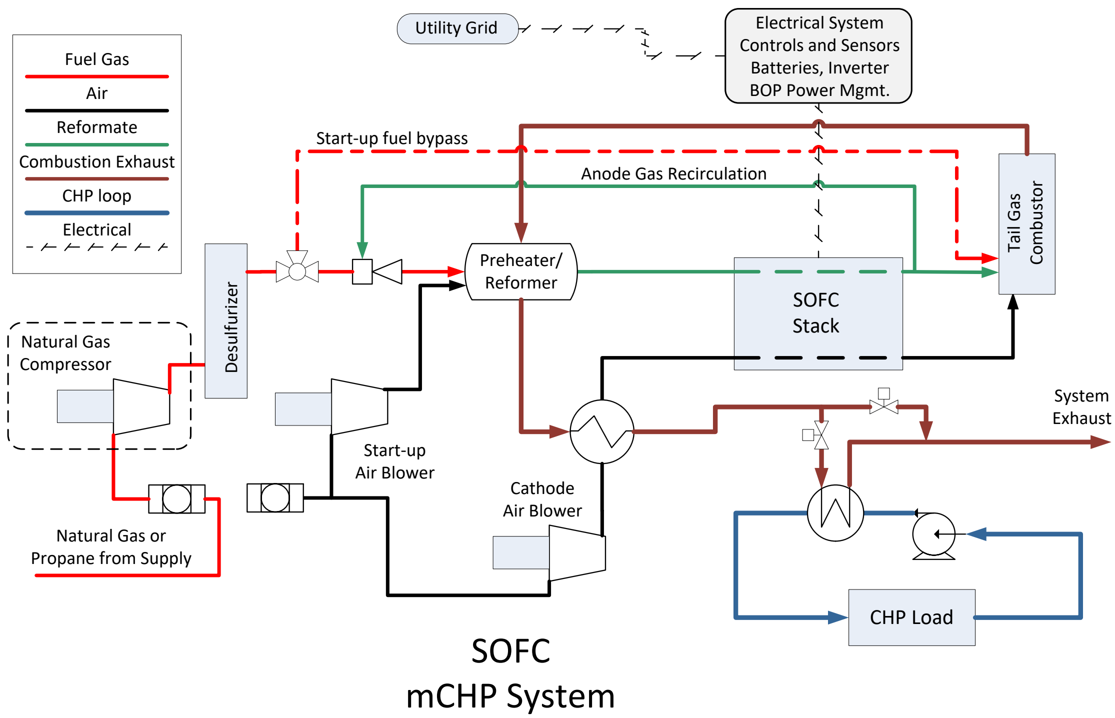


Figure 4-4. Representative SOFC CHP system

As the stack heats and fuel can be increased, more anode recirculation will occur. Current draw can begin at a stack temperature determined by the manufacturer. The start-up blower will be reduced and eventually turned off to shift the reformer into steam reforming mode using water in the recirculated anode for reforming and heat from the tail gas burner to support the endothermic reaction. Once the stack reaches operating temperature, full power may be drawn from the stack. Stack and other system temperatures are managed by fuel and cathode air flow. Anode recirculation is passive and depends on the design of the aspirator. There is a potential for limiting the available stack turndown if insufficient steam is recirculated to support reforming. In developing our system performance estimates, we assume that the aspirator will be sized for approximately 50% load, with the higher fraction of recirculation at full load being generally beneficial. Alternatively, a hot gas blower might be used to provide greater turndown in exchange for additional cost and operating complexity. We did not include this option in our cost estimates.

Residual heat from the cathode is available to the CHP load as soon as the system has warmed sufficiently—typically before actually drawing power from the stack. Unlike the PEM system, the CHP system is not expected to cool the stack. Stack cooling depends primarily on cathode air flow, so additional heat can be directed to the heat load by increasing cathode air flow. To prevent the hot cathode outlet from overheating the CHP system at times of low demand, the system is designed to bypass cathode air directly to exhaust. Therefore, system exhaust may be hot and appropriate safety precautions and exit location requirements must be defined and observed. Routing of the hot exhaust is outside the scope of this study.

The ability of an SOFC system to follow electrical load is somewhat restricted because long-term reliability requires that ramp-rates be limited. Thus, an SOFC system will typically operate at near full load, with the grid either making up any unmet requirement or accepting any excess power. If the grid is not available, the SOFC system will need to keep running at or above its minimum power output, even if the power must be dumped to an air-cooled resistor bank. A hot standby condition is plausible but somewhat difficult for the SOFC system because of the sensitivity of the stack to internal temperature gradients. Generally, the SOFC stack will remain on and above minimum power to provide for critical loads and any other loads that may be within the overall capability of the stack. Generated power in excess of available load will be rejected through an air-cooled resistor bank.

4.5 Electrical System

4.5.1 Overview

The electrical system provides the interface between the fuel cell stack and the local electric utility grid. It also provides auxiliary power (24 volts DC [VDC]) for system components and, when hybridized with batteries, the capability for operation during grid outages. All systems considered in this cost study assume that a utility grid is available and that for normal operation, the fuel cell system will use the grid to manage start-up and load changes. To provide for critical load continuance during grid outage, the systems considered include battery capacity to allow rapid electrical load changes while limiting the speed of the fuel cell system response to achieve stable and reliable long-term operation. The batteries are maintained on trickle charge when the grid is available.

The electrical system schematic (Figure 4-5) expands the simple electrical system boxes shown in Figure 4-3 and Figure 4-4. The primary electrical system components are:

- Direct current/direct current (DC/DC) converter (interface between fuel cell stack and 24- or 48-VDC power bus)
- Direct current/alternating current (DC/AC) inverter (interface between DC bus and AC load)
- Energy storage (batteries [voltage matched to DC bus] and battery management [trickle charge, battery state-of-charge monitor])
- Thermal management (cooling for power electronics)
- Ancillary and protective devices such as fuses and circuit breakers, disconnects, lock-outs, cables, and connectors

Residential-scale grid-tied DC/AC inverters should include the transfer switch. Commercial installations will likely have additional power-generating capability; therefore, any transfer switch or other automatic grid disconnect will be provided outside the fuel cell system. All systems will include an appropriate manual disconnect to protect on-site personnel during maintenance and repair operations.

The assumed electrical system topology shown in Figure 4-5 was selected based on industry feedback and general knowledge of the components and the application. Other topologies are applicable and may be preferred for some applications. The components are sized assuming the fuel cell provides a near-constant net power to the local electrical bus (which may include additional power generation equipment). System parasitic power and battery trickle charge power connections are before the AC inverter. During grid outage, the battery provides the power required in excess of the fuel cell nominal power during load increases and absorbs any excess power generated during the transition from high power to low power. In order to maintain the battery at near full charge, a power dump (e.g., resistive load bank) may be required for rapid load decreases. Although the resistive bank would be application-specific, the cost of a representative resistor bank rated for 50% of nominal load is included in the electrical system costs. During off-grid operation, the peak loads were assumed to be no more than 10 times the maximum output power of the fuel cell with a duration of 5 seconds or less. This requirement sets the battery capacity, and batteries were sized to support this surge at less than 20% discharge.

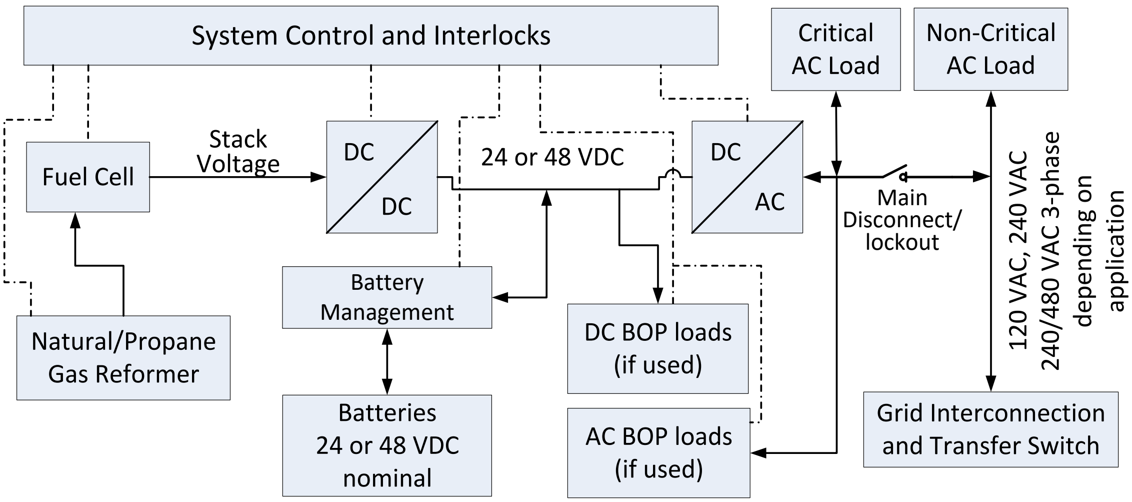


Figure 4-5. Electrical system schematic

The following sections provide more detail on each major component in the electrical system. The electrical systems for the SOFC and PEM systems are identical for this report. In actual practice, the SOFC system may require additional energy storage beyond that required by the PEM system because the PEM system can respond to load changes more quickly than the SOFC system. However, this difference is outweighed by the likely different load profiles associated with any given installation, particularly at the higher-capacity system sizes. Situation-specific battery sizing may be required.

4.5.2 DC/DC Converter

A single DC/DC converter is used to convert the load-variable voltage from the stack to DC bus voltage. The converter must accommodate the relatively wide stack output voltage, which is the input voltage for the converter. The converter is sized for 120% of the nominal output of the system. In a reformer-based system, the DC/DC converter is required to limit stack output power to the available reformate flow. The stack power limit may be determined by the fuel input flow parameters, or a stack voltage monitoring system, or both. The details of the control methodology are beyond the scope of this project. However, it is important to note that an active, rather than passive, converter will be required, thus limiting the available hardware options.

Due to the low stack voltage for the nominal 1-kW system, a 1.2-kW, 24-VDC output step-up (boost) converter is used for the small-scale systems. Step-down (buck) converters are used for the 5-, 10-, and 25-kW systems. Systems 5 kW and greater use a 48-VDC bus and battery assembly. Buck converters are well defined, consist of minimal components, and can be very efficient at high power levels. Hence, they are preferred for high-power applications where stack voltage permits. Both buck and boost topologies are typically non-isolated: high current levels may be achieved by multiple modules in parallel, an approach that may offer some redundancy in critical applications. Single modules that provide all the current are usually the lower-cost option.

Secondary DC/DC converters may be required to power the control electronics and miscellaneous support equipment in the system. The DC bus is assumed to be 24 VDC for the 1-kW system and 48 VDC for the larger systems. The range of equipment available for 24 VDC is generally good, so we have not included a secondary converter for the 1-kW system. Equipment for 48 VDC is less readily available, so we have included a DC/DC 48/24 converter rated for 10% of nominal load for 5-kW and higher systems. As production volumes increase, specialty 48-VDC pumps and blowers will probably be developed and will eliminate the need for this component. The controls will typically include internal DC/DC converters to achieve the tightly regulated voltage required for the sensing electronics and hardware. These “brick” converters, which have a relatively wide input voltage range, are typically included in the cost of the control hardware.

4.5.3 DC/AC Inverter

The fuel cell system will connect to the electrical grid either directly, in the case of residential applications, or potentially indirectly, for commercial and industrial applications where other sources of electrical power may be in operation. In either case, the interface between the DC bus and the AC power is an inverter that must be able to synchronize with the grid and meet utility requirements for safety and power quality.

Commercially available grid-tied inverters are primarily designed for photovoltaic (PV) systems. Generally, these high-input-voltage inverters are not appropriate for fuel cell systems. However, in discussions with several solar inverter manufacturers, we found that they are able to design appropriate inverters to meet the fuel cell requirements and expect that similar costs would apply at production volumes similar to their solar systems.

4.5.4 Energy Storage

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 discharge cycles and achieve acceptable lifetimes when properly managed. Batteries are nominally required only if grid power is not available to manage transients. For most applications, however, a fuel cell power generator is part of an overall plan to continue operation in the event of grid outage. Therefore, batteries are included in all system cost estimates. For cost estimation purposes, the batteries are sized primarily on the basis of expected surge conditions—10 times nominal power for 5 seconds to accommodate compressor or other heavily loaded motor starting power. Without grid power, the batteries must be able to maintain near-full load for a period of several minutes while the fuel processor and fuel cell are brought up to rated capacity. The batteries must also absorb roughly rated load for a period of several minutes if equipment with a high power draw stops suddenly during grid outage to absorb the excess power as the fuel processor ramps down. Generally, the surge requirement defines the required battery capacity.

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 regulates charging rate based on the implied state of charge, dropping to a trickle charge as battery voltage increases. The BMS also limits the minimum terminal voltage difference, tripping the system should battery terminal voltage become too low (indicating excess current draw for the state of charge of the battery).

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 batteries 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 gained through smaller size and weight is not enough to overcome the cost advantage enjoyed by lead acid batteries. 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 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.

4.5.5 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. At low power, inverters and converters are typically air cooled, so the rejected heat is not recoverable for CHP purposes. At higher powers, the power electronics may be air cooled or liquid cooled. If liquid-cooled power electronics are specified, thermal management hardware may be integrated with the main cooling loop and the heat recovered for CHP purposes. Because air-cooled equipment is generally available for the power levels being considered and would be less expensive than developing a separate cooling circuit, we did not include a secondary cooling loop.

4.5.6 Wiring and Ancillary Components

Wiring, connectors, support hardware, and other minor components of the electrical system were addressed as a 5 percentage adder.

5. Manufacturing Cost Analysis

5.1 System Cost Scope

As outlined in Section 4, two different fuel cell technologies with their associated BOP characteristics were considered. Due to the significant differences in stack fabrication and BOP hardware, the two technologies are considered separately in Sections 5.3 and 5.4. In addition to the stack for each technology, Battelle also developed a representative design for the fuel processing hardware and used DFMA® analysis on the reformers and heat exchangers for each system. The electrical system is the same for both systems; therefore, it is costed separately in Section 5.5, then incorporated into the total system costs for both technologies.

5.2 System Cost Approach

The manufacturing cost analysis approach consists of:

- 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 costs were developed from these factors, which were adjusted to the specifics of the system 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 BDI software. The specifics of the manufacturing cost calculations are shown in Appendices A-3 through A-26. The 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-3.

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-10.

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-4. 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 cost	$45/hr
Energy cost	$0.07/kWh
Overall plant efficiency	85%

5.2.2 Machine Costs

The basic machine rate equation used in the analysis is a function of equipment capital costs, labor and energy costs, and utilization. To allow for easy comparison between various cost studies, Battelle followed the machine cost protocols described in James et al. (2014).[5] Appendix A-1 provides details of our machine rate calculations for the various production processes used to manufacture the CHP systems.

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

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

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

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

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

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 its cost on 65% machine utilization overall and 40% markup for profit plus overhead when calculating its 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 the 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 CHP system manufacturing process.

5.3 PEM System Manufacturing Costs

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

5.3.1 PEM Stack Manufacturing Process

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

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

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

- One MEA
- One each cathode and anode bipolar plate
  - The anode and cathode plates are stacked back to back to provide coolant flow channels
- Seals between each item (three each repeat unit)

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

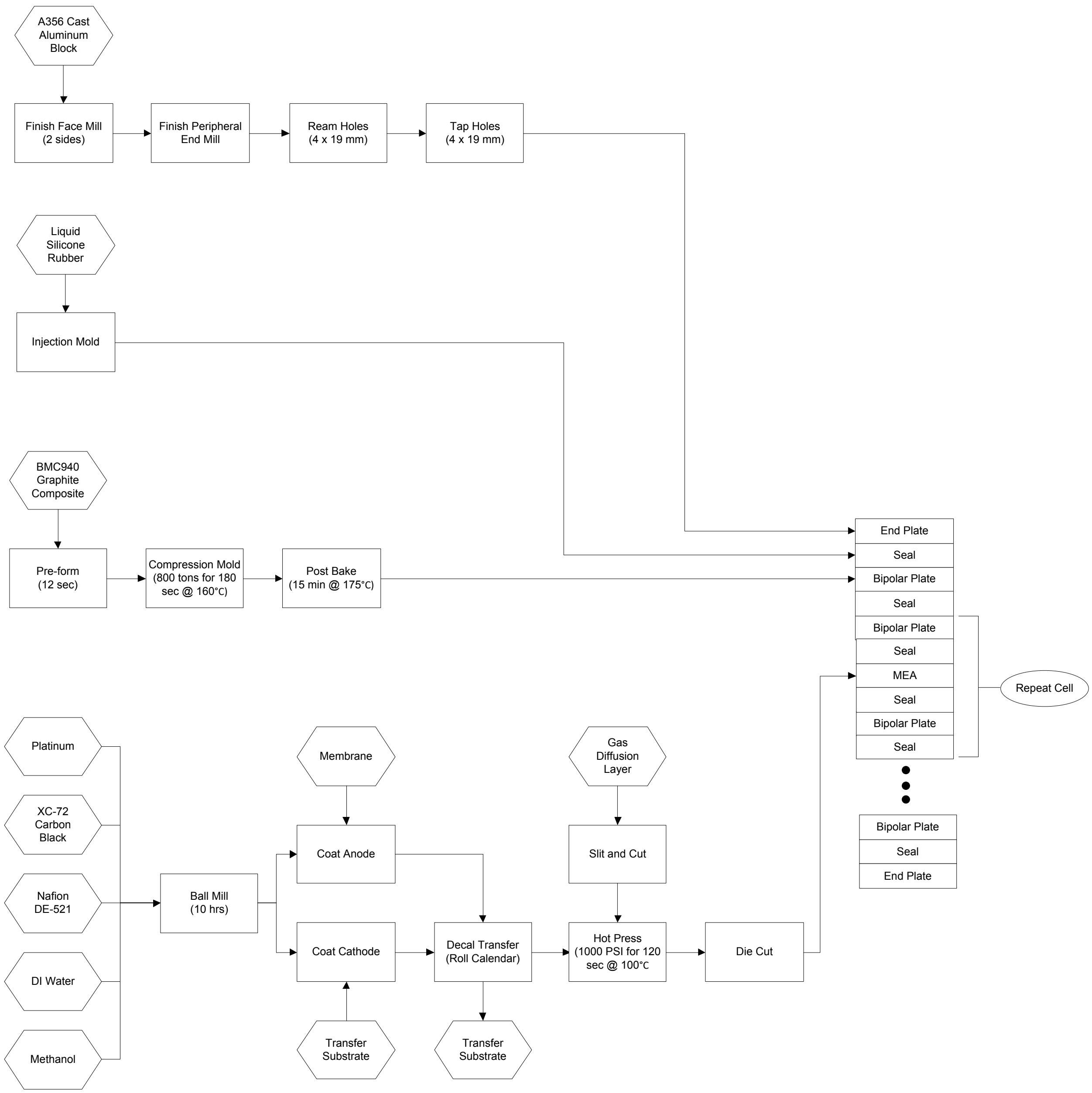


Figure 5-1. PEM fuel cell stack manufacturing process

5.3.1.1 PEM Stack Component Size and MEA Manufacturing Setup

MEAs for both the 1.2- and 6-kW stacks are assumed to have a 200-square-centimeter (cm^2) active area. Using a length-to-width ratio of 1.3, the active cell size was determined to be 125 millimeters (mm) by 160 mm. Using a 30-mm margin on all sides to allow for gas channels and tie rod holes, the overall cell size was determined to be 185 mm by 220 mm.

MEAs for both the 12- and 30-kW stacks are assumed to have a 400-cm^2 active area. The active cell is square with a size of 200 mm by 200 mm. Using a 30-mm margin on all sides to allow for gas channels and tie rod holes, the overall cell size was determined to be 260 mm by 260 mm.

Cell sizes are shown in Figure 5-2 and Figure 5-3.

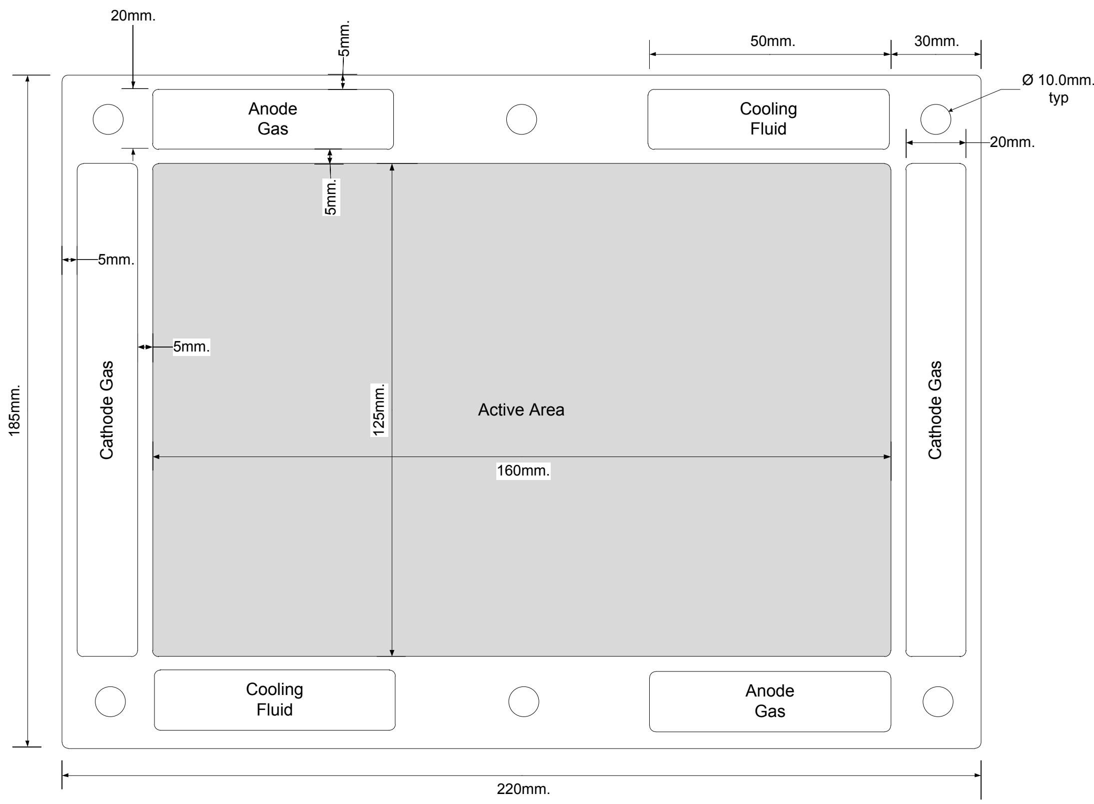


Figure 5-2. PEM system cell size – 200-cm^2 active area

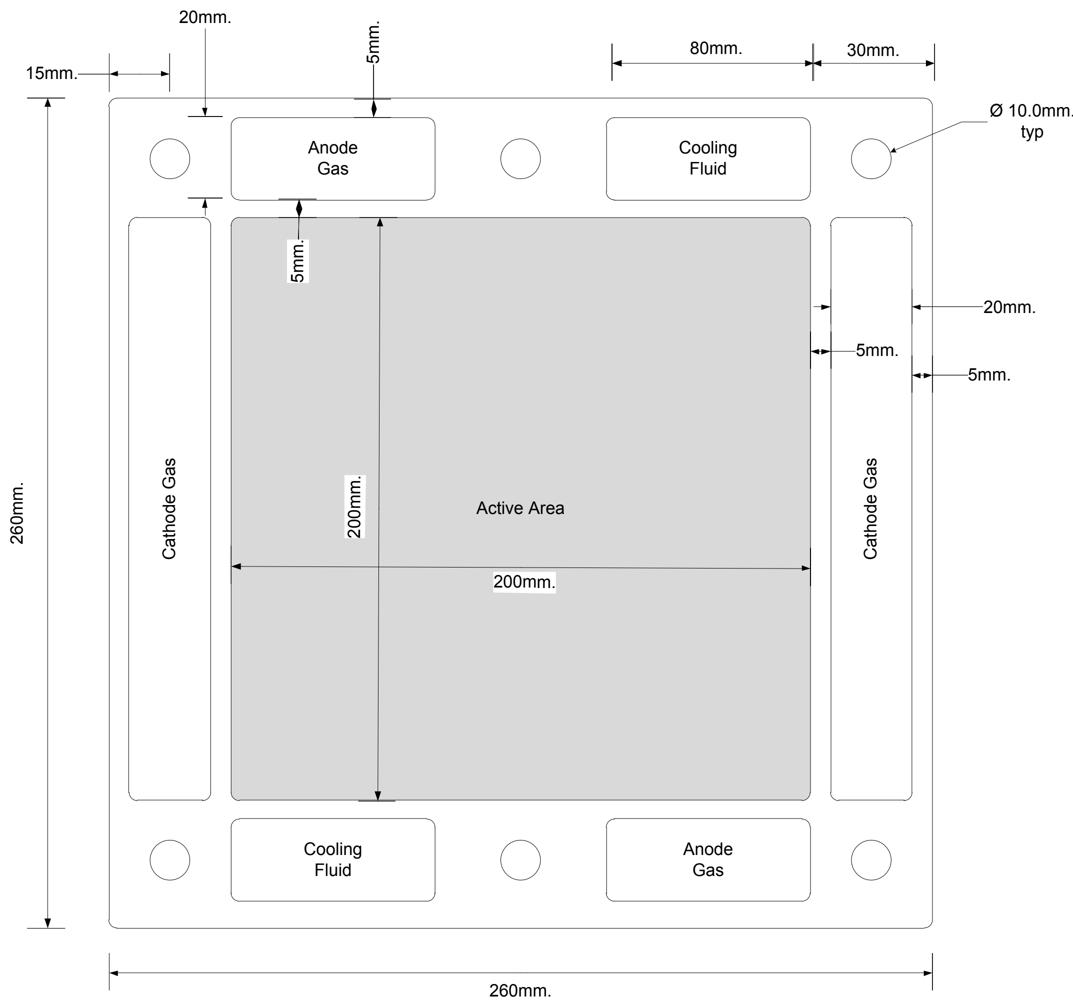


Figure 5-3. PEM system cell size – 400-cm² active area

5.3.1.2 PEM System Membrane Electrode Assembly

The MEA is built up in layers starting with the catalyzed membrane. The components of the catalyst ink are ball-milled into a uniform suspension. The anode layer is selectively slot die coated directly on the hydrated membrane and dried. The cathode layer is selectively slot die coated onto a transfer substrate and dried. The coated membrane and transfer substrate layers are heated and roll pressed, with the transfer substrate peeled away from the cathode layer following pressing. The catalyzed membrane is then hot pressed between two gas diffusion layers (GDLs) and die cut to final cell dimensions. The catalysts and GDLs are applied only to the active area. The die cutting process includes cutouts for the manifolds as shown in Figure 5-2 and Figure 5-3. Details of the analysis are shown in Appendices A-7 and A-8. For all production volumes, the component reject rate was assumed to be 2.5% for catalyst production, 2.5% for catalyst application, 3.0% for decal transfer, 0.5% for hot pressing, and 3.0% for die cutting. A detailed breakdown of material cost by MEA layer is provided in Table 5-2 and Table 5-4. The MEA cost summary is provided in Table 5-3 and Table 5-5.

Although the cells are identical for the 1.2-kW and 6-kW stacks, the higher volume production associated with the 6-kW stacks results in material and labor cost savings. Note that the GDL dominates the cost at low volume, becoming much less important at high production rates.

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Catalyst	$4.60	$4.13	$3.86	$3.74	$4.25	$3.93	$3.74	$3.66
Membrane	$6.47	$3.92	$2.37	$1.67	$4.56	$2.76	$1.67	$1.18
GDL	$51.32	$14.96	$4.36	$1.84	$21.68	$6.32	$1.84	$0.88
Transfer Substrate	$2.04	$0.28	$0.04	$0.01	$0.51	$0.07	$0.01	$0.01
Total Material Cost	$64.42	$23.29	$10.63	$7.27	$30.99	$13.08	$7.27	$5.73

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$64.42	$23.29	$10.63	$7.27	$30.99	$13.08	$7.27	$5.73
Labor	$0.39	$0.31	$0.30	$0.30	$0.32	$0.30	$0.30	$0.30
Machine	$0.62	$0.49	$0.47	$0.42	$0.50	$0.47	$0.42	$0.23
Scrap	$1.94	$0.69	$0.31	$0.21	$0.92	$0.38	$0.21	$0.16
Tooling	$6.81	$0.68	$0.17	$0.13	$1.36	$0.24	$0.13	$0.13
Part Total	$74.18	$25.45	$11.88	$8.32	$34.10	$14.47	$8.32	$6.53
# per Stack	22	22	22	22	110	110	110	110
Stack Total	$1,632.00	$559.99	$261.43	$183.05	$3,750.99	$1,591.59	$915.26	$718.80

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Catalyst	$8.26	$7.72	$7.41	$7.27	$8.01	$7.57	$7.32	$7.21
Membrane	$7.13	$4.32	$2.62	$2.01	$5.84	$3.54	$2.14	$2.01
GDL	$33.10	$9.65	$2.81	$2.18	$20.23	$5.90	$2.18	$2.18
Transfer Substrate	$0.55	$0.08	$0.02	$0.02	$0.25	$0.03	$0.02	$0.02
Total Material Cost	$49.04	$21.77	$12.85	$11.47	$34.33	$17.04	$11.66	$11.42

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$49.04	$21.77	$12.85	$11.47	$34.33	$17.04	$11.66	$11.42
Labor	$0.56	$0.54	$0.54	$0.54	$0.55	$0.54	$0.54	$0.54
Machine	$0.89	$0.86	$0.48	$0.35	$0.87	$0.86	$0.46	$0.32
Scrap	$1.45	$0.63	$0.36	$0.32	$1.01	$0.49	$0.33	$0.32
Tooling	$1.33	$0.24	$0.14	$0.14	$0.53	$0.15	$0.14	$0.14
Part Total	$53.28	$24.04	$14.38	$12.82	$37.28	$19.08	$13.13	$12.73
# per Stack	110	110	110	110	276	276	276	276
Stack Total	$5,860.96	$2,644.19	$1,581.29	$1,410.24	$10,288.18	$5,266.44	$3,623.61	$3,514.53

5.3.1.3 PEM System End Plates

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

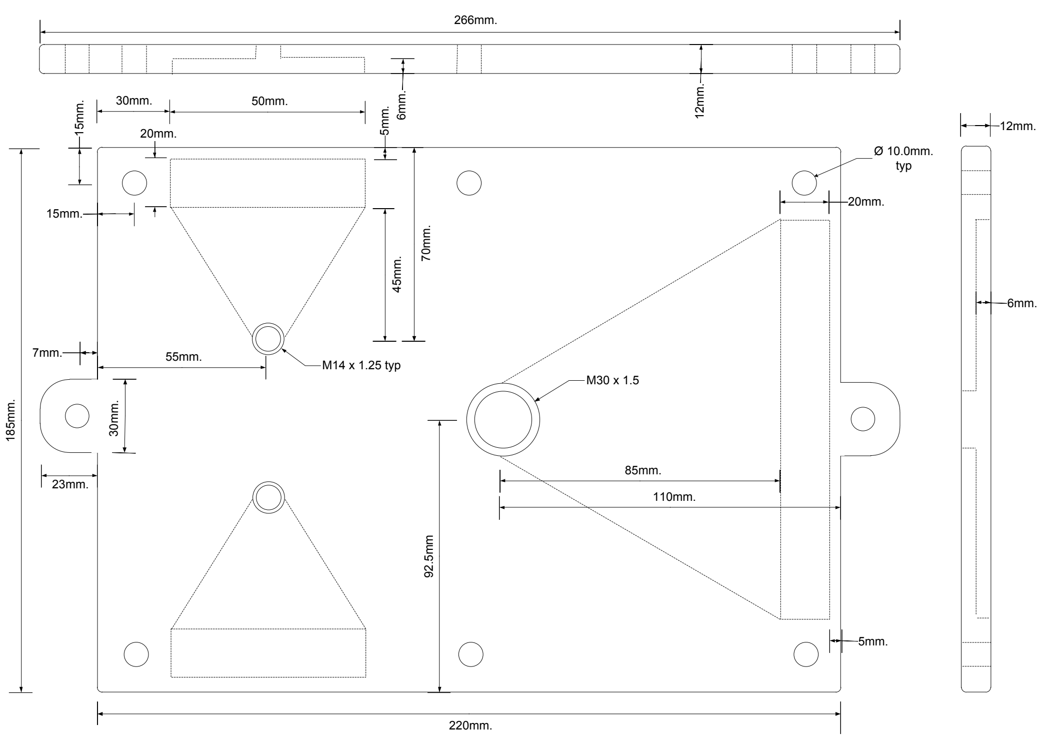


Figure 5-4. PEM system end plate size – 200-cm^2 active area

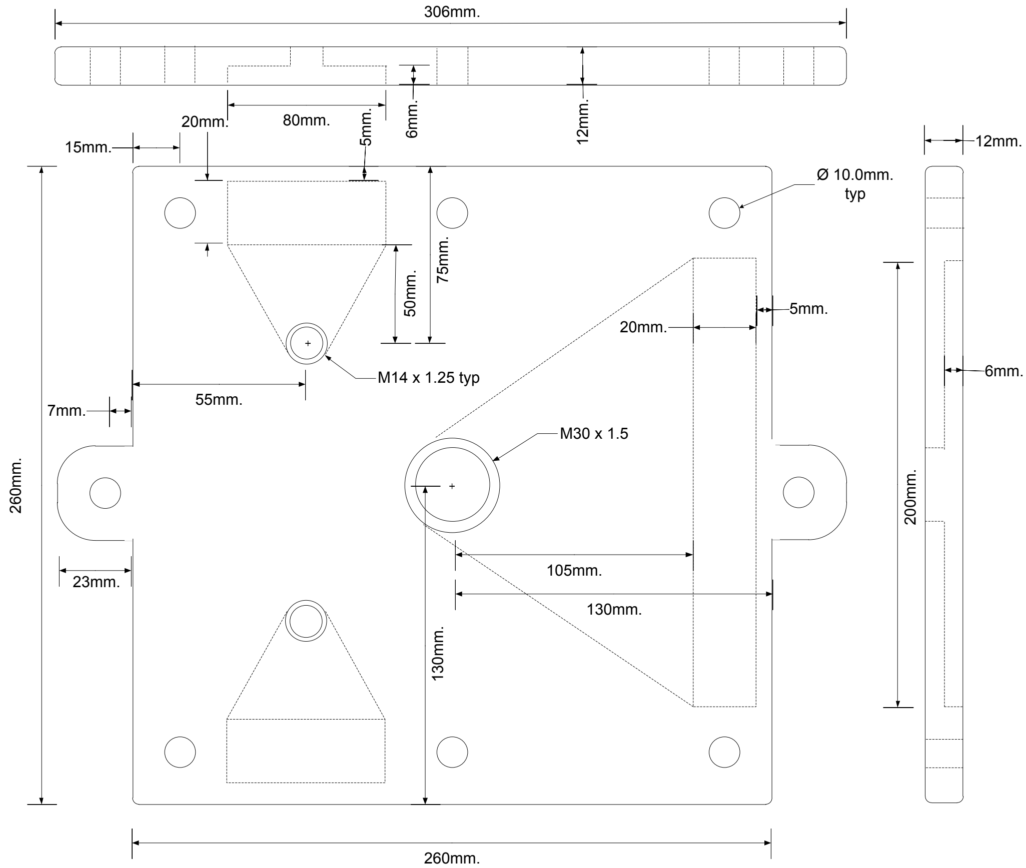


Figure 5-5. PEM system end plate size – 400-cm² active area

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

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$3.61	$3.30	$3.30	$3.30	$3.61	$3.30	$3.30	$3.30
Labor	$8.50	$4.11	$3.67	$3.63	$8.50	$4.11	$3.67	$3.63
Machine	$30.40	$14.70	$13.13	$9.18	$30.40	$14.70	$13.13	$9.18
Scrap	$0.21	$0.11	$0.10	$0.08	$0.21	$0.11	$0.10	$0.08
Tooling	$7.98	$0.80	$0.08	$0.05	$7.98	$0.80	$0.08	$0.05
Part Total	$50.70	$23.02	$20.28	$16.25	$50.70	$23.02	$20.28	$16.25
# per Stack	2	2	2	2	2	2	2	2
Stack Total	$101.40	$46.04	$40.57	$32.50	$101.40	$46.04	$40.57	$32.50

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$5.78	$5.42	$5.42	$5.42	$5.78	$5.42	$5.42	$5.42
Labor	$9.37	$4.97	$4.54	$4.50	$9.37	$4.97	$4.54	$4.50
Machine	$33.49	$17.79	$16.22	$7.45	$33.49	$17.79	$16.22	$7.45
Scrap	$0.24	$0.14	$0.13	$0.09	$0.24	$0.14	$0.13	$0.09
Tooling	$6.79	$0.68	$0.07	$0.04	$6.79	$0.68	$0.07	$0.04
Part Total	$55.67	$29.00	$26.37	$17.49	$55.67	$29.00	$26.37	$17.49
# per Stack	2	2	2	2	2	2	2	2
Stack Total	$111.35	$58.00	$52.74	$34.99	$111.35	$58.00	$52.74	$34.99

5.3.1.4 PEM System Bipolar Plates

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

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.63	$0.52	$0.52	$0.52	$0.52	$0.52	$0.52	$0.52
Labor	$0.47	$0.35	$0.33	$0.33	$0.36	$0.34	$0.33	$0.33
Machine	$1.96	$1.75	$0.66	$0.66	$1.77	$1.72	$0.70	$0.66
Scrap	$0.08	$0.07	$0.04	$0.04	$0.07	$0.07	$0.04	$0.04
Tooling	$6.02	$0.60	$0.11	$0.11	$1.25	$0.12	$0.11	$0.10
Part Total	$9.16	$3.28	$1.66	$1.65	$3.97	$2.77	$1.70	$1.65
# per Stack	23	23	23	23	111	111	111	111
Stack Total	$210.74	$75.43	$38.20	$38.06	$440.32	$306.98	$188.20	$182.79

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.86	$0.86	$0.86	$0.86	$0.86	$0.86	$0.86	$0.86
Labor	$0.97	$0.94	$0.94	$0.94	$0.95	$0.94	$0.94	$0.94
Machine	$4.93	$3.17	$1.94	$1.77	$4.90	$2.36	$1.78	$1.78
Scrap	$0.17	$0.13	$0.10	$0.09	$0.17	$0.11	$0.09	$0.09
Tooling	$0.71	$0.19	$0.17	$0.17	$0.28	$0.18	$0.17	$0.17
Part Total	$7.64	$5.29	$4.01	$3.84	$7.17	$4.44	$3.84	$3.84
# per Stack	111	111	111	111	277	277	277	277
Stack Total	$848.35	$587.30	$444.77	$425.84	$1,986.01	$1,229.37	$1,064.50	$1,064.08

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.42	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34
Labor	$0.47	$0.35	$0.33	$0.33	$0.36	$0.33	$0.33	$0.33
Machine	$1.96	$1.75	$0.66	$0.66	$1.77	$1.72	$0.70	$0.66
Scrap	$0.07	$0.06	$0.03	$0.03	$0.06	$0.06	$0.04	$0.03
Tooling	$6.02	$0.60	$0.11	$0.11	$1.25	$0.12	$0.11	$0.10
Part Total	$8.95	$3.10	$1.48	$1.48	$3.79	$2.59	$1.52	$1.47
# per Stack	23	23	23	23	111	111	111	111
Stack Total	$205.81	$71.37	$34.13	$34.00	$420.72	$287.38	$168.60	$163.18

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.57	$0.57	$0.57	$0.57	$0.57	$0.57	$0.57	$0.57
Labor	$0.97	$0.94	$0.94	$0.94	$0.95	$0.94	$0.94	$0.94
Machine	$4.93	$3.17	$1.94	$1.77	$4.90	$2.36	$1.78	$1.78
Scrap	$0.17	$0.12	$0.09	$0.08	$0.16	$0.10	$0.08	$0.08
Tooling	$0.71	$0.19	$0.17	$0.17	$0.28	$0.18	$0.17	$0.17
Part Total	$7.35	$5.00	$3.71	$3.54	$6.88	$4.14	$3.55	$3.55
# per Stack	111	111	111	111	277	277	277	277
Stack Total	$815.80	$554.76	$412.23	$393.29	$1,904.80	$1,148.15	$983.28	$982.86

5.3.1.5 PEM System Seals

The seals are injection molded from two-part liquid silicone rubber (LSR) material using a four-cavity tool-steel mold. The component reject rate was assumed to be 0.5%. Details of the analysis are shown in Appendix A-8. The anode and cooling seal cost summary is provided in Table 5-12 and Table 5-13; the cathode seal cost summary is provided in Table 5-14 and Table 5-15. With the configuration shown in Figure 5-2, the seal between the anode bipolar plate and the anode side of the MEA is identical to the seal between the back-to-back bipolar plates; the installed orientation is simply reversed. Thus, a single tool may be used for two of the three seals, increasing equipment utilization for the anode/cooling seal production. The seals require an orientation feature (tab) to provide external evidence that the seals are correctly installed.

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.20	$0.20	$0.19	$0.19	$0.20	$0.19	$0.19	$0.18
Labor	$0.09	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Machine	$0.13	$0.11	$0.11	$0.07	$0.12	$0.11	$0.07	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$4.48	$0.45	$0.13	$0.10	$0.90	$0.18	$0.10	$0.10
Part Total	$4.91	$0.84	$0.52	$0.44	$1.29	$0.56	$0.44	$0.37
# per Stack	44	44	44	44	220	220	220	220
Stack Total	$216.00	$36.93	$22.71	$19.14	$284.44	$123.94	$95.98	$82.16

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.22	$0.21	$0.20	$0.20	$0.21	$0.21	$0.20	$0.20
Labor	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08	$0.08
Machine	$0.12	$0.11	$0.07	$0.01	$0.11	$0.11	$0.01	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$1.29	$0.26	$0.14	$0.14	$0.51	$0.15	$0.14	$0.14
Part Total	$1.70	$0.66	$0.49	$0.43	$0.92	$0.55	$0.43	$0.43
# per Stack	220	220	220	220	552	552	552	552
Stack Total	$374.66	$144.75	$108.88	$95.03	$508.04	$304.17	$239.61	$238.32

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.17	$0.16	$0.16	$0.16	$0.17	$0.16	$0.16	$0.15
Labor	$0.04	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Machine	$0.06	$0.03	$0.03	$0.02	$0.03	$0.03	$0.02	$0.00
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$4.96	$0.50	$0.10	$0.06	$1.06	$0.11	$0.06	$0.06
Part Total	$5.23	$0.71	$0.30	$0.25	$1.29	$0.31	$0.26	$0.23
# per Stack	24	24	24	24	112	112	112	112
Stack Total	$125.43	$17.06	$7.30	$6.02	$143.96	$35.12	$28.61	$26.30

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.17	$0.16	$0.16	$0.15	$0.16	$0.16	$0.15	$0.15
Labor	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Machine	$0.03	$0.03	$0.02	$0.00	$0.03	$0.03	$0.00	$0.00
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$1.07	$0.11	$0.06	$0.06	$0.43	$0.09	$0.06	$0.06
Part Total	$1.29	$0.31	$0.26	$0.23	$0.64	$0.29	$0.24	$0.24
# per Stack	112	112	112	112	278	278	278	278
Stack Total	$144.44	$35.15	$28.62	$26.30	$178.94	$80.71	$65.46	$65.39

5.3.1.6 PEM System Stack Assembly

The stack components are assembled as illustrated in Figure 5-1. Pressure is applied to the completed stack using a hydraulic press, and the tie rods are installed to complete the stack assembly. Tie rod costs were estimated to be between $5.36 and $54.64 per stack depending on stack height, and gas fittings and other assembly hardware (inserts, washers, nuts) were estimated to be $38.87 per stack before applying learning curve analysis. Stack assembly times were estimated using the DFMA® software, and ranged from 0.30 hour to 2.32 hours depending on cell count. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45.00/hour, the average stack assembly costs were calculated as shown in Table 5-16 and Table 5-17. Details of the assembly cost learning curve calculations are provided in Appendix A-3.

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$44.23	$41.36	$38.68	$36.91	$54.07	$50.56	$47.28	$45.12
Labor	$20.74	$16.57	$16.15	$16.11	$71.20	$56.86	$55.43	$55.30
Total Assembly Cost	$64.97	$57.93	$54.83	$53.02	$125.27	$107.43	$102.71	$100.42

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$54.07	$50.56	$47.28	$45.12	$93.95	$87.85	$82.15	$78.38
Labor	$85.05	$67.93	$66.22	$66.06	$157.97	$126.17	$122.99	$122.71
Total Assembly Cost	$139.12	$118.49	$113.50	$111.18	$251.92	$214.02	$205.14	$201.09

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-10.

The stack testing and conditioning costs were calculated as shown in Table 5-18 and Table 5-19. The high stack failure rate would usually be expected to come down as higher volumes are reached and additional automation and quality control measures are instituted. In the absence of information on why the stack failure rates are high, we have to assume that the rate does not change with production volume. A sharp drop in machine cost per stack as production volumes change from 100 to 1,000 units/year reflects the low utilization rate in the case of the 100-unit volumes as well as the assumption that all stack testing is performed in-house regardless of production volume.

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$10.79	$4.62	$2.19	$1.37	$22.29	$10.53	$5.09	$3.12
Labor	$72.77	$72.33	$72.29	$72.28	$78.08	$76.57	$76.42	$76.41
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$68.73	$9.38	$4.76	$4.71	$69.61	$9.91	$5.13	$5.02
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1,374.50	$187.59	$95.16	$94.29	$1,392.20	$198.27	$102.56	$100.47
# per Stack	1	1	1	1	1	1	1	1
Stack Total	$1,374.50	$187.59	$95.16	$94.29	$1,392.20	$198.27	$102.56	$100.47

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$35.60	$16.89	$8.20	$5.11	$63.15	$30.16	$14.59	$10.55
Labor	$79.54	$77.74	$77.56	$77.54	$87.22	$83.87	$83.53	$83.51
Machine	$1,222.22	$101.26	$15.92	$15.92	$1,222.22	$101.26	$15.92	$15.92
Scrap	$70.39	$10.31	$5.35	$5.19	$72.24	$11.33	$6.00	$5.79
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1,407.75	$206.20	$107.03	$103.76	$1,444.83	$226.62	$120.04	$115.77
# per Stack	1	1	1	1	1	1	1	1
Stack Total	$1,407.75	$206.20	$107.03	$103.76	$1,444.83	$226.62	$120.04	$115.77

5.3.1.8 PEM Stack Cost Summary

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

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

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
MEA	$1,632.00	$559.99	$261.43	$183.05	$3,750.99	$1,591.59	$915.26	$718.80
Anode / Cooling Gasket	$216.00	$36.93	$22.71	$19.14	$284.44	$123.94	$95.98	$82.16
Cathode Gasket	$125.43	$17.06	$7.30	$6.02	$143.96	$35.12	$28.61	$26.30
Anode Bipolar Plate	$210.74	$75.43	$38.20	$38.06	$440.32	$306.98	$188.20	$182.79
Cathode Bipolar Plate	$205.81	$71.37	$34.13	$34.00	$420.72	$287.38	$168.60	$163.18
End plates	$101.40	$46.04	$40.57	$32.50	$101.40	$46.04	$40.57	$32.50
Assembly hardware	$44.23	$41.36	$38.68	$36.91	$54.07	$50.56	$47.28	$45.12
Assembly labor	$20.74	$16.57	$16.15	$16.11	$71.20	$56.86	$55.43	$55.30
Test and conditioning	$1,374.50	$187.59	$95.16	$94.29	$1,392.20	$198.27	$102.56	$100.47
Total	$3,930.86	$1,052.35	$554.32	$460.09	$6,659.30	$2,696.76	$1,642.50	$1,406.62
Cost per kW_{net}	$3,930.86	$1,052.35	$554.32	$460.09	$1,331.86	$539.35	$328.50	$281.32

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
MEA	$5,860.96	$2,644.19	$1,581.29	$1,410.24	$10,288.18	$5,266.44	$3,623.61	$3,514.53
Anode / Cooling Gasket	$374.66	$144.75	$108.88	$95.03	$508.04	$304.17	$239.61	$238.32
Cathode Gasket	$144.44	$35.15	$28.62	$26.30	$178.94	$80.71	$65.46	$65.39
Anode Bipolar Plate	$848.35	$587.30	$444.77	$425.84	$1,986.01	$1,229.37	$1,064.50	$1,064.08
Cathode Bipolar Plate	$815.80	$554.76	$412.23	$393.29	$1,904.80	$1,148.15	$983.28	$982.86
End plates	$111.35	$58.00	$52.74	$34.99	$111.35	$58.00	$52.74	$34.99
Assembly hardware	$54.07	$50.56	$47.28	$45.12	$93.95	$87.85	$82.15	$78.38
Assembly labor	$85.05	$67.93	$66.22	$66.06	$157.97	$126.17	$122.99	$122.71
Test and conditioning	$1,407.75	$206.20	$107.03	$103.76	$1,444.83	$226.62	$120.04	$115.77
Total	$9,702.41	$4,348.84	$2,849.06	$2,600.63	$16,674.07	$8,527.49	$6,354.37	$6,217.04
Cost per kW_{net}	$970.24	$434.88	$284.91	$260.06	$555.80	$284.25	$211.81	$207.23

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1,516.70	$597.43	$313.45	$236.50	$3,651.05	$1,662.38	$1,012.39	$837.70
Labor	$145.49	$123.66	$121.44	$121.24	$301.13	$267.57	$264.31	$264.02
Machine	$1,394.09	$227.51	$88.52	$77.54	$1,761.43	$593.13	$261.24	$207.98
Scrap	$115.45	$27.82	$13.49	$11.20	$186.56	$66.60	$36.84	$31.22
Tooling	$759.14	$75.91	$17.41	$13.61	$759.14	$107.07	$67.73	$65.69
Part Total	$3,930.86	$1,052.35	$554.32	$460.09	$6,659.30	$2,696.76	$1,642.50	$1,406.62

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$5,720.80	$2,695.17	$1,700.77	$1,542.81	$10,201.44	$5,386.13	$3,873.84	$3,798.77
Labor	$480.02	$443.47	$439.90	$439.59	$989.69	$937.99	$932.83	$932.38
Machine	$2,512.07	$964.03	$549.95	$466.63	$4,317.04	$1,749.71	$1,170.97	$1,114.60
Scrap	$268.97	$107.80	$66.39	$60.45	$445.36	$204.57	$146.12	$143.32
Tooling	$720.55	$138.38	$92.04	$91.15	$720.55	$249.10	$230.61	$227.97
Part Total	$9,702.41	$4,348.84	$2,849.06	$2,600.63	$16,674.07	$8,527.49	$6,354.37	$6,217.04

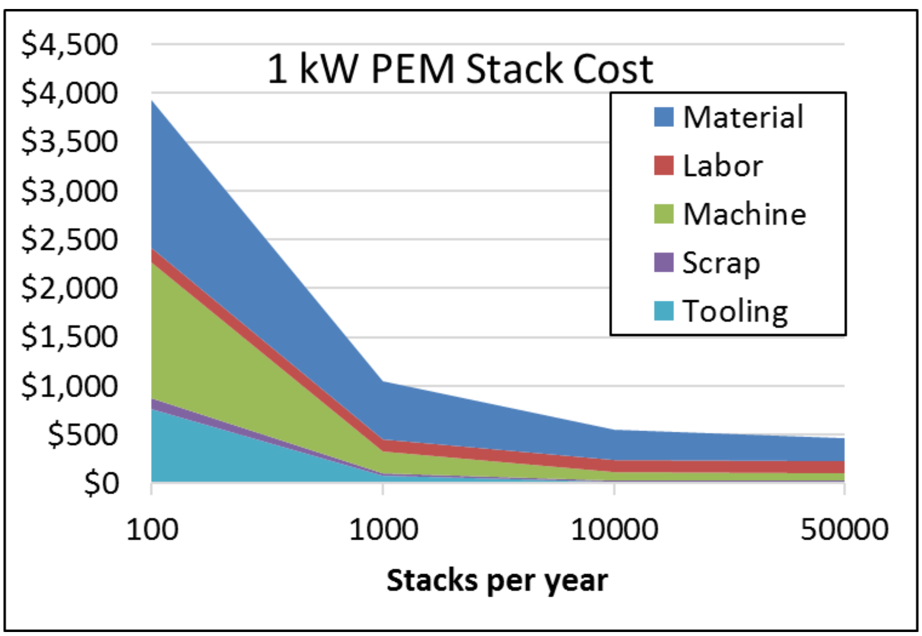


Figure 5-6. 1-kW PEM fuel cell stack cost volume trends

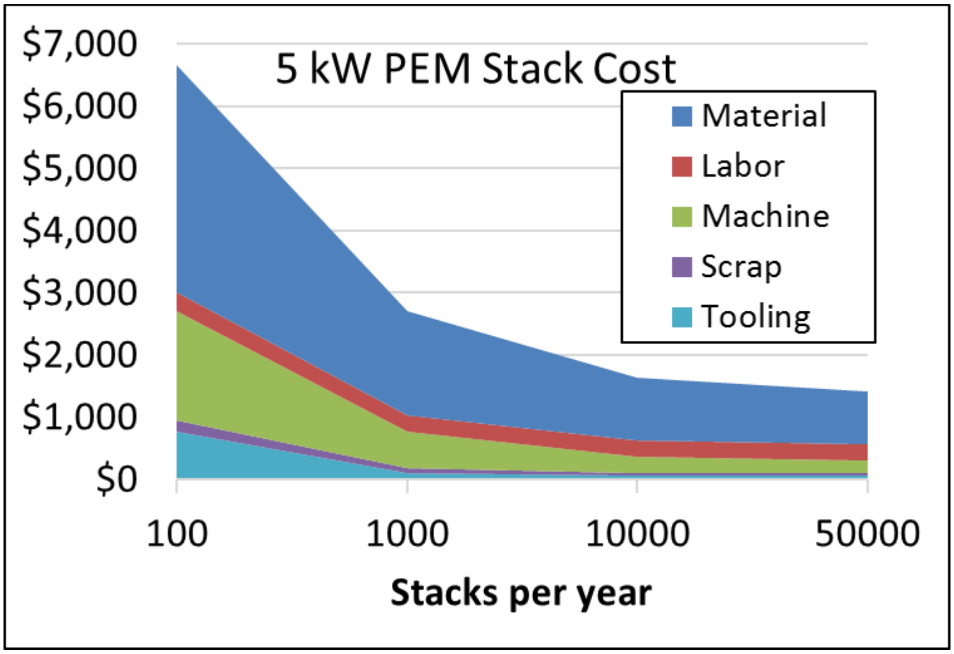


Figure 5-7. 5-kW PEM fuel cell stack cost volume trends

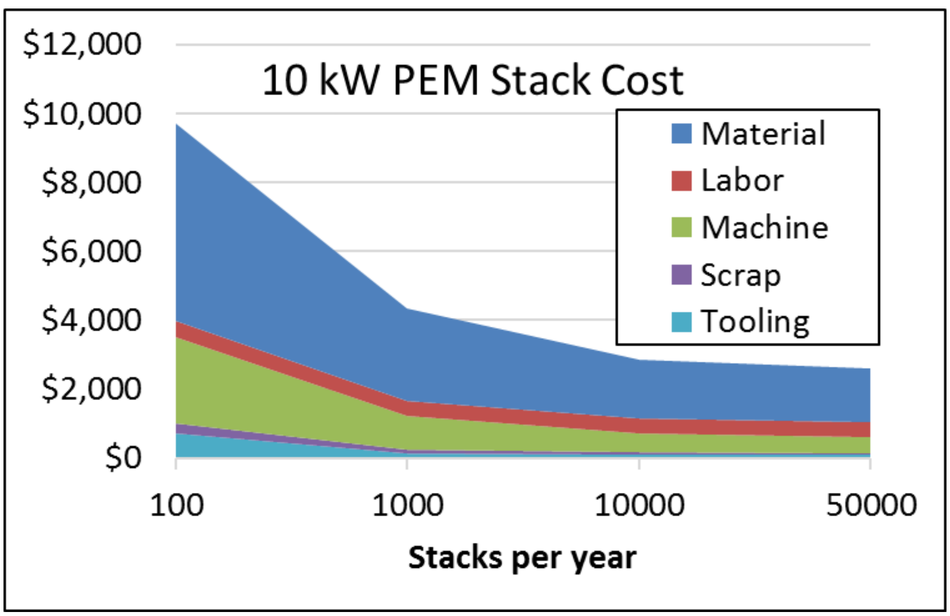


Figure 5-8. 10-kW PEM fuel cell stack cost volume trends

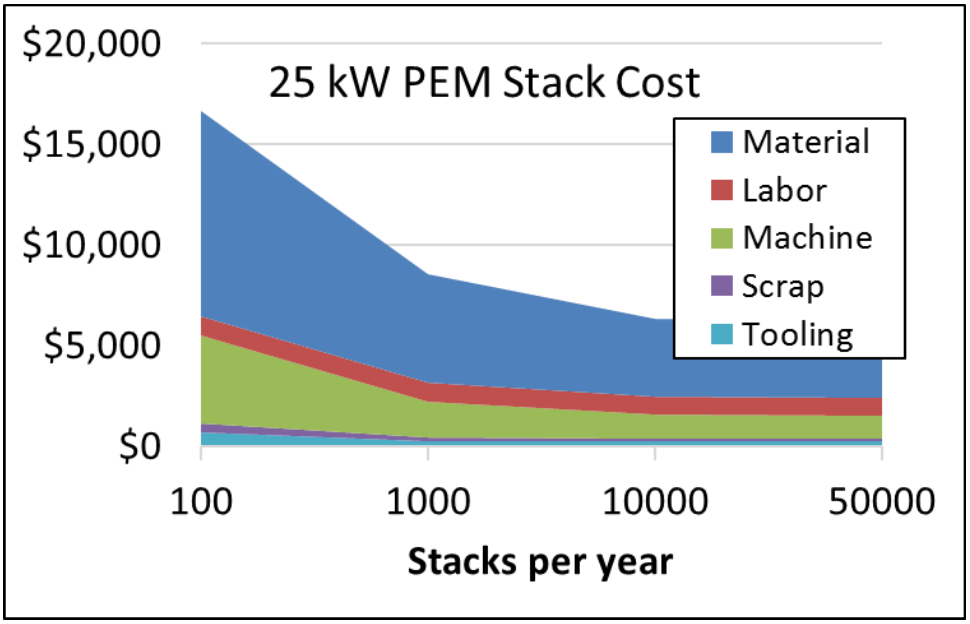


Figure 5-9. 25-kW PEM fuel cell stack cost volume trends

5.3.2 PEM System BOP Manufacturing Cost Assessment

Fuel processing systems for natural gas and propane, the fuels of choice for primary power and CHP applications, tend to be unique to each manufacturer with very little detailed information available to the public. To provide a basis for costing, representative fuel processing systems were designed by Battelle based on experience with smaller systems and conversations with various component suppliers. The Battelle-designed fuel processing systems were modeled with ChemCad® to define operating temperatures, pressures, heat loads, and other performance metrics. The ChemCad® model outputs were used to specify some items for commercial quotes and to define performance criteria for other non-standard components that were assumed to be fabricated in-house. Fabricated components were modeled using DFMA® software. For the PEM system, fabricated items included the reformer, steam generator, and water gas shift (WGS) and PrOx reactors. The reformate burner was based on a commercially available burner. While we recognize that some additional modifications will be required to manage the high-hydrogen/low-BTU wet anode gas, we believe that the final cost, after non-recurring engineering, should be representative. The heat exchangers shown in Figure 4-3 were quoted for one-off delivery by several heat exchanger manufacturers, as they have no experience with the higher production volumes evaluated in this study. Only one heat exchanger manufacturer was able to provide quotes for more than 1,000 units/order.

The reformer concept pricing was based on a reformer design patented by Catacel Corporation (now part of Johnson Matthey). The patent describes a single-tube, single-burner configuration suitable for systems up to approximately 25 kW. The steam generator is integrated with the reformer as a coil of finned tubing surrounding the multi-tube assembly and directly using the combustion gas from the reformer. The shift and PrOx reactors are pipe reactors with commercial granulated catalysts.

5.3.2.1 PEM System Steam Reformer

To provide a basis for DFMA® analysis, we assumed the steam reformer would be based on the design of the Catacel SSR® catalytic steam reformer (Figure 5-10). The conceptual design was drawn from patent no. 7,501,102, with guidance on sizing provided informally by Catacel. The reformer consists of a stack of catalyst-coated fans or stages and is scaled primarily by increasing the number of stages in the stack but also by adjusting stage diameter.

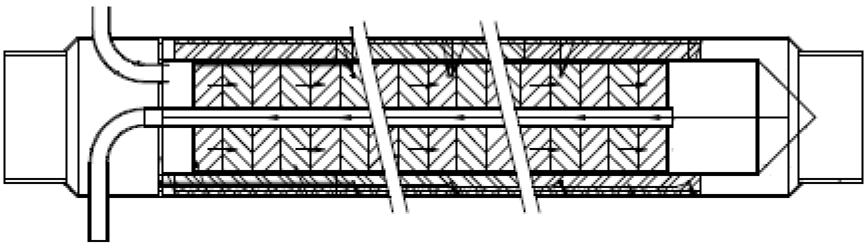


Figure 5-10. Catacel SSR® schematic diagram

We started by determining the required catalyst-coated surface area for each reformer, assuming approximately 600 square inches (in^2) (3,871 cm^2) of catalyst per kilowatt based on the Catacel SSR® design. For the systems under consideration, we used the reformer sizing parameters shown in Table 5-24.

Table 5-24. PEM System Reformer Sizing Parameters

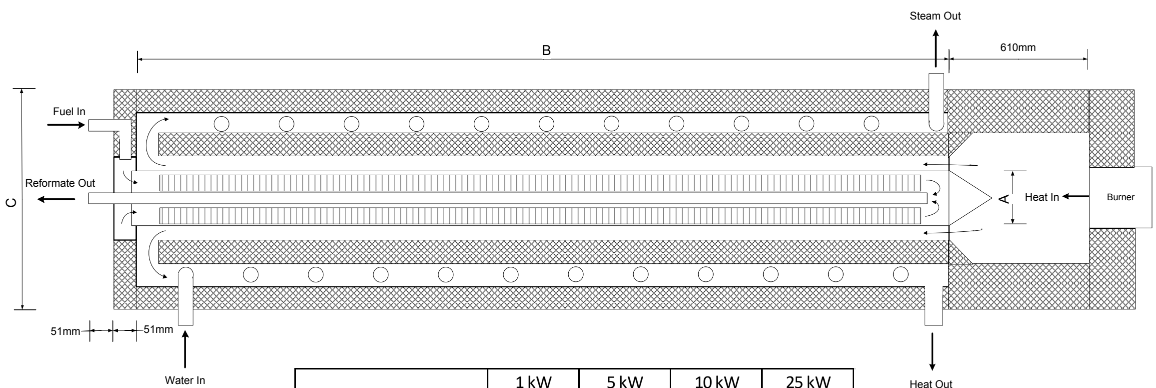
System Size (kW)	Reformer Size (kW)	Catalyst Area (cm^2)
1	1.20	4,614.18
5	6.00	23,070.92
10	12.00	46,141.84
25	30.00	115,354.61

We then iteratively determined the fan dimensions that gave us the required area, while keeping the number of flow stages at 20 or higher. The final reformer dimensions for each system are shown in Table 5-25.

Table 5-25. PEM System Reformer Dimensional Summary

	1 kW	5 kW	10 kW	25 kW
Overall Dia. (mm)	53	129	129	129
Overall Len. (mm)	682	634	1,015	2,197
Flow Stages	27	24	48	62
Final Catalyst Area (cm^2)	4,677	23,387	46,774	116,935

Figure 5-11 shows the conceptual reformer configuration for the systems. The catalyst fans are housed in concentric metal tubes that provide for combustion gas flow over the outside and counter-flow of the steam/fuel mixture being reformed. The tubes and transitions are rolled and welded from high alloy or stainless steel sheet. Reformate flows to the exit manifold through a central tube within the fan stack. Also illustrated in Figure 5-11 is a steam generator coil wrapped around the reformer and heated by the effluent combustion gas from the reformer. Integrating the steam generator in this way reduces both cost and heat loss compared to a separate steam generator. The steam generator coil is assumed to be a 25.4-mm (outside diameter) tube with 9.5-mm tall stainless steel fins continuously wound and brazed to the tube. Although shown as a loosely wound coil in Figure 5-11, for costing purposes the coils were assumed to be closely wound – that is, with the fin tips contacting adjacent fins on each coil and the coil occupying the available length. Table 5-26 and Table 5-27 summarize PEM reformer costs.



	1 kW	5 kW	10 kW	25 kW
Dia. A - mm(in)	53 (2.1)	129 (5.1)	129 (5.1)	129 (5.1)
Len. B - mm(in)	682 (26.8)	634 (25.0)	1015 (40.0)	2197 (86.5)
Dia. C - mm(in)	358 (14.1)	434 (17.1)	434 (17.1)	434 (17.1)

Figure 5-11. Reformer with steam generator schematic diagram

Table 5-26. PEM Reformer Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$188.75	$180.43	$179.00	$178.78	$324.19	$312.44	$309.58	$309.55
Process	$861.27	$687.43	$479.56	$436.36	$759.30	$664.78	$428.09	$397.49
Scrap	$52.50	$43.39	$32.93	$30.76	$54.17	$48.86	$36.88	$35.35
Tooling	$689.72	$68.97	$6.90	$6.90	$772.50	$77.25	$7.73	$7.73
Manufactured Parts	$1,792.23	$980.22	$698.39	$652.79	$1,910.17	$1,103.33	$782.28	$750.11
Purchased Parts	$310.82	$310.82	$310.82	$310.82	$362.08	$362.08	$362.08	$362.08
Assembly	$110.95	$88.62	$86.38	$86.19	$130.43	$104.18	$101.55	$101.32
Total Cost	$2,214.01	$1,379.66	$1,095.60	$1,049.80	$2,402.68	$1,569.58	$1,245.91	$1,213.51

Table 5-27. PEM Reformer Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$435.86	$422.31	$419.72	$419.70	$677.89	$664.80	$662.33	$662.31
Process	$1,479.73	$1,290.68	$763.30	$729.08	$1,935.38	$1,376.20	$1,026.49	$934.41
Scrap	$95.78	$85.65	$59.15	$57.44	$130.66	$102.05	$84.44	$79.84
Tooling	$910.69	$91.07	$9.11	$9.11	$1,289.92	$128.99	$12.90	$12.90
Manufactured Parts	$2,922.06	$1,889.70	$1,251.28	$1,215.32	$4,033.85	$2,272.04	$1,786.16	$1,689.45
Purchased Parts	$543.98	$543.98	$543.98	$543.98	$1,072.35	$1,072.35	$1,072.35	$1,072.35
Assembly	$160.77	$128.41	$125.18	$124.89	$182.48	$145.75	$142.08	$139.20
Total Cost	$3,626.82	$2,562.10	$1,920.44	$1,884.20	$5,288.68	$3,490.13	$3,000.59	$2,901.00

5.3.2.2 PEM System Shift and PrOx Reactors

To provide a basis for DFMA® analysis, we assumed that the shift and PrOx reactors would be designed as cylindrical containers sized to hold the appropriate volume of catalyst material as determined based on the required gas hourly space velocity (GHSV) for the reactor.

Although originally conceived as pipe reactors with granulated or pelletized catalyst, a major automotive catalyst supplier provided recommendations for sizing and cost estimating using cylindrical catalyst-coated ceramic monoliths approximately 2.5 inches (63.5 mm) in diameter and 6 inches (152 mm) long. Equivalent “half” monoliths at 3 inches (76 mm) long are also available. The supplier had previously provided information on 5.66-inch (144-mm) diameter full and half monoliths for our work on 100-kW and 250-kW systems, and suggested that 1.5-inch (38-mm) diameter monolith blocks could also be made available. The supplier suggested that, by selecting appropriate catalysts and varying the precious metal type and loading, the shift and PrOx reactors could be made to be essentially the same size. The cost estimates were compared to catalyst cost/quantity (or equivalently, space velocity) recommendations from other sources, including pelletized catalysts, and were found to be somewhat lower but not radically different. These reactors also compare reasonably well to the costs of automotive catalytic converters. This follows because the monoliths and catalyst-coating methodology were developed for automotive applications. The costs were rounded up to account for unknowns, including the preliminary nature of the estimates and the dependence on precious metal pricing. Generally, we have found that precious metal content is typically less than half of the cost of the catalyst—whether for a granulated, pelletized, or coated monolith; however, precious metal costs are enough of the catalyst cost to notably change the cost if metal prices change significantly. When considering the production of 10,000 to 50,000 large systems per year, the total quantity of catalyst required could in fact push precious metal prices higher. As noted for the fuel cell catalyst, a robust recycling program would alleviate most of this concern. Because these reactors have significant commonality with automotive catalytic converters, a recycling process is already in place.

The shift/PrOx reactor dimensions for each system are shown in Table 5-28.

Table 5-28. PEM Shift/PrOx Reactor Dimensions Summary

	1 kW	5 kW	10 kW	25 kW
Monolith Dia. (mm)	38	64	64	144
Full Blocks	1	1	3	1
Half Blocks	0	1	0	1
Len. A (mm)	203	292	533	292
Len. B (mm)	153	238	238	507
Dia. C (mm)	46	71	71	151
Dia. D (mm)	13	19	25	38

Example reactor configurations, applicable to either shift or PrOx, are shown in Figure 5-12. The shift reactor operates at modest temperatures and low pressure, allowing the use of 18-gage 316L stainless steel sheet for the primary container construction. The cylindrical shell was formed by stamping two identical clamshell halves. The catalyst monoliths are wrapped with compliant high-temperature felt and placed between the two clamshells, which are then welded together. The outlet cap could be incorporated with the stamping; however, for our analysis it was fabricated separately and welded to the clamshell halves as the last process in reactor assembly. The outlet caps are formed by stamping circular disks and welding a short tubing section to the disk before the disk is welded to the clamshells. The reactor cost summaries are shown in Table 5-29 and Table 5-30 (shift reactor) and Table 5-31 and Table 5-32 (PrOx reactor).

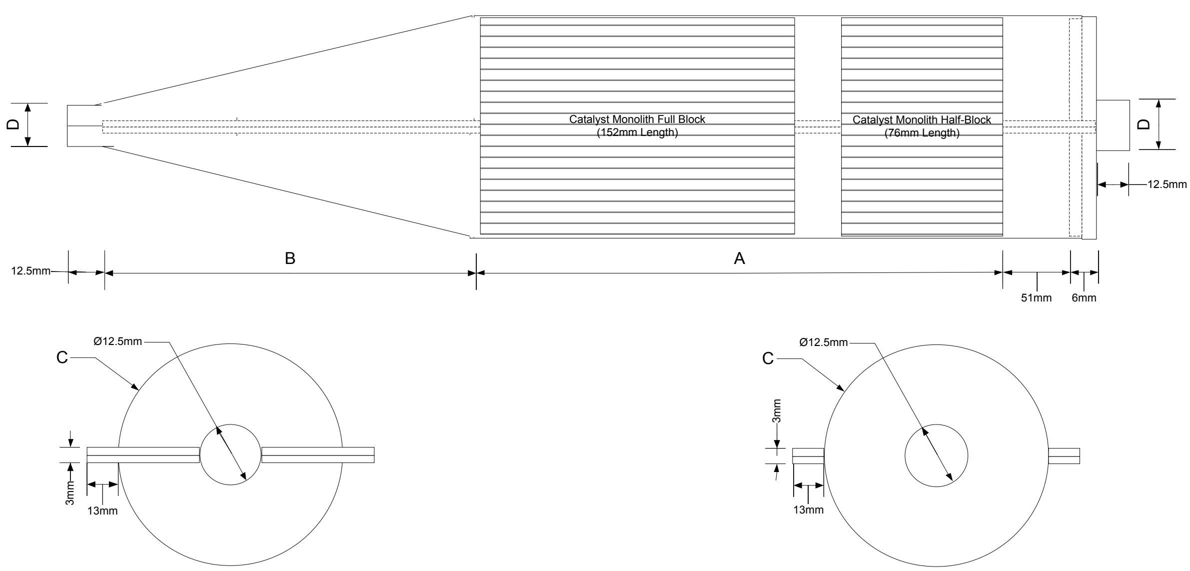


Figure 5-12. Shift/PrOx reactor schematic diagram

Table 5-29. PEM Shift Reactor Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$18.87	$13.30	$12.95	$12.82	$37.85	$29.40	$28.53	$28.20
Process	$4.93	$4.93	$4.93	$4.93	$6.81	$6.81	$6.81	$6.81
Scrap	$1.19	$0.91	$0.89	$0.89	$2.23	$1.81	$1.77	$1.75
Tooling	$87.15	$8.71	$0.87	$0.17	$114.87	$11.49	$1.15	$0.23
Manufactured Parts	$112.14	$27.85	$19.65	$18.81	$161.76	$49.50	$38.25	$36.98
Catalyst	$243.29	$184.43	$139.81	$115.20	$1,218.56	$923.75	$700.26	$577.00
Purchased Parts	$2.53	$2.53	$2.53	$2.53	$4.50	$4.50	$4.50	$4.50
Assembly	$3.81	$3.05	$2.97	$2.96	$5.55	$4.43	$4.32	$4.31
Total Cost	$361.77	$217.86	$164.96	$139.50	$1,390.37	$982.18	$747.33	$622.80

Table 5-30. PEM Shift Reactor Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$52.26	$43.20	$42.32	$41.98	$109.58	$100.26	$97.72	$97.65
Process	$7.67	$7.67	$7.67	$7.67	$10.82	$10.82	$10.82	$9.59
Scrap	$3.00	$2.54	$2.50	$2.48	$6.02	$5.55	$5.43	$5.36
Tooling	$140.85	$14.09	$1.41	$0.28	$205.90	$20.59	$2.06	$0.41
Manufactured Parts	$203.78	$67.50	$53.90	$52.42	$332.32	$137.23	$116.03	$113.02
Catalyst	$2,027.41	$1,536.91	$1,165.07	$960.00	$4,188.79	$3,175.37	$2,407.14	$1,983.44
Purchased Parts	$7.24	$7.24	$7.24	$7.24	$9.37	$9.37	$9.37	$9.37
Assembly	$5.98	$4.77	$4.65	$4.64	$8.32	$6.65	$6.48	$6.46
Total Cost	$2,244.41	$1,616.42	$1,230.87	$1,024.30	$4,538.80	$3,328.61	$2,539.01	$2,112.29

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

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$18.87	$13.30	$12.95	$12.82	$37.85	$29.40	$28.53	$28.20
Process	$4.93	$4.93	$4.93	$4.93	$6.81	$6.81	$6.81	$6.81
Scrap	$1.19	$0.91	$0.89	$0.89	$2.23	$1.81	$1.77	$1.75
Tooling	$16.32	$1.63	$0.16	$0.03	$83.24	$8.32	$0.83	$0.17
Manufactured Parts	$41.31	$20.77	$18.94	$18.67	$130.13	$46.34	$37.94	$36.92
Catalyst	$279.78	$212.09	$160.78	$132.48	$1,372.73	$1,040.61	$788.85	$650.00
Purchased Parts	$1.30	$1.30	$1.30	$1.30	$4.50	$4.50	$4.50	$4.50
Assembly	$6.36	$5.08	$4.95	$4.94	$3.50	$2.80	$2.73	$2.72
Total Cost	$328.76	$239.25	$185.97	$157.39	$1,510.85	$1,094.25	$834.02	$694.14

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

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$52.26	$43.20	$42.32	$41.98	$109.58	$100.26	$97.72	$97.65
Process	$7.67	$7.67	$7.67	$7.67	$11.62	$11.62	$11.62	$10.28
Scrap	$3.00	$2.54	$2.50	$2.48	$6.06	$5.59	$5.47	$5.40
Tooling	$91.34	$9.13	$0.91	$0.18	$119.60	$11.96	$1.20	$0.24
Manufactured Parts	$154.27	$62.55	$53.41	$52.32	$246.86	$129.44	$116.00	$113.57
Catalyst	$2,331.52	$1,767.44	$1,339.83	$1,104.00	$4,718.75	$3,577.11	$2,711.68	$2,234.38
Purchased Parts	$7.24	$7.24	$7.24	$7.24	$9.37	$9.37	$9.37	$9.37
Assembly	$3.53	$2.82	$2.75	$2.74	$3.92	$3.13	$3.05	$3.04
Total Cost	$2,496.56	$1,840.05	$1,403.23	$1,166.30	$4,978.89	$3,719.04	$2,840.09	$2,360.35

5.3.3 PEM System BOP Cost Assumptions

The costs associated with the BOP components are tabulated in Table 5-33 and Table 5-34. Figure 5-13 through Figure 5-16 compare component costs at a subcategory level similar to the system schematic. At a production rate of 1,000 systems a year, the BOP hardware is estimated to cost more than $9,000 for one 1-kW system, increasing to more than $39,000 for 25 kW at the same production volume. Many component costs, including most sensors and regulators, remain the same regardless of system size, and are therefore similar to costs presented in the FY12 Material Handling Equipment (MHE) study.[6] Further, these costs do not vary significantly with system size. The power electronics required for grid connection and grid-outage operation are major contributors to the BOP cost, amounting for approximately 40% of the BOP cost at 25-kW and 50,000-unit production.

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

[6] Battelle. 2012. Manufacturing Cost Analysis of 10kW and 25kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Material Handling Applications. DOE Contract No. DE-EE0005250.

Table 5-33. PEM BOP Cost Summary: 1- and 5-kW Systems

Subassembly	Component Description	Annual Production: 1kW PEM Systems				Annual Production: 5kW PEM Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Supply	Filter	112	102	93	89	$112	$102	$93	$89
	Compressor/Flow Controller	$507	$406	$325	$309	$507	$406	$385	$374
	3-way valve (start-up bypass)	$107	$97	$87	$84	$107	$97	$87	$84
	Desulfurizer	$644	$99	$68	$61	$893	$162	$122	$111
Water Supply	Reformer Water Pump	$138	$110	$94	$91	$919	$767	$532	$378
	Water Filter	$31	$28	$23	$19	$31	$28	$23	$19
	DI Polisher	$43	$39	$35	$31	$43	$39	$35	$31
	Flow Meter	$233	$216	$195	$175	$233	$216	$195	$175
Fuel Processing	Reformer	$2,214	$1,380	$1,096	$1,050	$2,403	$1,570	$1,246	$1,214
	WGS Reactor	$362	$218	$165	$140	$1,390	$982	$747	$623
	PrOx Reactor	$329	$239	$186	$157	$1,511	$1,094	$834	$694
	PrOx Blower	$307	$276	$248	$241	$418	$376	$339	$329
	Steam Generator	$322	$301	$271	$244	$845	$791	$711	$640
	Superheater	$292	$182	$161	$135	$329	$205	$180	$152
	WGS Cooler	$179	$161	$147	$143	$341	$307	$280	$273
Air Supply (combustion)	Filter & Housing	$347	$333	$320	$307	$347	$333	$320	$307
	Blower (Anode Air)	$307	$276	$248	$241	$418	$376	$339	$329
	Flow Meter	$128	$115	$103	$97	$128	$115	$103	$97
Air Supply (cathode)	Blower (Cathode Air)	$307	$276	$248	$241	$418	$376	$339	$329
	Humidifier	$541	$378	$156	$89	$420	$290	$200	$165
	Flowmeter (Cathode Air)	$128	$115	$103	$97	$128	$115	$103	$97
Heat Recovery	Condenser #1	$174	$157	$143	$139	$363	$327	$298	$290
	Condenser #2	$174	$157	$143	$139	$363	$327	$298	$290
	PrOx Cooler	$94	$85	$77	$75	$130	$117	$106	$104
	CHP Load Heater	$157	$69	$60	$54	$264	$141	$128	$105
	Radiator	$146	$71	$61	$51	$382	$187	$161	$135
AC Power	DC/AC Inverter	$648	$603	$560	$521	$1,980	$1,841	$1,713	$1,593
	Transfer Switch	$105	$95	$85	$77	$308	$277	$249	$224
	Resistor Bank	$25	$23	$20	$20	$150	$135	$122	$118
DC Power	DC/DC Converter (Power)	$805	$646	$581	$558	$1,969	$1,575	$1,418	$1,361
	Batteries	$32	$31	$30	$29	$154	$146	$142	$139
Instrumentation and Controls	Control Module	$719	$647	$582	$565	$719	$647	$582	$565
	DC/DC Converter (Controls)	$34	$31	$28	$27	$134	$121	$109	$105
	Wiring & Connectors	$144	$131	$118	$106	$291	$265	$238	$214
	Temperature Sensors	$154	$129	$113	$110	$154	$129	$113	$110
	H2S Sensor	$243	$219	$210	$204	$243	$219	$210	$204
	Stack Anode Pressure Sensor	$226	$203	$182	$177	$226	$203	$182	$177
Assembly Components	Assorted Plumbing/Fittings	$351	$319	$285	$255	$602	$548	$495	$445
	Assembly Hardware	$35	$32	$29	$26	$60	$55	$49	$44
	Frame & Housing	$105	$96	$86	$77	$181	$164	$148	$133
+ Work Est.	Additional Work Estimate	$1,200	$900	$800	$700	$1,900	$1,500	$1,300	$1,200
	TOTAL BOP COST	**$13,149**	**$9,988**	**$8,565**	**$7,951**	**$22,515**	**$17,669**	**$15,274**	**$14,066**

Table 5-34. PEM BOP Cost Summary: 10- and 25-kW Systems

Subassembly	Component Description	Annual Production: 10kW PEM Systems				Annual Production: 25kW PEM Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Supply	Filter	$112	$102	$93	$89	$112	$102	$93	$89
	Compressor/Flow Controller	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3-way valve (start-up bypass)	$107	$97	$87	$84	$107	$97	$87	$84
	Desulfurizer	$1,255	$235	$186	$167	$1,562	$448	$373	$335
Water Supply	Reformer Water Pump	$1,034	$863	$620	$491	$1,960	$1,800	$1,242	$938
	Water Filter	$31	$28	$23	$19	$31	$28	$23	$19
	DI Polisher	$43	$39	$35	$31	$43	$39	$35	$31
	Flow Meter	$233	$216	$195	$175	$233	$216	$195	$175
Fuel Processing	Reformer	$3,627	$2,562	$1,920	$1,884	$5,289	$3,490	$3,001	$2,901
	WGS Reactor	$2,244	$1,616	$1,231	$1,024	$4,539	$3,329	$2,539	$2,112
	PrOx Reactor	$2,497	$1,840	$1,403	$1,166	$4,979	$3,719	$2,840	$2,360
	PrOx Blower	$617	$555	$500	$485	$672	$605	$545	$528
	Steam Generator	$1,281	$1,198	$1,078	$971	$2,219	$2,076	$1,869	$1,682
	Superheater	$432	$278	$245	$210	$662	$433	$381	$330
	WGS Cooler	$450	$405	$369	$360	$780	$702	$639	$624
Air Supply (combustion)	Filter & Housing	$347	$333	$320	$307	$495	$464	$445	$427
	Blower (Anode Air)	$617	$555	$500	$485	$672	$605	$545	$528
	Flow Meter	$128	$115	$103	$97	$144	$130	$117	$113
Air Supply (cathode)	Blower (Cathode Air)	$617	$555	$500	$485	$672	$605	$545	$528
	Humidifier	$790	$553	$227	$130	$750	$550	$450	$420
	Flowmeter (Cathode Air)	$128	$115	$103	$97	$128	$115	$103	$97
Heat Recovery	Condenser #1	$550	$495	$451	$440	$953	$858	$782	$762
	Condenser #2	$550	$495	$451	$440	$953	$858	$782	$762
	PrOx Cooler	$149	$134	$122	$119	$258	$232	$212	$207
	CHP Load Heater	$441	$262	$213	$189	$1,029	$669	$518	$460
	Radiator	$580	$284	$243	$204	$1,004	$492	$422	$354
AC Power	DC/AC Inverter	$3,600	$3,348	$3,114	$2,896	$9,540	$8,872	$8,251	$7,674
	Transfer Switch	$308	$277	$249	$224	$710	$639	$575	$518
	Resistor Bank	$300	$270	$243	$236	$900	$810	$729	$707
DC Power	DC/DC Converter (Power)	$3,900	$3,000	$2,700	$2,592	$9,900	$7,200	$6,600	$6,300
	Batteries	$556	$527	$515	$504	$738	$700	$683	$670
Instrumentation and Controls	Control Module	$719	$647	$582	$565	$719	$647	$582	$565
	DC/DC Converter (Controls)	$251	$226	$203	$197	$627	$564	$508	$493
	Wiring & Connectors	$487	$442	$398	$358	$1,099	$999	$899	$809
	Temperature Sensors	$154	$129	$113	$110	$154	$129	$113	$110
	H2S Sensor	$243	$219	$210	$204	$243	$219	$210	$204
	Stack Anode Pressure Sensor	$226	$203	$182	$177	$226	$203	$182	$177
Assembly Components	Assorted Plumbing/Fittings	$899	$817	$735	$660	$1,442	$1,311	$1,180	$1,060
	Assembly Hardware	$90	$82	$74	$67	$144	$131	$118	$106
	Frame & Housing	$270	$245	$221	$199	$433	$393	$354	$319
+ Work Est.	Additional Work Estimate	$2,700	$2,100	$1,800	$1,600	$4,300	$3,400	$2,900	$2,700
	TOTAL BOP COST	$33,561	$26,463	$22,558	$20,738	$61,423	$48,879	$42,665	$39,279

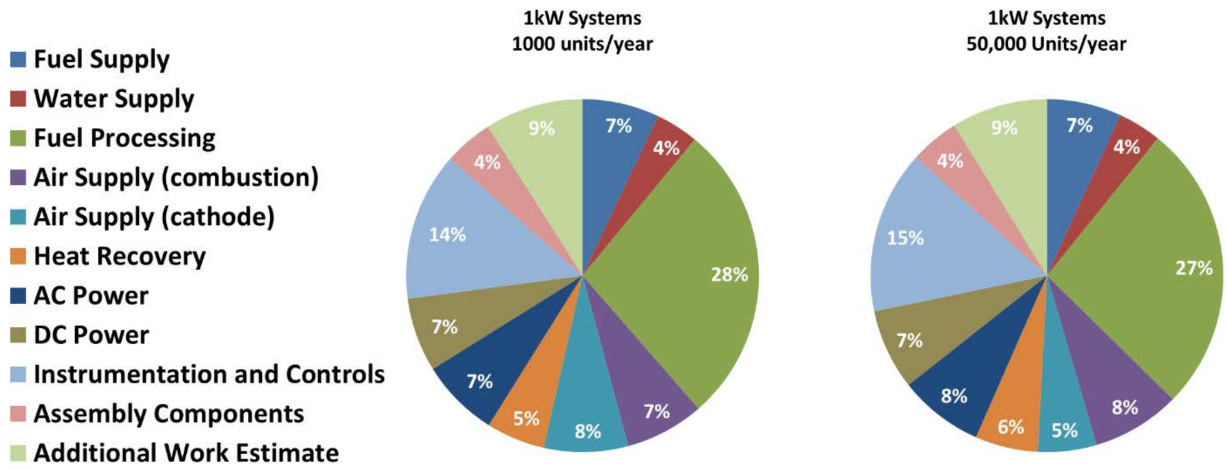


Figure 5-13. 1-kW PEM system BOP cost distribution

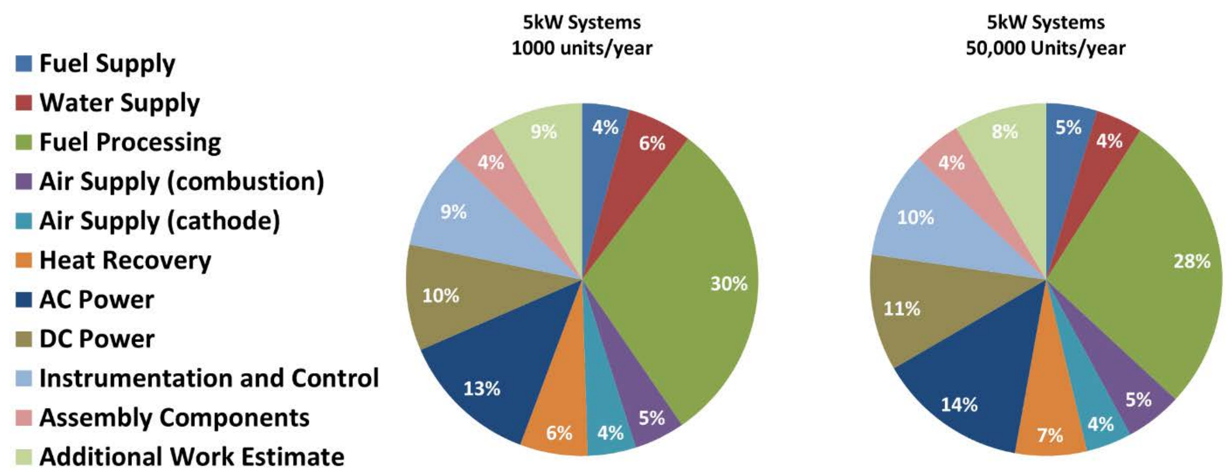


Figure 5-14. 5-kW PEM system BOP cost distribution

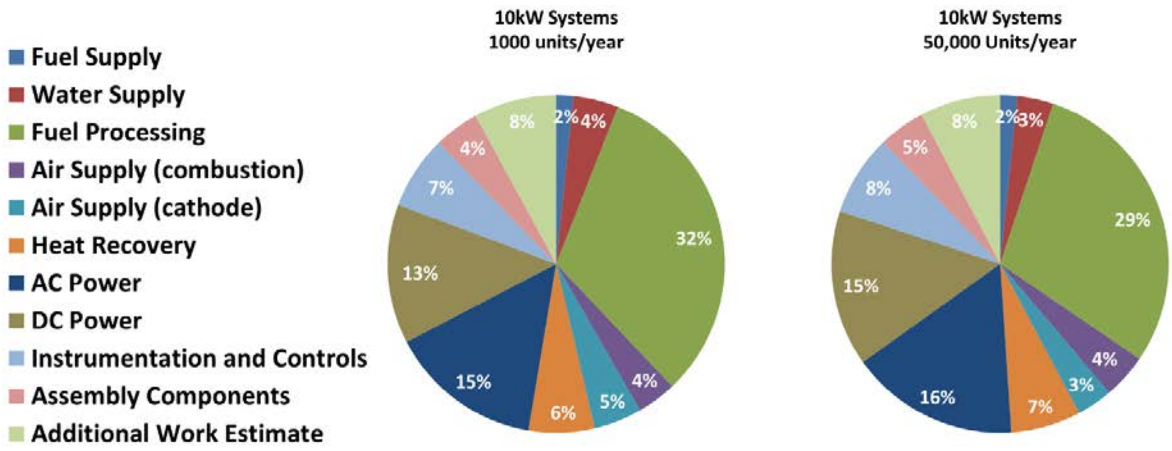


Figure 5-15. 10-kW PEM system BOP cost distribution

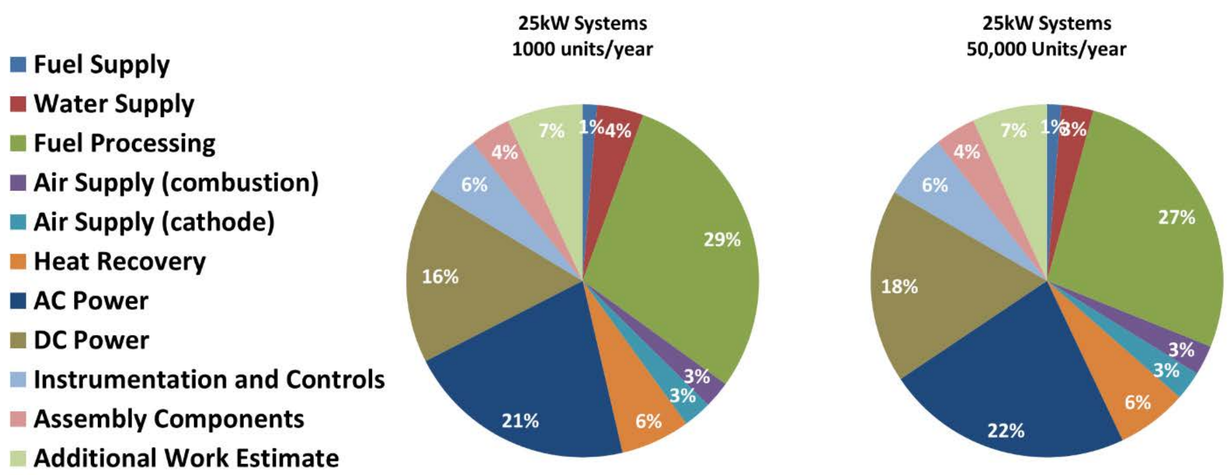


Figure 5-16. 25-kW PEM system BOP cost distribution

Cost trends for PEM system BOP elements are shown in Figure 5-17 through Figure 5-20.

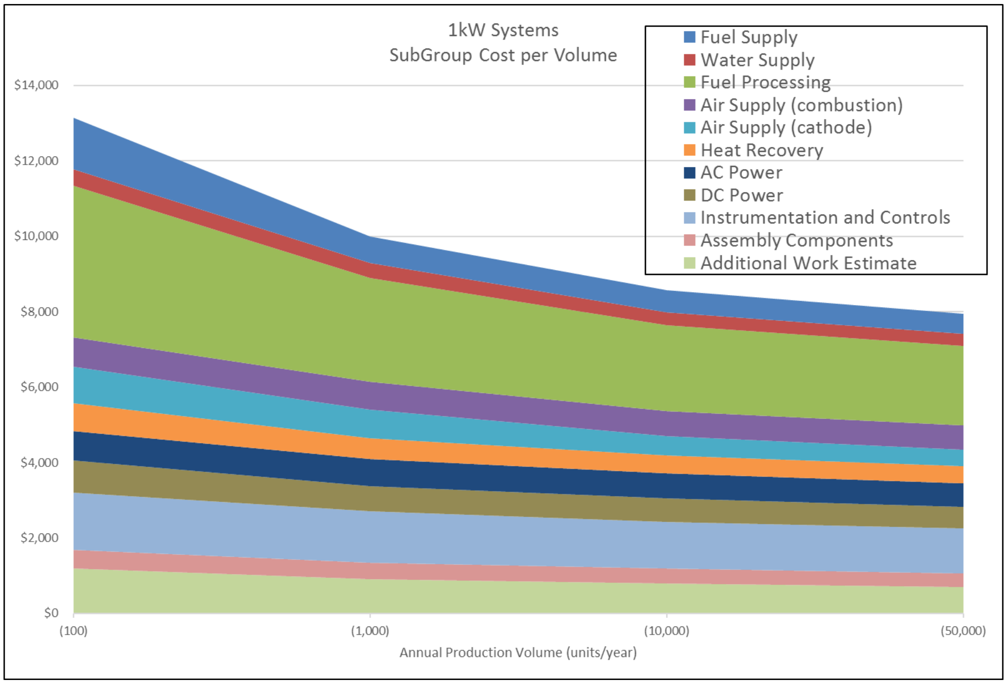


Figure 5-17. 1-kW PEM system BOP cost volume trends

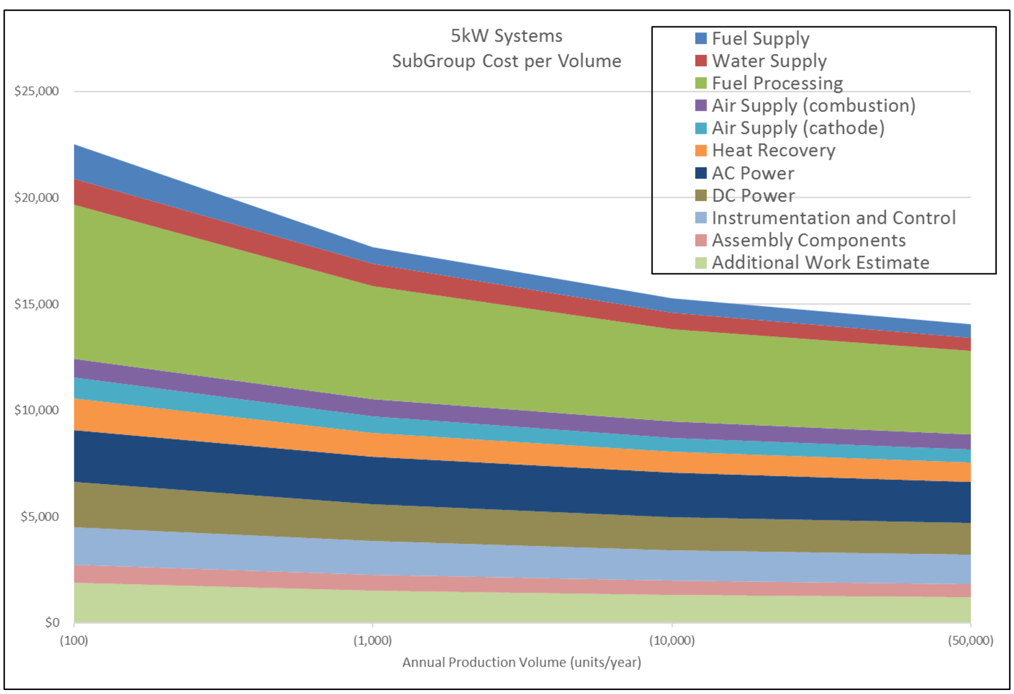


Figure 5-18. 5-kW PEM system BOP cost volume trends

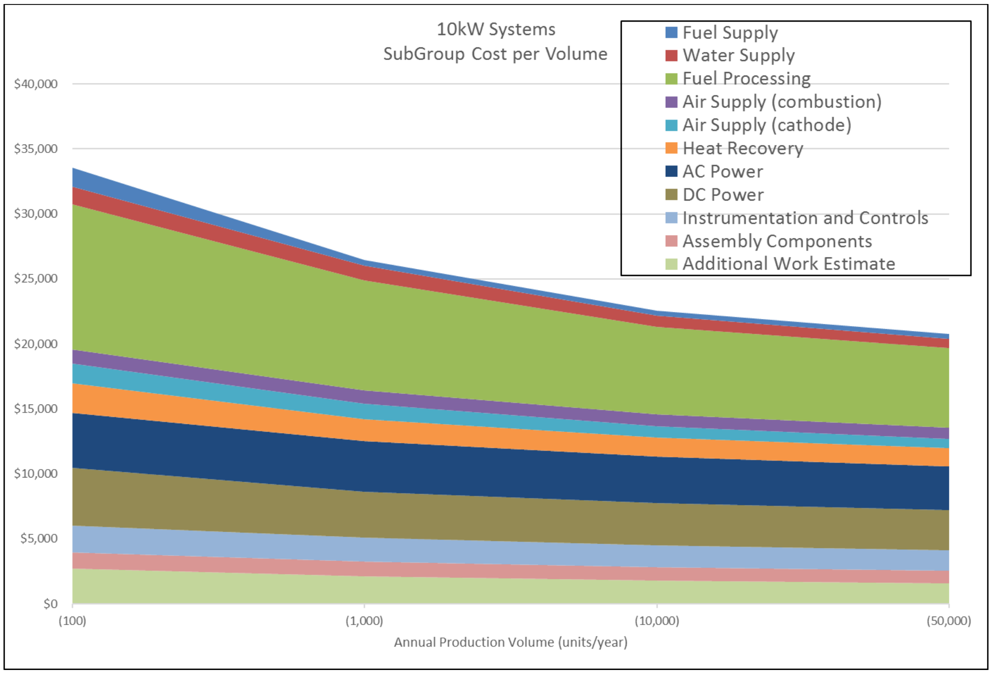


Figure 5-19. 10-kW PEM system BOP cost volume trends

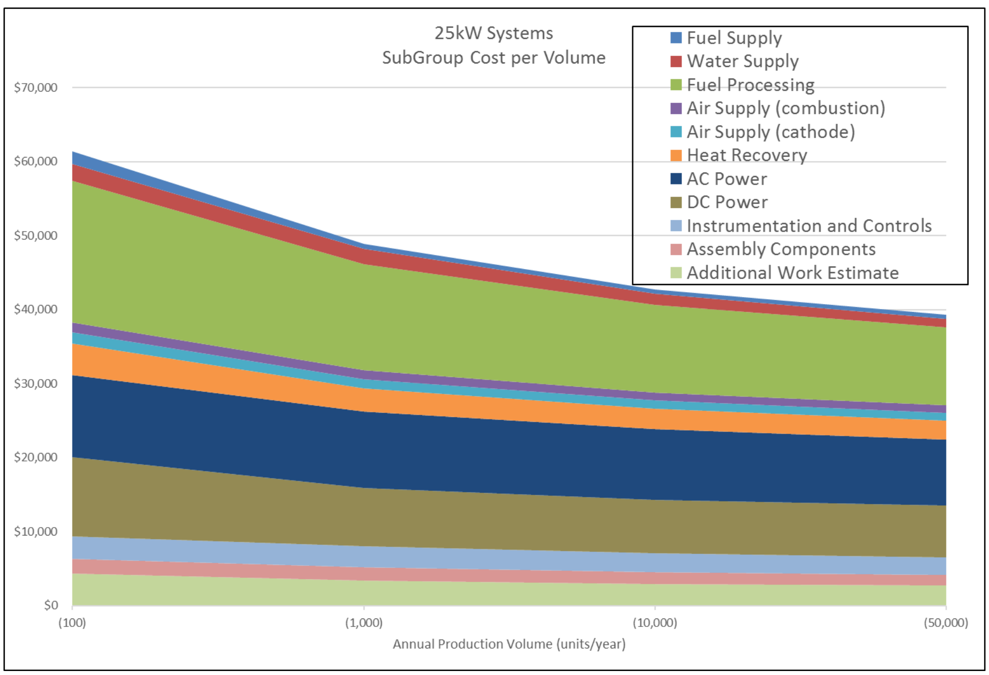


Figure 5-20. 25-kW PEM system BOP cost volume trends

5.3.4 PEM System Assembly and Learning Curve Assumptions

PEM system assembly hardware costs are accounted for in the BOP cost calculations. System assembly times were estimated using the DFMA® software. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45.00/hour, the average system assembly costs were calculated as shown in Table 5-35 and Table 5-36. Details of the learning curve analysis are provided in Appendix A-3.

Table 5-35. PEM Assembly Costs: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$130.93	$104.58	$101.94	$101.71	$130.93	$104.58	$101.94	$101.71
Total Assembly Cost	$130.93	$104.58	$101.94	$101.71	$130.93	$104.58	$101.94	$101.71

Table 5-36. PEM Assembly Costs: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$130.93	$104.58	$101.94	$101.71	$130.93	$104.58	$101.94	$101.71
Total Assembly Cost	$130.93	$104.58	$101.94	$101.71	$130.93	$104.58	$101.94	$101.71

5.3.5 PEM CHP System Testing

Following assembly, the PEM CHP 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 the 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 analysis are the same as stack testing and conditioning as shown in Appendix A-10. The calculated system testing costs are shown in Table 5-37 and Table 5-38.

Table 5-37. PEM Testing Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.64	$0.62	$0.62	$0.62	$3.12	$3.10	$3.10	$3.10
Labor	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88
Machine	$1,210.57	$89.61	$23.88	$23.88	$1,210.57	$89.61	$23.88	$23.88
Scrap	$40.73	$6.07	$4.03	$4.03	$40.81	$6.14	$4.11	$4.11
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1,357.83	$202.18	$134.42	$134.42	$1,360.39	$204.73	$136.97	$136.97

Table 5-38. PEM Testing Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$6.19	$6.19	$6.19	$6.19	$15.49	$15.49	$15.49	$15.49
Labor	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88	$105.88
Machine	$1,210.57	$89.61	$23.88	$23.88	$1,210.57	$89.61	$23.88	$23.88
Scrap	$40.91	$6.24	$4.20	$4.20	$41.19	$6.53	$4.49	$4.49
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1,363.56	$207.93	$140.16	$140.16	$1,373.14	$217.50	$149.74	$149.74

5.3.6 PEM System Capital Cost Assumptions

Table 5-39 summarizes the cost assumptions for the components that make up the total PEM system capital cost.

Table 5-39. 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 yrs	N/A
Discount Rate	7.0%	Guidance for govt project cost calculations per OMB Circular 94
Forklift Cost	$30,000	With extra battery and charger.
Crane Cost	$7,350	Assumes 1-ton capacity jib crane with hoist
Real Estate Cost	$125,000/acre	Assumes vacant land, zoned industrial Columbus, OH
Contingency Margin	10%	Assumed 10% additional work estimate

Production station use was estimated to determine the number of individual process lines required to support various product demand levels. This information, along with equipment cost quotes, was used to determine production station equipment costs. The production facility estimation is based on the floor area required for production equipment, equipment operators, and support personnel. Guidelines used for this analysis were developed by Prof. Jose Ventura at Pennsylvania State University[7] and are detailed in Appendix A-4. Capital cost summaries are provided in Table 5-40 and Table 5-41.

[7] Ventura, J.A. 2001. Facility Layout and Material Handling MS PowerPoint Presentations. Penn State Personal Web Server. Accessed December 2016. http://www.personal.psu.edu/jav1/.

Table 5-40. PEM Capital Cost Summary: 1- and 5-kW Systems

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

Table 5-41. PEM Capital Cost Summary: 10- and 25-kW Systems

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

5.4 SOFC System Manufacturing Costs

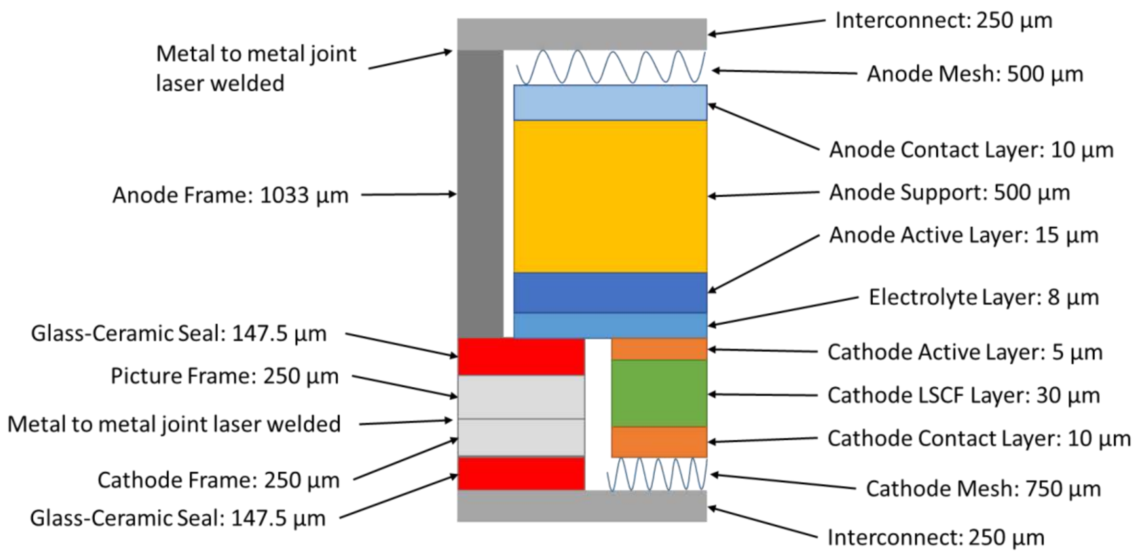
An SOFC system, as described in Section 4, includes a stack and the BOP (fuel processor, support hardware, fuel and air supply, controls and sensors, and electrical equipment). This section discusses the stack manufacturing process to achieve the design specifications in Table 4-3, considers custom fabricated components, and concludes with a summary of subassemblies created from commercially available hardware.

5.4.1 SOFC Stack Manufacturing Process and Cost Assumptions

The SOFC fuel cell stack consists of two end plates and the appropriate number of repeat units. Repeat units include:

- One interconnect and anode frame (these may be integrated into a single piece)
- One cell (anode, electrolyte, cathode) and picture frame (the picture frame supports the entire periphery of the electrolyte)
- Cathode frame
- One cathode mesh and one anode mesh
    - The anode and cathode meshes sandwich the cell to provide flow cavities and a compliant electrical path from the cell to the interconnects
- Seals between each frame, the cell, and the interconnect

Figure 5-21 and Figure 5-22 illustrate the layer configuration and orientation.



Note: Not to scale; parts depicted as shown for clarity.

Figure 5-21. Detail assembly of SOFC cell

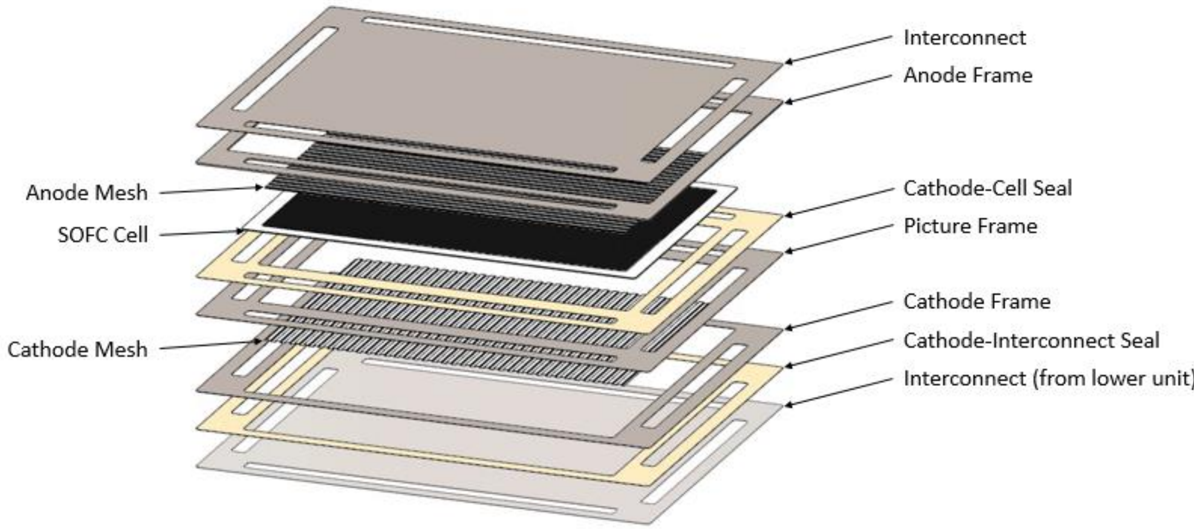


Figure 5-22. Cell repeat unit showing major components

This study focuses only on the primary manufacturing and assembly processes shown in Figure 5-23 and Figure 5-24.

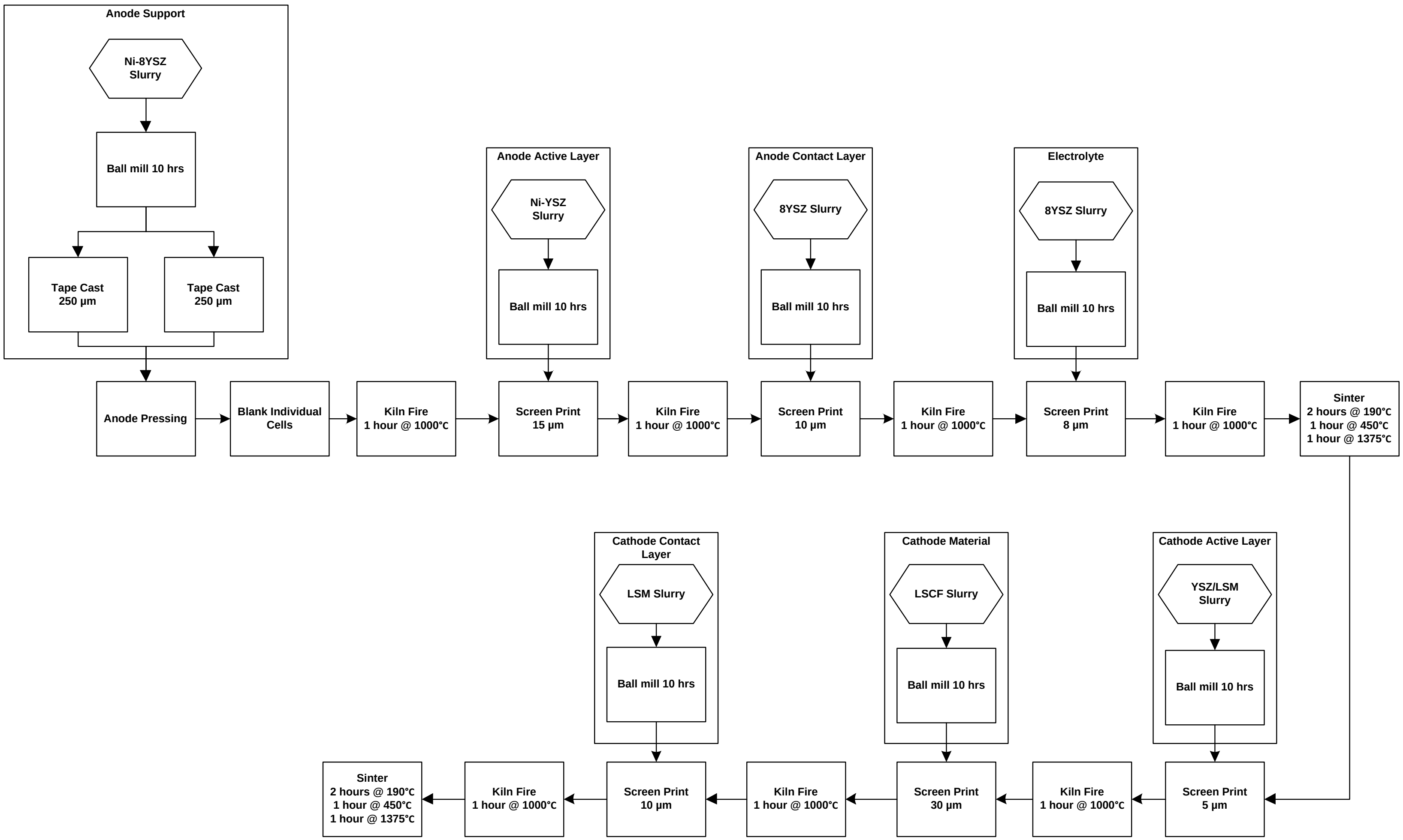


Figure 5-23. SOFC cell manufacturing process

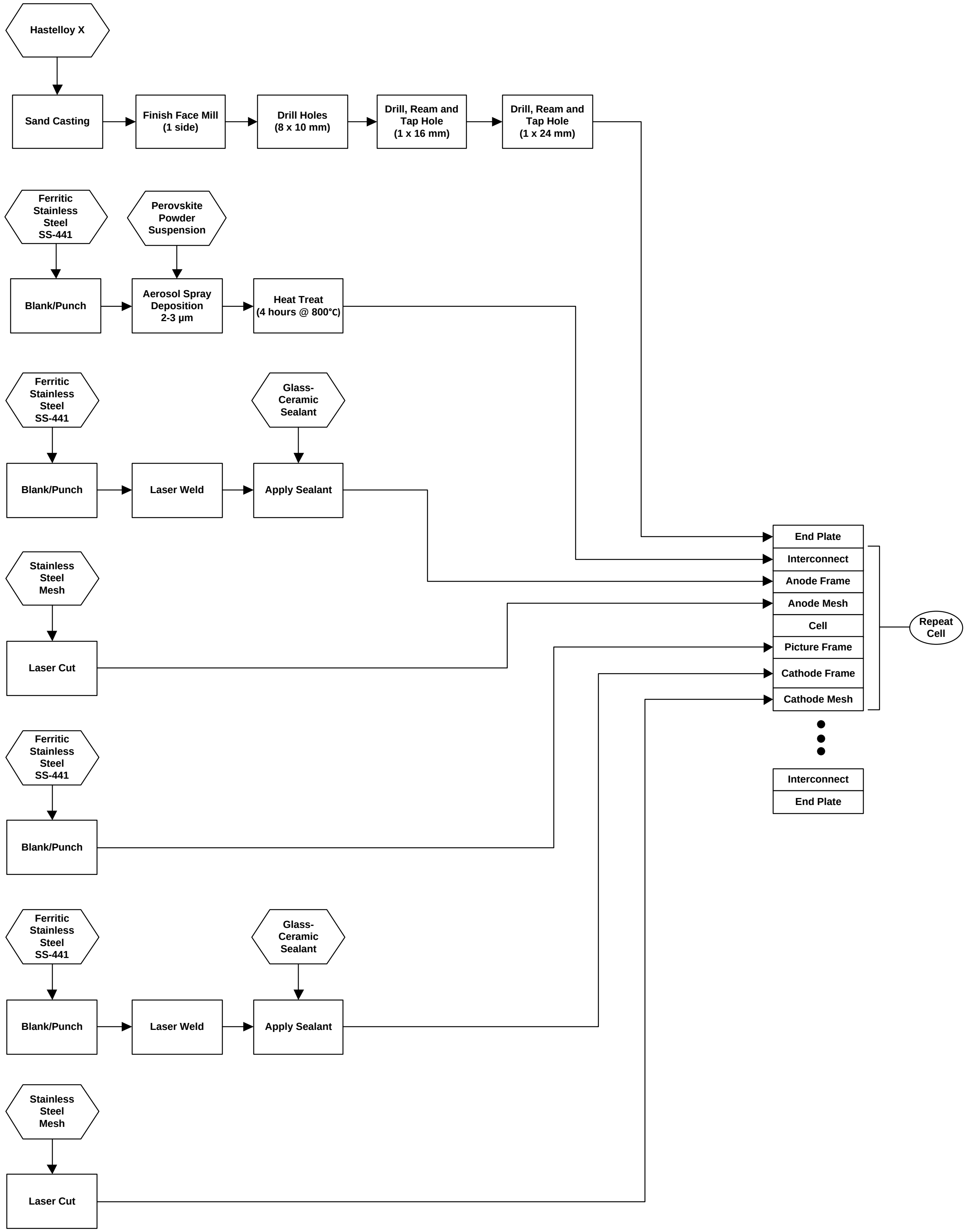


Figure 5-24. SOFC cell assembly process

5.4.1.1 SOFC Stack Component Size and Ceramic Cell Manufacturing Setup

Ceramic cell assemblies for both the 1- and 5-kW stacks are assumed to have a 201-cm^2 active area. Using a length-to-width ratio of 1.5, the active cell size was determined to be 116 mm by 173 mm. Using a 10-mm margin on all sides, the overall cell size was determined to be 136 mm by 234 mm.

Ceramic cell assemblies for both the 10- and 25-kW stacks are assumed to have a 400-cm^2 active area. Using a length-to-width ratio of 1.5, the active cell size was determined to be 164 mm by 244 mm. Using a 10-mm margin on all sides, the overall cell size was determined to be 184 mm by 264 mm.

Cell sizes are shown in Figure 5-25 and Figure 5-26.

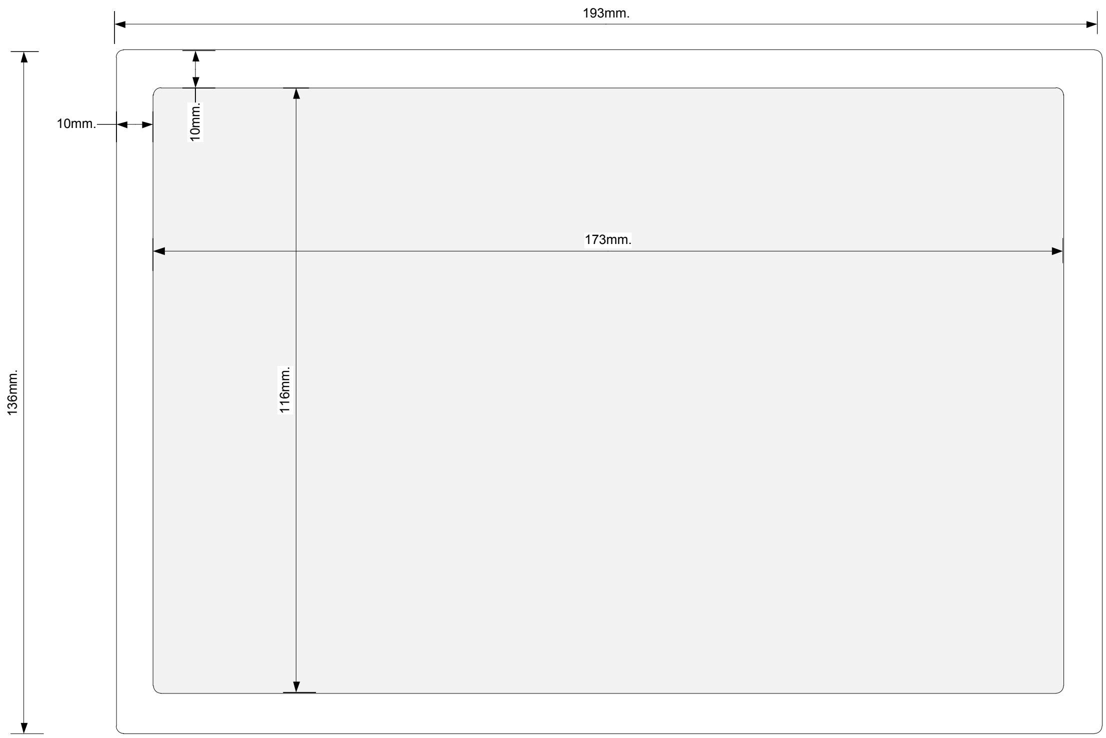


Figure 5-25. SOFC cell size – 201-cm^2 active area

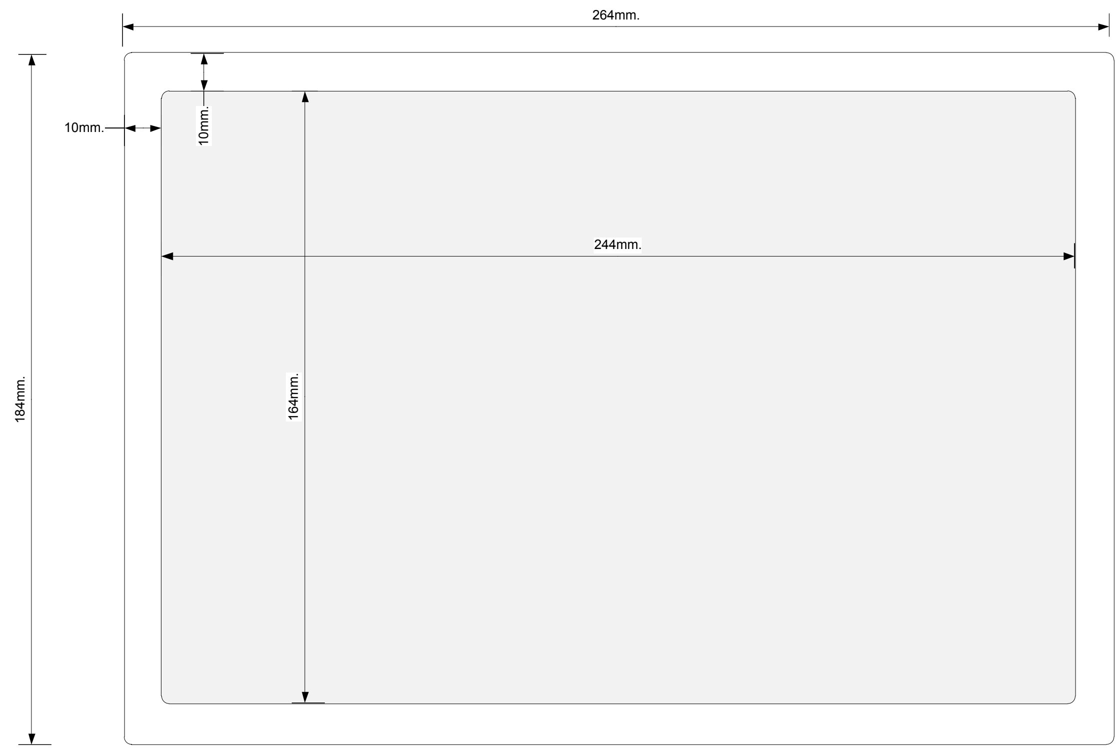


Figure 5-26. SOFC cell size – 400-cm² active area

5.4.1.2 SOFC System Ceramic Cell

The SOFC system's ceramic cell is built up in layers. Each layer starts as an aqueous ceramic slurry that is ball-milled into a uniform suspension, as detailed in Appendix A-12. The anode support is created by tape casting as detailed in Appendix A-22, and blanking as detailed in Appendix A-13. Subsequent layers are screen-printed onto the anode support, as detailed in Appendix A-14. All layers are infrared-conveyor-dried following application, and then kiln-fired, as detailed in Appendix A-15. The cell is sintered twice, following application of the electrolyte layer and following application of the final cathode layer, as detailed in Appendix A-16 The cell is then trimmed to its final configuration as detailed in Appendix A-17. The resulting ceramic cell costs are shown in Table 5-42 and Table 5-43.

Table 5-42. SOFC Ceramic Cell Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4.42	$2.48	$1.65	$1.51	$2.85	$1.84	$1.50	$1.45
Labor	$3.87	$3.20	$3.15	$3.14	$3.28	$3.15	$3.14	$3.14
Machine	$7.04	$6.31	$5.78	$2.51	$6.33	$5.71	$2.42	$1.79
Scrap	$0.47	$0.36	$0.32	$0.21	$0.38	$0.32	$0.21	$0.19
Tooling	$0.20	$0.11	$0.10	$0.10	$0.12	$0.10	$0.10	$0.10
Part Total	$15.99	$12.46	$10.99	$7.47	$12.95	$11.13	$7.37	$6.67
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$335.89	$261.64	$230.74	$156.82	$1,385.69	$1,190.83	$788.96	$714.13

Table 5-43. SOFC Ceramic Cell Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4.68	$3.11	$2.76	$2.70	$3.94	$2.88	$2.72	$2.69
Labor	$4.11	$4.00	$3.99	$3.99	$4.03	$4.00	$3.99	$3.99
Machine	$9.45	$8.02	$3.83	$2.91	$9.37	$5.28	$3.17	$2.78
Scrap	$0.55	$0.46	$0.32	$0.29	$0.53	$0.37	$0.30	$0.29
Tooling	$0.17	$0.14	$0.14	$0.14	$0.14	$0.14	$0.14	$0.14
Part Total	$18.97	$15.73	$11.05	$10.04	$18.02	$12.67	$10.32	$9.89
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$2,029.33	$1,683.26	$1,181.84	$1,073.76	$4,828.14	$3,394.67	$2,765.60	$2,650.26

5.4.1.3 SOFC System End Plates

The SOFC system end plates align with the fuel cell stack across the length of the plate and overhang the stack by 30 mm on all sides to accommodate the eight tie rods that press and hold the stack together. The end plate has two reamed and tapped holes for mounting anode and cathode gas connectors, as shown in Figure 5-27 and Figure 5-28.

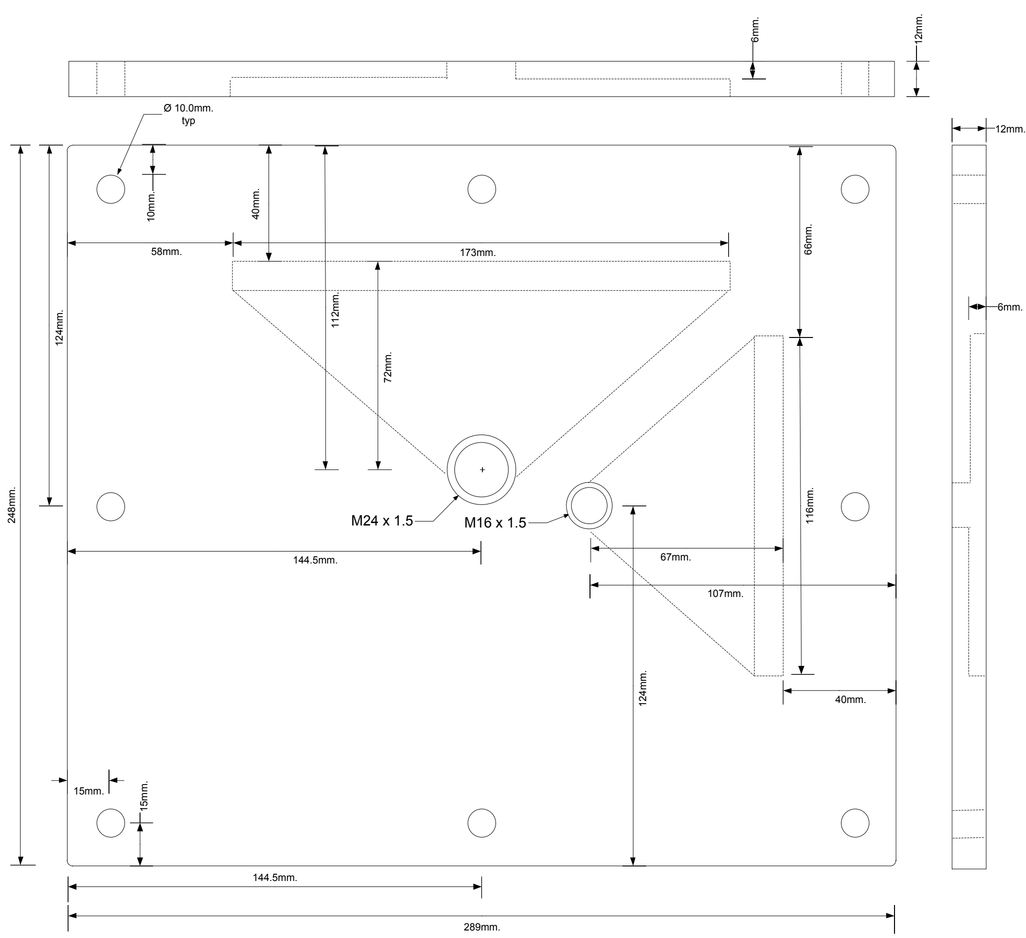


Figure 5-27. SOFC system end plate size – 201cm² active area

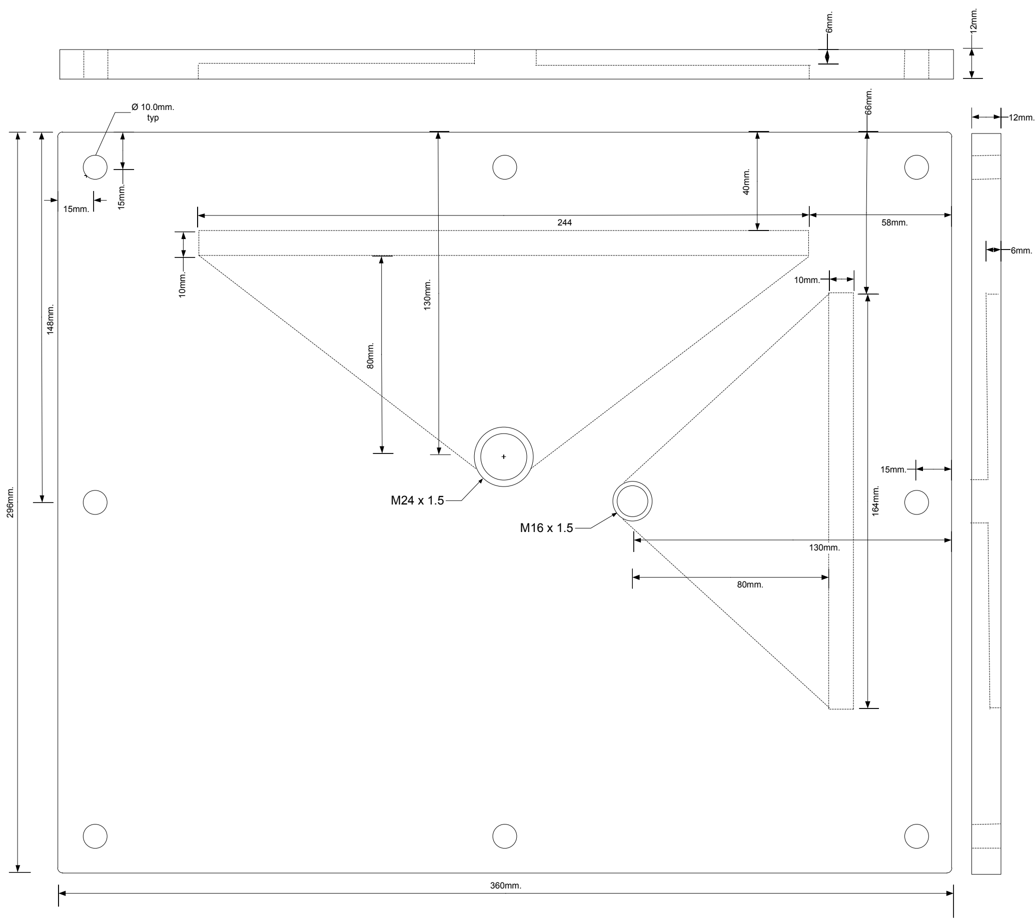


Figure 5-28. SOFC system end plate size – 400-cm² active area

The process selected to produce the end plates was die casting A560 stainless steel. The die-cast plate is then moved to a CNC drilling center to face one side; drill and ream the eight tie rod holes; and drill, ream, and tap the gas connector holes. The end plate cost analysis is detailed in Appendix A-24 and summarized in Table 5-44 and Table 5-45.

Table 5-44. SOFC End Plate Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$224.43	$191.51	$191.51	$191.51	$224.43	$191.51	$191.51	$191.51
Labor	$16.69	$12.26	$11.82	$11.78	$16.69	$12.26	$11.82	$11.78
Machine	$45.99	$45.99	$23.33	$15.72	$45.99	$45.99	$23.33	$15.72
Scrap	$1.44	$1.26	$1.14	$1.10	$1.44	$1.26	$1.14	$1.10
Tooling	$18.26	$1.83	$0.18	$0.11	$18.26	$1.83	$0.18	$0.11
Part Total	$306.82	$252.85	$227.98	$220.22	$306.82	$252.85	$227.98	$220.22
# per Stack	2	2	2	2	2	2	2	2
Stack Total	$613.64	$505.69	$455.96	$440.45	$613.64	$505.69	$455.96	$440.45

Table 5-45. SOFC End Plate Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$314.91	$285.54	$285.54	$285.54	$314.91	$285.54	$285.54	$285.54
Labor	$19.24	$14.85	$14.41	$14.37	$19.24	$14.85	$14.41	$14.37
Machine	$56.14	$56.14	$20.09	$20.09	$56.14	$56.14	$20.09	$20.09
Scrap	$1.96	$1.79	$1.61	$1.61	$1.96	$1.79	$1.61	$1.61
Tooling	$18.59	$1.86	$0.19	$0.11	$18.59	$1.86	$0.19	$0.11
Part Total	$410.84	$360.17	$321.83	$321.71	$410.84	$360.17	$321.83	$321.71
# per Stack	2	2	2	2	2	2	2	2
Stack Total	$821.67	$720.34	$643.65	$643.43	$821.67	$720.34	$643.65	$643.43

5.4.1.4 SOFC System Interconnects

The interconnects are manufactured from 3-mm thick ferritic stainless steel (SS-441) sheet. The material is stamped into a rectangular blank, then punched to provide the anode and cathode gas path openings. For all volumes, the process scrap rate for the stamping operation was assumed to be 0.5%. Following stamping, the interconnects are laser-etched on both sides to create the anode and cathode lateral gas paths, then spray coated with a perovskite material. The coated interconnects are heat-treated at 1,000°C for 4 hours. Details of the analysis are provided in Appendix A-18. The interconnect cost summary is provided in Table 5-46 and Table 5-47.

Table 5-46. SOFC Interconnect Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.91	$0.66	$0.52	$0.45	$0.71	$0.56	$0.45	$0.41
Labor	$0.41	$0.34	$0.34	$0.34	$0.35	$0.34	$0.34	$0.34
Machine	$1.60	$1.53	$1.52	$0.67	$1.53	$1.52	$0.64	$0.34
Scrap	$0.11	$0.09	$0.09	$0.05	$0.09	$0.09	$0.05	$0.04
Tooling	$3.55	$0.36	$0.11	$0.10	$0.70	$0.14	$0.10	$0.09
Part Total	$6.59	$2.98	$2.57	$1.60	$3.39	$2.64	$1.57	$1.22
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$138.37	$62.52	$53.93	$33.67	$362.56	$282.47	$168.11	$130.08

Table 5-47. SOFC Interconnect Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.11	$0.87	$0.71	$0.68	$1.00	$0.80	$0.68	$0.68
Labor	$0.46	$0.44	$0.43	$0.43	$0.44	$0.43	$0.43	$0.43
Machine	$2.22	$2.19	$1.01	$0.40	$2.20	$1.76	$0.55	$0.37
Scrap	$0.14	$0.13	$0.08	$0.05	$0.13	$0.11	$0.06	$0.05
Tooling	$0.91	$0.18	$0.13	$0.12	$0.36	$0.14	$0.12	$0.12
Part Total	$4.83	$3.81	$2.35	$1.69	$4.14	$3.24	$1.85	$1.66
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$516.58	$407.16	$251.98	$181.10	$1,109.42	$869.60	$495.03	$444.41

5.4.1.5 SOFC Frames

The SOFC repeat unit contains three frames as illustrated in Figure 5-21 and Figure 5-22:

- The anode frame supports the interconnect on the anode side and provides space for the anode and anode mesh.
- The picture frame supports the entire periphery of the electrolyte and is sealed (weld or glass seal) to the anode frame.
- The cathode frame supports the interconnect on the cathode side and provides space for the cathode mesh.

The anode, picture, and cathode frames are manufactured from 1.033-mm, 0.25-mm, and 0.25-mm thick (respectively) ferritic stainless steel (SS-441) sheet. The material is stamped into a rectangular blank, then punched to provide the required gas path openings and active area relief. For all volumes, the process scrap rate for the stamping operation was assumed to be 0.5%. Details of the analysis are shown in Appendix A-19. The frame cost summaries are provided in Table 5-48 through Table 5-53. The tooling cost differences are primarily the result of different configurations resulting in different total shearing lengths of the tooling.

Table 5-48. SOFC Anode Frame Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.92	$0.72	$0.72	$0.72	$0.72	$0.72	$0.72	$0.72
Labor	$0.12	$0.02	$0.02	$0.01	$0.03	$0.02	$0.01	$0.01
Machine	$0.11	$0.03	$0.03	$0.02	$0.04	$0.03	$0.02	$0.01
Scrap	$0.01	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$3.73	$0.37	$0.11	$0.10	$0.73	$0.15	$0.10	$0.10
Part Total	$4.88	$1.15	$0.88	$0.87	$1.53	$0.91	$0.87	$0.85
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$102.47	$24.24	$18.41	$18.22	$163.84	$97.67	$92.62	$90.94

Table 5-49. SOFC Anode Frame Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.16	$1.16	$1.16	$1.16	$1.16	$1.16	$1.16	$1.16
Labor	$0.04	$0.02	$0.02	$0.02	$0.03	$0.02	$0.02	$0.02
Machine	$0.05	$0.04	$0.04	$0.01	$0.04	$0.04	$0.04	$0.02
Scrap	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01
Tooling	$0.95	$0.19	$0.13	$0.13	$0.38	$0.15	$0.13	$0.13
Part Total	$2.22	$1.42	$1.36	$1.33	$1.62	$1.38	$1.36	$1.33
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$237.03	$151.93	$145.46	$141.89	$434.35	$369.66	$363.19	$357.09

Table 5-50. SOFC Picture Frame Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.22	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
Labor	$0.06	$0.02	$0.01	$0.01	$0.02	$0.01	$0.01	$0.01
Machine	$0.06	$0.02	$0.02	$0.02	$0.03	$0.02	$0.02	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$4.41	$0.44	$0.13	$0.12	$0.87	$0.17	$0.12	$0.12
Part Total	$4.76	$0.65	$0.34	$0.33	$1.09	$0.38	$0.33	$0.31
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$99.86	$13.74	$7.08	$6.88	$116.40	$40.55	$34.82	$33.31

Table 5-51. SOFC Picture Frame Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.28	$0.28	$0.28	$0.28	$0.28	$0.28	$0.28	$0.28
Labor	$0.03	$0.02	$0.01	$0.01	$0.02	$0.02	$0.01	$0.01
Machine	$0.04	$0.03	$0.02	$0.01	$0.03	$0.02	$0.02	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$1.14	$0.23	$0.16	$0.15	$0.46	$0.18	$0.15	$0.15
Part Total	$1.50	$0.55	$0.48	$0.46	$0.79	$0.50	$0.48	$0.46
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$160.26	$59.14	$51.47	$48.75	$211.94	$135.23	$127.56	$123.27

Table 5-52. SOFC Cathode Frame Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.22	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17	$0.17
Labor	$0.06	$0.02	$0.01	$0.01	$0.02	$0.01	$0.01	$0.01
Machine	$0.06	$0.02	$0.02	$0.02	$0.03	$0.02	$0.02	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$3.45	$0.34	$0.10	$0.10	$0.68	$0.14	$0.09	$0.09
Part Total	$3.79	$0.56	$0.31	$0.30	$0.90	$0.34	$0.30	$0.29
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$79.64	$11.70	$6.46	$6.30	$96.11	$36.42	$31.90	$30.51

Table 5-53. SOFC Cathode Frame Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.27	$0.27	$0.27	$0.27	$0.27	$0.27	$0.27	$0.27
Labor	$0.03	$0.02	$0.01	$0.01	$0.02	$0.02	$0.01	$0.01
Machine	$0.04	$0.03	$0.02	$0.01	$0.03	$0.02	$0.02	$0.01
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Tooling	$0.87	$0.17	$0.12	$0.12	$0.35	$0.14	$0.12	$0.12
Part Total	$1.22	$0.49	$0.43	$0.41	$0.67	$0.45	$0.43	$0.41
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$130.49	$52.29	$46.34	$43.80	$180.49	$120.97	$115.01	$110.84

5.4.1.6 SOFC Laser Welding

To minimize the requirement for glass ceramic seals and reduce any potential for leaks, certain sets of metallic components are penetration-laser-welded together prior to assembly. Specifically, the anode frame is joined to the interconnect and the cathode frame is joined to the cell picture frame. The laser path tracks inside the frame perimeter and outside any closed gas ports. Details of the analysis are shown in Appendix A-26. The sealing cost summary is provided in Table 5-54 and Table 5-55.

Table 5-54. SOFC Laser Welding Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	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	$0.25	$0.24	$0.23	$0.23	$0.24	$0.23	$0.23	$0.23
Machine	$67.02	$6.56	$0.52	$0.11	$13.03	$1.16	$0.11	$0.11
Scrap	$0.34	$0.03	$0.00	$0.00	$0.07	$0.01	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$67.61	$6.83	$0.76	$0.35	$13.33	$1.41	$0.34	$0.34
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$1,419.76	$143.49	$15.86	$7.35	$1,426.63	$150.36	$36.91	$36.51

Table 5-55. SOFC Laser Welding Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29	$0.29
Machine	$13.00	$1.13	$0.13	$0.13	$5.07	$0.34	$0.13	$0.13
Scrap	$0.07	$0.01	$0.00	$0.00	$0.03	$0.00	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$13.35	$1.42	$0.42	$0.42	$5.39	$0.63	$0.42	$0.42
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$1,428.55	$152.28	$44.71	$44.70	$1,444.31	$168.04	$111.97	$111.97

5.4.1.7 SOFC System Ceramic-Glass Sealing

A ceramic-glass sealant is applied between the cell, picture frame, and interconnect prior to assembling onto the stack. The primary components are lanthanum oxide and borosilicate glass in an organic solvent paste. The paste is applied as a 0.25-mm bead using a robotic applicator. The scrap rate was assumed to be 3.0%. Details of the analysis are shown in Appendix A-20. The sealing cost summary is provided in Table 5-56 and Table 5-57.

Table 5-56. SOFC Ceramic-Glass Sealing Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.12	$0.79	$0.55	$0.49	$0.87	$0.61	$0.49	$0.49
Labor	$0.59	$0.54	$0.54	$0.54	$0.55	$0.54	$0.54	$0.54
Machine	$161.77	$16.01	$1.43	$0.13	$31.59	$2.99	$0.13	$0.06
Scrap	$5.06	$0.54	$0.08	$0.04	$1.02	$0.13	$0.04	$0.03
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$168.54	$17.87	$2.60	$1.19	$34.03	$4.27	$1.19	$1.12
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$3,539.25	$375.33	$54.53	$25.04	$3,641.74	$456.50	$126.92	$119.86

Table 5-57. SOFC Ceramic-Glass Sealing Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.09	$0.77	$0.63	$0.63	$0.95	$0.67	$0.63	$0.63
Labor	$0.69	$0.68	$0.68	$0.68	$0.68	$0.68	$0.68	$0.68
Machine	$31.55	$2.94	$0.08	$0.08	$12.45	$1.03	$0.14	$0.04
Scrap	$1.03	$0.14	$0.04	$0.04	$0.44	$0.07	$0.04	$0.04
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$34.36	$4.52	$1.43	$1.43	$14.52	$2.45	$1.50	$1.39
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$3,676.15	$483.44	$153.08	$153.08	$3,890.08	$655.27	$400.80	$372.73

5.4.1.8 SOFC Mesh

Each cell has an anode and cathode mesh that each act as an electrical conduit between the electrodes and the interconnect while allowing sufficient space for gas flow over the cell surface. They are created from 0.08-mm stainless steel that has been expanded and corrugated to the proper height, 0.5 mm for the anode and 0.75 mm for the cathode. The material is then laser-cut to final dimension. Details of the analysis are shown in Appendix A-25. The mesh cost summaries are provided in Table 5-58 and Table 5-59 (anode mesh) and Table 5-60 and Table 5-61 (cathode mesh).

Table 5-58. SOFC Anode Mesh Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.30	$0.91	$0.64	$0.50	$1.01	$0.71	$0.50	$0.40
Labor	$0.10	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09
Machine	$0.10	$0.10	$0.10	$0.07	$0.10	$0.10	$0.06	$0.04
Scrap	$0.01	$0.01	$0.00	$0.00	$0.01	$0.00	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1.51	$1.12	$0.84	$0.67	$1.22	$0.91	$0.66	$0.54
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$31.76	$23.43	$17.70	$13.99	$130.11	$97.69	$70.92	$57.26

Table 5-59. SOFC Anode Mesh Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.30	$0.92	$0.65	$0.57	$1.13	$0.80	$0.57	$0.57
Labor	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11
Machine	$0.12	$0.12	$0.06	$0.04	$0.12	$0.12	$0.04	$0.03
Scrap	$0.01	$0.01	$0.00	$0.00	$0.01	$0.01	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1.54	$1.15	$0.81	$0.71	$1.36	$1.03	$0.71	$0.70
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$164.27	$122.71	$87.06	$76.30	$365.38	$275.12	$191.05	$188.67

Table 5-60. SOFC Cathode Mesh Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.38	$0.97	$0.68	$0.54	$1.08	$0.76	$0.53	$0.42
Labor	$0.11	$0.09	$0.09	$0.09	$0.10	$0.09	$0.09	$0.09
Machine	$0.10	$0.10	$0.10	$0.07	$0.10	$0.10	$0.07	$0.04
Scrap	$0.01	$0.01	$0.00	$0.00	$0.01	$0.00	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1.60	$1.18	$0.89	$0.70	$1.28	$0.96	$0.70	$0.56
# per Stack	21	21	21	21	107	107	107	107
Stack Total	$33.56	$24.72	$18.64	$14.73	$137.37	$102.93	$74.65	$60.24

Table 5-61. SOFC Cathode Mesh Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.36	$0.96	$0.68	$0.59	$1.18	$0.83	$0.59	$0.59
Labor	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11
Machine	$0.12	$0.12	$0.06	$0.04	$0.12	$0.12	$0.04	$0.03
Scrap	$0.01	$0.01	$0.00	$0.00	$0.01	$0.01	$0.00	$0.00
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1.60	$1.19	$0.85	$0.74	$1.42	$1.07	$0.74	$0.73
# per Stack	107	107	107	107	268	268	268	268
Stack Total	$171.06	$127.61	$90.53	$79.34	$380.31	$285.96	$198.68	$196.26

5.4.1.9 SOFC Stack Assembly

The stack components are assembled as shown in Figure 5-24. Pressure is applied to the completed stack using a hydraulic press, and the tie rods are installed to complete the stack assembly. Tie rod costs were estimated to be between $1.76 and $13.20 per stack depending on stack height, and gas fittings and other assembly hardware (inserts, washers, nuts) were estimated to be $215.67 per stack before applying learning curve analysis. Stack assembly times were estimated using the DFMA® software, and ranged from 0.30 to 2.32 hours depending on cell count. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45.00/hour, the average stack assembly costs were calculated as detailed in Appendix A-3 and summarized in Table 5-62 and Table 5-63.

Table 5-62. SOFC Stack Assembly Costs: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$218.65	$204.44	$191.18	$182.42	$222.53	$208.02	$194.53	$185.64
Labor	$25.33	$20.23	$19.72	$19.68	$93.28	$74.50	$72.62	$72.46
Total Assembly Cost	$243.98	$224.67	$210.90	$202.10	$315.81	$282.52	$267.16	$258.09

Table 5-63. SOFC Stack Assembly Costs: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$220.95	$206.61	$193.20	$184.35	$228.87	$214.02	$200.12	$190.95
Labor	$111.43	$89.00	$86.75	$86.56	$265.57	$212.11	$206.77	$206.29
Total Assembly Cost	$332.38	$295.61	$279.95	$270.90	$494.44	$426.13	$406.89	$397.24

5.4.1.10 SOFC Stack Brazing

Following assembly, the stack is furnace-brazed to cure the ceramic-glass sealant. The component scrap rate following brazing was assumed to be 0.5%. Details of the analysis are shown in Appendix A-21. The stack brazing cost summary is provided in Table 5-64 and Table 5-65.

Table 5-64. SOFC Stack Brazing Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4.43	$2.11	$1.02	$0.90	$13.36	$6.36	$4.57	$4.52
Labor	$1.39	$0.92	$0.87	$0.87	$2.65	$2.17	$2.12	$2.12
Machine	$6.24	$6.24	$6.24	$6.24	$15.85	$15.85	$15.85	$6.46
Scrap	$0.37	$0.29	$0.25	$0.25	$0.98	$0.75	$0.70	$0.40
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$12.44	$9.56	$8.38	$8.26	$32.83	$25.13	$23.23	$13.50

Table 5-65. SOFC Stack Brazing Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$21.43	$10.35	$9.03	$9.03	$39.95	$24.00	$22.62	$22.62
Labor	$3.48	$3.01	$2.96	$2.96	$6.92	$6.45	$6.40	$6.40
Machine	$22.18	$22.18	$22.18	$14.15	$48.35	$48.35	$36.29	$19.28
Scrap	$1.46	$1.10	$1.06	$0.81	$2.94	$2.44	$2.02	$1.49
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$48.56	$36.64	$35.23	$26.94	$98.17	$81.23	$67.33	$49.78

5.4.1.11 SOFC Stack Testing and Conditioning

Following assembly, the stack is placed on a test stand and subjected to a 6-hour test and conditioning cycle to assess its fitness for installation into a system. The cycle consists of a 2-hour warm-up, 2 hours at full power, and a 2-hour cool-down. The test reject rate was assumed to be 5.0%. Because it is not possible to disassemble the brazed stack, a failed stack is considered to be scrap, resulting in relatively high scrap costs associated with this task. Details of the analysis are shown in Appendix A-23. The stack testing and conditioning summary is provided in Table 5-66 and Table 5-67.

Table 5-66. SOFC Stack Testing and Conditioning Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$42.35	$20.18	$9.64	$6.45	$127.75	$60.87	$32.73	$31.34
Labor	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76
Machine	$1,207.66	$86.70	$25.87	$25.87	$1,207.66	$86.70	$25.87	$25.87
Scrap	$424.13	$102.39	$67.99	$59.15	$521.89	$188.11	$125.71	$115.78
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1,831.90	$367.03	$261.28	$249.24	$2,015.06	$493.45	$342.08	$330.76

Table 5-67. SOFC Stack Testing and Conditioning Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$204.55	$97.80	$62.67	$62.67	$381.23	$193.69	$156.97	$156.97
Labor	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76	$157.76
Machine	$1,207.66	$86.70	$25.87	$25.87	$1,207.66	$86.70	$25.87	$25.87
Scrap	$594.10	$244.01	$171.53	$159.56	$842.52	$418.03	$327.86	$315.19
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$2,164.08	$586.27	$417.84	$405.87	$2,589.17	$856.18	$668.47	$655.80

5.4.1.12 SOFC Stack Cost Summary

Total SOFC stack component and manufacturing costs are summarized in Table 5-68 through Table 5-71.

Table 5-68. SOFC Stack Component Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	**1,000**	10,000	50,000	100	1,000	10,000	50,000
Ceramic Cells	$335.89	$261.64	$230.74	$156.82	$1,385.69	$1,190.83	$788.96	$714.13
Interconnects	$138.37	$62.52	$53.93	$33.67	$362.56	$282.47	$168.11	$130.08
Anode Frame	$102.47	$24.24	$18.41	$18.22	$163.84	$97.67	$92.62	$90.94
Anode Mesh	$31.76	$23.43	$17.70	$13.99	$130.11	$97.69	$70.92	$57.26
Cathode Frame	$79.64	$11.70	$6.46	$6.30	$96.11	$36.42	$31.90	$30.51
Cathode Mesh	$33.56	$24.72	$18.64	$14.73	$137.37	$102.93	$74.65	$60.24
Picture Frame	$99.86	$13.74	$7.08	$6.88	$116.40	$40.55	$34.82	$33.31
Laser Weld	$1,419.76	$143.49	$15.86	$7.35	$1,426.63	$150.36	$36.91	$36.51
Glass Ceramic Sealing	$3,539.25	$375.33	$54.53	$25.04	$3,641.74	$456.50	$126.92	$119.86
End Plates	$613.64	$505.69	$455.96	$440.45	$613.64	$505.69	$455.96	$440.45
Assembly hardware	$218.65	$204.44	$191.18	$182.42	$222.53	$208.02	$194.53	$185.64
Assembly labor	$25.33	$20.23	$19.72	$19.68	$93.28	$74.50	$72.62	$72.46
Stack Brazing	$12.44	$9.56	$8.38	$8.26	$32.83	$25.13	$23.23	$13.50
Test and conditioning	$1,831.90	$367.03	$261.28	$249.24	$2,015.06	$493.45	$342.08	$330.76
Total Cost per Stack	$8,482.51	$2,047.76	$1,359.87	$1,183.04	$10,437.79	$3,762.22	$2,514.24	$2,315.64
Cost per kW_{net}	$8,482.51	$2,047.76	$1,359.87	$1,183.04	$2,087.56	$752.44	$502.85	$463.13

Table 5-69. SOFC Stack Component Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Ceramic Cells	$2,029.33	$1,683.26	$1,181.84	$1,073.76	$4,828.14	$3,394.67	$2,765.60	$2,650.26
Interconnects	$516.58	$407.16	$251.98	$181.10	$1,109.42	$869.60	$495.03	$444.41
Anode Frame	$237.03	$151.93	$145.46	$141.89	$434.35	$369.66	$363.19	$357.09
Anode Mesh	$164.27	$122.71	$87.06	$76.30	$365.38	$275.12	$191.05	$188.67
Cathode Frame	$130.49	$52.29	$46.34	$43.80	$180.49	$120.97	$115.01	$110.84
Cathode Mesh	$171.06	$127.61	$90.53	$79.34	$380.31	$285.96	$198.68	$196.26
Picture Frame	$160.26	$59.14	$51.47	$48.75	$211.94	$135.23	$127.56	$123.27
Laser Weld	$1,428.55	$152.28	$44.71	$44.70	$1,444.31	$168.04	$111.97	$111.97
Glass Ceramic Sealing	$3,676.15	$483.44	$153.08	$153.08	$3,890.08	$655.27	$400.80	$372.73
End Plates	$821.67	$720.34	$643.65	$643.43	$821.67	$720.34	$643.65	$643.43
Assembly Hardware	$220.95	$206.61	$193.20	$184.35	$228.87	$214.02	$200.12	$190.95
Assembly Labor	$111.43	$89.00	$86.75	$86.56	$265.57	$212.11	$206.77	$206.29
Stack Brazing	$48.56	$36.64	$35.23	$26.94	$98.17	$81.23	$67.33	$49.78
Test and Conditioning	$2,164.08	$586.27	$417.84	$405.87	$2,589.17	$856.18	$668.47	$655.80
Total Cost	$11,880.41	$4,878.69	$3,429.14	$3,189.87	$16,847.88	$8,358.40	$6,555.23	$6,301.76
Cost per kW_{net}	$1,188.04	$487.87	$342.91	$318.99	$673.92	$334.34	$262.21	$252.07

Table 5-70. SOFC Stack Manufacturing Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$933.32	$752.97	$691.21	$667.24	$1,622.95	$1,250.63	$1,099.37	$1,056.43
Labor	$334.83	$299.26	$296.08	$295.80	$787.93	$739.37	$734.80	$734.41
Machine	$6,301.21	$829.64	$278.58	$139.62	$6,963.43	$1,441.83	$461.54	$322.36
Scrap	$554.40	$128.20	$82.11	$69.26	$696.14	$252.82	$163.45	$149.41
Tooling	$358.75	$37.70	$11.91	$11.12	$367.35	$77.56	$55.08	$53.03
Part Total	$8,482.51	$2,047.76	$1,359.87	$1,183.04	$10,437.79	$3,762.22	$2,514.24	$2,315.64

Table 5-71. SOFC Stack Manufacturing Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$2,280.83	$1,777.87	$1,599.36	$1,564.18	$3,937.28	$3,064.09	$2,800.17	$2,784.63
Labor	$940.18	$886.73	$881.74	$881.32	$2,006.39	$1,924.09	$1,915.92	$1,915.19
Machine	$7,396.43	$1,783.58	$649.70	$466.49	$9,257.67	$2,586.06	$1,214.10	$997.82
Scrap	$795.32	$330.31	$226.41	$208.54	$1,158.65	$579.28	$448.36	$429.19
Tooling	$469.32	$101.68	$73.34	$70.71	$490.37	$207.02	$178.73	$176.92
Part Total	$11,882.08	$4,880.17	$3,430.55	$3,191.23	$16,850.37	$8,360.54	$6,557.28	$6,303.76

SOFC stack cost volume trends are shown in Figure 5-29 through Figure 5-32.

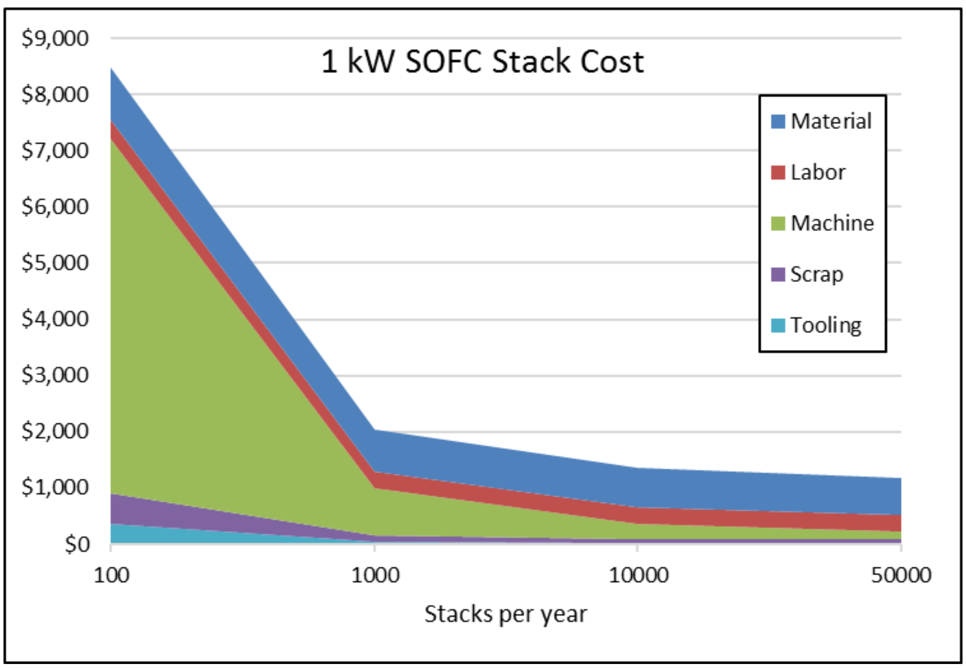


Figure 5-29. 1-kW SOFC stack cost volume trends

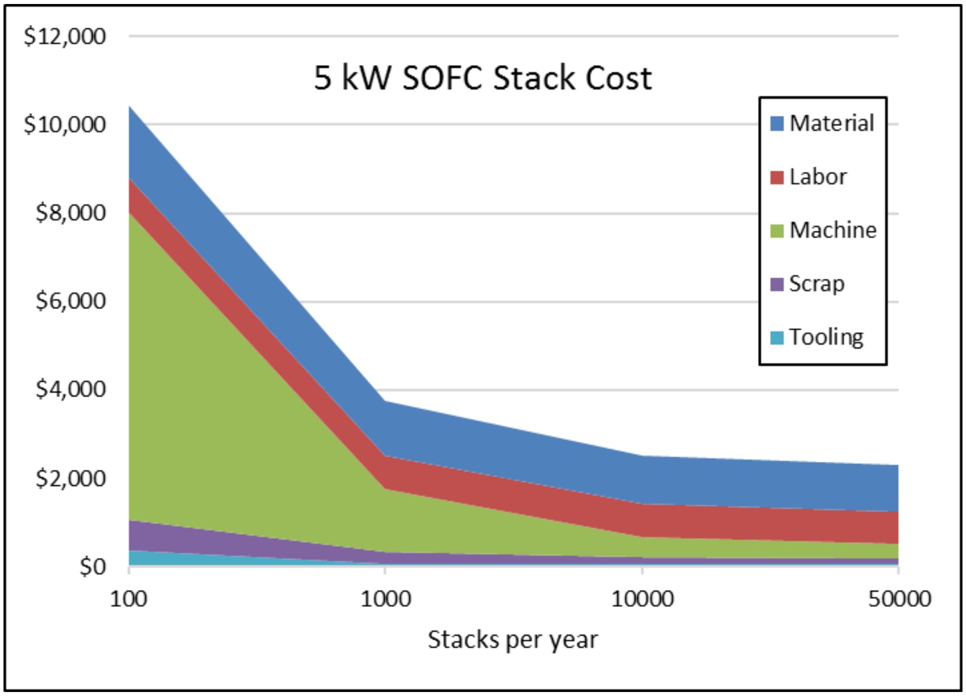


Figure 5-30. 5-kW SOFC stack cost volume trends

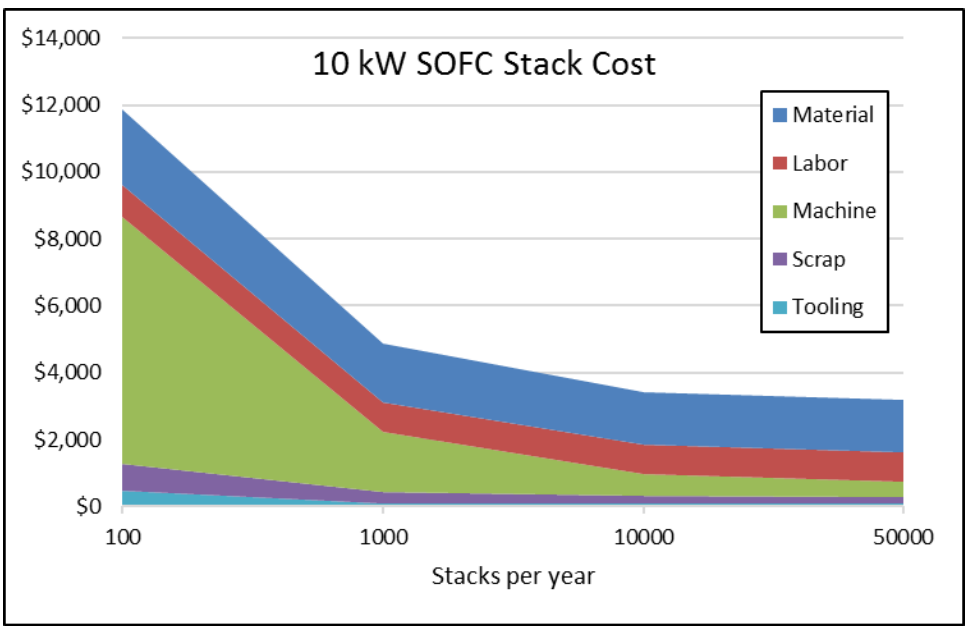


Figure 5-31. 10-kW SOFC stack cost volume trends

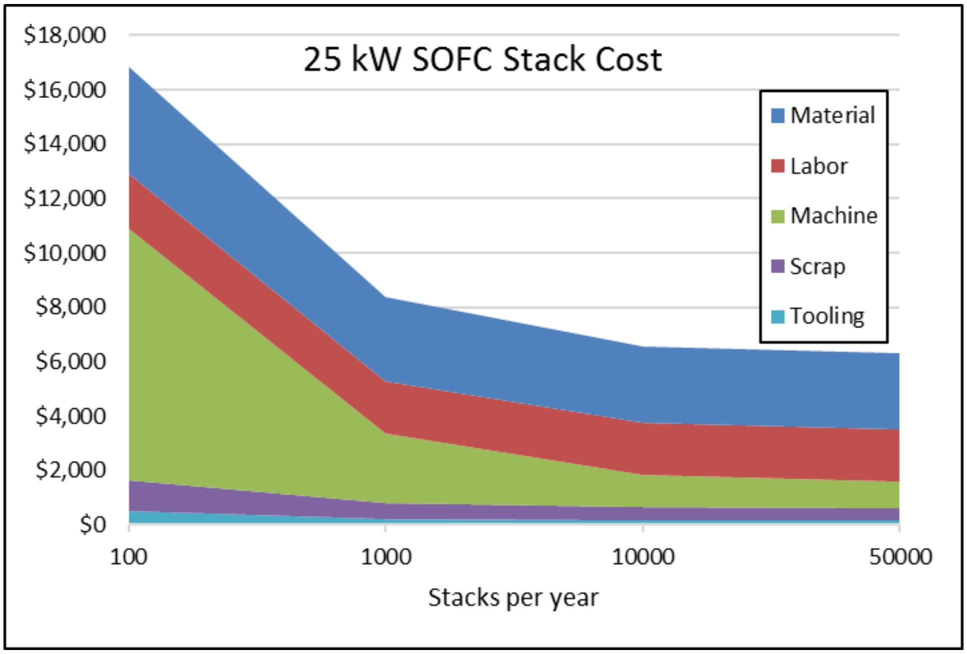


Figure 5-32. 25-kW SOFC stack cost volume trends

5.4.2 SOFC System BOP Manufacturing Cost Assessment

Fuel processing systems for natural gas and propane, the fuels of choice for primary power and CHP applications, tend to be unique to each manufacturer with very little detailed information available to the public. To provide a basis for costing, representative fuel processing systems were designed by Battelle based on experience with smaller systems and conversations with various component suppliers. The Battelle-designed fuel processing systems were modeled with ChemCad® to define operating temperatures, pressures, heat loads, and other performance metrics. The ChemCad® model outputs were used to specify some items for commercial quotes and to define performance criteria for other non-standard components that were assumed to be fabricated in-house. Fabricated components were modeled using DFMA® software. For the SOFC system, fabricated items included the reformer and WGS and PrOx reactors. The reformate burner was based on a commercially available burner. While we recognize that some additional modifications will be required to manage the high-hydrogen/low-BTU wet anode gas, we believe that the final cost, after non-recurring engineering, should be representative. The heat exchangers shown in Figure 5-35 were quoted for one-off delivery by several heat exchanger manufacturers, as they have no experience with the higher production volumes evaluated in this study. Only one heat exchanger manufacturer was able to provide quotes for more than 1,000 units/order.

The reformer concept pricing was based on a reformer design patented by Catacel Corporation (now part of Johnson Matthey). The patent describes a single-tube, single-burner configuration suitable for systems up to approximately 25 kW. The shift and PrOx reactors are pipe reactors with commercial granulated catalysts.

5.4.2.1 SOFC System Steam Reformer

To provide a basis for DFMA® analysis, we assumed the steam reformer would be based on the design of the Catacel SSR® catalytic steam reformer (Figure 5-33). The conceptual design was drawn from patent no. 7,501,102, with guidance on sizing provided informally by Catacel. The reformer consists of a stack of catalyst-coated fans or stages and is scaled primarily by increasing the number of stages in the stack but also by adjusting stage diameter.

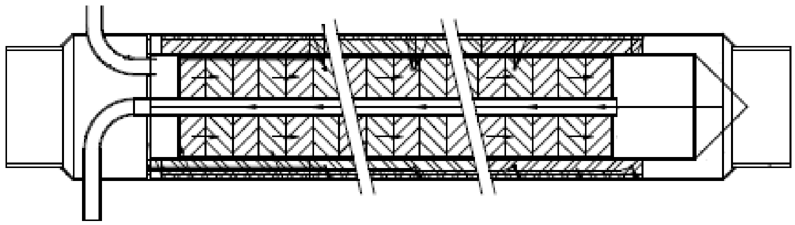
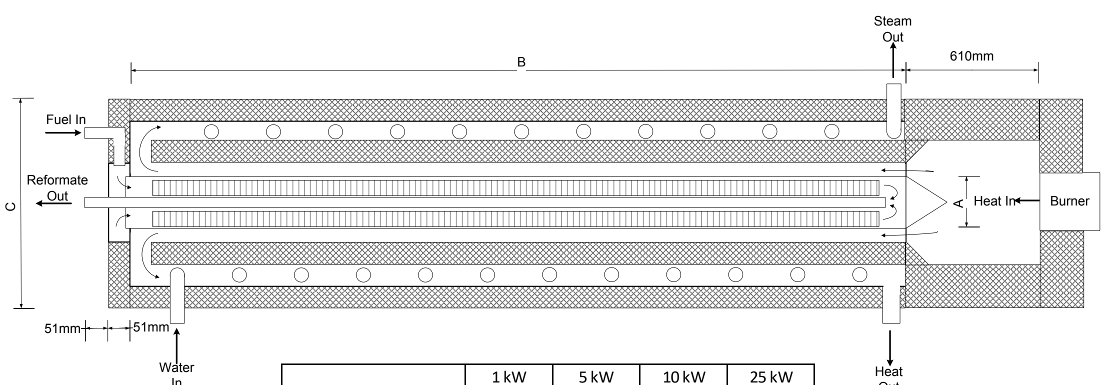


Figure 5-33. Catacel SSR® schematic diagram

We started by determining the required coated catalyst surface area for each reformer based on approximately 600 in^2 (3,871 cm^2) of catalyst per kilowatt based on the Catacel SSR® design. For the systems under consideration, we used the reformer sizing parameters shown in Table 5-72. A schematic is shown in Figure 5-34. The SOFC system reformer is sized to approximately 45% of the size of the PEM system reformer because some methane breakthrough is acceptable, in fact desirable, for SOFC stack cooling from internal reforming. An additional factor in the downsizing is the higher electrical efficiency of the SOFC system.

Table 5-72. SOFC System Reformer Sizing Parameters

System Size (kW)	Reformer Size (kW)	Catalyst Area (cm^2)
1	0.65	2,491.66
5	3.24	12,458.30
10	6.48	24,916.60
25	16.20	62,291.49



	1 kW	5 kW	10 kW	25 kW
Dia. A - mm(in)	53 (2.1)	129 (5.1)	129 (5.1)	129 (5.1)
Len. B - mm(in)	682 (26.8)	634 (25.0)	1015 (40.0)	2197 (86.5)
Dia. C - mm(in)	358 (14.1)	434 (17.1)	434 (17.1)	434 (17.1)

Figure 5-34. Reformer with steam generator schematic diagram

The fans are housed in concentric metal tubes that provide for combustion gas flow over the outside and counter-flow of the steam/fuel mixture being reformed. The tubes and transitions are rolled and welded from high alloy or stainless steel sheet. Reformate flows to the exit manifold through a central tube within the fan stack. We then iteratively determined the fan dimensions to give the required area, while keeping the number of flow stages at 20 or higher. The final reformer dimensions for each system size are shown in Table 5-73.

Table 5-73. SOFC System Reformer Dimensions Summary

	1 kW	5 kW	10 kW	25 kW
Overall Diameter (mm)	53	129	129	129
Overall Length (mm)	473	448	643	1,284
Flow Stages	27	24	48	65
Final Catalyst Area (cm^2)	2,526	12,629	25,258	63,145

SOFC CHP system reformer cost summaries are provided in Table 5-74 and Table 5-75.

Table 5-74. SOFC Reformer Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$46.63	$43.12	$41.75	$41.52	$111.88	$104.43	$101.64	$101.57
Process	$694.79	$626.70	$409.26	$358.86	$625.14	$625.14	$356.62	$317.02
Scrap	$37.07	$33.49	$22.55	$20.02	$36.85	$36.48	$22.91	$20.93
Tooling	$454.77	$45.48	$4.55	$4.55	$513.37	$51.34	$5.13	$5.13
Manufactured Parts	$1,233.25	$748.79	$478.11	$424.95	$1,287.24	$817.38	$486.31	$444.66
Purchased Parts	$17.23	$17.23	$17.23	$17.23	$28.12	$28.12	$28.12	$28.12
Assembly	$61.96	$49.49	$48.24	$48.13	$73.09	$58.38	$56.91	$56.78
Total Cost	$1,312.44	$815.51	$543.58	$490.31	$1,388.46	$903.88	$571.34	$529.55

Table 5-75. SOFC Reformer Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$161.49	$151.78	$149.16	$149.14	$219.07	$207.27	$204.65	$204.63
Process	$1,307.27	$710.42	$682.72	$640.15	$1,645.39	$1,297.71	$861.90	$801.69
Scrap	$73.44	$43.11	$41.59	$39.46	$93.22	$75.25	$53.33	$50.32
Tooling	$579.35	$57.94	$5.79	$5.79	$744.36	$74.44	$7.44	$7.44
Manufactured Parts	$2,121.55	$963.24	$879.27	$834.55	$2,702.04	$1,654.67	$1,127.33	$1,064.08
Purchased Parts	$29.97	$29.97	$29.97	$29.97	$36.10	$36.10	$36.10	$36.10
Assembly	$89.61	$71.57	$69.77	$69.61	$138.68	$110.76	$107.97	$105.78
Total Cost	$2,241.13	$1,064.79	$979.01	$934.13	$2,876.81	$1,801.52	$1,271.39	$1,205.96

5.4.2.2 SOFC System Cathode Recuperative Heat Exchanger

The SOFC system heat exchanger basic design is based on the Catacel HEP™ air-to-air heat exchanger, shown in Figure 5-35 (dimensions in inches), and documented in U.S. patent no. 8,047,272,B2.

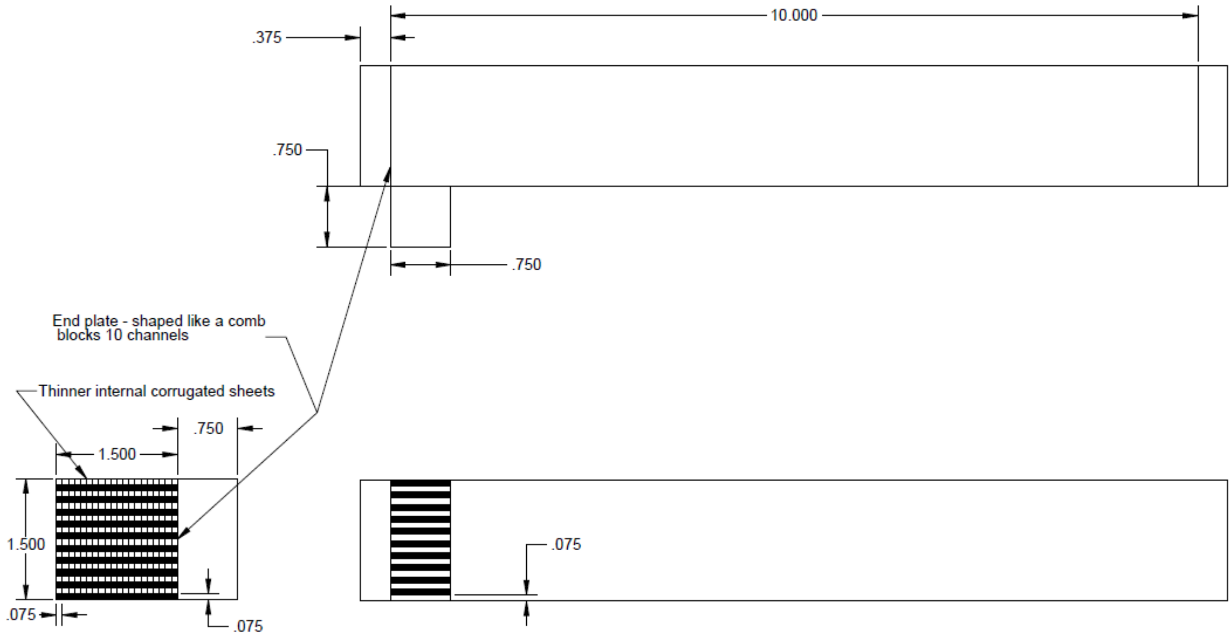


Figure 5-35. SOFC system basic heat exchanger design dimensions

We began by determining the required heat transfer area, then scaling the heat exchanger dimensions accordingly. Typical finning machines are limited to finned strip widths of around 250 mm, which limits the length of the heat exchanger heat transfer surface. We also assumed that the heat exchanger height, which is the same as the fin height, and the fin spacing are in accordance with the HEP™ design. These assumptions result in the following constraints:

- The heat exchanger height is 38 mm for all sizes.
- The heat exchanger width is at least 38 mm for all sizes.
- The fin spacing is 2 mm for all sizes.
- The heat exchanger length does not exceed 254 mm for all sizes.
- Once the length reached 254 mm, the heat exchanger width was expanded to increase the heat transfer area.

These constraints resulted in heat exchangers with the dimensions shown in Table 5-76.

Table 5-76. SOFC System Heat Exchanger Dimensions Summary

	1 kW	5 kW	10 kW	25 kW
Width (mm)	38	91	183	457
Height (mm)	38	38	38	38
Length (mm)	254	254	254	254
Flow Channels	20	48	96	240
Heat Trans Area (cm^2)	1,423	3,319	6,571	16,326

The heat exchangers are primarily fabricated from 0.005-inch Inconel sheet, with the shell and connection points being made of heavier material to simplify welding. The heat exchangers are furnace-brazed to yield a leak-free assembly.

SOFC system heat exchanger costs are summarized in Table 5-77 and Table 5-78.

Table 5-77. SOFC Heat Exchanger Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$4.71	$4.26	$3.89	$3.81	$11.79	$10.66	$10.05	$9.96
Process	$29.05	$29.05	$29.05	$23.46	$68.75	$68.75	$68.75	$46.98
Scrap	$1.69	$1.67	$1.65	$1.36	$4.03	$3.97	$3.94	$2.85
Tooling	$90.50	$9.05	$0.91	$0.91	$122.33	$12.23	$1.22	$1.22
Part Cost	$125.95	$44.02	$35.49	$29.53	$206.90	$95.61	$83.97	$61.01
Assembly	$31.22	$24.94	$24.31	$24.25	$57.01	$45.54	$44.39	$44.29
Total Cost	$157.17	$68.96	$59.80	$53.79	$263.91	$141.15	$128.36	$105.30

Table 5-78. SOFC Heat Exchanger Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$22.37	$20.22	$19.57	$19.50	$53.15	$48.99	$48.28	$48.25
Process	$134.91	$134.91	$105.45	$82.80	$333.10	$333.10	$224.33	$173.88
Scrap	$7.86	$7.76	$6.25	$5.12	$19.31	$19.10	$13.63	$11.11
Tooling	$173.39	$17.34	$1.73	$1.73	$330.44	$33.04	$3.30	$3.30
Part Cost	$338.54	$180.22	$133.01	$109.15	$736.01	$434.25	$289.55	$236.55
Assembly	$102.43	$81.81	$79.75	$79.57	$293.44	$234.37	$228.47	$223.84
Total Cost	$440.97	$262.04	$212.76	$188.72	$1,029.45	$668.62	$518.02	$460.39

5.4.3 SOFC System BOP Cost Assumptions

The costs associated with the BOP components are tabulated in Table 5-79 and Table 5-80.

Figure 5-36 through Figure 5-39 compare component costs at a subcategory level similar to the system schematic. A category titled "Additional Work Estimate" is included to capture any small contingencies not specifically itemized in this report. This includes 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.

For components not detailed above, the items are assumed to be commercially available; therefore, quotes or budgetary pricing were used.

Table 5-79. SOFC BOP Cost Summary: 1- and 5-kW Systems

Subassembly	Component Description	Annual Production: 1kW SOFC Systems				Annual Production: 5kW SOFC Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Supply	Filter	$112	$102	$93	$89	$112	$102	$93	$89
	Compressor	$507	$406	$385	$374	$682	$570	$520	$494
	3-way valve (start-up bypass)	$107	$97	$87	$84	$107	$97	$87	$84
	Desulfurizer	$644	$99	$68	$61	$893	$162	$122	$111
Fuel Processing	Ejector	$342	$308	$277	$269	$342	$308	$277	$269
	Pre-Reformer	$1,312	$816	$544	$490	$1,388	$904	$571	$530
	Tail Gas Combustor	$467	$421	$384	$373	$467	$421	$384	$373
Start-up Air Supply (CPOX)	Filter & Housing	$347	$333	$320	$307	$347	$333	$320	$307
	Blower (Anode Air)	$307	$276	$248	$241	$307	$276	$248	$241
	Flow Meter	$117	$105	$94	$92	$137	$123	$111	$108
Cathode Air	Blower (Cathode Air)	$307	$276	$248	$241	$418	$376	$339	$329
	Flowmeter (Cathode Air)	$137	$123	$111	$108	$144	$130	$117	$113
Heat Recovery	Cathode Air Heater	$157	$69	$60	$54	$264	$141	$128	$105
	CHP Load Heater	$135	$122	$111	$108	$355	$319	$291	$284
	CHP Bypass Valve	$166	$149	$134	$130	$198	$178	$160	$155
AC Power	DC/AC Inverter	$1,080	$1,004	$934	$869	$1,980	$1,841	$1,713	$1,593
	Transfer Switch	$105	$95	$85	$77	$308	$262	$209	$188
	Resistor Bank	$25	$23	$20	$20	$150	$135	$122	$118
DC Power	DC/DC Converter (Power)	$805	$646	$581	$558	$1,969	$1,575	$1,418	$1,361
	Batteries	$32	$31	$30	$29	$154	$146	$142	$139
Instrumentation and Controls	Control Module	$719	$647	$582	$565	$719	$647	$582	$565
	DC/DC Converter (Controls)	N/A	N/A	N/A	N/A	$134	$121	$109	$105
	Wiring & Connectors	$162	$147	$133	$120	$288	$261	$235	$212
	Temperature Sensors	$20	$16	$14	$14	$20	$16	$14	$14
	Current Sensor	$21	$19	$16	$16	$21	$19	$16	$20
	Voltage Sensor	$49	$44	$40	$39	$49	$44	$40	$39
	H2S Sensor	$243	$219	$210	$204	$243	$219	$210	$204
	Stack Anode Pressure Sensor	$226	$203	$182	$177	$226	$203	$182	$177
Assembly Components	Assorted Plumbing/Fittings	$407	$370	$335	$300	$488	$444	$400	$360
	Assembly Hardware	$41	$37	$33	$30	$49	$44	$40	$36
	Frame & Housing	$122	$111	$100	$90	$147	$133	$120	$108
+ Work Est.	Additional Work Estimate	$900	$700	$600	$600	$1,100	$900	$800	$800
	TOTAL BOP COST	$10,122	$8,012	$7,062	$6,726	$14,205	$11,450	$10,121	$9,628

Table 5-80. SOFC BOP Cost Summary: 10- and 25-kW Systems

Subassembly	Component Description	Annual Production: 10kW SOFC Systems				Annual Production: 25kW SOFC Systems			
		(100)	(1,000)	(10,000)	(50,000)	(100)	(1,000)	(10,000)	(50,000)
Fuel Supply	Filter	$112	$102	$93	$89	$112	$102	$93	$89
	Compressor	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3-way valve (start-up bypass)	$107	$97	$87	$84	$107	$97	$87	$84
	Desulfurizer	$1,255	$235	$186	$167	$1,562	$448	$373	$335
Fuel Processing	Ejector	$342	$308	$277	$269	$342	$308	$277	$269
	Pre-Reformer	$2,241	$1,065	$979	$934	$2,877	$1,802	$1,271	$1,206
	Tail Gas Combustor	$467	$421	$384	$373	$467	$421	$384	$373
Start-up Air Supply (CPOX)	Filter & Housing	$347	$333	$320	$307	$495	$464	$445	$427
	Blower (Anode Air)	$307	$276	$248	$241	$466	$420	$378	$366
	Flow Meter	$144	$130	$117	$113	$133	$120	$108	$105
Cathode Air	Blower (Cathode Air)	$617	$555	$500	$485	$672	$605	$545	$528
	Flowmeter (Cathode Air)	$144	$130	$117	$113	$144	$130	$117	$113
Heat Recovery	Cathode Air Heater	$441	$262	$213	$189	$1,029	$669	$518	$460
	CHP Load Heater	$537	$484	$441	$430	$931	$838	$764	$745
	CHP Bypass Valve	$235	$211	$190	$184	$415	$374	$336	$326
AC Power	DC/AC Inverter	$3,600	$3,348	$3,114	$2,896	$9,540	$8,872	$8,251	$7,674
	Transfer Switch	$308	$277	$249	$224	$710	$639	$575	$518
	Resistor Bank	$300	$270	$243	$236	$900	$810	$729	$707
DC Power	DC/DC Converter (Power)	$3,900	$3,000	$2,700	$2,592	$9,900	$7,200	$6,600	$6,300
	Batteries	$556	$527	$515	$504	$738	$700	$683	$670
Instrumentation and Controls	Control Module	$719	$647	$582	$565	$719	$291	$262	$254
	DC/DC Converter (Controls)	$251	$226	$203	$197	$627	$564	$508	$493
	Wiring & Connectors	$484	$440	$396	$356	$1,077	$979	$881	$793
	Temperature Sensors	$20	$16	$14	$14	$20	$16	$14	$14
	Current Sensor	$32	$29	$25	$33	$32	$29	$25	$33
	Voltage Sensor	$49	$44	$40	$39	$49	$44	$40	$39
	H2S Sensor	$243	$219	$210	$204	$243	$219	$210	$204
	Stack Anode Pressure Sensor	$226	$203	$182	$177	$226	$203	$182	$177
Assembly Components	Assorted Plumbing/Fittings	$507	$461	$415	$375	$748	$680	$610	$550
	Assembly Hardware	$51	$46	$41	$37	$75	$68	$61	$55
	Frame & Housing	$152	$138	$124	$112	$224	$204	$183	$165
+ Work Est.	Additional Work Estimate	$1,400	$1,100	$1,000	$1,000	$2,100	$1,700	$1,500	$1,400
	TOTAL BOP COST	**$20,094**	**$15,599**	**$14,205**	**$13,538**	**$37,682**	**$30,014**	**$27,011**	**$25,471**

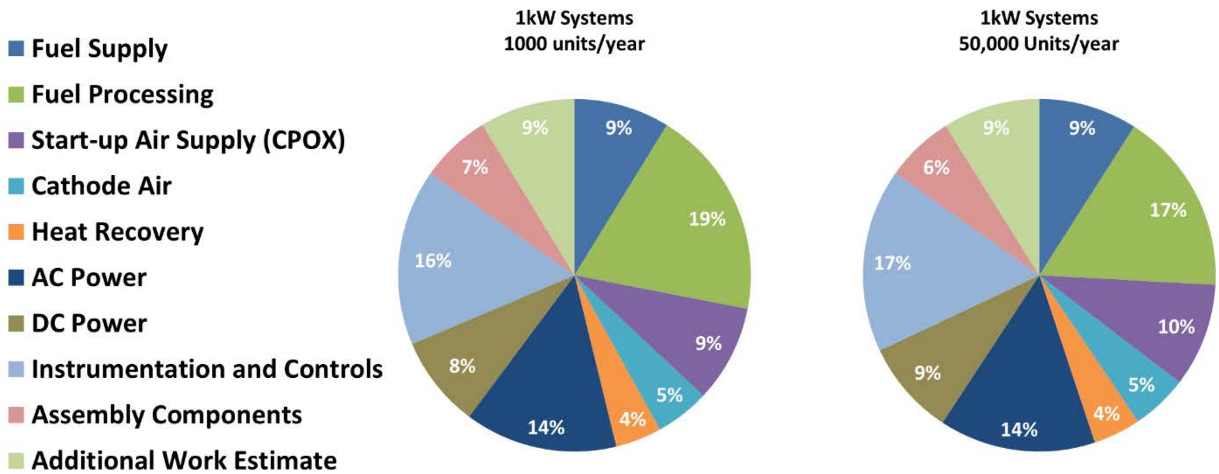


Figure 5-36. 1-kW SOFC system BOP cost distribution

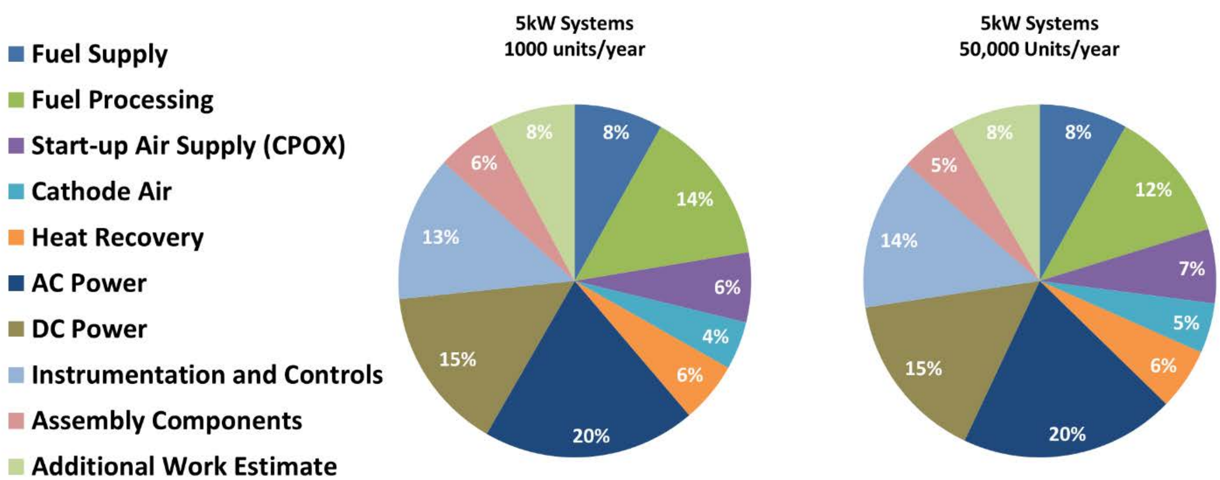


Figure 5-37. 5-kW SOFC system BOP cost distribution

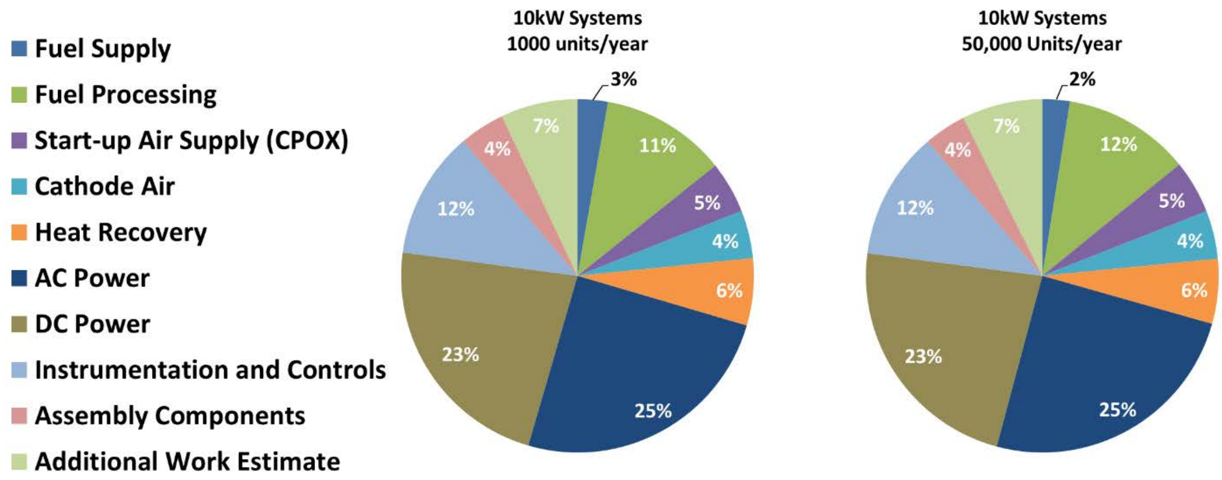


Figure 5-38. 10-kW SOFC system BOP cost distribution

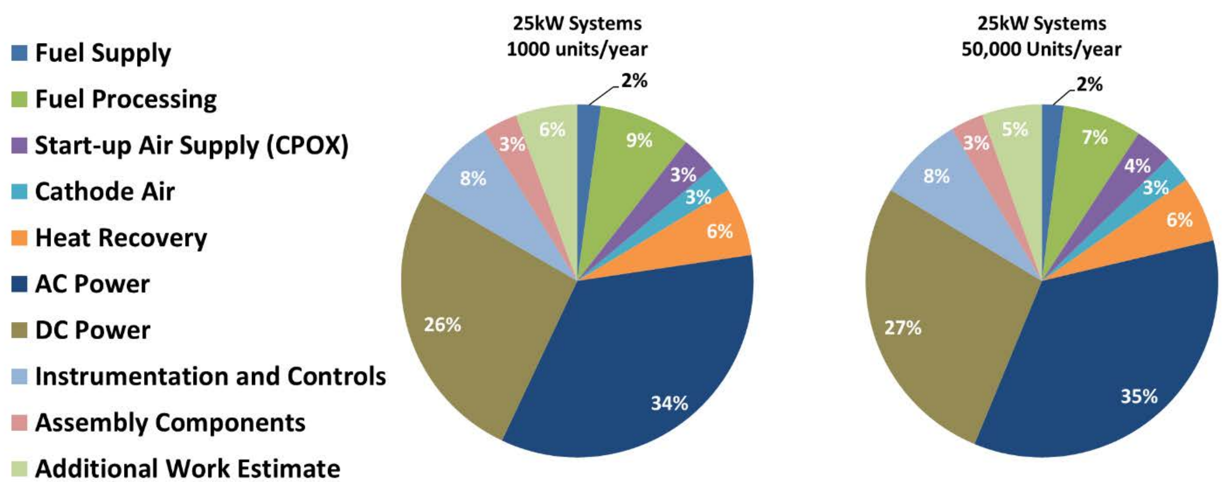


Figure 5-39. 25-kW SOFC system BOP cost distribution

Figure 5-40 through Figure 5-43 show SOFC system BOP cost volume trends.

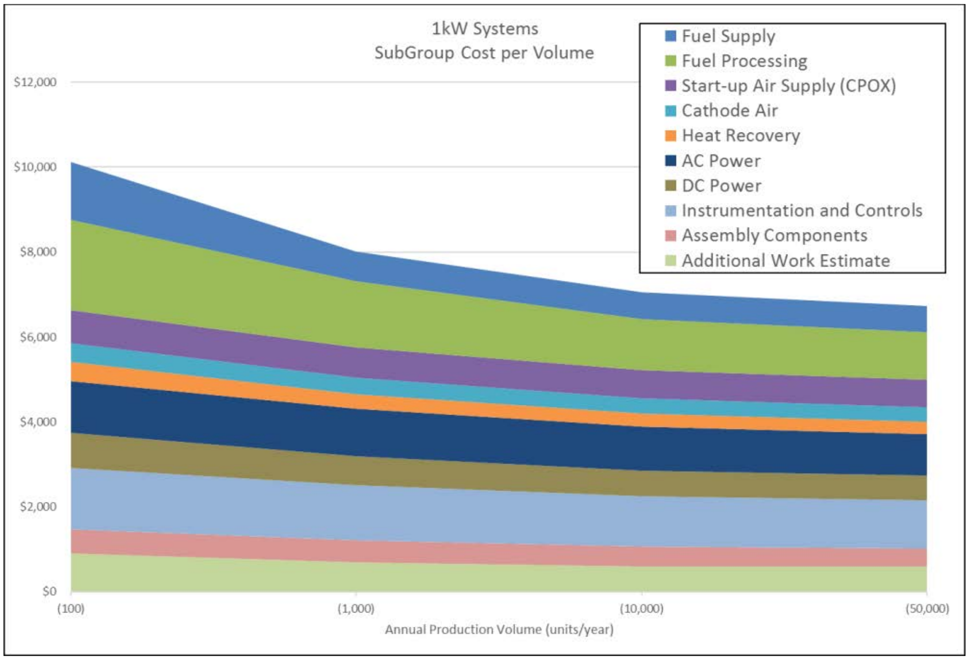


Figure 5-40. 1-kW SOFC system BOP cost volume trends

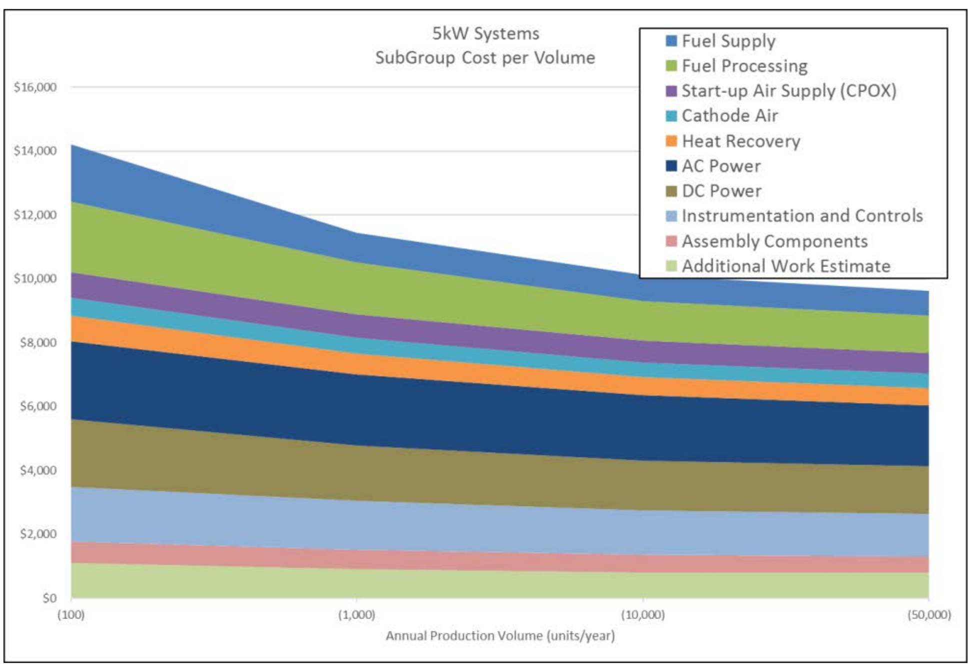


Figure 5-41. 5-kW SOFC system BOP cost volume trends

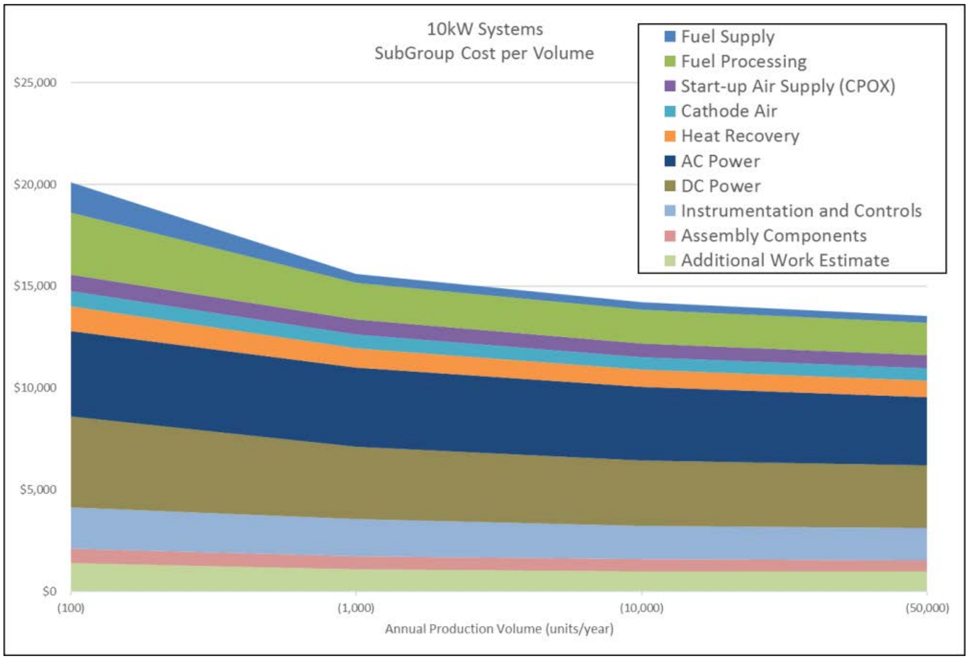


Figure 5-42. 10-kW SOFC system BOP cost volume trends

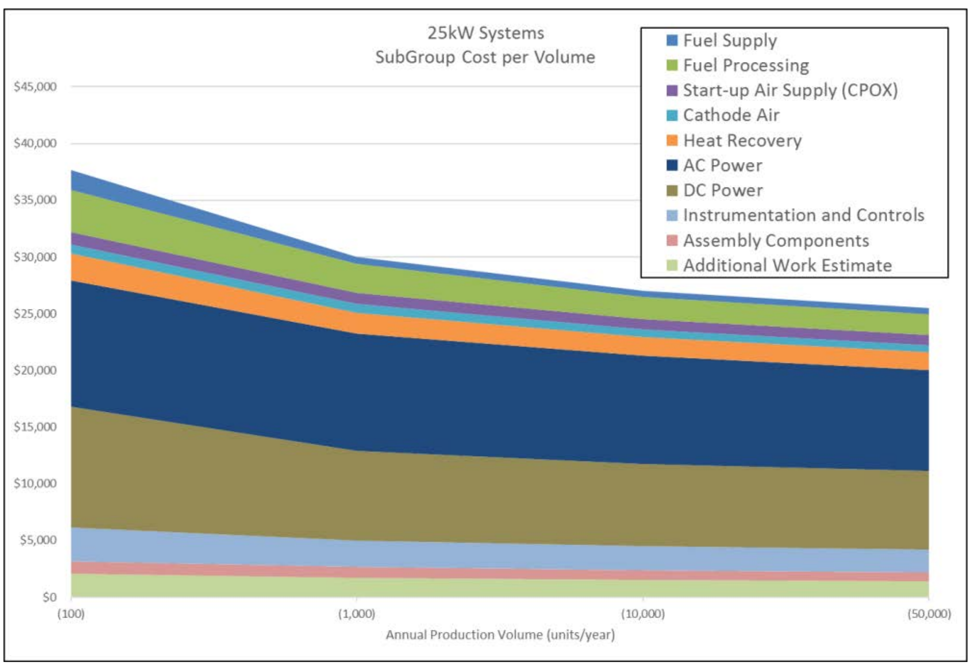


Figure 5-43. 25-kW SOFC system BOP cost volume trends

5.4.4 SOFC System Assembly and Learning Curve Assumptions

The SOFC system assembly hardware costs are accounted for in the BOP cost calculations. System assembly times were estimated using the DFMA® software. After applying learning curve analysis to the assembly times and multiplying by the standard labor rate of $45.00/hour, the average stack assembly costs were calculated as detailed in Appendix A-3 and summarized in Table 5-81 and Table 5-82.

Table 5-81. SOFC Assembly Costs: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$109.97	$87.83	$85.62	$85.42	$109.97	$87.83	$85.62	$85.42
Total Assembly Cost	$109.97	$87.83	$85.62	$85.42	$109.97	$87.83	$85.62	$85.42

Table 5-82. SOFC Assembly Costs: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Materials	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$109.97	$87.83	$85.62	$85.42	$109.97	$87.83	$85.62	$85.42
Total Assembly Cost	$109.97	$87.83	$85.62	$85.42	$109.97	$87.83	$85.62	$85.42

5.4.5 SOFC System Testing

Following assembly, the SOFC CHP system is tested and conditioned to determine its fitness for installation in the field. Total test time is assumed to be 6 hours. The cycle consists of a 2-hour warm-up, 2 hours at full power, and a 2-hour cool-down. The test reject rate was assumed to be 5.0%. The calculated system testing costs are shown in Table 5-83 and Table 5-84.

Table 5-83. SOFC Testing Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.88	$0.86	$0.86	$0.86	$4.31	$4.29	$4.29	$4.29
Labor	$146.73	$146.29	$146.24	$146.24	$146.73	$146.29	$146.24	$146.24
Machine	$1,136.32	$139.91	$74.63	$74.63	$1,136.32	$139.91	$74.63	$74.63
Scrap	$12.97	$2.90	$2.24	$2.24	$13.00	$2.93	$2.27	$2.27
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
System Total	$1,296.90	$289.96	$223.97	$223.97	$1,300.36	$293.42	$227.44	$227.43

Table 5-84. SOFC Testing Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$8.58	$8.58	$8.58	$8.58	$21.44	$21.44	$21.44	$21.44
Labor	$146.73	$146.29	$146.24	$146.24	$146.73	$146.29	$146.24	$146.24
Machine	$1,136.32	$139.91	$74.63	$74.63	$1,136.32	$139.91	$74.63	$74.63
Scrap	$13.05	$2.98	$2.32	$2.32	$13.18	$3.11	$2.45	$2.45
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
System Total	$1,304.68	$297.75	$231.77	$231.77	$1,317.67	$310.75	$244.76	$244.76

5.4.6 SOFC System Capital Cost Assumptions

Table 5-85 summarizes the cost assumptions for the components that make up the total SOFC system capital cost.

Table 5-85. Summary of SOFC System 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 yrs	N/A
Discount Rate	7.0%	Guidance for govt 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

Machine utilization was used to determine the number of machines required to support various product demand levels. This information, along with equipment cost quotes, was used to determine production station equipment costs. The production facility estimation is based on the floor area required for production equipment, equipment operators, and support personnel. Guidelines used for this analysis were developed by Prof. Jose Ventura at Pennsylvania State University[8] and are detailed in Appendix A-11. Capital cost breakdowns are provided in Table 5-86 and Table 5-87.

[8] Ventura, J.A. 2001. Facility Layout and Material Handling MS PowerPoint Presentations. Penn State Personal Web Server. Accessed December 2016. http://www.personal.psu.edu/jav1/.

Table 5-86. SOFC Capital Cost Summary: 1- and 5-kW Systems

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Production Stations	6	7	26	120	6	8	45	200
Construction Cost	$630,194	$765,494	$3,296,961	$15,358,856	$630,194	$849,590	$5,761,181	$25,080,420
Forklifts	$18,000	$21,000	$78,000	$360,000	$18,000	$24,000	$135,000	$600,000
Cranes	$22,050	$25,725	$95,550	$441,000	$22,050	$29,400	$165,375	$735,000
Real Estate	$50,508	$53,312	$111,114	$359,053	$50,508	$55,026	$171,715	$564,991
Contingency	$72,075	$86,553	$358,163	$1,651,891	$72,075	$95,802	$623,327	$2,698,041
Total Cost	$792,827	$952,084	$3,939,788	$18,170,800	$792,827	$1,053,817	$6,856,598	$29,678,453
Equivalent Annual Capital Cost	$74,837	$89,870	$371,888	$1,715,195	$74,837	$99,473	$647,214	$2,801,436
Annual Capital Cost per System	$748.37	$89.87	$37.19	$34.30	$748.37	$99.47	$64.72	$56.03

Table 5-87. SOFC Capital Cost Summary: 10- and 25-kW Systems

	10 kW				25 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Production Stations	6	8	53	240	6	15	94	445
Construction Cost	$630,194	$849,590	$6,890,747	$30,987,397	$630,194	$1,825,893	$12,084,713	$56,624,862
Forklifts	$18,000	$24,000	$159,000	$720,000	$18,000	$45,000	$282,000	$1,335,000
Cranes	$22,050	$29,400	$194,775	$882,000	$22,050	$55,125	$345,450	$1,635,375
Real Estate	$50,508	$55,026	$199,060	$670,170	$50,508	$86,124	$313,478	$1,176,972
Contingency	$72,075	$95,802	$744,358	$3,325,957	$72,075	$201,214	$1,302,564	$6,077,221
Total Cost	$792,827	$1,053,817	$8,187,940	$36,585,524	$792,827	$2,213,356	$14,328,204	$66,849,429
Equivalent Annual Capital Cost	$74,837	$99,473	$772,884	$3,453,415	$74,837	$208,925	$1,352,481	$6,310,113
Annual Capital Cost per System	$748.37	$99.47	$77.29	$69.07	$748.37	$208.93	$135.25	$126.20

5.5 Electrical System Cost Assumptions

The cost for the electrical system is primarily driven by the power electronics (DC/DC converter and DC/AC inverter.) These components are somewhat more expensive for CHP and primary power applications than for back-up power because of safety and performance requirements applied by the utility for devices connected to the grid. The system controller and sensors represent the next largest portion of the cost. Protective devices and interconnecting components complete the remainder of the electrical system cost.

5.5.1 DC/DC and DC/AC 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 are included to allow the converter to be used to assist with system management. Specifically, the converter is typically coordinated with the reformer/fuel cell through the control system to limit current draw in relationship to the fuel flow to the reformer to avoid overloading the stack. Because 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 loading and number of cells. Output voltage was regulated 24 VDC for the 1-kW system and 48 VDC for all other output power levels. Because the size of the cells used for the 1-kW system yields a low stack output voltage, a boost-type converter is required. For all others, buck converters are appropriate. Converters are based on 120% of the nominal output of the system size to allow for parasitic loads and short-term overload. For example, for the 5-kW system, a 6-kW power converter was selected.

Most of the commercially available grid-tie DC/AC inverters are designed for PV systems and are not appropriate for fuel cells due to their excessively high input voltage (typically ~300 to 500 VDC). However, several solar inverter manufacturers noted that they could design an appropriate inverter for fuel cells. They expected the cost of fuel cell inverters to be similar to, if not less than, PV inverters because designing an inverter for a fuel cell is less complicated. Design simplification results from relatively steady input at known voltage; there is no need for maximum power point tracking (MPPT) system control, which is needed to manage solar arrays. The simplification is somewhat offset by the larger conductor size and heat management required for the higher current associated with the lower input voltage. For cost estimating, we assumed that PV inverter costs would be representative. Inverters are sized based on 120% of the nominal output of the system size to allow for parasitic loads and short-term overload.

Recently, hybrid DC/AC inverters have been developed to integrate a secondary high-power DC/DC port into the primary DC/AC inverter specifically for connection to storage systems operating in parallel with the primary power source (typically solar for the existing commercial products). The cost is comparable to a single DC/AC inverter. Currently, the smallest size available in the market is 30 kW.

The DC/DC, DC/AC and hybrid DC/AC hardware costs were estimated based on the cost of similar hardware already in limited production that was obtained from the manufacturers. These costs were blended with costs for systems appropriate for PV systems currently being produced in high volume. The PV systems operate at higher voltage but are a reasonable approximation for the necessary systems. Table 5-88 and Table 5-89 show the cost breakdown for increasing power and increasing production volumes on a dollars-per-watt basis for the DC/DC converter and the DC/AC inverter, respectively; Table 5-90 shows the cost breakdown per watt for the 25-kW hybrid system and increasing production volume.

Table 5-88. DC/DC Converter Costs per Watt

	Number of Units			
	100	1,000	10,000	50,000
Power (W)	$/W			
1,200	0.67	0.54	0.48	0.46
6,000	0.33	0.26	0.24	0.23
12,000	0.33	0.25	0.23	0.22
30,000	0.33	0.24	0.22	0.21

Table 5-89. DC/AC Inverter Costs per Watt

	Number of Units				
	1	100	1,000	10,000	50,000
Power (W)	$/W				
1,200	$0.60	$0.54	$0.50	$0.47	$0.43
6,000	$0.37	$0.33	$0.31	$0.29	$0.27
12,000	$0.33	$0.30	$0.28	$0.26	$0.24
30,000	$0.32	$0.29	$0.27	$0.25	$0.23

Table 5-90. Hybrid Three-Port DC/AC Inverter Costs per Watt

	Number of Units			
	100	1,000	10,000	50,000
Power (W)	($/W)			
30,000	$0.45	$0.42	$0.39	$0.36

5.5.2 Controller and Sensors

The system controller cost was estimated based on previous efforts completed at Battelle and original equipment manufacturer (OEM) automotive electronic control unit (ECU) cost. We assumed that the system controller is a custom circuit card assembly built around a microcontroller 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; as such, the cost of OEM ECUs was used to estimate the higher quantity cost of the controller. The current sensor and voltage sense circuitry are readily available, so the cost for those components could be obtained via internet search.

5.5.3 Protection and Interconnects

The contactors and fuses used in fuel cell applications typically require high current and low DC voltage ratings. The manufacturers that supply these types of devices are 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 based on figures from the Battelle 2011 report.[9]

5.5.3.1 Batteries

Energy storage is required to provide critical load support during grid outage. As outlined in Section 4, the batteries were sized for surge requirements. An alternative design approach might include sizing the batteries to provide near full operational power for the high-power portion of the day followed by recharging at night. This approach would be site specific so the base battery design is just the surge allowance. Battery costs were obtained from battery manufacturers on the basis of the design for 10 times of the nominal power for 5 seconds with a 10% depth-of-discharge. Table 5-91 shows the minimum requirements of the battery.

Table 5-91. Minimum Battery Requirements

System (kW)	Battery Rating		Battery Voltage (VDC)
	kW-hr	Amp-hr	
1.2	0.167	6.94	24
6	0.833	17.361	48
12	1.67	34.72	48
30	4.167	86.81	48

5.5.3.2 Transfer Switch

In addition to routinely offsetting grid power demand, the fuel cell system is designed to continue to produce power when the utility grid experiences a power outage. Therefore, the fuel cell system requires a transfer switch to rapidly disconnect the system from the grid and from unnecessary loads when the grid goes down or brown-out conditions occur. The cost of the transfer switch varies based on the switching current and the phase (single-phase or three-phase). The same transfer switch that is used for battery backup could be used for a fuel cell system. The situation could be more complex if there are several power sources on the site. For most residential and light commercial installations, this would not be the case. Some large commercial installations (such as hotels and hospitals) may have multiple back-up power sources on a dedicated internal microgrid that would require coordination and might use a single transfer switch for utility grid disconnect. Otherwise, each power source would require an individual transfer switch, likely resulting in an overall cost increase for the system. For this analysis, we assume a single transfer switch for each fuel cell system deployed.

[9] Battelle. 2011. The High Volume Manufacture Cost Analysis of 5 kW Direct Hydrogen Polymer Electrolyte (PEM) Membrane Fuel Cell for Backup Power Applications. DOE Contract No. DE-FC36-03GO13110.

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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. Because 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 System 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 both PEM and SOFC stacks have advanced so that stack cost is no longer the majority of a system cost—in fact, stack cost may represent only about 20% of the overall cost. In no case did stack costs for this study exceed 30% 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 because 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 due to longevity concerns associated with the CHP application. Table 6-1 summarizes the manufacturing processes that were evaluated.

Table 6-1. PEM Stack Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives Not Evaluated
Catalyst deposition	Slot die coating	Tape casting Nanostructure thin film Screen printing Spray coating
	Single head slot die with decal transfer	Dual head slot die Multi-pass slot die
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

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.[10] Consequently, in-house production is unlikely to be justified until yearly volumes significantly exceed the volumes considered for this report.

6.1.2 PEM System BOP Hardware Costs

BOP costs are strongly influenced by the cost of the electrical equipment: DC/DC converter, DC/AC inverter, and grid connection hardware. Based on feedback from suppliers, we found that these components used in continuous (as opposed to back-up) power applications will require more expensive topology and components to achieve the desired lifetimes. 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. Some costs are associated with our decision to use a high-power DC/DC converter prior to the inverter, which was largely driven by the expectation that any commercially attractive system would need to serve as back-up power for critical loads and would therefore need to interface with batteries for transient management. This approach differs from some previous analyses and clearly increases system cost compared to a system that can function only in parallel with the grid. Although we have taken no credit for critical load maintenance in our life cycle cost analysis, we believe that back-up power is a valuable feature of any type of on-site generation system.

Heat exchangers make up another significant cost category, especially for the PEM system. The PEM heat exchangers were scaled on the basis of a ChemCad® model of the system and assumed to be sized appropriately for their design load heat duty. To achieve the desired temperatures in a system subject to operation at off-design conditions might require additional control hardware, such as a bypass valve to limit heat transfer, that was not considered here. Alternatively, the system might simply operate at lower efficiency when in an off-design condition.

Blower selection depends significantly on system pressure drop at design flow rate. Absent an actual design, we assumed modest pressure drop. As pressure requirements increase, either through the cathode or through the combustion system for the reformer, blower requirements may increase notably with an attendant increase in cost. In most cases, the system designer has some leeway on the design to minimize pressure drop; this may be an important design decision, particularly for the 10- and 25-kW systems.

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

6.2 SOFC System Manufacturing Costs

6.2.1 SOFC Stack Manufacturing Costs

SOFC stack costs are based on the use of typical manufacturing processes for the construction of the individual cells. These include creation of the supporting anode, cell blanking, ceramic layer deposition, kiln firing, and sintering (Table 6-2).

Table 6-2. SOFC Stack Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives Not Evaluated
Ceramic deposition	Screen printing	Plasma spray coating
	Tape casting	
Interconnect	Sheet metal stamping, laser etching	Laser cutting, water jet cutting, chemical etching
	Spray deposition coating	CVD/PVD
Sealing	Bead deposition	Screen printing, tape casting
Picture frame	Sheet metal stamping	Laser cutting, water jet cutting.
End plate	Die casting + final machining	Stamping, welding
	Machine from block (not chosen)	

Alternative and innovative manufacturing techniques were not evaluated. Based on industry feedback, the techniques used for the cost analysis are consistent with existing processes used by SOFC stack component manufacturers.

6.2.2 SOFC System BOP Hardware Costs

The SOFC system BOP associated with stack support is considerably simpler than for PEM systems, leading to lower cost. However, as for PEM systems, the design chosen is the result of Battelle's engineering judgment tempered by industry input rather than analysis of existing commercial systems. The BOP related to heat recovery is also simpler for SOFC systems than for PEM systems and can yield higher-quality heat. However, the high-temperature materials and components that are required may partially offset the cost savings achieved through simplicity.

As for the PEM system, SOFC BOP hardware cost estimates are strongly influenced by electrical system components. The same limitations mentioned for the PEM system analysis apply for SOFC systems. The SOFC system should include additional energy storage (batteries) to compensate for the relatively slow response of the stack to changes in electrical load. Additional batteries beyond those required for PEM systems were not included in our analysis, as the required capacity will be a function of specific application requirements. In the absence of an active CHP market at the 25-kW and below scale, it is difficult to estimate the required battery capacity.

The BOP estimates for the SOFC system presume that lower effectiveness reforming is adequate because some methane introduced to the stack will be reformed *in situ*, benefiting stack thermal management. We assumed that a reformer approximately half the size of a similar-scale PEM system reformer would be acceptable. Appropriate scaling of the reformer to satisfy the specific requirements set by a stack manufacturer could result in higher or lower costs. Similarly, we assumed anode recirculation using an eductor. Performance of the eductor could impact overall system performance and efficiency and will likely limit turndown to 2:1 for the SOFC system. Alternative methods, such as high-temperature blower recirculated anode gas, could provide better turndown if desired for some applications, but high-temperature blowers represent a significantly higher initial expense and unknown life. Proven high-temperature blowers for anode recirculation do not seem to exist at this scale, so they were not considered for this analysis.

BOP hardware cost estimates included here exhibit limited cost savings at high volume. This results from the specialized nature of the BOP components, particularly the expense of the higher-temperature materials necessary to achieve adequate life.

Bulk commodity materials used in much of the hardware have relatively fixed costs unless purchased at very low quantities, where prices are very high. Conversely, certain specialty components (e.g., fuel reformers and compact heat exchangers) required to meet the rigorous specification of the CHP system are currently custom designed and are not available at high volumes. The volume discounts applied were based on general scaling parameters that may not reflect the benefits of industry standardization and/or more specific design efforts yielding lower overall costs.

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 primary power and CHP, we have isolated the BOP components associated with providing heat and power. Specifically, the PEM CHP-BOP includes:

- the power conversion hardware to convert the output of the fuel cell into line power and manage transients and
- the heat exchanger that interfaces with the location heat use system.

All other components, including instrumentation and controls, are grouped into the fuel cell BOP category.

The SOFC CHP-BOP includes the equivalent components plus the bypass valves needed to protect the location heat use heat exchanger if there is no or low heat load. Because the fuel for these fuel cell systems is either natural gas or propane, fuel reforming is considered part of the fuel cell BOP hardware.

The CHP BOP costs are dominated by the power electronics—the DC/DC converter and the DC/AC inverter which represent, for example, approximately 85% (PEM) and 83% (SOFC) of the CHP-BOP cost for 25-kW systems at 1,000 per year. These components become an increasingly larger fraction of the total system cost because stack costs are decreasing with volume. This trend holds for both PEM and SOFC systems. Stack costs are projected to become a smaller fraction of overall system cost as production volumes increase.

7.1 PEM CHP Systems

This section presents the results of the analyses of four manufacturing volumes for 1-, 5-, 10-, and 25-kW PEM CHP fuel cell systems, including fuel cell stack, BOP, and overall system costs. Figure 7-1 and Figure 7-2 show the distribution of costs for each size for a production volume of 1,000 units per year. For small systems, the fuel cell BOP hardware dominates the cost because the cost of controls and sensors is mostly independent of size. There is also a contribution from the base cost of having the multiple heat exchangers and components as shown in the schematic (see Figure 4-3). The number of fittings and connections is the same regardless of size.

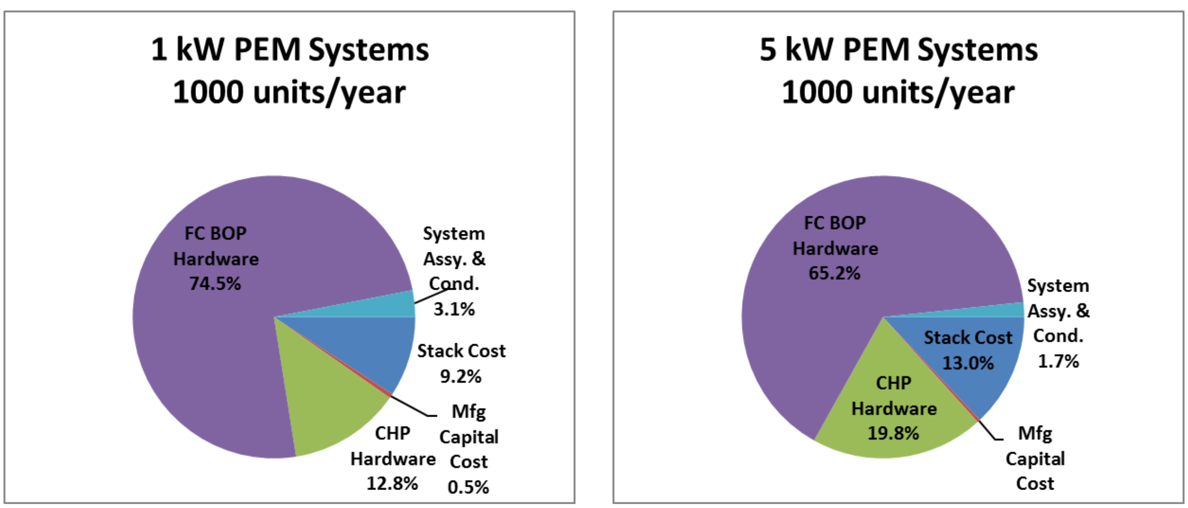
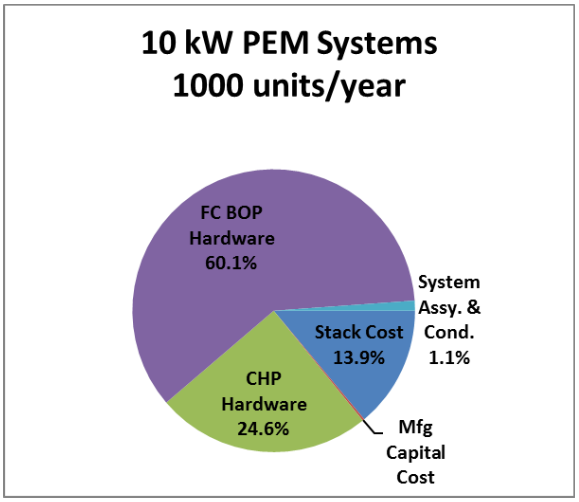


Figure 7-1. 1- and 5-kW PEM system costs at 1,000 units per year



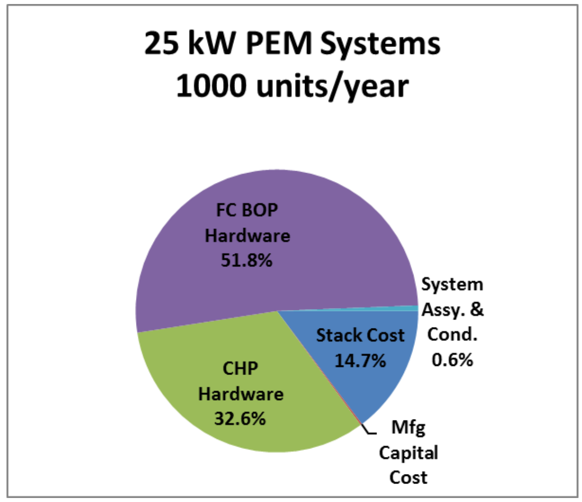


Figure 7-2. 10- and 25-kW PEM system costs at 1,000 units per year

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

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

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

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

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$3,931	$1,052	$554	$460
	Stack manufacturing capital cost	$567	$57	$22	$21
	CHP hardware	$1,772	$1,465	$1,336	$1,259
	FC BOP hardware	$11,377	$8,523	$7,228	$6,692
	System assembly, test, and conditioning	$1,542	$349	$278	$278
Total System Costs	Total system cost, pre-markup	$19,190	$11,447	$9,419	$8,710
	System cost per kW_{net}, pre-markup	$19,190	$11,447	$9,419	$8,710
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$28,784	$17,170	$14,128	$13,064
	System cost per kW_{net}, with markup	$28,784	$17,170	$14,128	$13,064

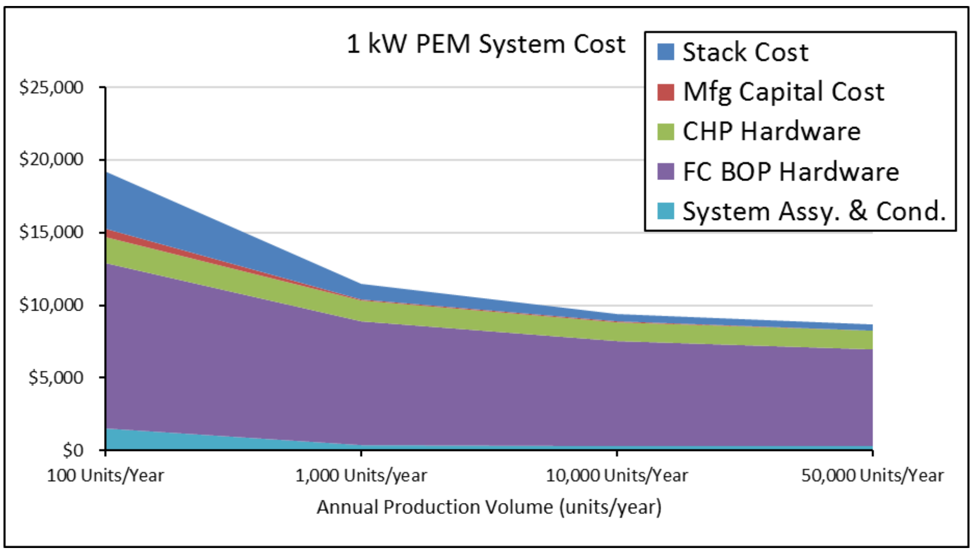


Figure 7-3. 1-kW PEM system cost volume trends

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

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$6,659	$2,697	$1,643	$1,407
	Stack manufacturing capital cost	$567	$71	$30	$30
	CHP hardware	$4,824	$4,115	$3,772	$3,541
	FC BOP hardware	$17,691	$13,553	$11,502	$10,525
	System assembly, test, and conditioning	$1,545	$352	$281	$280
Total System Costs	Total system cost, pre-markup	$31,286	$20,788	$17,227	$15,782
	System cost per kW_{net}, pre-markup	$6,257	$4,158	$3,445	$3,156
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$46,930	$31,183	$25,841	$23,674
	System cost per kW_{net}, with markup	$9,386	$6,237	$5,168	$4,735

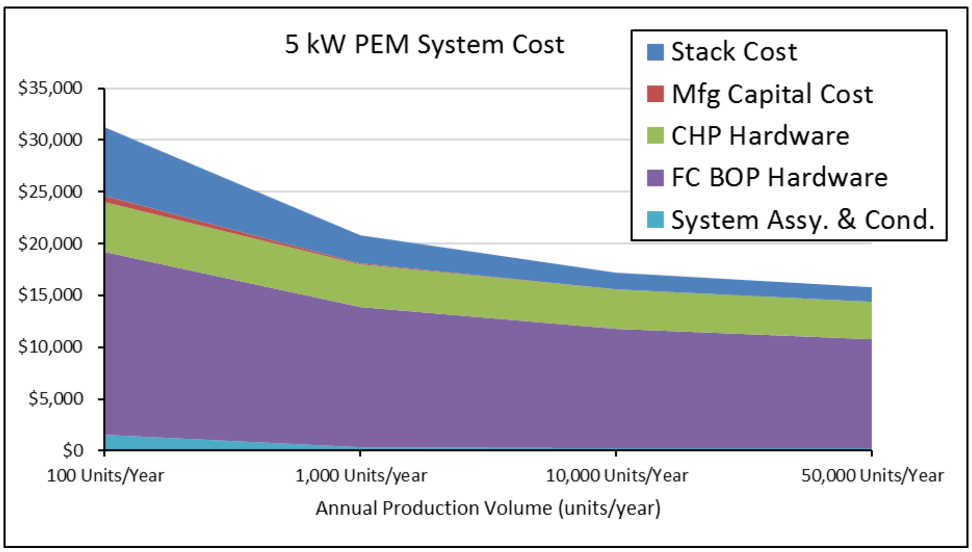


Figure 7-4. 5-kW PEM system cost volume trends

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

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$9,702	$4,349	$2,849	$2,601
	Stack manufacturing capital cost	$567	$71	$39	$38
	CHP hardware	$9,104	$7,684	$7,033	$6,641
	FC BOP hardware	$24,457	$18,779	$15,525	$14,097
	System assembly, test, and conditioning	$1,548	$355	$284	$283
Total System Costs	Total system cost, pre-markup	$45,379	$31,238	$25,730	$23,660
	System cost per kW_{net}, pre-markup	$4,538	$3,124	$2,573	$2,366
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$68,068	$46,857	$38,595	$35,491
	System cost per kW_{net}, with markup	$6,807	$4,686	$3,860	$3,549

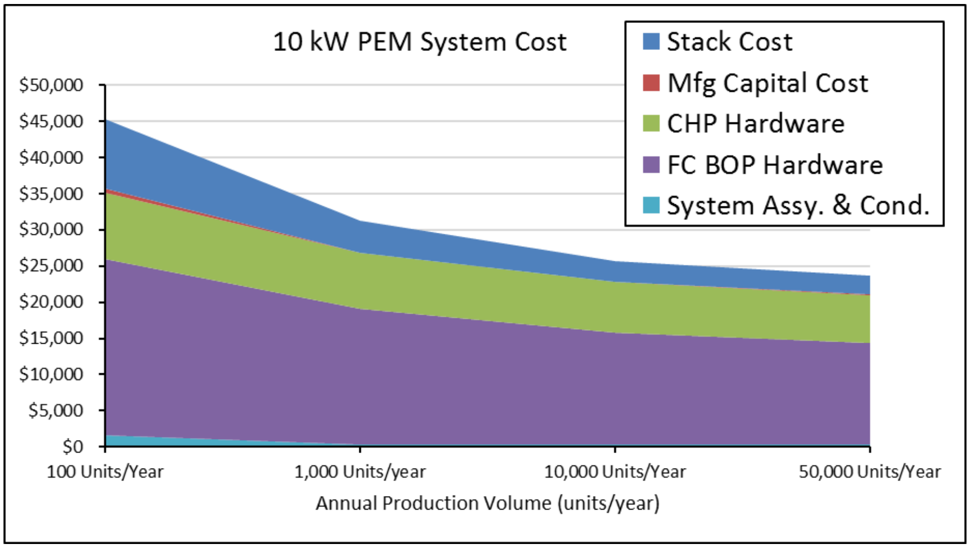


Figure 7-5. 10-kW PEM system cost volume trends

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

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$16,674	$8,527	$6,354	$6,217
	Stack manufacturing capital cost	$567	$101	$65	$64
	CHP hardware	$22,817	$18,890	$17,356	$16,329
	FC BOP hardware	$38,606	$29,990	$25,309	$22,950
	System assembly, test, and conditioning	$1,558	$365	$293	$293
Total System Costs	Total system cost, pre-markup	$80,221	$57,873	$49,378	$45,852
	System cost per kW_{net}, pre-markup	$3,209	$2,315	$1,975	$1,834
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$120,332	$86,809	$74,067	$68,779
	System cost per kW_{net}, with markup	$4,813	$3,472	$2,963	$2,751

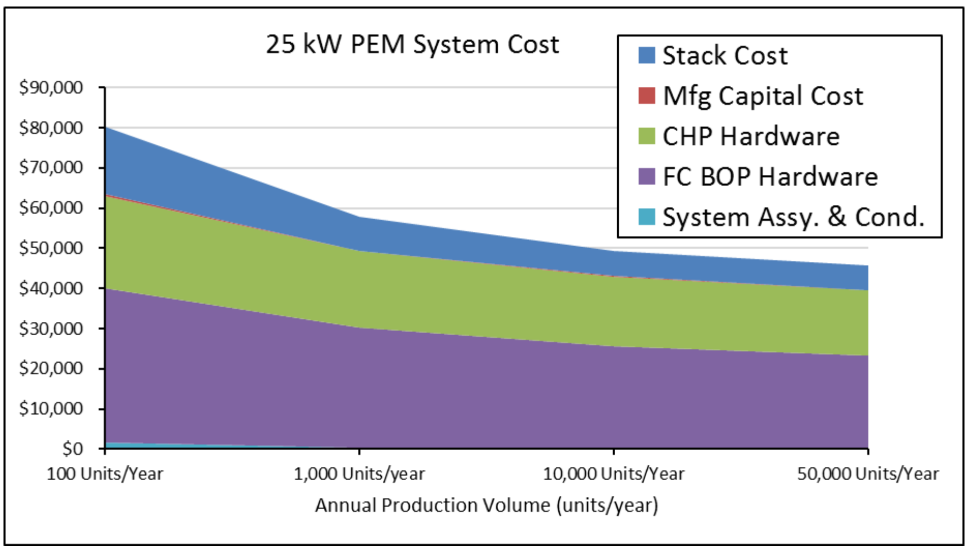


Figure 7-6. 25-kW PEM system cost volume trends

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

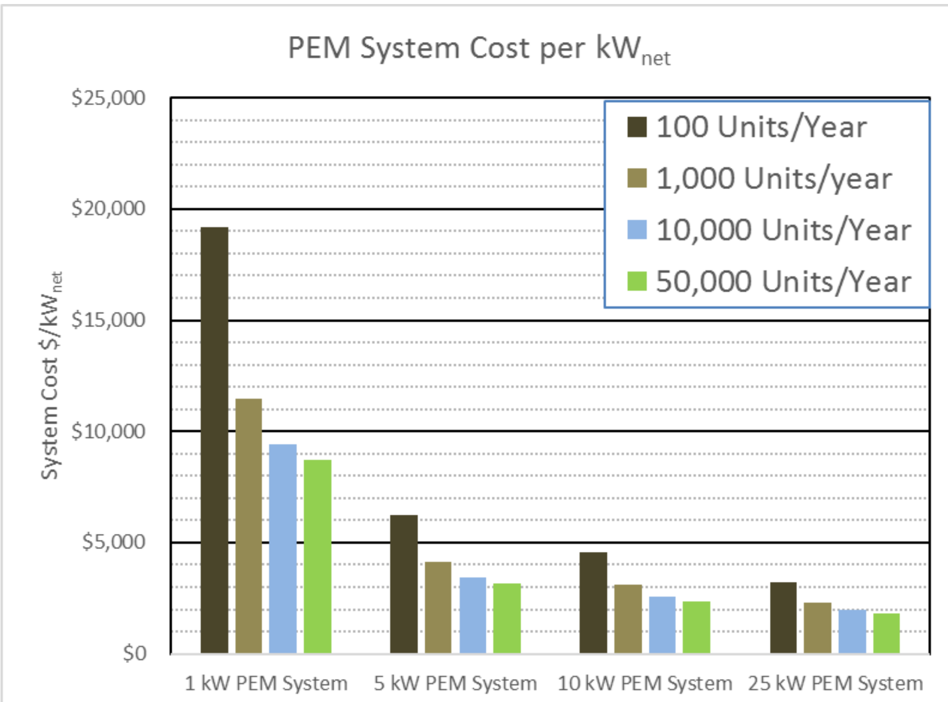


Figure 7-7. Pre-markup cost per kilowatt for PEM systems

7.2 SOFC CHP Systems

This section presents the results of the analyses of four manufacturing volumes for 1-, 5-, 10-, and 25-kW CHP SOFC systems, including fuel cell stack, BOP, and overall system costs. Figure 7-8 and Figure 7-9 show the distribution of costs for each size for a production volume of 1,000 units per year. As noted in the discussion of PEM systems, the fuel cell BOP hardware dominates the cost for small systems because the cost of controls and sensors is mostly independent of size. The SOFC BOP—both the CHP portion and the fuel cell related hardware—is simpler than in PEM systems, yielding a notable advantage in overall cost, particularly at low volumes and small sizes.

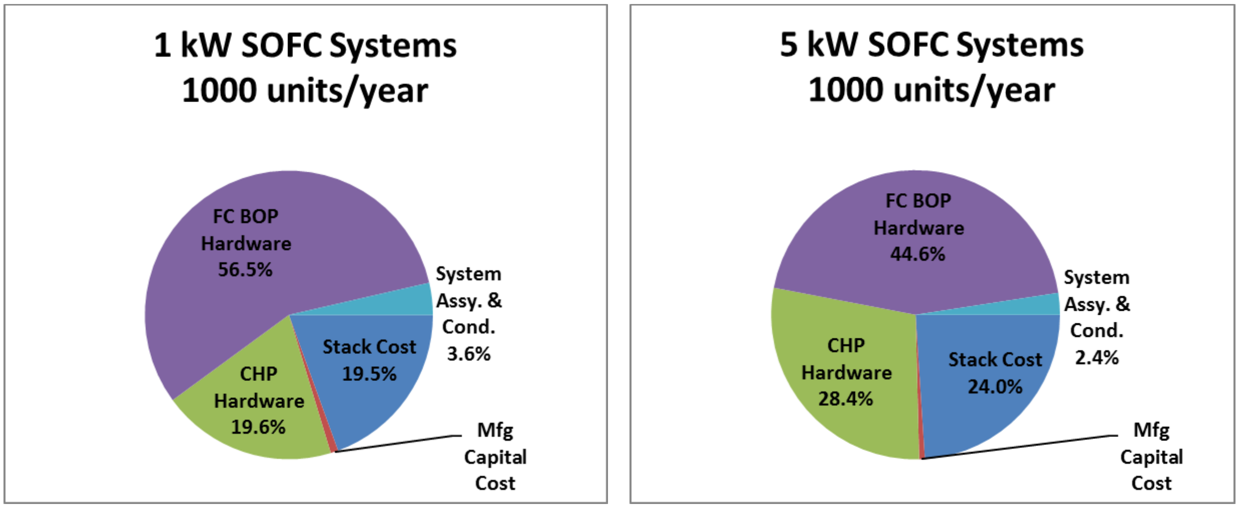


Figure 7-8. 1- and 5-kW SOFC system costs at 1,000 units per year

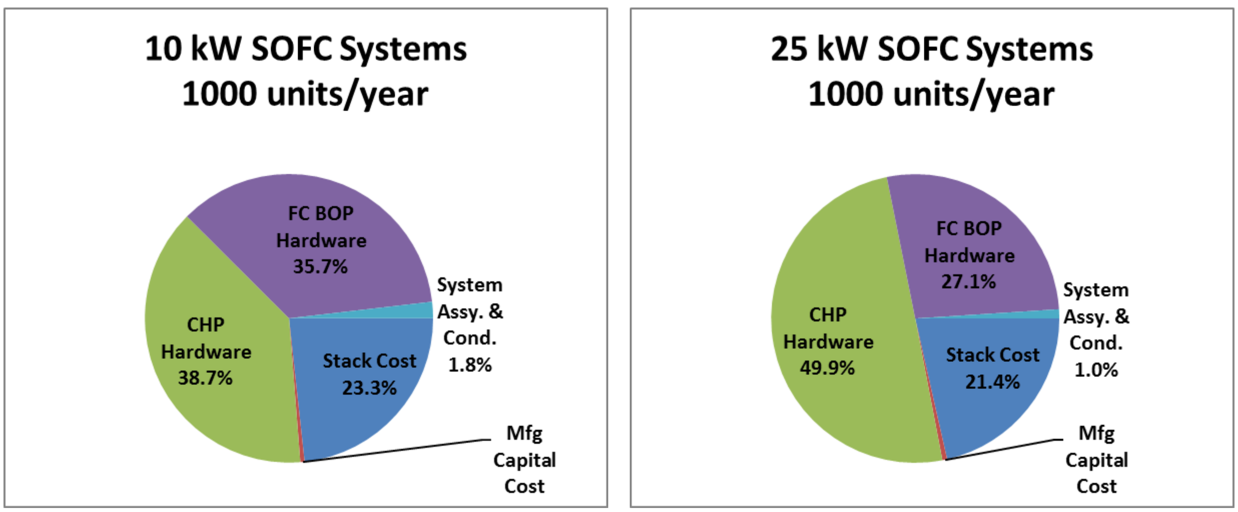


Figure 7-9. 10- and 25-kW SOFC system costs at 1,000 units per year

The manufacturing capital cost (the investment required to produce the systems) is relatively small on a per-stack basis even for limited numbers of units. This is largely due to the use of job-shop/outsource manufacturing for the lower volumes, while production machine and labor efficiency benefit the overall cost as volumes increase and manufacturing is brought in house to better manage costs and quality. All systems and sizes assume that final testing, evaluation, and burn-in (if required) will be done in house as a quality control (QC) measure. Hence, there is a baseline capital investment for all sizes and volumes. The 25-kW SOFC systems exhibit a higher per-stack capital cost than other PEM or SOFC systems. This represents the investment needed to bring most of the production in house. While significant investment is needed, the benefit is lower net cost of the system when the capital costs are amortized over a reasonable machine life.

Table 7-5 through Table 7-8 provide the estimated cost values. Figure 7-10 through Figure 7-13 graphically show the pre-markup cost trend with increasing manufacturing volume that is represented in Table 7-5 through Table 7-8.

Table 7-5. Cost Summary for 1-kW SOFC CHP System

	Description	100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$8,483	$2,048	$1,360	$1,183
	Stack manufacturing capital cost	$748	$90	$37	$34
	CHP hardware	$2,348	$2,069	$1,895	$1,790
	FC BOP hardware	$7,774	$5,944	$5,166	$4,936
	System assembly, test, and conditioning	$1,407	$378	$310	$309
Total System Costs	Total system cost, pre-markup	$20,760	$10,528	$8,768	$8,253
	System cost per kW_{net}, pre-markup	$20,760	$10,528	$8,768	$8,253
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$31,139	$15,791	$13,153	$12,379
	System cost per kW_{net}, with markup	$31,139	$15,791	$13,153	$12,379

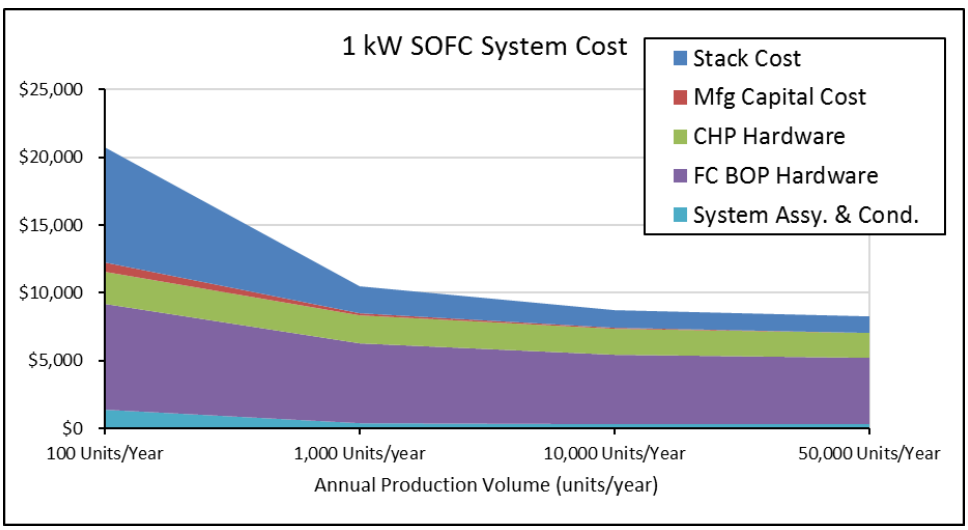


Figure 7-10. 1-kW SOFC system cost volume trends

Table 7-6. Cost Summary for 5-kW SOFC CHP System

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$10,438	$3,762	$2,514	$2,316
	Stack manufacturing capital cost	$748	$99	$65	$56
	CHP hardware	$5,112	$4,456	$4,054	$3,838
	FC BOP hardware	$9,093	$6,995	$6,067	$5,790
	System assembly, test, and conditioning	$1,410	$381	$313	$313
Total System Costs	Total system cost, pre-markup	$26,802	$15,693	$13,013	$12,313
	System cost per kW_{net}, pre-markup	$5,360	$3,139	$2,603	$2,463
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$40,203	$23,540	$19,519	$18,469
	System cost per kW_{net}, with markup	$8,041	$4,708	$3,904	$3,694

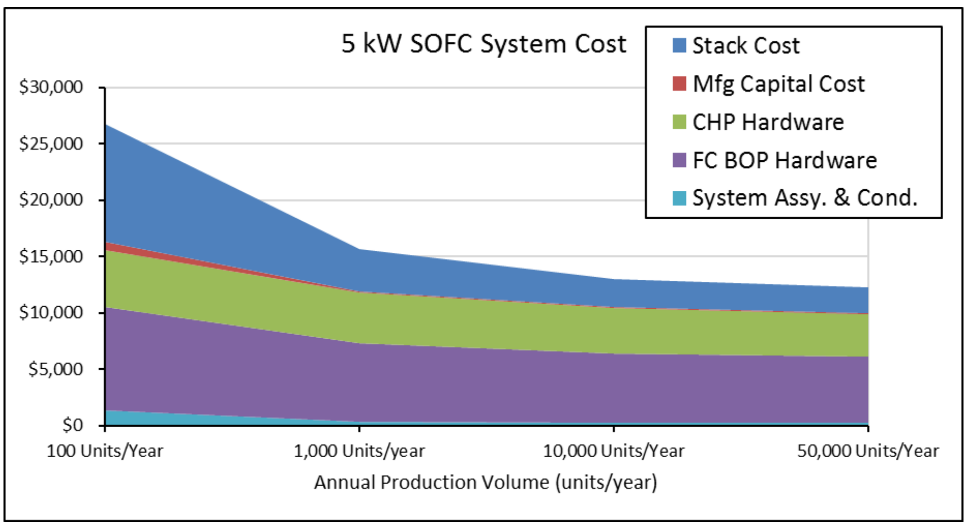


Figure 7-11. 5-kW SOFC system cost volume trends

Table 7-7. Cost Summary for 10-kW SOFC CHP System

	Description	100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$11,880	$4,879	$3,429	$3,190
	Stack manufacturing capital cost	$748	$99	$77	$69
	CHP hardware	$9,436	$8,117	$7,452	$7,067
	FC BOP hardware	$10,658	$7,482	$6,753	$6,471
	System assembly, test, and conditioning	$1,415	$386	$317	$317
Total System Costs	Total system cost, pre-markup	$34,137	$20,963	$18,029	$17,114
	System cost per kW_{net}, pre-markup	$3,414	$2,096	$1,803	$1,711
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$51,206	$31,444	$27,043	$25,671
	System cost per kW_{net}, with markup	$5,121	$3,144	$2,704	$2,567

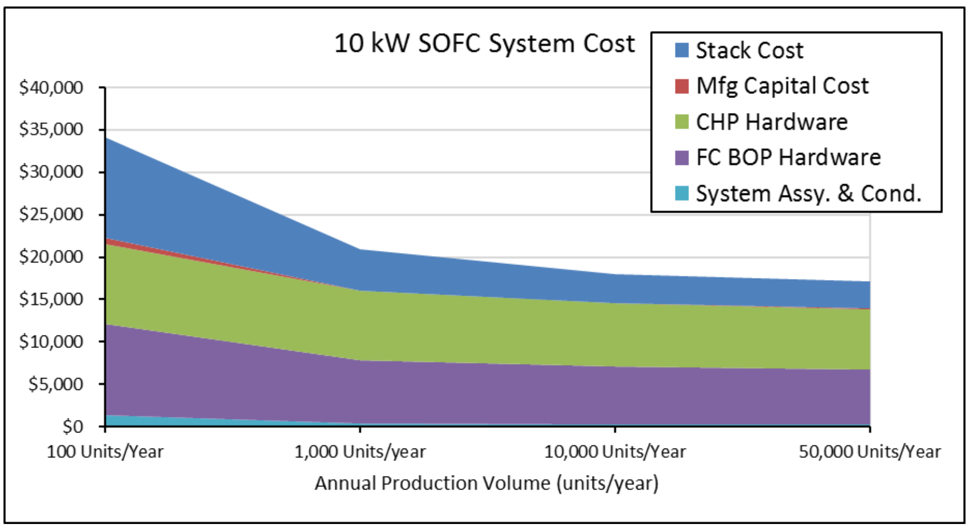


Figure 7-12. 10-kW SOFC system cost volume trends

Table 7-8. Cost Summary for 25-kW SOFC CHP System

Description		100 Units/Yr	1,000 Units/Yr	10,000 Units/Yr	50,000 Units/Yr
Subassembly Component Costs	Total stack manufacturing cost, with scrap	$16,848	$8,358	$6,555	$6,302
	Stack manufacturing capital cost	$748	$209	$135	$126
	CHP hardware	$23,134	$19,433	$17,939	$16,939
	FC BOP hardware	$14,548	$10,581	$9,073	$8,532
	System assembly, test, and conditioning	$1,428	$399	$330	$330
Total System Costs	Total system cost, pre-markup	$56,706	$38,980	$34,032	$32,229
	System cost per kW_{net}, pre-markup	$2,268	$1,559	$1,361	$1,289
	Sales markup	50%	50%	50%	50%
	Total system cost, with markup	$85,059	$58,470	$51,048	$48,344
	System cost per kW_{net}, with markup	$3,402	$2,339	$2,042	$1,934

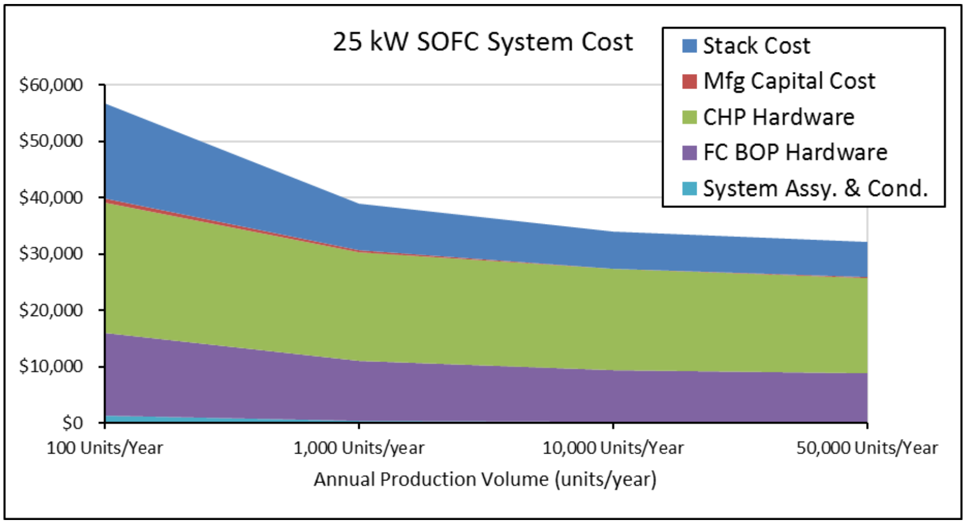


Figure 7-13. 25-kW SOFC system cost volume trends

Figure 7-14 shows the cost per kilowatt (excluding mark-up) for each of the sizes and production volumes. As expected, there is benefit to increased total production and system size on cost-per-kilowatt capacity. The trends in Figure 7-14 figure into the life cycle cost analysis. When considering a 5-year life for the system and the higher production rate, larger systems offer attractive payback periods because they are able to generate electrical power at rates competitive with utility rates. The cost analysis does not place any value on grid outage response, though that may be a significantly beneficial factor in many locations.

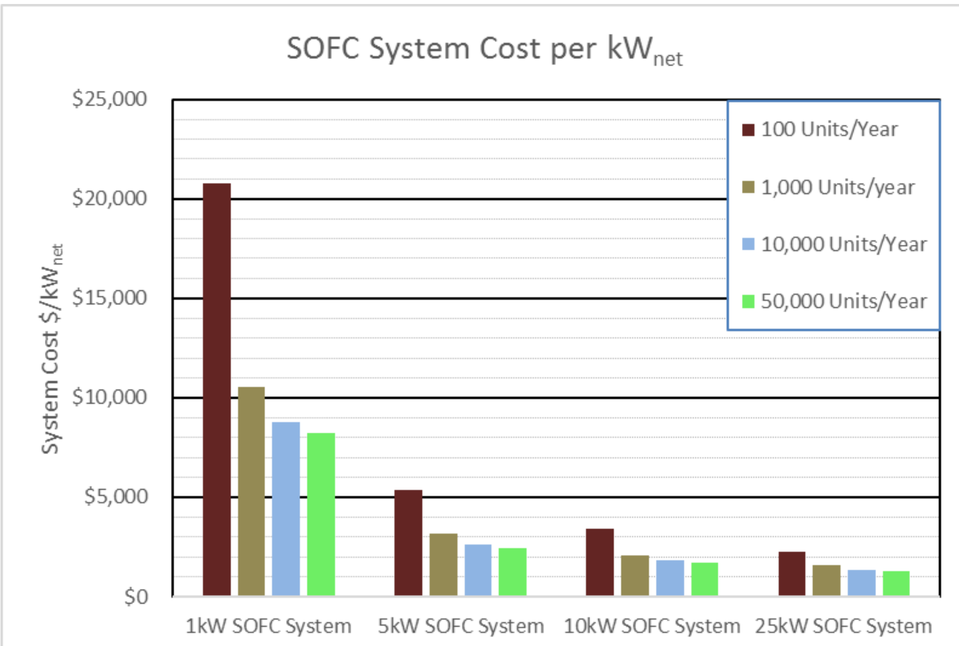


Figure 7-14. Cost per kilowatt for SOFC system

7.3 Future Cost Reduction

The following discussion identifies potential areas for product or manufacturing improvement. Additional work and discussion are 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 neither the PEM nor SOFC systems analyzed here have been optimized for cost. Neither design specifically reflects installed equipment and is therefore predisposed to improvement. 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. For example, a low-cost hydrogen purification membrane technology could potentially eliminate the PrOx reactor, blower, and associated heat exchanger and control hardware.

A review of the cost tables and sensitivity analysis shows that power electronics are major contributors to the overall cost. Having discrete DC/DC and DC/AC hardware implies redundancy in some components (e.g., control interface and power connections) and a lack of optimization to purpose. Specialization and integration of the power conditioning and grid interface functions offer attractive opportunities for cost reduction. CHP and primary power applications require power electronics rated for continuous, long-term use. Response to grid-outage conditions requires that energy storage and load-following control hardware be incorporated, as we have included here. However, an alternate power electronics topology able to accommodate the variable input voltage from the fuel cell and independently interface with energy storage (batteries) to achieve the necessary surge and transient response could reduce the cost of these components significantly.

As the sensitivity analysis shows, additional BOP improvements (e.g., heat exchangers, blowers) have the potential to impact cost. Blowers in particular are sensitive to overall system pressure drop, so system design changes that enable lower overall system pressure drop are potentially beneficial. The caveat is that we have assumed relatively aggressive pressure drop characteristics, so there is a potential for blower requirements to increase rather than decrease.

A final comment on the manufacturing process is appropriate. The scrap and reject rates assumed here are those recommended by our industry contacts as representative of the state of the art. Failure rates of 5% (SOFC systems) to 15% (PEM systems) at final test are unacceptable for mass-produced hardware. It is essential to develop effective QC measures and robust fabrication processes to reduce those rates to less than 0.5%.

8. Sensitivity Analysis

8.1 PEM System

The sensitivity analysis of the costs for the 25-kW stacks at the 1,000- and 10,000-unit production volumes explores the impact of slight variations to the assumptions for the major contributing cost factors and highlights their significance. The cost factors for the analysis were chosen because of their significant contribution to the cost and/or the difficult nature of precisely assessing their magnitude, such as the cost of platinum. The analysis demonstrates the effect on the overall cost of the system based on reasonable variations to each factor. The results of the sensitivity analyses are illustrated in Figure 8-1 and Figure 8-2, which show the relative importance of the major cost drivers.

The following cost factors were varied for the analysis:

- Hybrid three-port DC/AC inverter ($/unit)
    - In place of having both the DC/AC inverter and DC/DC converter
    - Assumed to be $16,072 for DC/AC inverter and DC/DC converter at 1,000 units/year
    - Assumed to be $14,851 for DC/AC inverter and DC/DC converter at 10,000 units/year
    - New technology that is currently available for 25-kW systems in solar applications
- Current density (amperes per square centimeter [A/cm^2])
    - Assumed to be 0.4 A/cm^2
    - Adjusted to 0.6 A/cm^2 to see effect
- Platinum loading (milligrams per square centimeter [mg/cm^2]
    - Assumed to be 0.4 mg/cm^2
    - Varied by +0.1 mg/cm^2, -0.25 mg/cm^2
- Shift/PrOx catalyst cost
    - Assumed to be $7,048 at 1,000 units/year
    - Assumed to be $5,379 at 10,000 units/year
    - Varied by ±20%
- Heat exchangers
    - Assumed total cost of $4,244 at 1,000 units/year
    - Assumed total cost of $3,736 at 10,000 units/year
    - Varied by ±20%
- Platinum cost (troy ounces [tr. oz.])
    - Assumed to be $1,294/tr. oz.
    - Platinum cost impact evaluation assumes 0.4 mg/cm^2 loading
    - Varied by ±25%
    - Varied by ±50%
- Blowers
    - Selection dependent on system pressure drop
    - Assumed blower output pressure of ~1 psig
    - Varied to blower output pressure of ~2 psig (resulting in specification of different blowers)

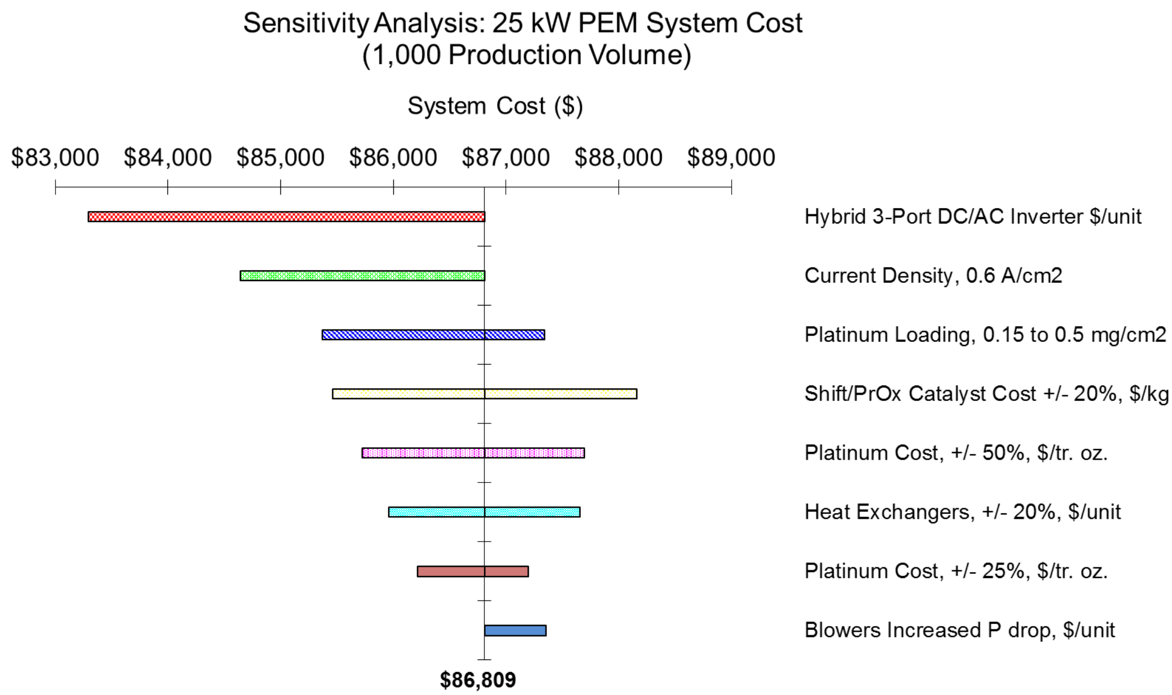


Figure 8-1. PEM sensitivity analysis: 25-kW system cost – 1,000-unit production volume

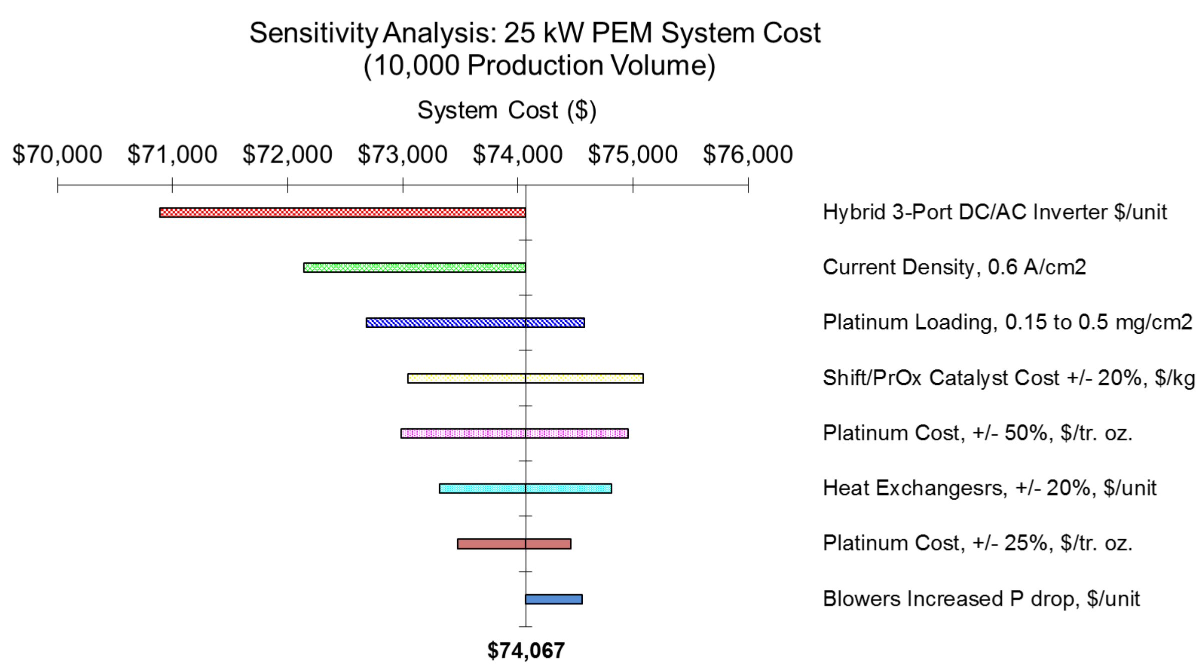


Figure 8-2. PEM sensitivity analysis: 25-kW system cost – 10,000-unit production volume

Implementation of the hybrid three-port DC/AC inverter has the greatest overall effect to the system cost for the factors studied. For the 25-kW system, this new technology is a realistic option as they are being used in solar power installations in this size range. For the smaller systems, this option is not currently available. The current density, platinum loading, and shift/PrOx catalyst cost all have close to equal impact on their potential to decrease the cost of the overall system. The heat exchangers have a greater influence on the PEM system than the SOFC system because there are many more heat exchangers in the PEM system. Platinum cost is somewhat of a wild card and is difficult to predict due to the price volatility of the precious metal. For this analysis, a platinum cost of $1294 per tr. oz. was assumed and then varied by both ±25% and ±50% because over the last 10 years it has been as high as $2,192 per tr. oz. and as low as $806 per tr. oz. This also contributes greatly to other factors such as the catalyst application scrap rate and platinum loading. Pressure drop of the system (thus requiring a different blower) had the least effect of the factors studied.

8.2 SOFC System

The sensitivity analysis of the costs for the 25-kW SOFC system components at the 1,000- and 10,000-unit production volumes explores the impact of specific variations to the assumptions for major contributing cost factors and highlights their significance. The cost factors were chosen because of their significant contribution to system costs and/or the difficult nature of precisely assessing their magnitude (for example, items such as high-temperature heat exchangers that are not commercial off-the-shelf items, or specialty production items such as grid-tied inverters). The analysis demonstrates the effect to the overall cost of the system based on reasonable variations to each factor. The results of the sensitivity analyses are illustrated in Figure 8-3 and Figure 8-4, which show the relative importance of the major cost drivers.

The following cost factors were varied for the analysis:

- Hybrid three-port DC/AC inverter ($/unit)
    - In place of having both the DC/AC inverter and DC/DC converter
    - Assumed to be $16,072 for DC/AC inverter and DC/DC converter at 1,000 units/year
    - Assumed to be $14,851 for DC/AC inverter and DC/DC converter at 10,000 units/year
    - New technology that is currently available for 25-kW systems in solar applications
- SOFC stack
    - Assumed to be $8,358 at 1,000 units/year
    - Assumed to be $6,555 at 10,000 units/year
    - Varied by ±20%
- Blowers
    - Selection dependent on system pressure drop
    - Assumed blower output pressure of ~1 psig
    - Varied to blower output pressure of ~2 psig (resulting in specification of different blowers)
- Heat exchangers
    - Assumed total cost of $1,507 at 1,000 units/year
    - Assumed total cost of $1,282 at 10,000 units/year
    - Varied by ±20%
- Pre-reformer
    - Assumed to be $1,802 at 1,000 units/year
    - Assumed to be $1,271 at 10,000 units/year
    - Varied by ±20%

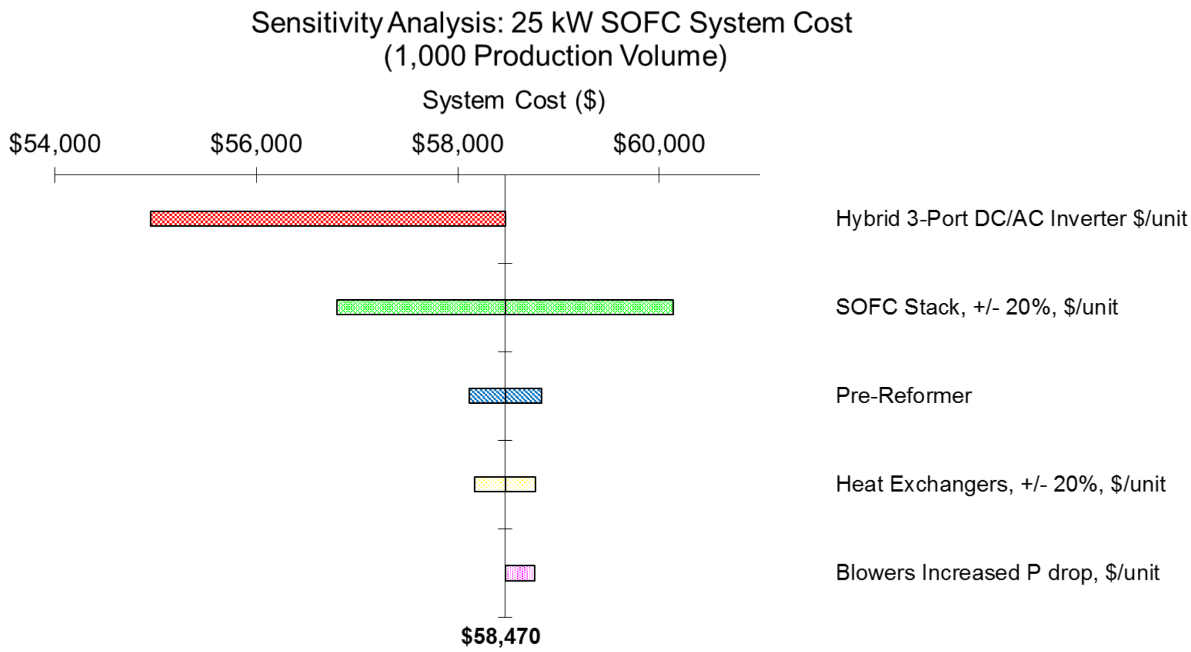


Figure 8-3. SOFC sensitivity analysis: 25-kW system cost – 1,000-unit production volume

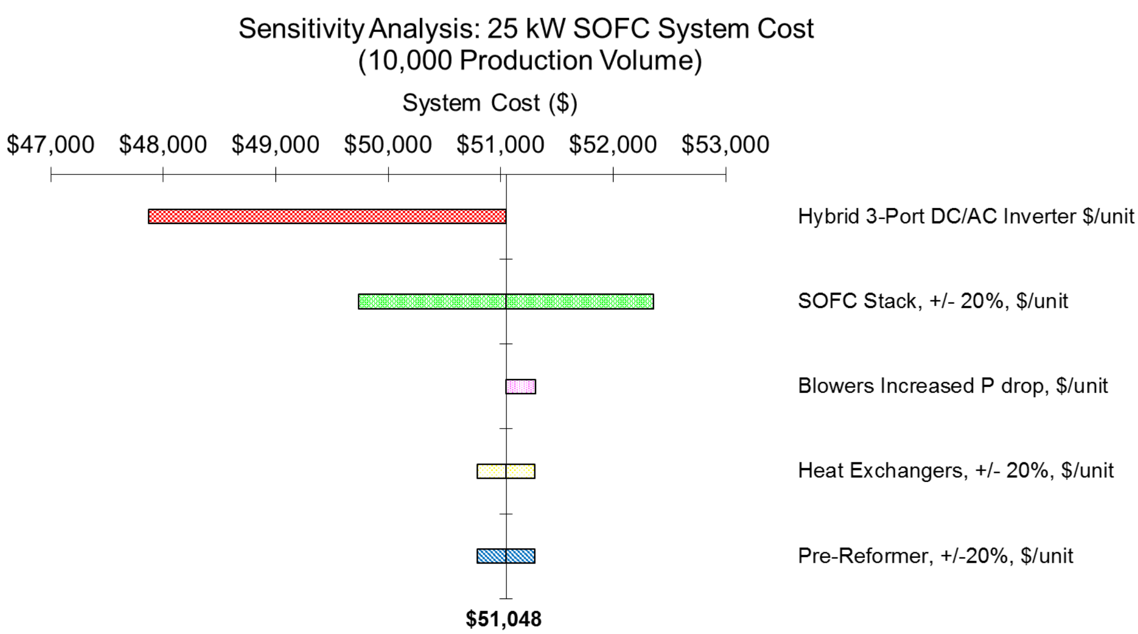


Figure 8-4. SOFC sensitivity analysis: 25-kW system cost – 10,000-unit production volume

Implementation of the hybrid three-port DC/AC inverter has the greatest overall effect to the system cost for the factors studied. For the 25-kW system, this new technology is a realistic option as they are being used in solar power installations in this size range. For the smaller systems, this option is not currently available. The SOFC stack has the next greatest potential to decrease the cost of the overall system. The heat exchangers have less of an effect on the SOFC system than on the PEM system because there are many more heat exchangers in the PEM system. Likewise, the pre-reformer has less of an effect on the SOFC system than on the PEM system because it is smaller. Similar to the PEM system, pressure drop of the system (thus requiring a different blower) had little effect.

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9. Life Cycle Cost Analyses of Fuel Cells

Fuel cell systems will compete with utilities for primary power and CHP applications. In addition, when the parameters exist to provide a value proposition (mainly high grid electricity costs and a need for significant heat load), fuel cell systems will compete with natural gas micro-turbines and reciprocating engines. CHP fuel cell systems may offer a number of advantages over conventional technologies, including efficiency, reduced maintenance, reliability, long life, and environmental benefits.

This analysis compares the life cycle costs of fuel-cell-powered CHP systems for restaurants when compared to the grid in areas where electricity costs are high. The analysis is based on Battelle's analysis of the manufacturing costs of the fuel cell system with a nominal 50% markup. The characteristics of operation are based on grid-connected systems, and the driving factor for sizing the fuel cell system is heat load. Through modeling work for a commercial client, Battelle has access to hundreds of restaurant load profiles in southern California over the two-year period from July 2012 to July 2014. These profiles include hourly energy usage data. Figure 9-1 and Figure 9-2 show a typical electric load profile of a restaurant in southern California for a week in January and July, respectively. The profiles are similar throughout the year.

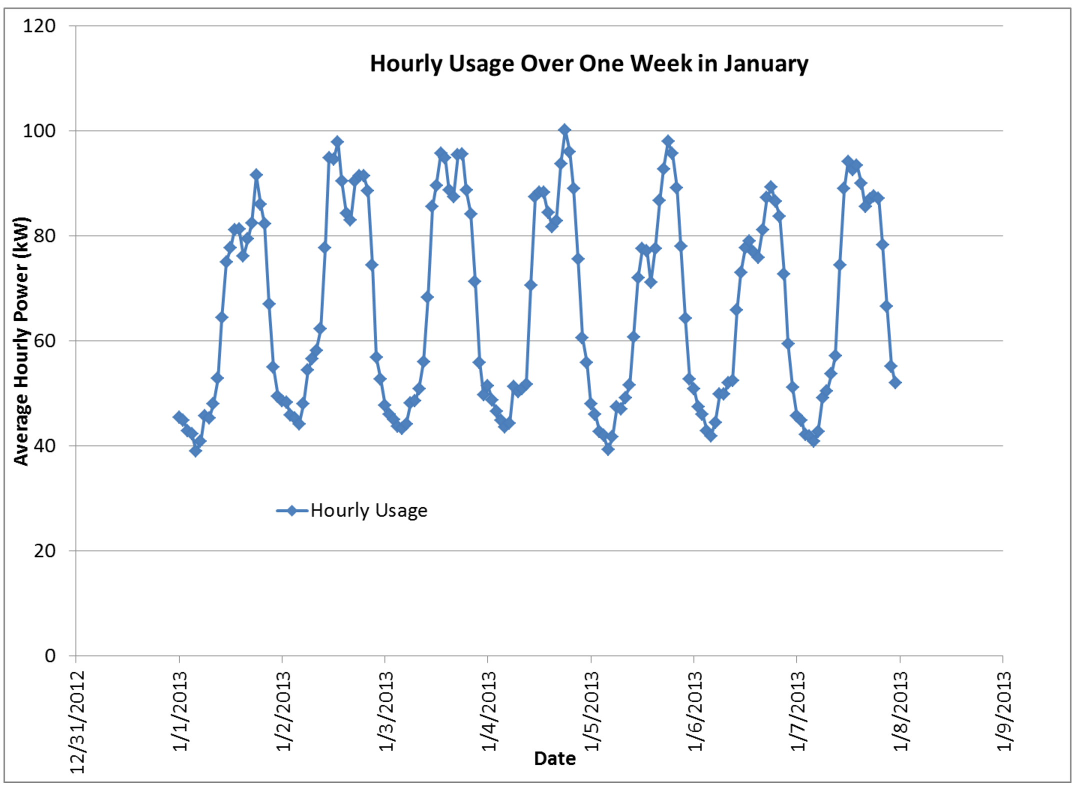

Figure 9-1. Hourly energy usage data for a typical restaurant in Southern California in January

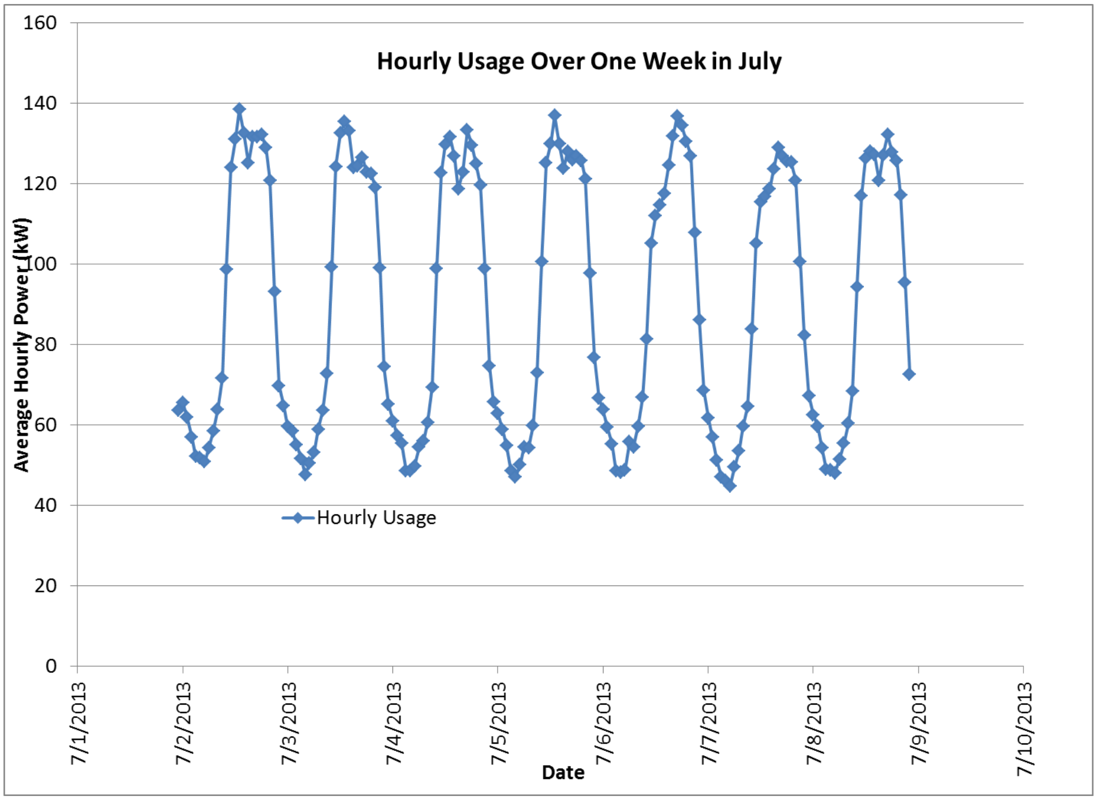

Figure 9-2. Hourly energy usage data for a typical restaurant in Southern California in July

Through cooperation with a national restaurant chain, Battelle was able to obtain detailed data of utility usage for the past two years. For this life cycle cost analysis, annual data (from July 2015 through June 2016) were obtained for 42 stores across the United States. This analysis focuses on stores in San Diego and Honolulu. Both of these locations have relatively high electricity costs; however, San Diego enjoys low natural gas prices, whereas Honolulu's natural gas prices are an order of magnitude higher.

Because the minimum total energy load of a typical restaurant is greater than 25 kW, we performed the life cycle cost using 25-kW systems. For this analysis, both systems were initially assumed to operate 24 hours a day, 7 days a week. A 25-kW system in San Diego does not cover the minimum electrical load seen by the restaurant, but will cover the critical loads in the event of a loss of power. During the restaurant's operating hours, the heat provided by a 25-kW system was slightly less than the required duty, thus ensuring that all of the excess heat from the fuel cell system was used. At night, it was assumed that no heat load was used. The resulting natural gas and electric usage was then calculated. As seen in Figure 9-3, the annual savings in utility costs were calculated to be $36,900 and $36,600 for a PEM and SOFC CHP system, respectively.

In the San Diego market, a value proposition exists, even without the combined heat portion, although it is much stronger with the CHP added. This is due to the large spark spread that exists in southern California with high electricity costs and low natural gas prices. Figure 9-3 illustrates just the pure differences in monthly utility costs for a San Diego restaurant, without taking into consideration the capital or maintenance costs of the system. Similar savings were seen by both the PEM and the SOFC systems because the low cost of natural gas minimizes the effect of the efficiency advantage for the SOFC system.

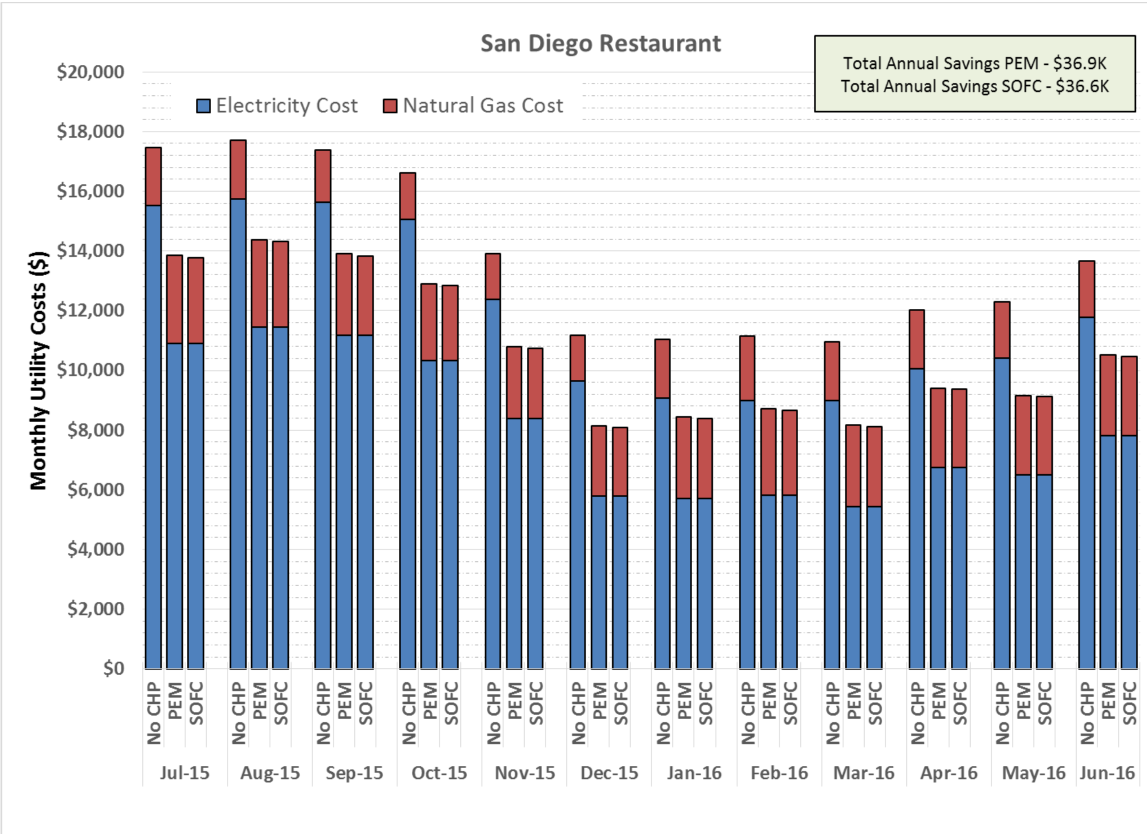

Figure 9-3. Monthly utility cost savings resulting from deployment of a 25-kW fuel cell CHP system in a San Diego restaurant

Deployment of a 25-kW system in the Honolulu restaurant (Figure 9-4) had load match characteristics similar to the San Diego locations: electric power supplied was less than the minimum load seen by the restaurant, but covered the critical loads in the event of a loss of power. During the restaurant's operating hours, the heat supplied by the fuel cell system was slightly less than the required duty, thus ensuring that all of the excess heat from the fuel cell system was used. As in the San Diego case, it was assumed there was no heat load during off hours. The resulting natural gas and electric usage was then calculated. As seen in Figure 9-4, the annual savings in utility costs were calculated to be $16,000 and $23,100 for a PEM and SOFC CHP system, respectively. Only the pure differences in monthly utility costs are illustrated in Figure 9-4; the capital or maintenance costs of the system were not considered.

A major difference in the Hawaii market is that natural gas prices are extremely high; therefore, in order to enable any value proposition, the combined heat portion of the system is required. The high price of natural gas also shows up in the delta between the savings for the SOFC system and the PEM system. The higher savings for the SOFC system are facilitated by the increased efficiency. For this analysis, it was assumed that the system was operated 24/7.

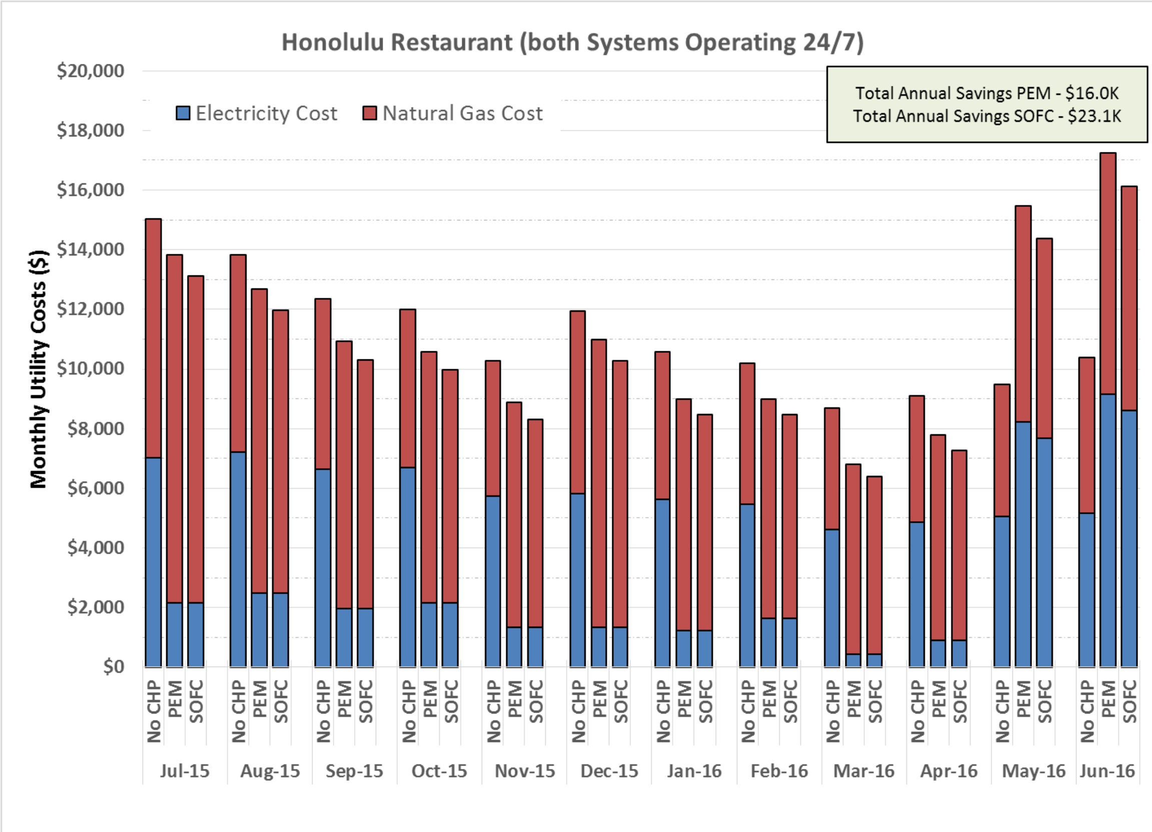

Figure 9-4. Monthly utility cost savings resulting from deployment of a 25-kW fuel cell CHP system in a Honolulu restaurant

The same analysis was repeated for the Honolulu restaurant assuming that the PEM fuel cell was shut down during the evening hours (when no heat load was present). Daily shutdowns are not feasible with the SOFC system due to the impact of cooling/heating cycles on overall life. As shown in Figure 9-5, shutting down the PEM system at night results in additional savings of approximately $7,000 annually. This is the result of high electricity costs with the negative spark spread. Again, because of this negative spark spread, the value proposition does not exist without the combined heat portion of the system.

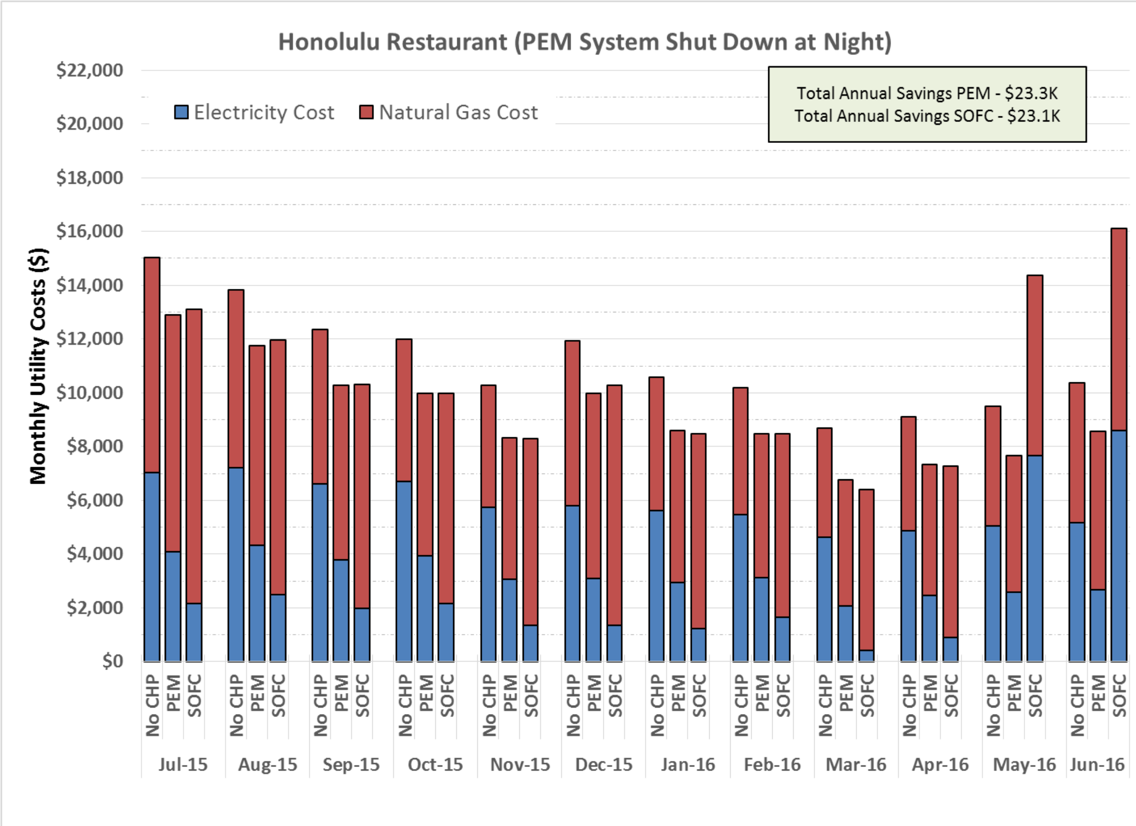

Figure 9-5. Monthly utility costs savings resulting from deployment of a 25-kW fuel cell CHP system in a Honolulu restaurant with the PEM system shut down when no heat load is present

Table 9-1 through Table 9-4 show the annual cost comparison for the San Diego restaurant when deploying a fuel cell CHP system versus utilities only. Production volumes of 1,000 and 10,000 units per year for the PEM and SOFC systems are shown. The annual savings for the Honolulu store exhibited very similar characteristics.

Table 9-1. Annual Cost Comparison When Using a PEM CHP System in a San Diego Restaurant with a Production Volume of 1,000 Units per Year

	Fuel Cell	Utilities Only
Cost of System	$86,809	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$24,683	N/A
Annual Consumables	$1,252	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$32,373	$22,184
Annual Total	$155,087	$165,410
Annual Savings	$10,323	

Table 9-2. Annual Cost Comparison When Using a PEM CHP System in a San Diego Restaurant with a Production Volume of 10,000 Units per Year

	Fuel Cell	Utilities Only
Cost of System	$74,067	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$21,434	N/A
Annual Consumables	791.15	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$32,373	$22,184
Annual Total	$151,377	$165,410
Annual Savings	$14,033	

Table 9-3. Annual Cost Comparison When Using a SOFC CHP System in a San Diego Restaurant with a Production Volume of 1,000 Units per Year

	Fuel Cell	Utilities Only
Cost of System	$58,470	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$17,457	N/A
Annual Consumables	$521	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$31,663	$22,184
Annual Total	$146,420	$165,410
Annual Savings	$18,990	

Table 9-4. Annual Cost Comparison When Using a SOFC CHP System in a San Diego Restaurant with a Production Volume of 10,000 Units per Year

	Fuel Cell	Utilities Only
Cost of System	$51,048	N/A
Installation Cost	$10,000	N/A
Annual Cost of Capital (10%)	$15,586	N/A
Annual Consumables	$460	N/A
Annual O & M Costs	$750	N/A
Annual Electricity Utility Cost	$96,028	$143,226
Annual Gas Utility Cost	$31,663	$22,184
Annual Total	$144,487	$165,410
Annual Savings	$20,922	

Figure 9-6 shows the various cash flows for the four cases with the San Diego store; the figure also lists the payback period and 5-year internal rate of return (IRR) and net present value (NPV). The annual savings listed do not reflect the annual cost of capital as this is accounted for in the IRR and NPV calculations.

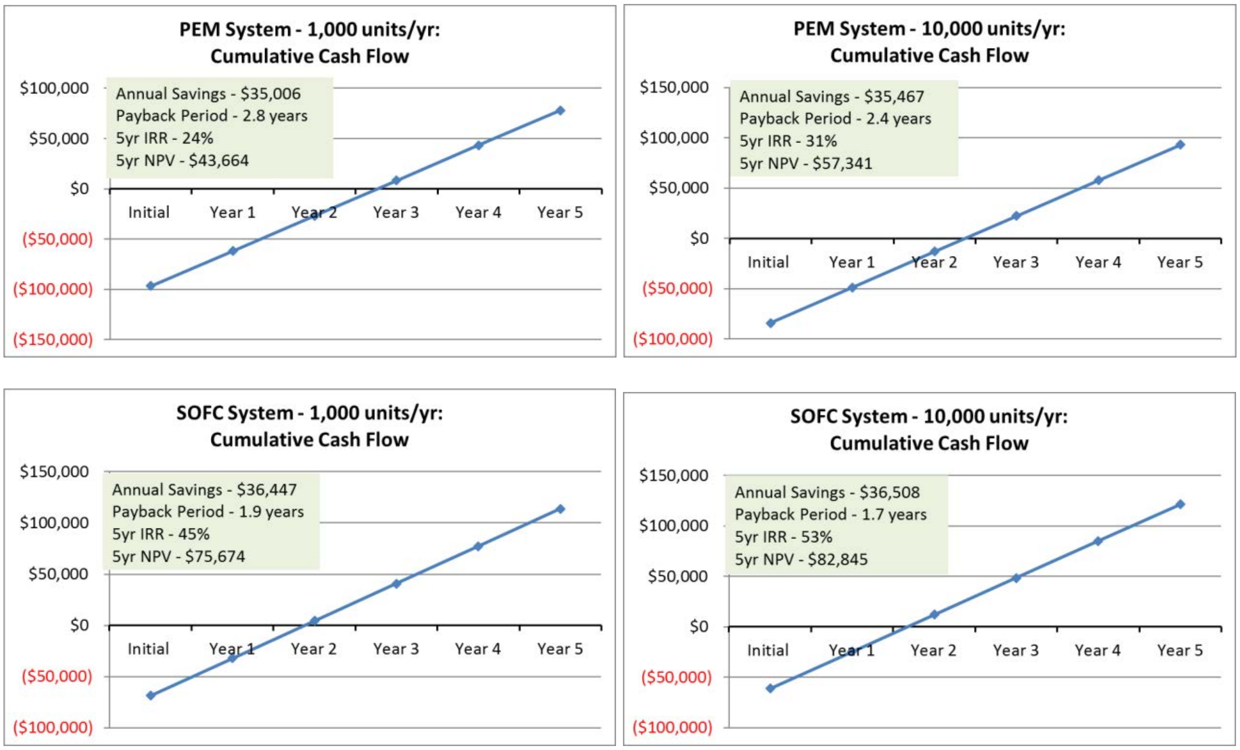

Figure 9-6. Cumulative cash flows for PEM and SOFC systems with production volumes of 1,000 and 10,000 units per year in the San Diego restaurant

Although there would be significant benefit resulting from continued power availability during an electrical grid outage, no credit has been assumed for this analysis. The value of continued power could represent significant savings by avoiding loss of refrigerated items and by being able to continue operation during an outage. Though not needed to make the case for this example, this added benefit along with incentives for energy efficiency could open up an even broader market. However, the market that exists for opportunities that meet the criteria similar to this example is significant.

Two key assumptions in this analysis are the system efficiencies and lifetimes. The efficiencies were assumed to be 30% and 40% electrical, while the overall system efficiencies were assumed to be 80% and 90%, for the PEM and SOFC systems respectively. These efficiencies are achievable, but they have not yet been shown on a reliable basis in a commercial application. Similarly, lifetimes were assumed to be 5 years (or greater than 40,000 hours). While 5-year lifetimes are achievable, both PEM and SOFC systems will need to demonstrate this durability on a consistent basis in actual field applications to mitigate the risk for a restaurant (or other commercial entity) considering system installation.

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10 Conclusions

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

10.1 System Cost Summary

The summary pie charts for 1,000 units per year (Figure 10-1) (repeated from Section 7) emphasize that the BOP costs dominate the final cost for both PEM and SOFC systems. The stack represents a maximum of 27% of the total system cost. Within the BOP costs, the major contributors are the power electronics (in CHP Hardware) and the fuel processing system (in FC BOP). Both areas have potential for innovation and development to decrease the costs summarized in Figure 10-1.

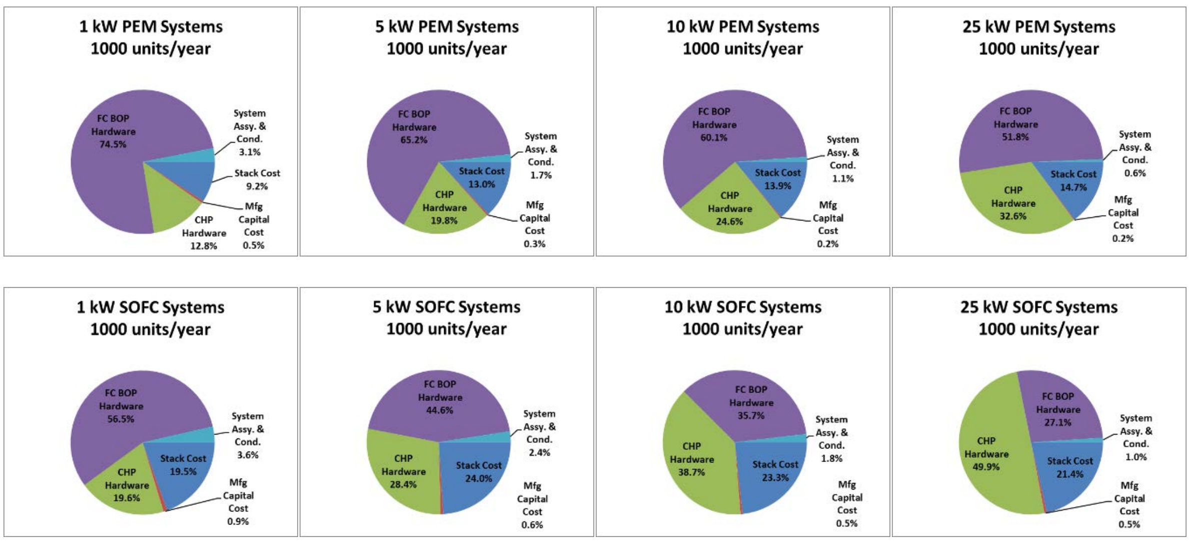

Figure 10-1. Fuel cell system cost distribution

Also notable in the pie charts and analysis is the small influence of capital cost in the final cost, even at low production volumes. An important feature of primary power and CHP systems is that space and weight requirements are less stringent than for mobile applications (e.g., MHE), allowing less customization and the use of more commonly available hardware and production equipment. In this analysis, we have assumed that all processes except stack testing and final system testing would be outsourced until the production volumes would result in production station utilization above approximately 40%. The calculation for outsourcing versus producing in-house is shown in Appendix A-1. This ensures that capital investment, once made, will be distributed across an appropriate number of systems. Although not considered in the analysis, it is important to note that commonality between the 10- and 25-kW MEA assemblies, for example, would potentially permit in-house fabrication sooner if both size systems were being produced, yielding higher total production rates for common parts.

The total costs for each size and the two representative production volumes are shown in Table 10-1 (PEM system) and Table 10-2 (SOFC system). A sales markup of 50% was integrated into the overall cost and is called out separately. The restaurant life cycle cost analysis of Section 9 uses the highlighted values for the 25-kW system.

Table 10-1. PEM System Cost

PEM Systems	1 kW		5 kW		10 kW		25 kW	
Description	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr
Total stack manufacturing cost, with scrap	$1,052	$554	$2,697	$1,643	$4,349	$2,849	$8,527	$6,354
Stack manufacturing capital cost	$57	$22	$71	$30	$71	$39	$101	$65
CHP Hardware	$1,465	$1,336	$4,115	$3,772	$7,684	$7,033	$18,890	$17,356
BOP	$8,523	$7,228	$13,553	$11,502	$18,779	$15,525	$29,990	$25,309
System assembly, test, and conditioning	$349	$278	$352	$281	$355	$284	$365	$293
Total system cost, pre-markup	$11,447	$9,419	$20,788	$17,227	$31,238	$25,730	$57,873	$49,378
System cost per kW_{net}, pre-markup	$11,447	$9,419	$4,158	$3,445	$3,124	$2,573	$2,315	$1,975
Sales markup	50%	50%	50%	50%	50%	50%	50%	50%
Total system cost, with markup	$17,170	$14,128	$31,183	$25,841	$46,857	$38,595	$86,809	$74,067
System cost per kW_{net}, with markup	$17,170	$14,128	$6,237	$5,168	$4,686	$3,860	$3,472	$2,963

Table 10-2. SOFC System Cost

SOFC Systems	1 kW		5 kW		10 kW		25 kW	
Description	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr	1,000/ yr	10,000/ yr
Total stack manufacturing cost, with scrap	$2,048	$1,360	$3,762	$2,514	$4,879	$3,429	$8,358	$6,555
Stack manufacturing capital cost	$90	$37	$99	$65	$99	$77	$209	$135
CHP Hardware	$2,069	$1,895	$4,456	$4,054	$8,117	$7,452	$19,433	$17,939
FC BOP Hardware	$5,944	$5,166	$6,995	$6,067	$7,482	$6,753	$10,581	$9,073
System assembly, test, and conditioning	$378	$310	$381	$313	$386	$317	$399	$330
Total system cost, pre-markup	$10,528	$8,768	$15,693	$13,013	$20,963	$18,029	$38,980	$34,032
System cost per kW_{net}, pre-markup	$10,528	$8,768	$3,139	$2,603	$2,096	$1,803	$1,559	$1,361
Sales markup	50%	50%	50%	50%	50%	50%	50%	50%
Total system cost, with markup	$15,791	$13,153	$23,540	$19,519	$31,444	$27,043	$58,470	$51,048
System cost per kW_{net}, with markup	$15,791	$13,153	$4,708	$3,904	$3,144	$2,704	$2,339	$2,042

Figure 10-2 and Figure 10-3 show the after-markup cost per $kW_{electrical}$ and per kW_{total} for PEM and SOFC systems. As a stated in Section 4 of this report, the PEM system is assumed to have an electrical efficiency of 30% and total efficiency (with heat recovery) of 80%; likewise, the SOFC system has an electrical efficiency of 40% and total efficiency of 90%. Figure 10-3 suggests that PEM systems can achieve near parity on an installed-cost basis with SOFC systems at sites where heat load can be utilized (the differences on a total-kilowatt-delivered basis are within the margin of error for this analysis). An important point to note for Figure 10-3 is the integration of heat recovery with the reformer as well as the stack to improve overall efficiency and to deliver heat to the CHP load at a higher temperature; this approach allows the PEM CHP system to achieve higher total efficiency than would normally be possible when only recovering lower temperature stack heat.

When considering the value of the heat delivered in terms of natural gas and electric costs avoided, the economic benefit of a continuously operating system versus a back-up power system becomes apparent if the difference between electric power and natural gas cost on a comparable energy basis (the “spark spread”) is characterized by electric prices higher than gas prices by at least $0.12/kW-hr. A particular advantage of a fuel cell system compared to alternatives (e.g., natural gas reciprocating engine or gas turbine) is longer expected life in continuous operation coupled with simple maintenance requirements. Very low noise and emissions enable siting in urban and environmentally sensitive areas.

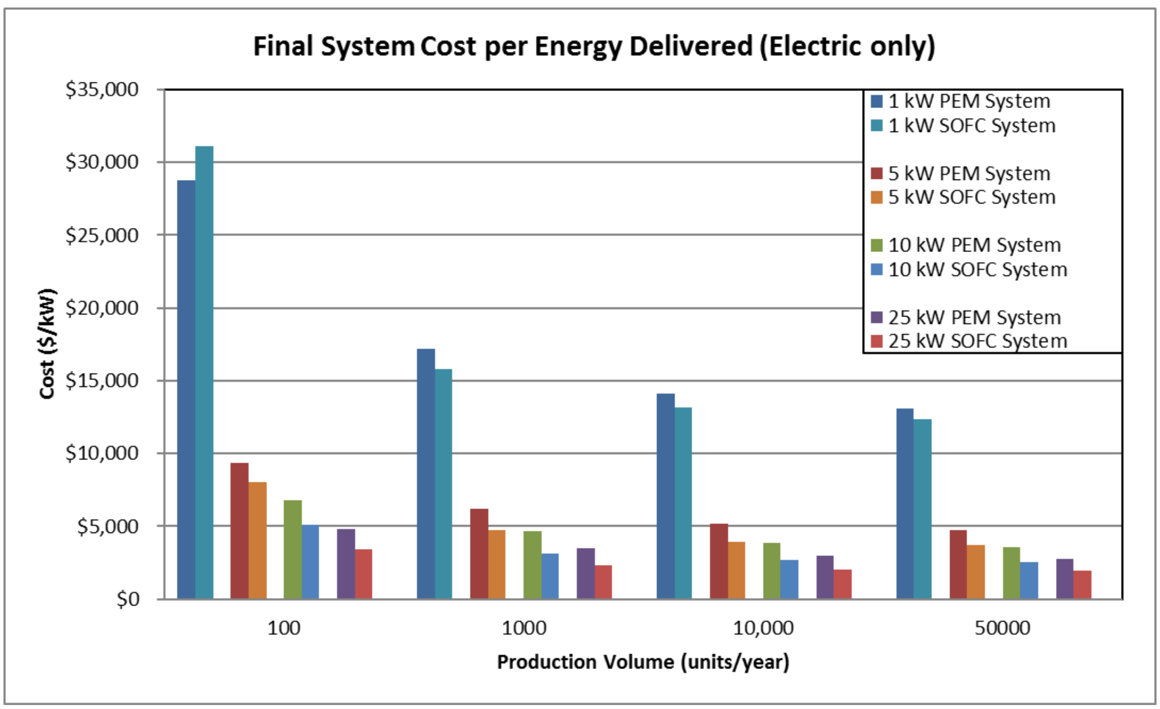

Figure 10-2. Final system cost of electric power delivered

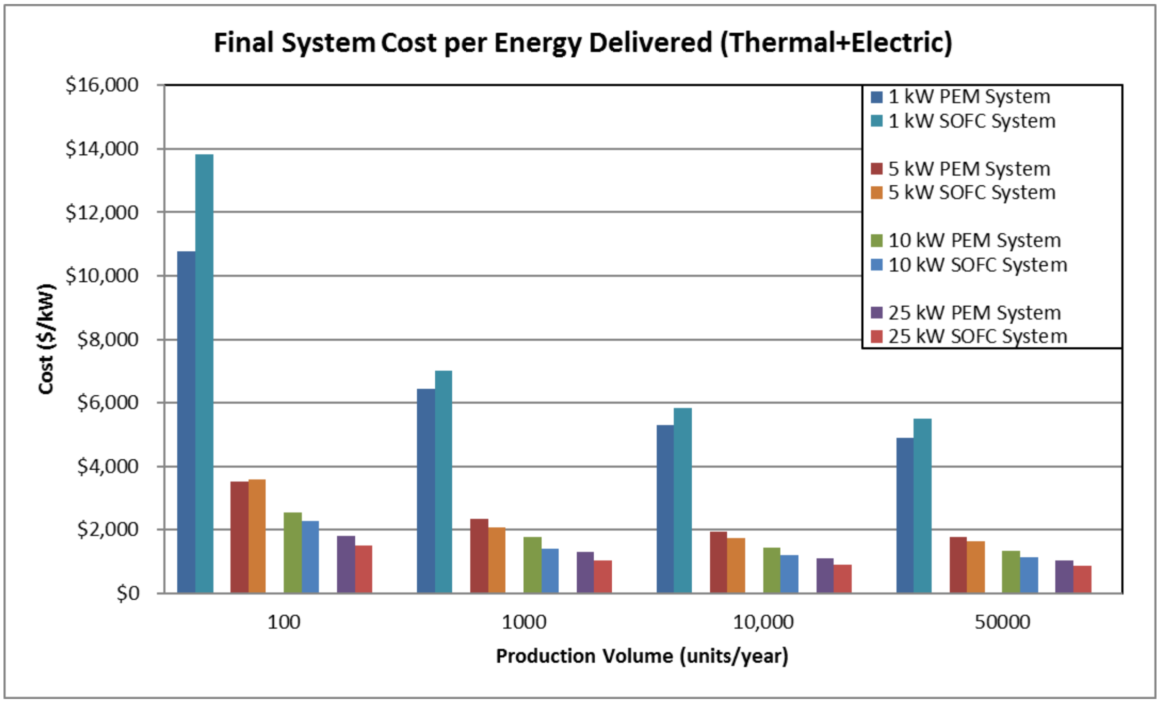

Figure 10-3. Final system cost of energy delivered (thermal and electric)

10.2 Value Proposition

Although there are no currently available manufactured products available for the primary power and CHP markets at 25 kW and below, our analysis suggests a definitely attractive value proposition under specific utility rate conditions. The best value proposition is achieved in areas with high electricity cost and low natural gas costs and for installations with a significant heating load, such as the water and space heating loads for restaurants, health care facilities, and similar locations.

For a typical restaurant application, the analysis in Section 9 suggests a roughly 2- to 3-year payback with existing system cost estimates for production volumes of 1,000 units per year or greater. The monthly savings for a typical restaurant in San Diego provided in Section 9 do not include any allowance for the value of continued power availability during an electrical grid outage. Continued power could represent a major savings by preventing refrigerated product loss, with even more economic benefit if food service operations can continue (even on a limited menu basis) during the outage.

There is only a minor difference between SOFC and PEM systems in terms of estimated savings, with the SOFC system favored for the restaurant analysis. The value proposition favoring the SOFC system for this application is primarily the lower first cost of the SOFC system and a higher assumed overall system efficiency. For other applications where water must be heated to higher temperature or where process conditions require higher temperatures, the SOFC system will show greater benefit. The nominal benefit of the SOFC system must be tempered by the recognition that SOFC stack technology is not as far advanced or as well proven as PEM technology, so it represents a greater risk currently. If the automotive PEM systems develop as expected, those systems will likely benefit from attendant cost and technology improvements, potentially bringing first cost closer to SOFC systems. As indicated in Section 9, a PEM system may be preferred for applications where overnight shutdown is favored or where time-of-day pricing places a premium on operation only during a portion of the day.

10.3 Sensitivity and Future Market Impact

The sensitivity analysis in Section 8 suggests that adapting the three-port inverter technology in place of discrete DC/DC and DC/AC components offers early opportunity for cost reduction. Because these inverters are being specifically developed for the solar industry now, the cost would be expected to decrease in the near future. The solar versions are not directly applicable to fuel cells, but variants based on the same technology and benefiting from the solar developments are possible in the short term. Section 8 indicates that some factors which are likely to improve in the future, such as current density and platinum loading, will have overall cost benefits, and that these factors are more important than the cost of platinum, which can be volatile.

The choice to define a dual-use system capable of both grid-connected and off-grid operation increases power electronics cost because a higher-power DC/DC converter plus batteries to permit transient response is needed. We have also included a resistor bank to address conditions where the minimum site load is lower than the minimum fuel cell power. Requiring that the system operate with or without an applied thermal heat load also increases system cost slightly. For PEM systems, a full load radiator is required. For SOFC systems, high-temperature bypass valves are required. The components may not be appropriate for all applications, and some cost could be eliminated by assuming that the system operates only when the grid is available. However, with a beneficial spark spread, the back-up power-capable system pays for itself in a few years. For areas without a beneficial spark spread, the site-specific life cycle cost analysis should include the value of avoided losses associated with typical grid outage conditions. Grid outage operation will be more valuable in areas with lower grid reliability.

As fuel-cell-powered MHE increases market penetration and as automotive use of fuel cells increases, we expect that a CHP/primary power market will develop, initially for areas with conducive utility pricing and critical grid outage conditions. Because of the maturity being achieved with PEM systems in MHE and automotive markets, PEM CHP will likely lead SOFC deployment due to higher confidence that system life and maintenance costs will be satisfactory. As SOFC technology matures and achieves long demonstrated lifetimes in real-world applications, the lower cost basis should enable future market penetration.

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

The basic machine rate equation from James et al. (2014)[11] is:

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

where:

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

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

(TR + TS) = 6,000 ∗ U

Input assumptions based on our previous work and on the assumptions shown in Table 3 of the James et al. paper[11] results in the following:

Expected equipment lifetime	20	yrs
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:

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

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

N_i = number of item i required for production station

C_i = capital cost of item i

L_i = expected life of item i

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

		Cost	Units Per Station	Expected Life
Bipolar Plate Compression Molding				
1,000 ton fast-acting press	Wabash 1000H-48	$650,000	1	20
Heated platens, 15"x12", 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:

	Ni	Ci	Li	C_{Cap}
Bipolar Plate Compression Molding				
1,000-ton fast-acting press	1	$650,000	20	$600,000
Heated platens, 15"x12", 4.5 kW, controller	1	$12,500	10	$25,000
Arbor or hand-operated hydraulic pre-mold press	1	$400	20	$400
Electronic scale, industrial, gram resolution	1	$6,000	10	$12,000
Small industrial oven	1	$1,000	20	$1,000
Total				$638,400

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

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

where:

n = unique pieces of equipment making up production station

Ni = number of item i required for production station

Vi = voltage supplied to item i

Ai = current draw of item i

Di = duty cycle of item i

This yields the following:

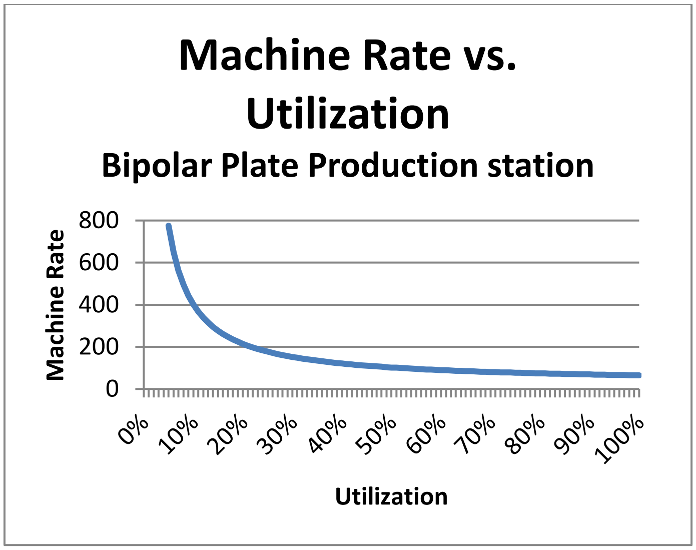
	N_i	V_i	A_i	D_i	P
Bipolar Plate Compression Molding					
1,000-ton fast-acting press	1	460	150	96%	66.24
Heated platens, 15"x12", 4.5 kW, controller	1	230	25	25%	1.44
Arbor or hand-operated hydraulic pre-mold press	1	0	0	10%	0.00
Electronic scale, industrial, gram resolution	1	120	1	100%	0.12
Small industrial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

LTPEM Production Station	Baseline Cost	Power Cost (/hr))	Labor Cost (/hr)	100% Utilization Machine Rate
Bipolar Plate Compression Molding	$638,400	$1.50	$45.00	$64.70
Platinum Catalyst Preparation	$37,000	$0.01	$9.00	$11.18
Slot Die Coating	$94,892	$0.90	$22.50	$62.20
Decal Transfer	$58,400	$0.74	$22.50	$26.66
GDL Slit and Cut	$87,700	$0.45	$22.50	$28.09
MEA Hot Pressing	$499,400	$0.80	$22.50	$52.58
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	$41,300	$0.37	$14.85	$17.64

SOFC Production Station	Baseline Cost	Power Cost (/hr))	Labor Cost (/hr)	100% Utilization Machine Rate
High Volume Slurry Production	$20,000	$0.33	$4.50	$6.00
Low Volume Slurry Production	$17,500	$0.07	$4.50	$5.78
Tape Casting	$283,000	$1.16	$45.00	$62.25
Anode Pressing	$77,600	$0.32	$45.00	$27.79
Anode Blanking	$125,000	$0.00	$45.00	$29.83
Screen Printing	$66,612	$0.81	$45.00	$49.71
Kiln Firing	$393,000	$16.10	$14.85	$53.99
Sintering	$500,000	$16.10	$14.85	$60.26
Laser Cutting	$35,000	$9.26	$14.85	$33.81
Sheet Metal Stamping	$150,000	$1.61	$45.00	$55.40
Interconnect	$365,860	$2.98	$90.00	$114.43
End Plates	$416,000	$6.50	$90.00	$120.89
Sealing	$27,500	$1.59	$14.85	$48.21
Stack Assembly	$550	$0.00	$45.00	$45.03
Stack Brazing	$500,000	$16.10	$14.85	$60.26
Testing and Conditioning	$41,300	$0.37	$14.85	$17.64

A-1.1 Make vs Buy Decision

As indicated in James et al. (2014)[12], 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:

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

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

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

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

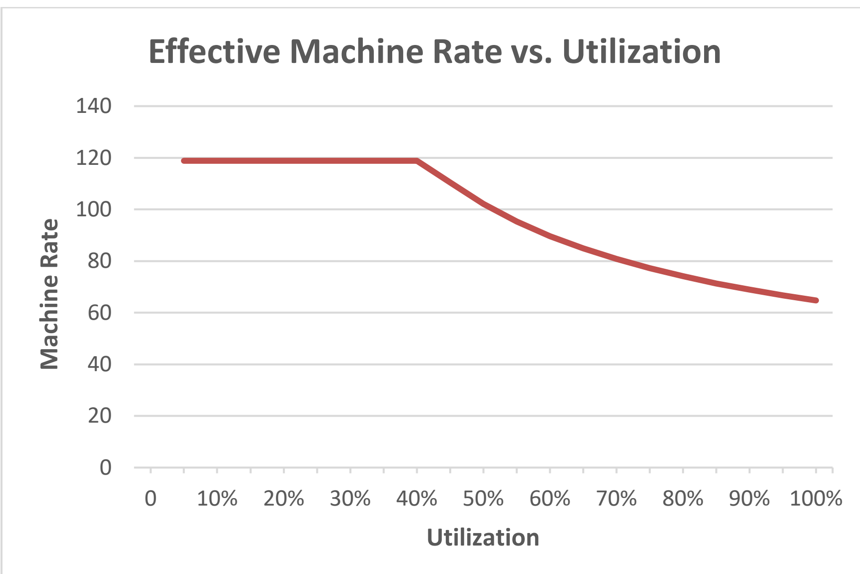
To achieve an equivalent in-house rate, the minimum utilization is:

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

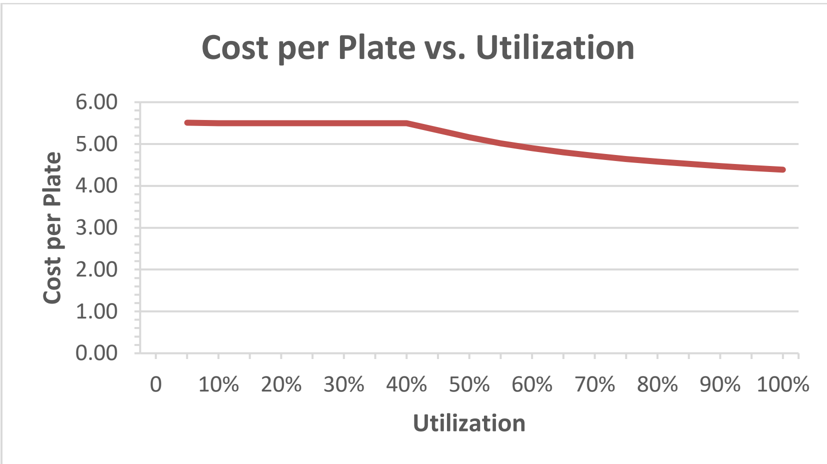
$$U = \frac{\$37.42}{(\$118.83 - \$27.31)} = 0.409$$

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

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



This can be further illustrated by estimating the production per unit for bipolar plates. Each plate contains 0.691 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 50 parts/hour, yielding a maximum annual capacity of 300,000 plates per year, and requires 0.5 operator time per machine. Using the above equations, the bipolar plate unit cost as a function of 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 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

A-2.1 Background

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

From the *Cost Estimator's Reference Manual* (1995),[13] 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 is the cost of the 10,000th unit.

A-2.2 Preliminary Analysis

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

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

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

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

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

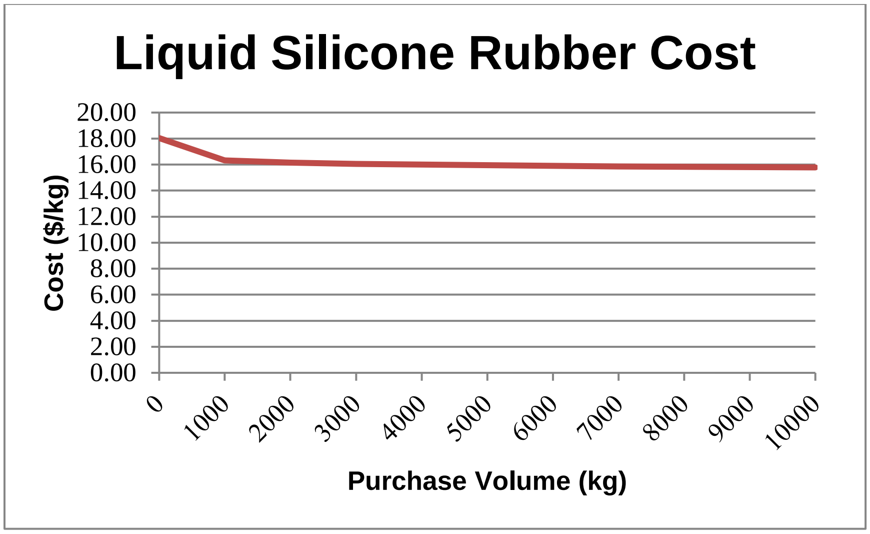
$A = Y / X^b = 15.40 / 55{,}000^{(-0.0145)} = \$18.04$

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

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

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

The corresponding cost chart would appear as:



For specialty materials, like the GDL in the 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:

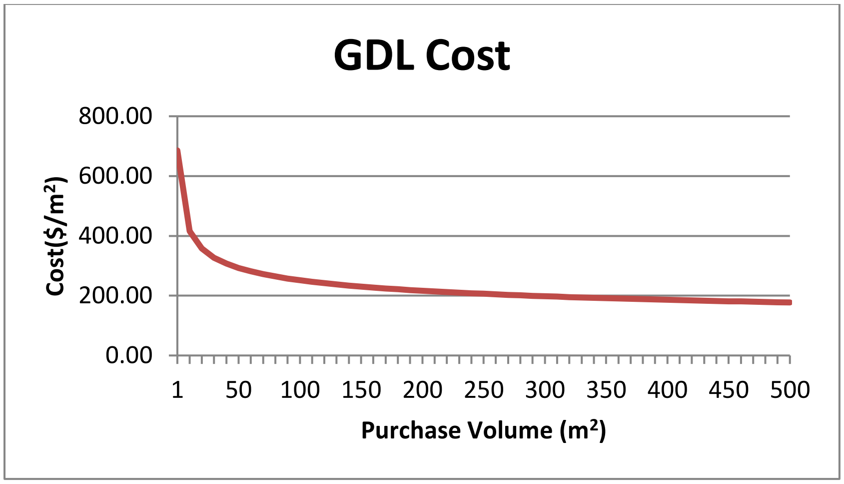
$$A = Y / X^b = 56.00 / 100{,}000^{(-0.21759)} = \$685.72$$

For a purchase of 3 and 45 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 of LTPEM material:

LTPEM Material	Units	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	$100.00	100,000	0.75	-0.4150	$11,890.15
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	$0.53	30,000	0.80	-0.3219	$14.64
Natural Gas	m^3	$0.0028	1,000	0.99	-0.0145	$0.32

The following learning curve parameters were used for the cost analysis of SOFC material:

SOFC Material	Units	Y	X	m	b	A
NiO	kg	$32.00	2,500	0.90	-0.1520	$105.11
8YSZ	kg	$40.00	2,500	0.90	-0.1520	$131.39
LSM	kg	$85.00	2,500	0.90	-0.1520	$279.20
LSCF	kg	$85.00	2,500	0.90	-0.1520	$279.20
LO	kg	$52.00	2,500	0.90	-0.1520	$170.81
Ni-YSZ	kg	$36.00	2,500	0.90	-0.1520	$118.25
LSM-YSZ	kg	$62.50	2,500	0.90	-0.1520	$205.29
Perovskite Coating	kg	$150.00	2,500	0.90	-0.1520	$492.71
SS-441 Stainless Steel Sheet	kg	$2.50	3,000	0.85	-0.2345	$16.34
SS-441 Stainless Steel Mesh	kg	$89.23	100,000	0.90	-0.1520	$513.48
Hastelloy X	kg	$30.36	2,000	0.90	-0.1520	$96.40
Borosilicate glass	kg	$2.00	2,500	0.85	-0.2345	$12.52
Water	kg	$0.10	160	0.85	-0.2345	$0.33
Binder	kg	$2.50	2,500	0.85	-0.2345	$15.65
Dispersant	kg	$1.27	2,500	0.85	-0.2345	$7.95
A560 Stainless Steel	kg	$2.50	3,000	0.97	-0.0439	$3.55
Nitrogen	m^3	$0.53	30,000	0.80	-0.3219	$14.64
Hydrogen	m^3	$0.53	30,000	0.80	-0.3219	$14.64
Natural Gas	m^3	$0.0028	1,000	0.99	-0.0145	$0.32
Carrier Film	m^2	$0.32	30,000	0.55	-0.8625	$2,326.22

A-2.3 High Quantity Purchased Material Cost

For the annual system volumes used, the material purchase volume can be extremely large. For example, to manufacture bipolar plates for 50,000 100-kW systems requires over 60,000 metric tons of BMC940 material. According to the learning curve equation, a bulk purchase of this size would cost $0.188/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 tables 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:

$$Y_q = \mathrm{Max}(12.55 \times (60\times10^6)^{-0.2345}, 2.43 \times 0.85) = \mathrm{Max}(0.188, 2.065) = \$2.065$$

A-2.4 Special Cases

Platinum prices are dictated by the precious metals spot markets and are generally not subject to purchase volume reductions. This correlates 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 falling 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. Since 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.

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Appendix A-3: Assembly Cost Learning Curve Calculations

A-3.1 Background

The Boothroyd Dewhurst, Inc. (BDI) Design for Assembly (DFA) software produces assembly times based on hand assembly at its most efficient. Using the 5-kW PEM as an example, the assembly time was estimated to be 3.070 hours.

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

From the *Cost Estimator's Reference Manual* (1995),[14] the general learning curve equation is:

$Y = AX^b$

where:

Y = time or cost per cycle or unit

A = time or cost for first cycle or unit

X = number of cycles or units

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

A-3.2 Analysis

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

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

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

$A = Y / X^b = 1.044 / 100^{(-0.23447)} = 3.074$ hrs

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

$$\overline{C}_{100} = \frac{\left(\sum_{i=1}^{100} 3.074 * i^{(-0.23447)}\right)}{100} = 1.345\ hrs$$

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

The time to assemble all subsequent units is assumed to be A, making the average time to assemble n units (n > 100) is calculated as:

$$\overline{C}_n = \frac{\left(\left(\sum_{i=1}^{100} A * i^{(-0.23447)}\right) + \left(Y_{100} * (n - 100)\right)\right)}{n}$$

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

1st Year Average Assembly Time (hrs)				
Stack Type	Stacks per year			
	100	1,000	10,000	50,000
1.2 kW PEM Stack	0.392	0.313	0.305	0.304
6-kW PEM Stack	1.345	1.074	1.047	1.045
12-kW PEM Stack	1.606	1.283	1.251	1.248
30-kW PEM Stack	2.984	2.383	2.323	2.318
1.2-kW SOFC Stack	0.478	0.382	0.373	0.372
6-kW SOFC Stack	1.762	1.407	1.372	1.369
12-kW SOFC Stack	2.105	1.681	1.639	1.635
30-kW SOFC Stack	5.016	4.007	3.906	3.897

The average system assembly times are:

1st Year Average Assembly Time (hrs)				
System Type	Systems per year			
	100	1,000	10,000	50,000
CHP PEM System	3.484	2.783	2.712	2.706
CHP SOFC System	2.077	1.659	1.617	1.614

Appendix A-4: LTPEM Production Facility Estimation

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

A-4.1 Equipment Footprint

The line utilization calculations provide the equipment count for a particular production station. 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:

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:

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

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

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

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

Personnel allowance = 1×20 ft^2 = 20 ft^2

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

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

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

Floor space allocation = 130 + 87 + 27 + 20 + 92 = 356 ft^2

The PEM fuel cell stack production was broken up into nine 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 DFM process analyses for a and t, and estimating time for b, resulted in the following:

PEM Production Station	a	b	t	n'	1/n'
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
Slit and Cut	1,800	600	10,547	5.14	0.19
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
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 stations requiring multiple operators can utilize a floating operator working between three machines. The exception is catalyst production: we assume that the 10-hour milling time per catalyst batch permits one operator to operate five machines.

To obtain a rough estimate of the number of operators required during any one shift, we 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 station utilization (assuming a single operator is trained to perform multiple tasks). Using the station utilization numbers for 10,000 6-kW stacks per year, we have:

PEM Production Station	Stations	Utilization	Operators per station	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
Slit and Cut	1	0.163	0.50	0.08
Hot Press	1	0.163	0.50	0.08
Die Cutting	1	0.023	1.00	0.02
Bipolar Plate	5	0.774	0.50	1.94
End Plate	1	0.242	2.00	0.48
Seal Injection Molding	2	0.866	0.50	0.87
Stack Assembly	2	0.855	1.00	1.71
Stack Test and Conditioning	3	0.972	0.33	0.96
System Assembly	5	0.919	1.00	4.60
System Test	7	0.952	0.33	2.20
Total				12.97

Rounding up to 13 machine operators per shift, and assuming approximately one support staff per four operators for purchasing, quality control (QC), and maintenance, the facility needs to support a total of 17 employees. Ventura provides estimates for the following additional facilities:

Food service: 15 ft^2/employee
Restrooms: 2 toilets + 2 sinks per 15 employees (estimated at 25 ft^2 per fixture)
Parking: 276 ft^2/employee

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

Facility	Space Required (ft^2)
Food Service	195
Restrooms	100
Parking	3,588
Office	288

Estimated total factory building floor space can be estimated as:

$$\text{Equipment} + \text{Food service} + \text{Restrooms} + \text{Office} = 9{,}746 \text{ ft}^2$$

Assuming a construction cost of \$250/ ft^2, the estimated cost of factory construction is approximately \$2,436,500.

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:

$$((\text{Factory space} + \text{Parking space})^{1/2} + 60)^2 = 30{,}791 \text{ ft}^2 = 0.71 \text{ acre}$$

Assuming a real estate cost of \$125,000/acre, the estimated total real estate cost is approximately \$88,360.

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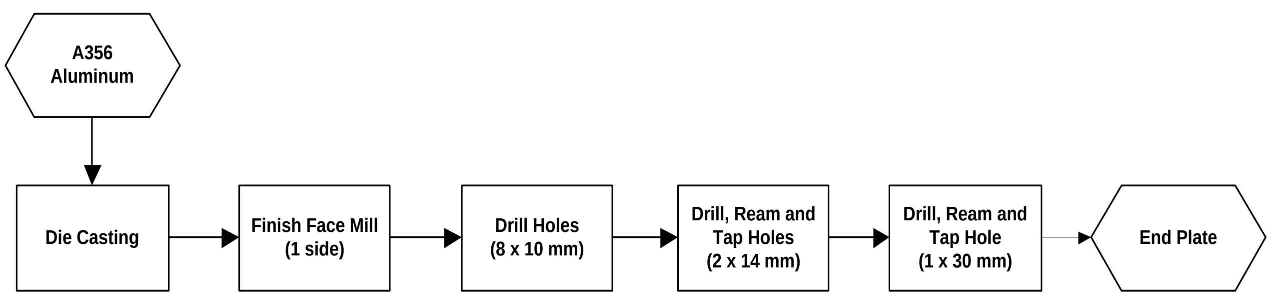
Appendix A-5: LTPEM End Plate Manufacturing Process

A-5.1 Model Approach

- Use standard Boothroyd Dewhurst, Inc. (BDI) cell machining cost analysis
  - Near net shape workpiece
  - Face mill bottom
  - Drill tie rod holes
  - Drill, ream, and tap gas connector mounting holes

A-5.2 Process Flow

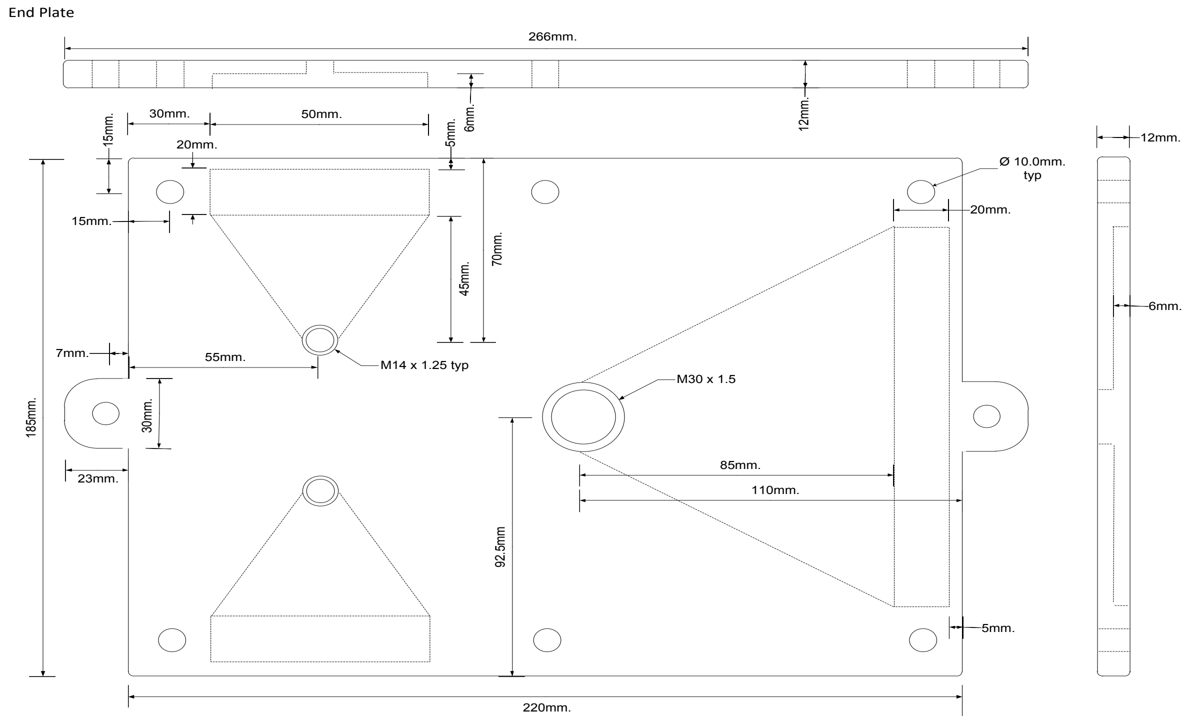


A-5.3 Background

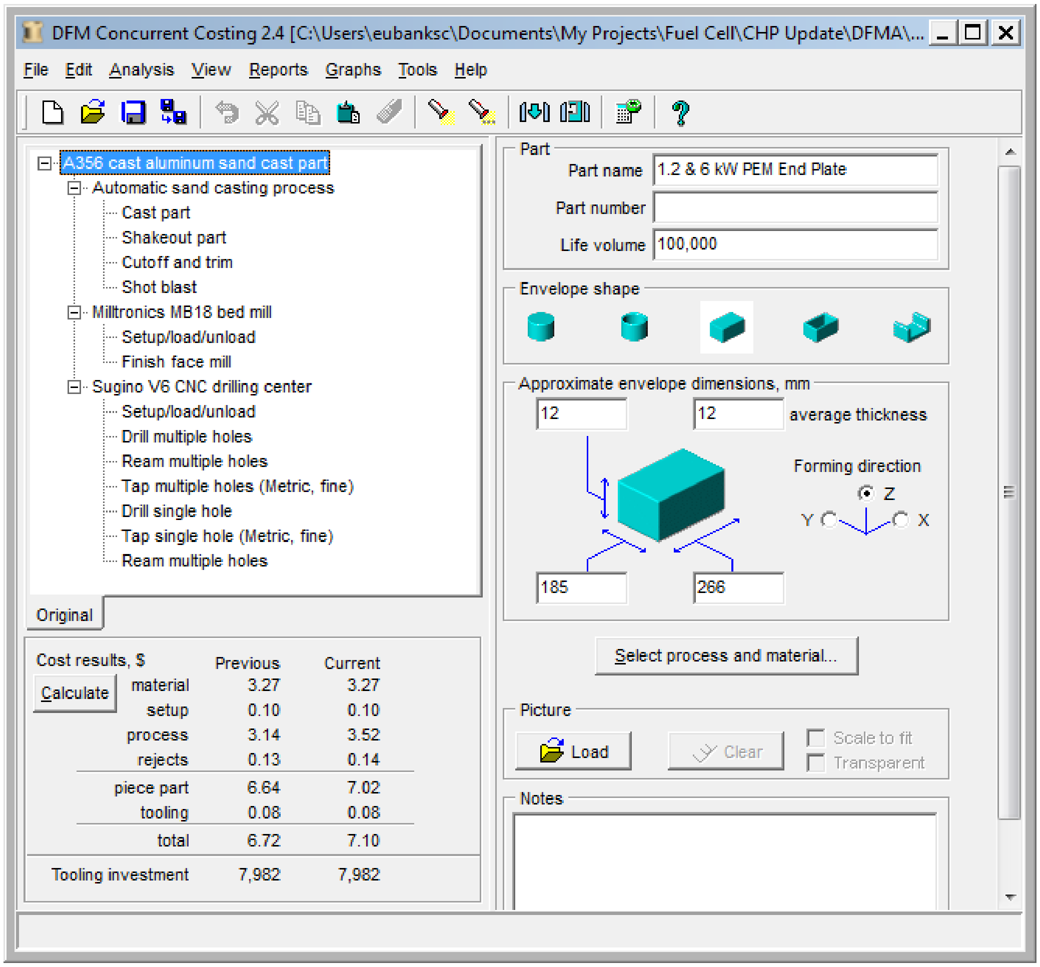
The BDI software provides preprogrammed cost models for the casting and cell machining operations used to manufacture the fuel cell stack end plates. The end plates need to be rigid in order to apply even pressure across the face of the stack. The process selection for the LTPEM end plate was sand casting of A356 aluminum to near net shape, followed by finish machining of the stack contact face, drilling the tie rod holes, and drilling, reaming and tapping the holes for fuel, exhaust, and cooling flows.

A-5.4 Preliminary Analysis

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



A-5.5 DFM Software Analysis



The BDI software estimates a 17.65-hour machine setup time, and calculates the total manufacturing time for the end plates as 246 sec, making the total machine time for annual production of 1,000 6-kW stacks:

Machine time = (246 sec/part / 3,600) × 2,000 parts + 17.65 = 154.3 hrs

Machine utilization is:

Utilization = 154.3 / 6,000 = 2.6%

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

In-house rate = $120.89 / 0.026 = $4,649.62
Job shop rate = 1.4 × ($120.89 / 0.65) = $260.37

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 = 308.6 hours.

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

Material cost = $2.425/kg

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

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

where:

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

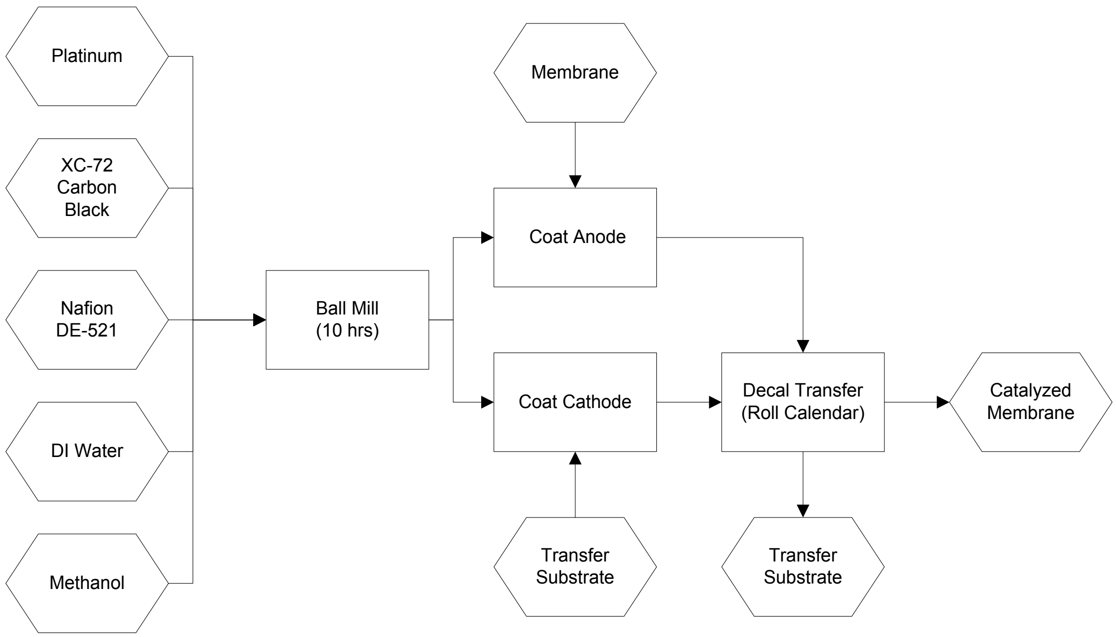
Annual tooling cost = ($7,982 / 5 yrs) $\times$ Roundup((2,000 parts/yr $\times$ 5 yrs) / 100,000 parts/tool) = $1,596.40

Appendix A-6: LTPEM Platinum Catalyst Coating Process

A-6.1 Model Approach

- Catalyst ink preparation operation
  - Compute machine setup labor time based on user input
  - Compute required batch size based on part batch size and catalyst loading
  - Compute catalyst ink material unit cost based on usage
  - Compute catalyst ink processing time and machine utilization
- Anode catalyst ink slot die deposition to membrane operation
  - Compute processing time based on production size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute material unit cost based on usage
  - Compute required heater area based on drying time and substrate speed
  - Compute total anode ink deposition processing time and machine utilization
- Cathode catalyst ink slot die deposition to transfer substrate operation
  - Compute processing time based on batch size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute material unit cost based usage
  - Compute required heater area based on drying time and substrate speed
  - Compute total cathode ink deposition processing time and machine utilization
- Cathode catalyst ink decal transfer calendaring operation
  - Compute processing time based on batch size and substrate speed
  - Compute number of setups based on purchased roll length
  - Compute setup labor time based on user input and number of setups required
  - Compute required heater area based on heating time and substrate speed
  - Compute decal transfer processing time and machine utilization

A-6.2 Process Flow



A-6.3 Background

U.S. patent no. 7,141,270 reported that the wet platinum catalyst composition 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

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

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

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

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

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

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

All 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 http://www.frontierindustrial.com/), where 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, followed by the hot-pressing operation to apply the GDL.

A-6.4 Preliminary Analysis

A-6.4.1 Batch Volume

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

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

$$125.0\text{-mm width} \times 160.0\text{-mm length} = 200.0\ \text{cm}^2$$

Material densities for the catalyst components are as follows:

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

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

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

Yielding a wet catalyst density of:

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

The Pt content of the wet catalyst is:

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

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

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

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

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

Yielding a dry catalyst density of:

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

The Pt content of the dry catalyst is:

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

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

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

The total Pt loading for this design is 0.4 mg/cm^2 with cathode loading in a 2:1 ratio relative to anode loading, making the loadings 0.27 mg/cm^2 and 0.13 mg/cm^2 for the cathode and anode, respectively, which will require wet deposition to depths of 53 and 27 microns, respectively, resulting in dry layer depths of 16 and 8 microns. Therefore, to coat both sides of the membrane with a total loading 0.4 mg/cm^2 will require a total coated depth of 80 microns (0.008 cm):

$$Wet\ catalyst\ weight = 0.85\ g/cm^3 \times (200.0 \times 0.008)\ cm^3 = 1.36\ g/part$$

The 6-kW stack requires 110 cells. Based on producing 1,000 stacks per year, the required annual production before scrap is:

$$Annual\ production = 110\ parts/stack \times 1{,}000\ stacks = 110{,}000\ parts$$

$$Catalyst\ batch\ size = 110{,}000\ parts \times 1.36\ g/part \times 0.001\ kg/g = 149.6\ kg$$

A-6.4.2 Catalyst Ink Material Cost

Material cost of the ink is calculated using the weight percents of the slurry constituents multiplied by the raw material cost to determine a cost per kilogram. Material pricing was obtained from suppliers and supplier web sites in February 2014. Platinum cost is very volatile, with a 3-year monthly range of $1,677/tr.oz. to $832/tr.oz. For this analysis, we will assume a price equal to the 3-year average of $1,294/tr.oz. ($41,602/kg) for April 2016 delivery. Bulk costs for DE-521 were estimated at $160, which translates to a price of about $1,344/kg. Bulk costs for XC-72 catalyst grade carbon black were quoted by WeiKu Information and Technology and others at around $900/MT ($0.90/kg). Bulk costs for Methanol were quoted by Methanex 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 × 23.64 kg = 180.12 kg
- Nafion DE-521: 0.72 × 23.64 kg = 2,161.44 kg
- Vulcan XC-72: 0.09 × 23.64 kg = 270.18 kg
- Methanol: 0.065 × 23.64 kg = 195.13 kg
- DI water: 0.065 × 23.64 kg = 195.13 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 = $684.41/kg
- Vulcan XC-72 = $1.42/kg
- Methanol = $1.05/kg
- DI water = $0.29/kg

The cost of the ink is:

Material cost = (0.06 × 41,602) + (0.72 × 444.12) + (0.09 × 1.24) + (0.065 × 0.92) + (0.065 × 0.19)

Material cost = $2,816.07/kg = $2.816/g

Total annual catalyst material cost before scrap is:

$2,816.07/kg × 149.6 kg = $421,284.10

A-6.4.3 Catalyst Ink Processing

The first step is to weigh the materials out and place them in the mill. We will assume a manual process consisting of a measurement step and a material handling step. The BDI 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 that total handling time for material preparation can be estimated as:

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

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 kW-hr/ton. The calculations are complex owing to the large number of inputs to the calculations.

In "Technical Notes 8, Grinding," R.P. King develops a relationship based on fundamental physical models of ball mill processing (see http://www.mineraltech.com/MODSIM/ModsimTraining/Module6/Grinding.pdf). He assumes a 35% volumetric loading ratio, of which milling balls represents 10% of the total charge volume. Given a mill with diameter d and length l, the total catalyst charge volume is:

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

Patterson Industries offers simple torque drive batch ball mills in 42-inch diameter × 48-inch length (1.067-m diameter × 1.219-m length), and 48-inch diameter × 60-inch length (1.219-m diameter × 1.524-m length). 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 149.6 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 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 presently have no information about this part of the process, one approach would be to use 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 in-H_2O (13.4 kPa) for their 2-HP (1.5-kW) unit. Using an equivalent vacuum sieve with a 1.5-in (0.038-m) diameter hose and 80% transfer efficiency, the flow rate is:

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

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

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

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

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

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

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

$$\text{Material removal time} = 8.1 \times 149.6 = 1211.8 \text{ sec} = 20.2 \text{ min}$$

We 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 149.6 kg of catalyst:

Process time = 1 batch × (10 + 0.5 + (1.8 / 60) + (2 × (20.2 / 60))) hrs = 11.2 hrs

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

Roundup(11.2 / 6,000) = 1 mill

Machine utilization is:

11.2 / 6,000 = 0.19%

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

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

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

A-6.4.4 Catalyst Ink Deposition

As indicated previously, one approach to catalyst deposition involves a two-step process. The anode catalyst is applied to the membrane and the cathode catalyst 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. Both the membrane application and decal creation are direct deposition processes to a substrate material, one being to the membrane itself, and the other to a carrier substrate (commonly a polyester or polyimide material). The patches will be centered in the full cell size envelope of 185 mm × 220 mm.

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

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

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

A-6.4.4.1 Material Cost

Membrane material is sold in widths of 12-inch (0.305-m) and 24-inch (0.610-m) widths with lengths of 50 or 100 meters. Common thin films (polyimide, polyethylene) used as transfer media tend to be either 0.4 or 0.8 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 rectangular, orientation is an important issue in terms of minimizing scrap. Three widthwise cells will take up 555 mm of membrane width, while two lengthwise cells will take up 440 mm of membrane width, so the widthwise orientation will result in less overall scrap. The material length required will be:

> Material length = (110,000 parts / 3 part widths/part length) × 220 mm part length / 1,000 = 8,066.6 meters

The total material area required before scrap is:

> Membrane area = 8,066.7 m × 0.610 m = 4,920.7 m^2
>
> Transfer substrate area = 8,066.7 m × 0.8 m = 6,453.4 m^2

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

> Membrane cost = \$60.16/m^3
>
> Transfer substrate cost = \$1.16/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 110,000 parts is:

> Number of setups = Roundup(Carrier length (m) / Roll length (m))
>
> Membrane: Number of setups = Roundup (8,066.7 / 100) = 81
>
> Transfer substrate: Number of setups = Roundup (8,066.7 / 1,000) = 9

A-6.4.4.2 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:

> Maximum coating speed = 157.18 × 0.987coating thickness (µm) mm/sec

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

> Anode maximum coating speed = 157.18 × 0.98727 = 111.9 mm/sec = 6.65 m/min
>
> Cathode maximum coating speed = 157.18 × 0.98753 = 77.53 mm/sec = 4.69 m/min

Part throughput is calculated as:

> Throughput (parts/hour) = Coating speed (m/min) × Parts per part length (parts) / Part length (m) × 60 min/hour
>
> Anode: Throughput = 6.65 × 3 / (220 / 1,000) × 60 = 5,440.9 parts/hr
>
> Cathode: Throughput = 4.69 × 3 / (220 / 1,000) × 60 = 3,837.3 parts/hr

Total machine time to set up and produce 110,000 parts is:

Anode machine time = (81 setups × 0.5 hr/setup) + (110,000 parts / 5,440.9 parts/hr) = 60.72 hrs

Cathode machine time = (9 setups × 0.5 hr/setup) + (110,000 parts / 3,837.3 parts/hr) = 33.17 hrs

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

Roundup((60.72 + 33.17) / 6,000) = 1 coater

Machine utilization is:

(60.72 + 33.17) / 6,000 = 1.56%

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

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

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

A-6.4.4.3 Tooling Cost

Slot dies are precision machined and assembled to provide uniform coating thickness. The cost can vary widely depending on the coating fluid properties and die size. Frontier Industries estimates a stainless steel fixed die cost of $14,000, 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:

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

where:

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

Anode annual tooling cost = $\frac{1}{5}$ (($14,000 + (4 × $3,500)) × Roundup((110,000 parts/yr × 5 yrs) / 500,000 parts/tool)) = $12,200

Cathode annual tooling cost = $\frac{1}{5}$ (($14,000 + (4 × $3,500)) × Roundup((110,000 parts/yr × 5 yrs) / 500,000 parts/tool)) = $12,200

A-6.4.5 Catalyst Ink Drying

Following deposition, the catalyst ink is dried, usually by means of 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 heating panels are generally sold with various energy watt densities and in standard-sized units and assembled to provide the necessary heating area. Using the Casso Solar Type FB as an example, standard watt densities are 15 and 25 W/in^2 (23 and 39 kW/m^2) with standard width of 12 inches (0.305 m) and lengths in 12-inch increments up to 60 inches (1.524 m). They note that 25 W/in^2

corresponds to an emitter temperature of 880°C, and that the conversion efficiency of electrical power to usable radiant energy is up to 80%.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler et al. (1978)[15] indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 l/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 l/min.

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

Anode liquid removed per area = 0.335 g/cm^3 $\times$ 0.0027 cm = 0.0009 g/cm^2

Cathode liquid removed per area = 0.335 g/cm^3 $\times$ 0.0053 cm = 0.0018 g/cm^2

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

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

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

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

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

The required dryer length is:

Anode dryer length = 0.75 min $\times$ 6.65 m/min = 5.0 m

Cathode dryer length = 1.50 min $\times$ 4.69 m/min = 7.0 m

Sizing for the maximum dryer length, and assuming 12-inch $\times$ 36-inch panels fitted two across the drying conveyor, we calculate 14 total infrared panels required.

A-6.4.6 Catalyst Layer Decal Transfer

The roll-to-roll decal transfer operation can be either by a semi-continuous process where the material is indexed into a standard heated platen press (see James et al. [2010], Section 4.4.6.1)[16] or by preheating and passing through heated rollers in a calendaring process. For the preliminary analysis, we will assume a calendaring process.

A-6.4.6.1 Setup

Decal transfer setup consists of loading, threading, and aligning the anode and cathode into the calendaring rollers. For costing purposes, we will take the setup time as a user input and assume a value

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

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

of 0.5 hour. The number of setups is a function of the shortest roll stock length, so that the number of required setups to run 36,000 parts is the same as the number of setups for the anode slot die coating:

Number of setups = 81

A-6.4.6.2 Calendaring

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

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

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

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

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

Common polymers (polytetrafluoroethylene [PTFE], polyester, polyimide) have specific heats 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
- Platinum: 0.13 J/g-°C
- Carbon black: 4.18 J/g-°C

The specific heat of the catalyst is:

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

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

Anode dry catalyst volume = 200 cm^2 × 0.0008 cm = 0.16 cm^3

Cathode dry catalyst volume = 200 cm^2 × 0.0016 cm = 0.32 cm^3

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

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

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

Anode oven dwell time = ((2.2 g/cm^3 × 0.504 cm^3 × 1.2 J/g-°C) + (0.515 g/cm^3 × 0.16 cm^3 × 2.88 J/g-°C)) × 75°C / 368 W = 0.856 sec/part

Cathode oven dwell time = ((2.2 g/cm^3 × 0.504 cm^3 × 1.2 J/g-°C) + (0.515 g/cm^3 × 0.32 cm^3 × 2.88 J/g-°C)) × 75°C / 368 W = 0.366 sec/part

For the calendaring process, the layers will be moving together, so the worst case heating time of 0.854 seconds is used to determine the required oven length. At a substrate speed of 5 m/min (8.33 cm/sec), the required heating length of about 0.071 meters, which can be accomplished using four 12-inch by 24-inch infrared panels (two for each layer).

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

Parts per hour = 300 m/hr / 0.220 m × 3 parts per width = 4,091 parts/hr

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:

Anode machine time = (81 setups × 0.5 hr/setup) + (110,000 parts / 4,091 parts/hr) = 67.38 hrs

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

Roundup(67.38 / 6,000) = 1 calendar machine

Machine utilization is:

67.38 / 6,000 = 1.12%

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

In-house rate = $26.26 / 0.0112 = $2,344.64

Job shop rate = 1.4 × ($26.26 / 0.65) = $56.56

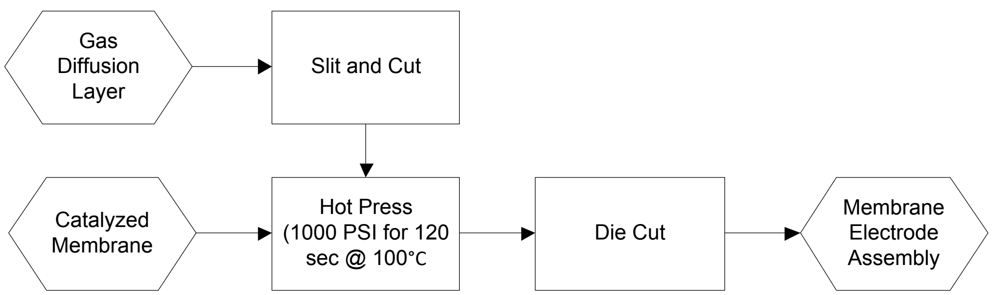
Appendix A-7: LTPEM MEA Hot Pressing Process

A-7.1 Model Approach

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

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

A-7.2 Process Flow



A-7.3 Background

Directed Technologies, Inc. (DTI) (James et al., 2010)[17] reported hot pressing conditions for MEA fabrication as 160°C for 90 seconds using heated platens of 0.5 m wide by 1.5 m long for processing 0.5-m wide roll materials. They estimated a reset period of 3 seconds to open the press, index the materials, and reclose the press.

Therdthianwong et al. (2007)[18] found that the most suitable hot pressing conditions for MEA fabrication to be 100°C and 1,000 psi (70 kg/cm^2) for 2 minutes, stating that these conditions "…provided the highest 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."

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

[18] Therdthianwong, A, Manamayidthidarn, P., and Therdthianwong, S. 2007. Investigation of membrane electrode assembly (MEA) hot-pressing parameters for proton exchange membrane fuel cell. *Energy*, 32(12): 2401–2411.

A-7.4 Preliminary Analysis

The 6-kW stack cells for this analysis will have a total active area of:

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

The 6-kW stack cells for have a total MEA area of:

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

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

A-7.4.1 Material

GDL material is typically sold in either 0.4- or 0.8-meter widths and will be cut to the size of the active area plus a 2.5 mm margin on all sides, making the final dimensions 130 mm wide by 165 mm long. Six widthwise cells will take up 780 mm of GDL width, while four lengthwise cells will take up 660 mm of membrane width, so the widthwise orientation will result in less overall scrap. Assuming 2 GDL layers per MEA, the material length required will be:

Material length = ((2 × 110,000 parts) / 6 part widths/part length) × 165 mm part length / 1,000 = 6,050.0 m

The GDL material usage is calculated as:

Material usage = 0.8 m × 6,050.0 m = 4,840.0 m^2

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

Material cost = $282.53/$m^2$

A-7.4.2 Setup

GDL material is available up to a maximum of 800-meter lengths, so that the number of setups required to run 220,000 parts is:

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

Membrane: Number of setups = Roundup (6,050 / 800) = 8

A-7.4.3 GDL Slit and Cut

The GDL is cut to shape by slitting the 800 mm wide bulk roll into strips of the pre-determined width of 130 mm, then cutting the strips to the required length of 165 mm. We assume a single machine operation with one full-time operator. The limiting rate is the shearing operation, which is estimated to be 50 cuts/minute, or 300 cuts per hour. Each shearing operation produces 6 parts, making the total number of required operations:

Number of cuts = Roundup((2 × 110,000 parts) / 6 parts/operation) = 36,667 cuts

At a rate of 300 cuts/hour, the total slitting and cutting time is:

Total operation time = 36,667 cuts / 300 cuts/hr = 12.22 hrs

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

Roundup(12.22 / 6,000) = 1 machine

Machine utilization is:

12.22 / 6,000 = 0.20%

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

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

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

A-7.4.4 MEA Hot Press Tooling

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

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

The overall die length is:

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

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

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

where:

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

Annual tooling cost = $\frac{1}{5}$ (($15,600/m^2 × 1.14 m^2) × Roundup(((110,000 parts/yr / 15 parts/cycle) × 5 yrs) / 100,000 cycles/tool)) = $3,556.80

A-7.4.5 MEA Hot Press

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

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

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

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

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

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

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

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

Parts/hr = 15 parts/cycle / ((124 + 12.5) / 3,600) hrs/cycle = 395.6 parts/hr

The total machine time for processing and setup is:

Machine processing time = (110,000 parts / 395.6 parts/hr) + (81 setups × 0.5 hr/setup) = 318.6 hrs

Total machine labor time for processing and setup:

Machine labor time = 1 operator/machine × 318.6 hrs = 318.6 hrs

Machine utilization is:

318.6 / 6,000 = 5.31%

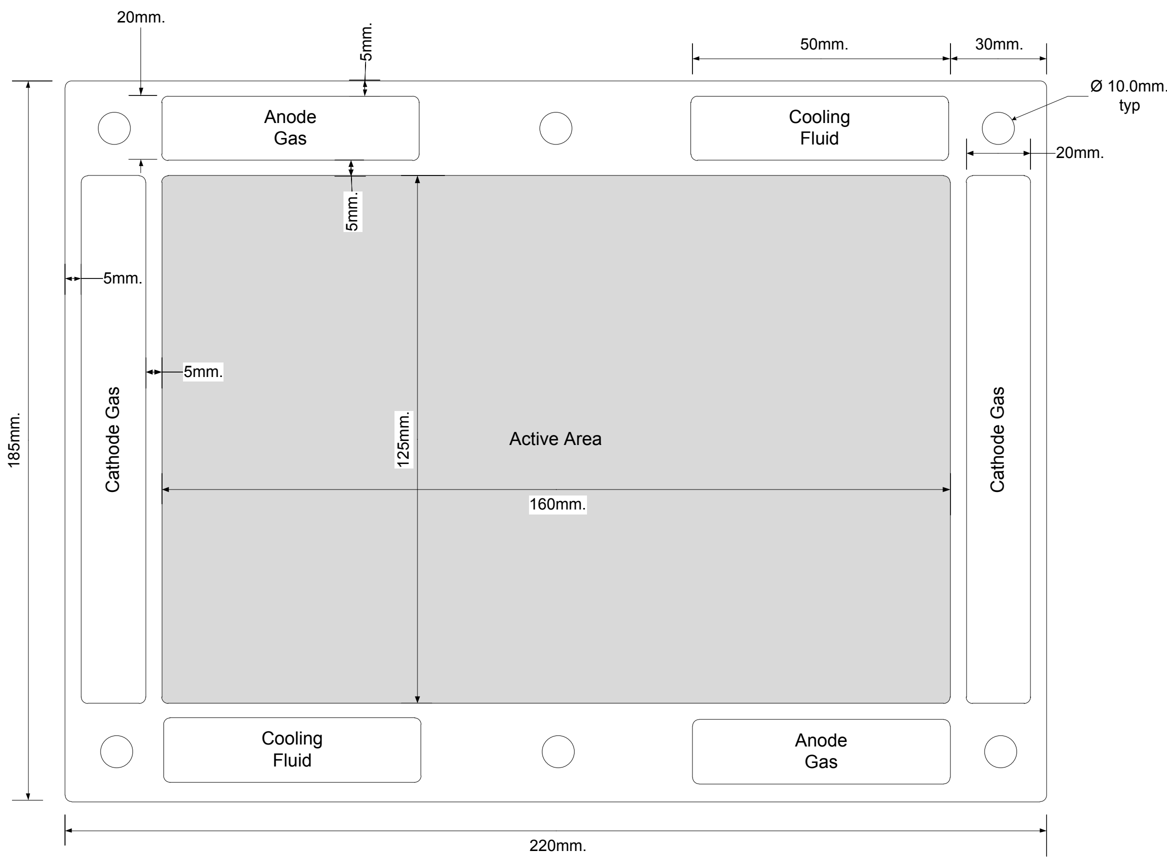
Machine rate was determined in accordance with Appendix A-1 as:

In-house rate = $52.58 / 0.0531 = $481.73

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

A-7.4.6 MEA Die Cutting

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



A-7.4.7 Tooling

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

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

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

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

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

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

Therefore the total die cutting length is:

Die cutting length (mm) = 3,310.0 + 4,420.0 + (15 × 1,396.5) = 28,677.4 mm

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

Tooling rate = $230 / (2 × 2,706) mm = $0.04/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 six-cavity die (six parts per cycle) and amortizing over a 5-year production life, the total annual tooling cost is:

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

where:

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

Total production = Annual production × 5

Annual tooling cost = (28,677.4 mm/die × $0.04/mm) / 5 yrs) × Roundup(((110,000 parts/yr / 15 parts/cycle) × 5 yrs) / 30,000 cycles/tool) = $458.84

A-7.4.8 Setup

The total number of setup operations will be dictated by the length of the membrane at 100 meters. As shown above, the number of roll setups is 81. Assuming 0.5 hour per setup, the total setup time is:

Setup time = 81 × 0.5 hr = 40.5 hrs

A-7.4.9 Die Cutting

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

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

Press force = 28,677.4 mm/die × 0.7 mm × 76 N/mm^2 = 1,526 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 – 0.025 kW/kN. Assuming a 50% capacity margin and using the upper end of the motor power rating, the maximum required press energy input is:

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

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

Processing time = 110,000 parts / 15 parts/cycle / 1,800 cycles/hr = 4.1 hrs

The total machine time for processing and setup is:

Machine processing time = 40.5 + 4.1 = 44.6 hrs

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

Roundup(44.6 / 6,000) = 1 machine

Machine utilization is:

44.6 / 6,000 = 0.74%

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

In-house rate = $30.15 / 0.0074 = $4,074.32

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

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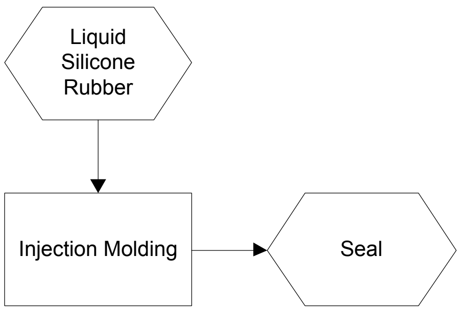
Appendix A-8: LTPEM Seal Injection Molding Process

A-8.1 Model Approach

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

A-8.2 Process Flow



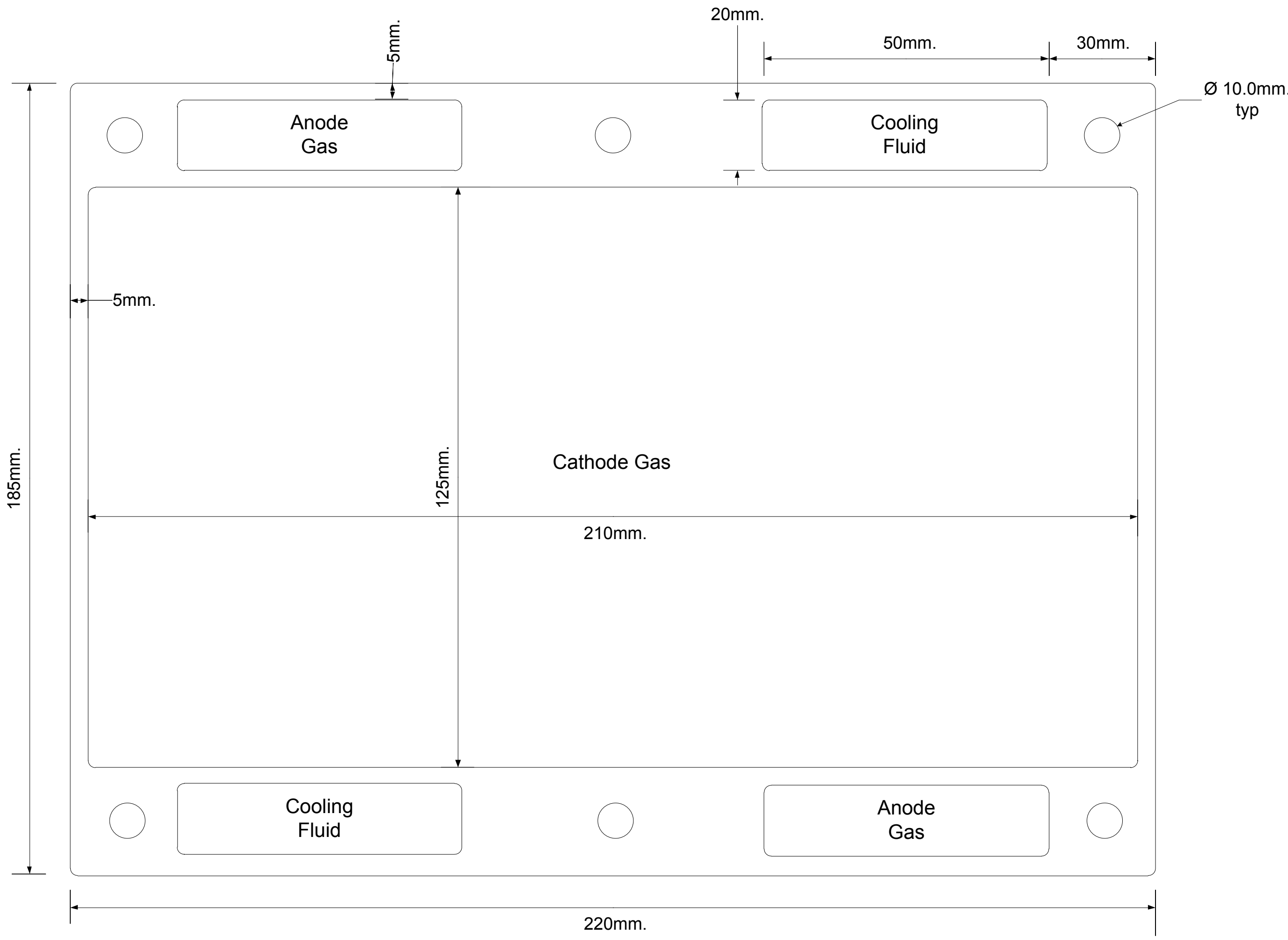
A-8.3 Background

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

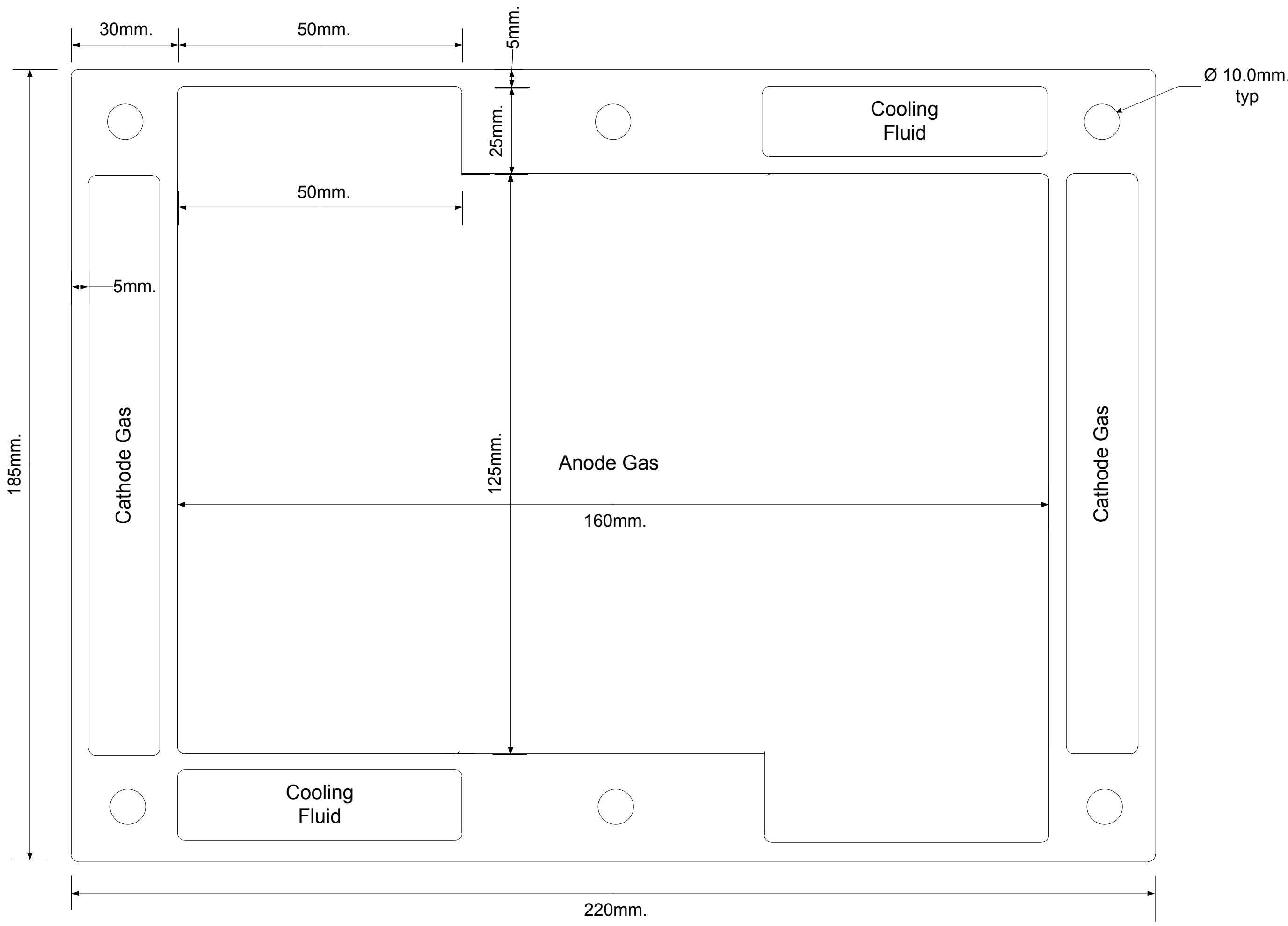
A-8.4 Preliminary Analysis

The stack contains three seals (cathode, anode and cooling) per cell plus two cathode seals on each end of the stack. To manufacture 1,000 6-kW stacks consisting of 110 cells each requires a total of 110,000 each anode and cooling seals, and 112,000 cathode seals. The seal features and dimensions are shown below for reference.

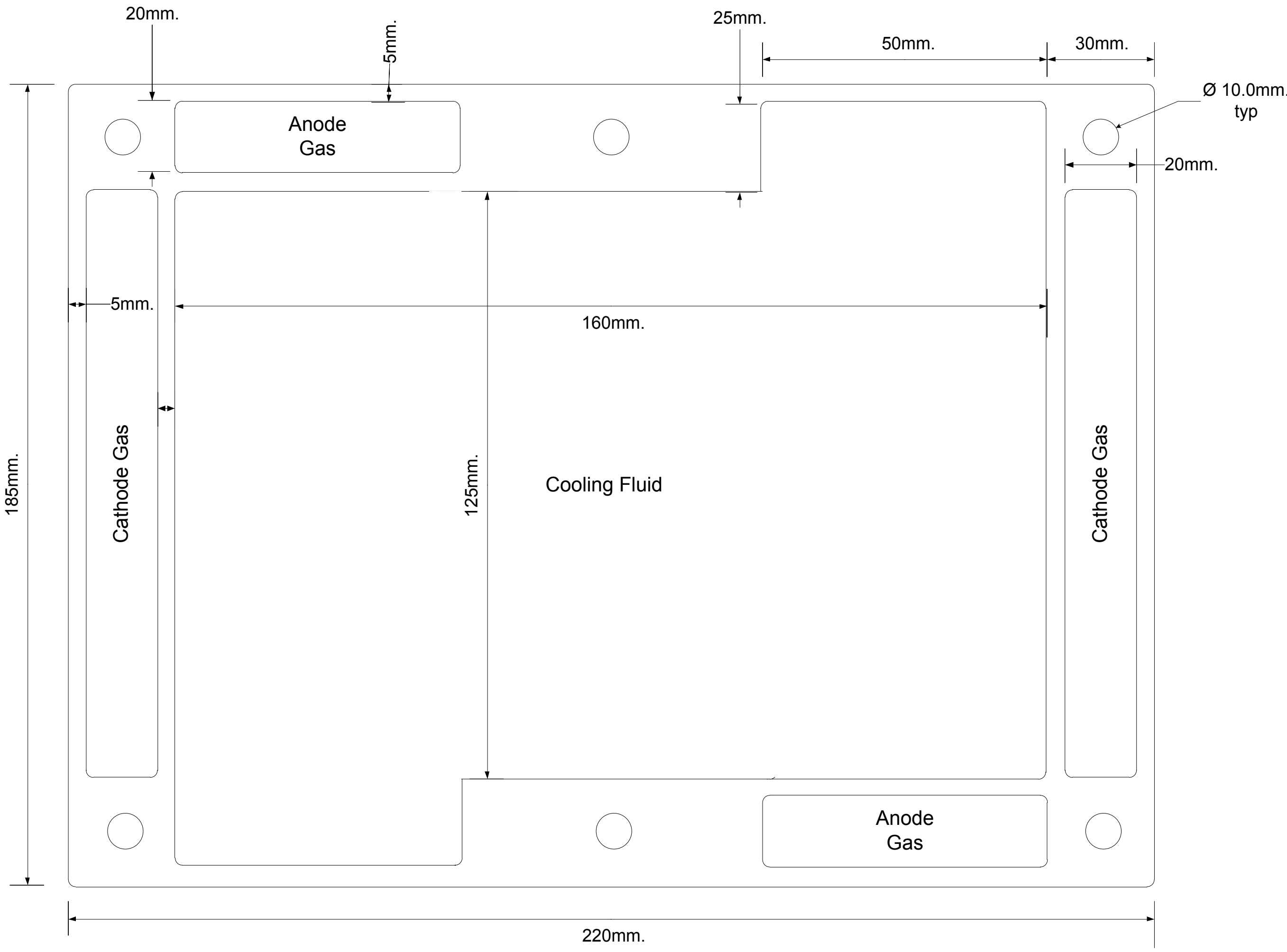
A-8.4.1 Cathode Seal



A-8.4.2 Anode Seal

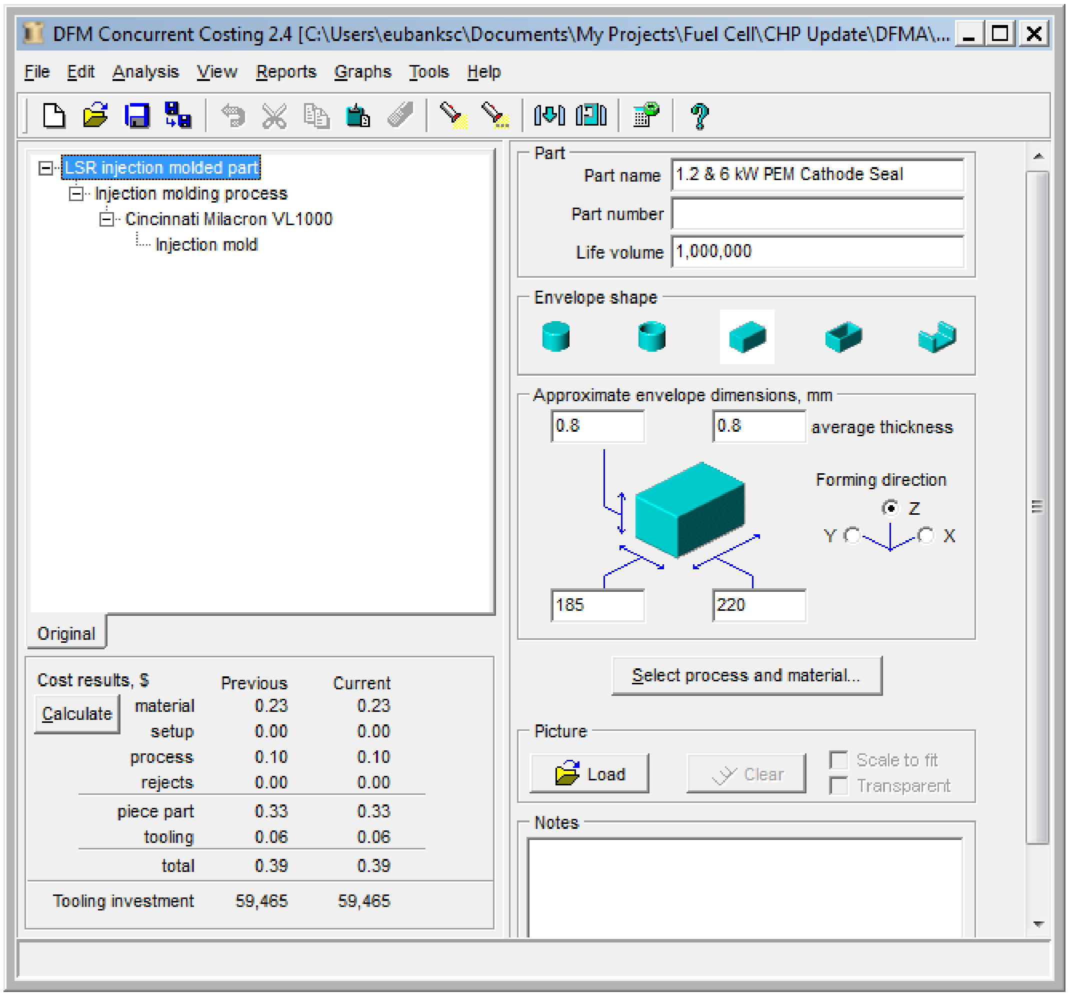


A-8.4.3 Cooling Seal



A-8.5 DFM Software Analysis

A-8.5.1 Cathode Seal



The BDI estimate for the 6-kW cathode seal is a 2-hour machine setup time, and the BDI software calculates the total manufacturing cycle time as 9.66 sec for a four-cavity mold, making the total machine time for annual production of 1,000 stacks:

Machine time = (9.66 sec/cycle / 4 parts/cycle / 3,600) $\times$ 112,000 parts + 2 = 77.1 hrs

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

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

Material usage = 0.010 kg/part $\times$ 112,000 parts = 1,120 kg

Tooling cost is $50,127 and it is assumed that the tool is capable of producing 1,000,000 parts. Amortizing over a 5-year production life, the total annual tooling cost is:

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

where:

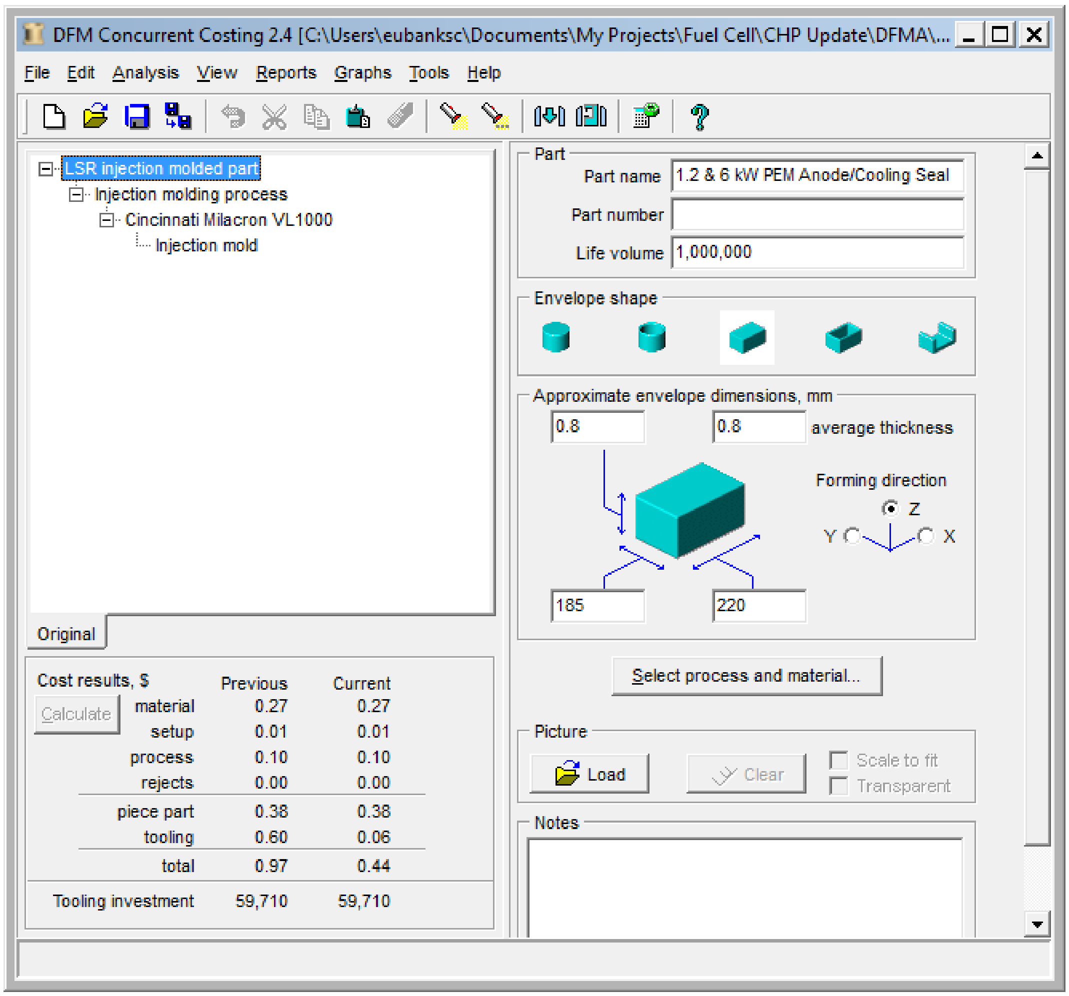
$$\text{Number of tools purchased} = \text{Roundup}(\text{Total production} / \text{Tool life})$$

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

$$\text{Annual tooling cost} = \tfrac{1}{5}(\$59{,}465 \times \text{Roundup}((112{,}000 \text{ parts/yr} \times 5 \text{ yrs}) / 1{,}000{,}000 \text{ parts/tool})) = \$59{,}465$$

A-8.5.2 Anode/Cooling Seal

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



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

Machine time = (9.66 sec/cycle / 4 parts/cycle / 3,600) × 220,000 parts + 2 = 149.6 hrs

Tooling cost for the anode/cooling seal is $59,640 and it is assumed that the tool is capable of producing 1,000,000 parts. Amortizing over a 5-year production life, the total annual tooling cost is:

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

where:

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

Annual tooling cost = $\frac{1}{5}$ (($59,710) × Roundup((72,000 parts/yr × 5 yrs) / 1,000,000 parts/tool)) = $11,928.00

Total machine time to mold the three gaskets is 226.7 hours, making the machine utilization:

Utilization = 226.7 / 6,000 = 3.8%

Machine rate was determined in accordance with Appendix A-11 as:

In-house rate = $26.04 / 0.038 = $685.26

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

Assuming one full-time operator per two molding machines, the total machine time is equal to half of 226.7 hours, or 113.35 hours.

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

Material usage = 0.012 kg/part × 220,000 parts = 2,640 kg

The three gaskets require a total of 3,760 kg of material. The material cost was determined in accordance with Appendix A-12 as:

Material cost = $16.10/kg

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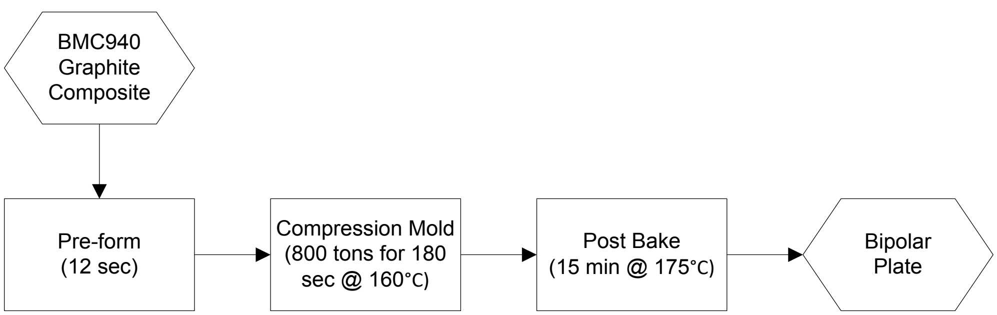
Appendix A-9: LTPEM Bipolar Plate Compression Molding Process

A-9.1 Model Approach

- Setup operation
  - Machine setup labor time based on user input
  - Tooling cost based on input insert and platen cost and life
- Pre-form operation
  - Measure and pre-form labor time based on user input
  - Part material unit cost based on usage
- Compression mold
  - Part handling time based on part size per BDI formula; 4 second 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 formula and throughput; 4 second minimum

A-9.2 Process Flow



A-9.3 Background

A supplier of composite bipolar plates for PEM fuel cell stacks provided the following information regarding their 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 120-230 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: 30-60 sec
    - Mold temp: 300-320°F (149-160°C)
    - Recommended tonnage: >40MPa on projected part area
    - Press close speed: <2 sec after material begins flowing
    - Post-mold bake at 350°F for 15 min

A-9.4 Preliminary Analysis

Unlike injection molding, compression molding requires that a pre-measured, usually pre-formed, and generally preheated amount of material be loaded into the 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 preheating was mentioned by the manufacturer or the material spec sheet.

The bipolar plates for this analysis will be:

185 mm width $\times$ 220 mm length = 407 cm^2

Process values will be calculated based on annual production of 1,000 6-kW stacks per year. The 6-kW stack requires 111 anode bipolar plates and 111 cathode bipolar plates, requiring annual production of 111,000 of each type of plate.

A-9.4.1 Setup

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

A-9.4.2. Material Cost

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

Cathode plate material required = 1.9 g/ cm^3 $\times$ 0.001 kg/g $\times$ (407 $\times$ .2) cm^3 $\times$ 1.05 $\times$ 111,000 parts = 18,025.6 kg

Anode plate material required = 1.9 g/ cm^3 $\times$ 0.001 kg/g $\times$ (407 $\times$ .3) cm^3 $\times$ 1.05 $\times$ 111,000 parts = 27,038.4 kg

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

Material cost = \$2.066/kg

A-9.4.3. Compression Molding Press Time

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

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

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 HP, but lists pressing speeds of only 20 ipm (0.3 ips). Cylinder bore sizes are listed as 26-inch to 30-inch diameter. To move a 30-inch diameter cylinder at 30 ips requires a pump delivery of:

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

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

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

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

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 a six 407 cm^2 bipolar plates, giving a factor of approximately 0.062 kW/cm^2 of plate area.

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

$$\text{Part girth} = \text{Part length} + \text{Part width} + \text{part depth}$$

$$\text{Handling time} = \text{Max}\left((0.60714 \times (\text{Part girth} / 25.4) - 4.57143), 4\right)$$

$$\text{Cathode plate handling time} = \text{Max}\left((0.60714 \times ((185 + 220 + 2) / 25.4) - 4.57143), 4\right) = 5.16\ \text{secs}$$

$$\text{Anode plate handling time} = \text{Max}\left((0.60714 \times ((185 + 220 + 3) / 25.4) - 4.57143), 4\right) = 5.18\ \text{secs}$$

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

Cathode plate cycle time = ((6 × 5.16) + 230 + 10) = 270.9 sec/cycle = 0.07525 hrs/cycle

Anode plate cycle time = ((6 × 5.18) + 230 + 10) = 271.1 sec/cycle = 0.07530 hrs/cycle

Throughput is calculated as:

Parts per hr = 6 parts/cycle / 0.07525 hrs/cycle = 79.7 parts/hr

Since throughput for each type of plate is essentially the same, we can calculate the total time required to process both sets of plates (222,000 parts) as:

Press machine time = 222,000 parts / 79.7 parts/hr + (2 × 4) hr setup = 2,793.4 hrs

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

Roundup(2,793.4 / 6,000) = 1 machine

Machine utilization across the machines is:

2,793.4 / 6,000 = 46.6%

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

In-house rate = $64.70 / 0.466 = $138.84

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

A-9.4.4 Tooling Cost

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

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

Platen width = ((2 × 220 mm) + (3 × 50 mm)) = 590 mm

Platen length = ((3 × 185 mm) + (4 × 50 mm)) = 755 mm

Platen area = 554 mm × 806 mm = 4,455 cm^2

Platen cost = (4,455 cm^2 × $1.333/ cm^2) + $3,500 = $9,438.52

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

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

where:

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

Total production = Annual production × 5

Annual insert tooling cost per plate = $\frac{1}{5}$ (($24.50 × 407 × 6) × Roundup((111,000 parts/yr / 6 parts/cycle × 5 yrs) / 100,000 parts/tool)) = $11,966

Annual platen tooling cost = $\frac{1}{5}$ (($9,438.52) × Roundup((222,000 parts/yr / 6 parts/cycle × 5 yrs) / 500,000 parts/tool)) = $1,887.57

A-9.4.5 Heated Platen Energy

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

Number of heaters = Ceiling (Platen width (cm) / 7.6

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

Number of heaters = Ceiling (59.0 cm / 7.6 cm) = 8

Platen power input = 8 heaters × (80.6 cm × 20 W/cm) = 12.9 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 electric griddles with rated energy inputs of 8 to 16 kW demonstrate a 25% duty cycle in actual use. Given that the surface areas, power densities, and manual work flow are comparable, we will assume a similar usage profile.

A-9.4.6 Post Bake Cycle

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

Parts per bake cycle = (79.7 parts/hr × 0.25 hrs) = 19.93 parts per bake cycle ≅ 20 parts/rack

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

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

Rack girth = (Parts per rack × (Part width (mm) + 50)) + (Part length (mm) + 50) + 10

Rack girth = (6 × (185 + 50)) + (220 + 50) + 10 = 1,690

Rack handling time = Max((0.60714 × ((1,690) / 25.4) - 4.57143), 4) = 35.8 sec

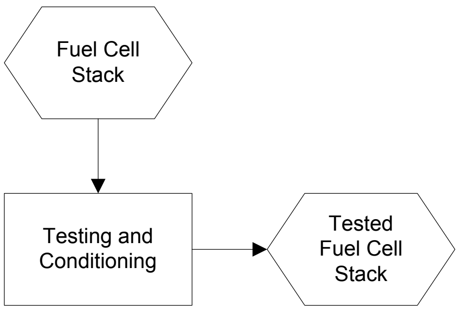
Given that the rack handling time is about 15% of the press dwell time, no additional labor time is incurred by the press operator to complete the tasks associated with the post-bake operation.

Appendix A-10: LTPEM Stack Testing and Conditioning Process

A-10.1 Model Approach

- Test and condition fuel cell stack

A-10.2 Process Flow



A-10.3 Background

Following assembly, the 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 H_2 consumption at full power is determined from the equation:

H_2 consumption mol/sec = (Current $\times$ Cells) / (2 $\times$ H_2 Cal/mol)

For a 6-kW stack current of 200 A and cell count of 36 cells we have:

H_2 consumption g/sec = 80 A $\times$ 110 Cells / (2 $\times$ 96,485 Cal/mol) = 0.0456 mol/sec

Converting to L/min:

H_2 consumption L/min = 1.2 $\times$ 0.0456 mol/sec $\times$ 60 $\times$ 2.016 / 0.0899 = 73.63 L/min

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

Air flow l/min: (2 / 1.2) $\times$ 73.63 L/min = 122.7 L/min

A-10.4 Preliminary Analysis

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

Setup labor time = 0.5 hr/stack $\times$ 1,000 stacks = 500 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 kg/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 hydrogen gas (H_2) = 2 grams, so the mass of 22.4 liters (stp) of H_2 is 2 g.

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

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

$$\text{Full power material usage} = ((73.63 \text{ l/min} / 1{,}000 \text{ l/m}^3) / 11.2 \text{ m}^3\text{/kg}) \times 60 \text{ min/hr} = 0.394 \text{ kg/hr}$$

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

25% rated power for 1 hr

100% rated power for 0.5 hr

25% rated power for 1 hr

Therefore, the total material usage of the hydrogen is:

$$H_2 \text{ usage} = 0.394 \text{ kg/hr} \times ((0.25 \times 1.0 \text{ hr}) + (1.0 \times 0.5 \text{ hr}) + (0.25 \times 1.0 \text{ hr})) \times 1{,}000 \text{ stacks} = 394 \text{ kg}$$

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

Material cost = $23.52/kg

We will assume that one test station (500 kW load bank) is capable of supporting three stacks during testing, making the total machine time for setup and test:

$$\text{Testing machine time} = ((2.5 \text{ hrs/stack} / 3) + (0.5 \text{ hr/stack})) \times 1{,}000 \text{ stacks} = 1{,}333 \text{ hrs}$$

Machine utilization across the seven machines is:

$$1{,}333 / 6{,}000 = 22.2\%$$

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

In-house rate = $17.64 / 0.222 = $79.46

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 an MEA), and reassembling the stack. Using the Boothroyd Dewhurst, Inc. (BDI) Design for Assembly software, the 6-kW stack assembly labor time was estimated to be 1.07 hours.

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

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

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

Scrap labor time = (((2 × 1.07 hrs/stack) / (1-0.05)) - (2 × 1.07 hrs/stack)) × 1,000 stacks = 113 hrs

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

Scrap value ($) = (($14.47/stack / (1-0.05)) - $14.47/stack) × 1,000 stacks = $761.58

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Appendix A-11: SOFC Production Facility Estimation

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

A-11.1 Equipment Footprint

The machine utilization calculations provide the equipment count for a particular production station. Using the application of the cathode layer as an example, each station consists of two pieces of equipment: the screen printer, and a heated conveyor for slurry drying, which have the following footprint dimensions:

Screen printer: 63 in x 55 in
Heated conveyor: 24 in x 36 in

Allowing a 3-foot (36-in) margin on all sides for maintenance access makes the total machine footprints:

Screen printer: $(63 + (2 \times 36)) \times (55 + (2 \times 36)) / 144\ in^2/ft^2 = 119\ ft^2$
Heated conveyor: $(24 + (2 \times 36)) \times (36 + (2 \times 36)) / 144\ in^2/ft^2 = 72\ ft^2$

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

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

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

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

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

Aisle allowance: $(119 + 72 + 27 + 20) \times 0.35 = 83\ ft^2$

The total floor space allocation for the screen printing station is:

Floor space allocation = $119 + 72 + 27 + 20 + 83 = 321\ ft^2$

SOFC fuel cell stack production was broken up into 15 primary work stations with total floor space allocations calculated using the above formulas as:

Production Station	Floor Space Allocation (ft^2)
High Volume Slurry Preparation	457
Low Volume Slurry Preparation	336
Tape Casting	655
Anode Pressing	551
Anode Blanking	318
Screen Printing	321
Kiln Firing	622
Sintering	598
Laser Cutting	221
Sheet Metal Stamping	185
Interconnects	589
End Plates	1,261
Sealing Line	395
Stack Assembly	422
Stack Brazing	598
Stack Test and Conditioning	252
System Assembly	598
System Test	252

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 DFM process analyses for a and t, and estimating time for b, resulted in the following:

SOFC Production Station	a	b	t	n'	1/n'
High Volume Slurry Preparation	1,907	600	36,000	15.12	0.07
Low Volume Slurry Preparation	1,887	600	36,000	15.23	0.07
Tape Casting	1,800	600	12,780	6.08	0.16
Anode Pressing	1,800	600	13,805	6.50	0.15
Anode Blanking	1,800	600	3,135	2.06	0.49
Screen Printing	4	4	23	3.38	0.30
Kiln Firing	4	4	15	2.38	0.42
Sintering	4	4	34	4.75	0.21
Laser Cutting	4	4	6.85	1.36	0.74
Sheet Metal Stamping	4	4	2	0.75	1.33
Interconnects	10	10	179	9.45	0.11
End Plates	30	30	295	5.42	0.18
Sealing Line	10	10	98.6	5.43	0.18
Stack Assembly	12,742	0	0	1.00	1.00
Stack Brazing	13	10	1,290	56.65	0.02
Stack Test and Conditioning	1,800	600	21,600	9.75	0.10
System Assembly	21,600	0	0	1.00	1.00
System Test	1,800	600	21,600	9.75	0.10

In general, we assume that a single operator is capable of operating a maximum of three machines in a cell arrangement. We will also assume that stations requiring multiple operators can utilize a floating operator working between three machines.

To obtain a rough estimate of the number of operators required during any one shift, we 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 station utilization (assuming a single operator is trained to perform multiple tasks). Using the station utilization numbers for 10,000 6-kW stacks per year we have:

Production Station	Stations	Utilization	Operators per station	Operators Per Shift
High Volume Slurry Preparation	1	0.311	0.33	0.10
Low Volume Slurry Preparation	1	0.085	0.33	0.03
Tape Casting	8	0.95	0.33	2.53
Anode Pressing	1	0.309	0.33	0.10
Anode Blanking	1	0.141	0.50	0.07
Screen Printing	16	0.985	0.33	5.25
Kiln Firing	11	0.935	0.50	5.14
Sintering	9	0.897	0.33	2.69
Laser Cutting	3	0.871	1.00	2.61
Sheet Metal Stamping	1	0.421	1.33	0.56
Interconnects	27	0.986	0.33	8.87
End Plates	1	0.273	0.33	0.09
Sealing Line	5	0.86	0.33	1.43
Stack Assembly	6	0.983	1.00	5.90
Stack Brazing	1	0.596	0.33	0.20
Stack Test and Conditioning	4	0.903	0.33	1.20
System Assembly	3	0.596	1.00	1.79
System Test	7	0.903	0.33	2.11
Total				16.03

Rounding up to 17 machine operators per shift, and assuming approximately one support staff per four operators for purchasing, QC, and maintenance, the facility needs to support 22 employees. Ventura provides estimates the following additional facilities:

Food service: 15 ft^2/employee
Restrooms: 2 toilets + 2 sinks per 15 employees (estimated at 25 ft^2 per fixture)
Parking: 276 ft^2/employee

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

Facility	Space Required (ft^2)
Food Service	255
Restrooms	200
Parking	4,692
Office	360

Estimated total factory building floor space can be calculated as:

$$\text{Equipment + Food service + Restrooms + Office} = 20{,}361 \text{ ft}^2$$

Assuming a construction cost of \$250/ft^2, the estimated cost of factory construction is approximately \$509,025.

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:

$$((\text{Factory space + Parking space})^{1/2} + 60)^2 = 47{,}647 \text{ ft}^2 = 1.09 \text{ acre}$$

Assuming a real estate cost of \$125,000/acre, the estimated total real estate cost is approximately \$136,727.

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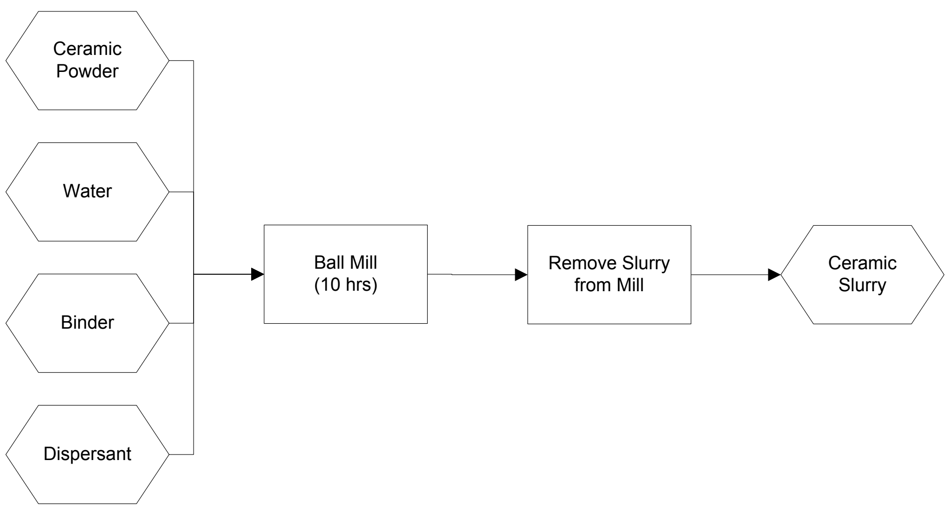
Appendix A-12: SOFC Ceramic Slurry Production Process

A-12.1 Model Approach

- Ceramic slurry preparation operation
  - Machine setup labor time based on user input
  - Compute required batch size based on part batch size and ceramic layer thickness
  - Compute ceramic slurry material unit cost based on usage
  - Compute ceramic slurry processing time and machine utilization

A-12.2 Process Flow



A-12.3 Background

The composition of typical SOFC ceramic slurries used in industry is not directly reported, and fundamental work seems to be continuing in the area of ceramic powder characterization.

In *Modern Ceramic Engineering* (2006),[19] D.W. Richerson lists a typical solvent-based slurry as:

- 70 wt% ceramic powder
- 14 wt% organic solvent (MEK/EtOH)
- 9 wt% binder (ethyl methacrylate)
- 1 wt% dispersant (fish oil)
- 6 wt% plasticizer (BBP/PEG)

[19] Richerson, D.W. 2006. Modern Ceramic Engineering: Properties, Processing, and Use in Design. CRC Press, Taylor & Francis Group, LLC. 707 p.

In their study of sintering and deformation, Cologna et al. (2010)[20], report using a water-based slurry in tape casting experiments as follows:

- Electrolyte: blade gap = 30 μm; dry thickness = 12 ± 2 μm; 60% reduction
  - 59 wt% YSZ (8% mol)
  - 14 wt% water
  - 26 wt% binder (Dow Duramax B-1000/B-1014)
  - 2 wt% dispersant (ammonium polyacrylate)

- Anode: blade gap = 500 μm; dry thickness = 270 ± 5 μm; 46% reduction
  - 26 wt% YSZ (8% mol)
  - 37 wt% NiO
  - 12 wt% water
  - 24 wt% binder
  - 1 wt% dispersant

Cologna's values are consistent with general "rule-of-thumb" thickness reduction of 50% seen on several web sites and used on some technical papers. Therefore, for cost purposes, we will assume that wet ceramic deposition will be twice the thickness of the required final ceramic layer thickness.

A-12.4 Preliminary Analysis

A-12.4.1 Anode Batch Volume

Slurry batch volume depends on the part size, casting width, and ceramic layer thickness.

The cells for this analysis are for a 6-kW stack at a production rate of 1,000 stacks per year. The deposition area for the anode will be:

$$136 \text{ mm width} \times 193 \text{ mm length} = 262.48 \text{ cm}^2$$

Material densities for the anode slurry components are as follows:

- ρ(YSZ) = 6.1 g/cm3
- ρ(NiO) = 6.7 g/cm3
- ρ(water) = 1.0 g/cm3
- ρ(binder) = 1.05 g/cm3
- ρ(dispersant) = 1.16 g/cm3

[20] Cologna, M., Sglavo, V., and Bertoldi, M. 2010. *Sintering and Deformation of Solid Oxide Fuel Cells Produced by Sequential Tape Casting.* International Journal of Applied Ceramic Technology 7(6): 803-813.

Based on the slurry composition as specified above, 100 grams of wet slurry has a volume of:

$$v = (26/6.1) + (37/6.7) + (12/1.0) + (25/1.05) + (1/1.16) = 45.50 \text{ cm}^3$$

Yielding a wet slurry density of:

$$\rho(\text{wet slurry}) = (100/45.50) = 2.20 \text{ g/cm}^3 = 2{,}200 \text{ kg/m}^3$$

The required dried depth of 500 microns requires a deposited wet depth of 1,000 microns. (Note that final anode depth will be achieved by casting two 250 micron tapes and pressing the tapes together to achieve the final desired thickness.) The weight of slurry material required per part is:

$$\text{Wet slurry weight} = 2.2 \text{ g/cm}^3 \times (262.48 \times 0.10) \text{ cm}^3 \times 0.001 \text{ kg/g} = 0.058 \text{ kg/part}$$

Batch sizes will be calculated based on a production schedule producing 1,000 stacks per year. The 6-kW stack requires 107 cells, requiring total slurry production of:

$$\text{Annual Slurry Production: } 107 \text{ parts/stack} \times 1{,}000 \text{ stacks} \times 0.058 \text{ kg/part} = 6{,}206 \text{ kg}$$

A-12.4.2 Anode Ceramic Slurry Material Cost

Material cost of the slurry is calculated using the weight percents of the slurry constituents multiplied by the raw material cost to determine a cost per kilogram. Ceramic material pricing was obtained from Inframat Advanced Materials in December 2013. Bulk cost for the dispersant was obtained from web quotes at around $2.50 for 2,500 kg. The cost of DI water is based on amortized distillation costs obtained from www.apswater.com.

Summarizing, the weight of each material contained in the slurry is:

- YSZ = 0.26 × 6,206 kg = 1,613 kg
- NiO = 0.37 × 6,206 kg = 2,296 kg
- Water = 0.12 × 6,206 kg = 745 kg
- Binder = 0.24 × 6,206 kg = 1,489 kg
- Dispersant = 0.01 × 6,206 kg = 62 kg

Material costs were determined in accordance with Appendix A-2 as:

- YSZ = $42.59
- NiO = $32.29
- Water = $0.084
- Binder = $2.725
- Dispersant = $2.917

The raw material cost of the slurry is:

Raw material cost = (0.26 × $42.59) + (0.37 × $32.29) + (0.12 × $0.084) + (0.24 × $2.725) + (0.01 × $2.917)

Raw material cost = $23.71/kg

The annual anode slurry cost before scrap is:

$23.71/kg × 6,206 kg = $147,144.26

A-12.4.3 Anode Ceramic Slurry 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 BDI 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 slurry is made up of 5 materials, so that total handling time for material preparation can be estimated as:

Material prep time = 5 × 21.4 sec = 107 sec = 1.8 min = 0.03 hrs

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 kW-hr/ton. The calculations are complex owing to the large number of inputs to the calculations.

In “Technical Notes 8, Grinding,” R.P. King develops a relationship based on fundamental physical models of ball mill processing (see http://www.mineraltech.com/MODSIM/ModsimTraining/Module6/Grinding.pdf). He assumes a 35% volumetric loading ratio, of which milling balls represents 10% of the total charge volume. Given a mill with diameter d and length l, the total catalyst charge volume is:

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

We note that production levels of 1,000 stacks per year will require a total of 8,277 kg of catalyst production per year across all layers, or about 33 kg per day. A volume of 50,000 stacks per year will require about 413,850 kg per year of slurry, or about 1,650 kg per day.

A web search identified a batch ball mill capable of 500-kg loading weight measuring 1.8 m diameter and 1.6 m long and consuming 3.7 kW of power. For 1,000 6-kW stacks, the total number of batches processed will be:

Roundup(6,206 / 500) = 13 batches

For other SOFC layers, the slurry volumes required will be smaller due to thinner deposition layers, ranging from 5 to 30 microns. The total depth of all subsequent layers is around 80 microns across 6 additional layers. Assuming similar density and composition profiles, we can expect slurry production for the remaining layers to be around 2,070 kg per year, or about 8.3 kg per day.

A web search identified a batch ball mill capable of 27 kg loading weight measuring 325 mm diameter and 325 mm long and consuming 0.75 kW of power.

Once the milling process is complete, the slurry will need to be separated from the milling balls and transferred to the coating machine. While we presently 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 slurry from the mill, and transfer the slurry to a transport container or directly to the coater reservoir.

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

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

Since the slurry forms 90% of the charge volume, the total charge volume is:

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

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

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

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

We will estimate the total transfer time to remove the slurry from the mill and transfer it to the coater as twice the slurry removal time. The total time required to remove the slurry from the mill would be:

$$\text{Material removal time} = 2 \times 8.1 \times 500\ \text{kg} = 8{,}100\ \text{sec} = 2.25\ \text{hrs}$$

Total machine time is:

$$(\text{Setup time} + \text{Material prep time} + \text{Milling time} + \text{Material removal time}) \times \text{Number of batches} = (0.5 + 0.03 + 10.0 + 2.25) \times 13 = 166.14\ \text{hrs}$$

Machine utilization is:

$$166.14 / 6{,}000 = 2.8\%$$

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

$$\text{In-house rate} = \$6.00 / 0.028 = \$214.29$$

$$\text{Job shop rate} = 1.4 \times (\$6.00 / 0.65) = \$12.92$$

For computing machine labor time, we assume one dedicated operator for the setup, material prep, and material removal operations, but only minimal labor time required during milling. The total machine labor time is then:

$$((0.5 + 0.03 + 2.25) \times 1\ \text{operator} + (10 \times 0.1\ \text{operator})) \times 13\ \text{batches} = 49.1\ \text{hrs}$$

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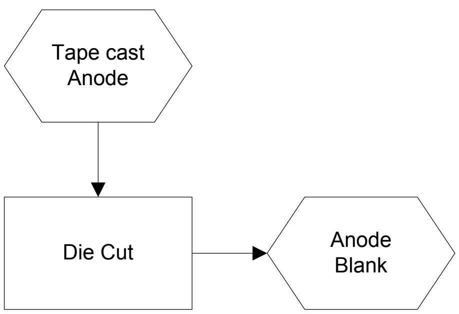
Appendix A-13: SOFC Anode Blanking Process

A-13.1 Model Approach

- Anode blanking operation
  - Machine setup labor time based on number of setups required to process material and input labor time
  - Tooling cost based on die cutting length and die life
  - Press machine time based on cutting force, cutting time, and throughput

A-13.2 Process Flow



A-13.3 Background

We will assume that the pre-fired anode tape has similar physical properties to those of elastomeric materials. The primary method for blanking elastomeric materials with standard features and tolerances is steel rule die cutting. The outline of the gasket is laid out and cut into a board. Strip steel is embedded into the board at a uniform height and mounted on a small stroke, fast acting press. The anode material is fed into the press where the steel rule die shears the material. The cutout areas of the blank are pushed out of the bulk material and the blanks stacked.

A-13.4 Preliminary Analysis

The cells for this analysis are for a 6-kW stack at a production rate of 1,000 stacks per year. The deposition area for the anode will be:

$$136 \text{ mm width} \times 193 \text{ mm length} = 262.48 \text{ cm}^2$$

The 6-kW stack requires 107 cells, requiring total annual production of:

$$\text{Annual production} = 107 \text{ parts/stack} \times 1{,}000 \text{ stacks} = 107{,}000 \text{ parts}$$

A-13.4.1 Setup

The number of setups for anode blanking will be the same as that for anode tape pressing, which is 15.

A-13.4.2 Tooling Cost

The primary factor contributing to steel rule die cost is the total cutting length of the die. For the anode, the cutting length (mm) is:

Cutting length = 2 × (136 + 193) = 658 mm

For press sizing, we assume a die length not to exceed 900 mm, making the total number of cavities six (one widthwise by six lengthwise). A steel-rule-die will have (2 × 6) = 12 136-mm outer edges, and (6 + 1) 193-mm inner cutting edges. Therefore the die cutting length is:

Die cutting length (mm) = (7 × 193) + (12 × 136) = 2,983 mm

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

Tooling rate = $230 / (2 × 2,706) mm = $0.04/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. Assuming a shorter die life of 20,000 cycle for the ceramic material, the total tooling cost per part for a four-cavity die (four parts per stroke) amortizing over a 5 year life can be calculated as:

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

where:

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

Annual tooling cost = $\frac{1}{5}$ ((2,983 mm/die × $0.04/mm) × Roundup((107,000 parts/yr / 6 parts/cycle × 5 yrs) / 20,000 parts/tool)) = $119.32

A-13.4.3 Die Cutting

The primary energy input to run the press is hydraulic pump motor power. The total force required to cut the material is the total shear area (cutting length × material thickness) multiplied by the material shear strength. Assuming that the unfired anode material has the approximate consistency of high-density polyethylene (HDPE), we will use 23 N/mm^2 as the shear strength, giving the total required press force as:

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

Press force = 2,983 mm/die × 0.5 mm × 23 N/mm^2 = 34.3 kN = 3.86 tons

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 required press energy input is:

Press energy = 34.3 kN × 1.5 × 0.025 kW/kN = 1.29 kW

Typical die cutting press speed ranges from 30 to 60 cycles/min (1,800 to 3,600 cycles/hour). Assuming the slower speed, part throughput is calculated as

Throughput = 6 parts per cycle × 1,800 cycles per hr = 10,800 parts/hr

The total machine time required to produce 1,000 6-kW stacks is:

Machine time = Setup time + Machine time = (0.5 hr/setup × 15 setups) + (107,000 parts / 10,800 parts/hr) = 17.4 hrs

Machine utilization is:

Machine utilization = 17.4 / 6,000 = 0.29%

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

In-house rate = \$29.83 / 0.0029 = \$10,286.20

Job shop rate = 1.4 × (\$29.83 / 0.65) = \$64.25

Assuming one operator per casting machine for both setup and operation, the machine labor time is equal to the total machine time of 17.4 hours.

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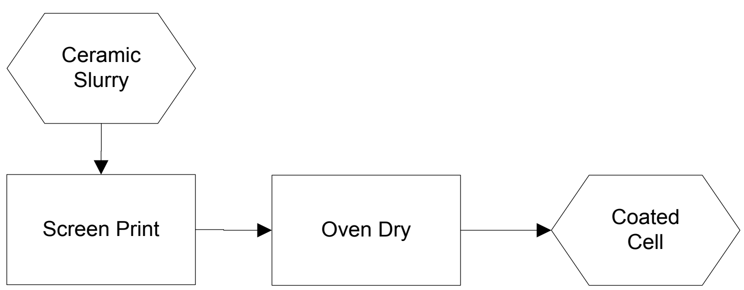
Appendix A-14: SOFC Screen Printing Process

Ceramic Screen Printing Process

A-14.1 Model Approach

- Screen Preparation
  - Compute tooling cost
  - Compute labor time for screen cleaning
  - Compute labor time and material cost for emulsion coating based on required ceramic layer thickness
  - Compute energy, machine time and labor time for masking and emulsion exposure
  - Compute energy, machine time and labor time for emulsion rinse and post-cure
- Screen Printing
  - Compute time for machine setup
  - Compute labor time for substrate load/unload
  - Compute machine time for screen printing operation
- Oven Drying
  - Compute required heater area based on drying time and required conveyor speed
  - Compute heater energy on energy watt density and heater area

A-14.2 Process Flow



A-14.3 Background

The mechanics of the screen preparation and printing process are described in several on-line sources, as well as a series of instructional videos produced by Cat Spit Productions found on YouTube. The calculations used for the screen preparation process were based on material and process specifications for Ulano QT-THIX emulsion and the article "Screen Coating Techniques" available from emulsion manufacturer Kiwo at http://www.kiwo.com/articles/. Technical details of the printing process were based on the article "Screen and Stencil Printing" available at http://archive.is/www.ami.ac.uk, and "The Basics of Printing Thick Film Inks" available at from DuPont Microcircuit Materials at http://www2.dupont.com/MCM/en_US/techtip/basics.html.

A-14.4 Preliminary Analysis

The cells for this analysis are for a 6-kW stack with anode deposition of:

136 mm width × 193 mm length = 262.48 cm^2

To develop the analysis, we will assume that the screen printing operation is being used to apply the anode active layer, which has a finished depth of 15 microns. Annual production rate is 1,000 stacks per year. The 6-kW stack requires 107 cells, requiring annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-14.4.1 Screen Tooling Cost

Screen size is determined based on pattern area. Dupont recommends a squeegee length of 10-20 mm beyond the pattern area (part width) on both sides, and squeegee travel of 50-80 mm beyond the pattern area (part length) on both ends. Bopp, a printing mesh manufacturer, recommends a screen width of 3 times the squeegee width and screen length of 2 times the squeegee travel. The minimum screen size can be calculated as:

Screen width = 3 × (Part width + 20)

Screen length = 2 × (Part length + 100)

For the two part sizes, the screen sizes are:

Screen width = 3 × (136 + 20) = 468 mm

Screen length = 2 × (193 + 100) = 586 mm

Screen area = 46.8 cm × 58.6 cm = 2,742.48 cm^2

The two primary wear items are the screen and the squeegee. Atlas screen supply company quotes triple durometer squeegee material for $2.05/inch ($0.81/cm). Squeegee cost is:

Squeegee cost = $0.81/cm × (136 + 20) / 10 = $12.64

AMI indicates that polymer squeegees may be changed daily in high volume production applications, indicating a useful life of around 5,000 to 6,000 parts. The squeegee tooling cost is:

Squeegee tooling cost = $12.64 × Roundup(107,000 parts / 5,000 parts/squeegee) = $278.08

Web quotes for fine mesh precision metal screens in 24-inch x 30-inch size ranged from $50 to $100, equating to about $0.02/cm^2, giving estimated screen costs of:

Screen cost = $0.02/cm^2 × 2,742.48 cm^2 = $54.85

AMI reports screen lives between 5,000 and 50,000 cycles. Given the nature of the ceramic inks used, we will assume the lower value of 5,000 cycles. Total screen tooling cost based on a life of 5,000 cycles and amortizing over a 5-year life is:

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

where:

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

Annual tooling cost = $\frac{1}{5}$ ((\$54.85) × Roundup((107,000 parts/yr × 5 yrs) / 5,000 parts/screen)) = \$1,173.79

A-14.4.2 Screen Preparation

Screen preparation is a manual process that consists of cleaning, emulsion coating, emulsion masking and exposure to high intensity light, emulsion rinsing and post cure using high intensity light. The primary cost component will be the labor involved in handling and coating the screen. An empirical formula developed by Boothroyd Dewhurst, Inc. (BDI) calculates a quantity called part girth, then calculates a theoretical total handling time (both load and unload) with a minimum value of 4 seconds. Adapting the formula for dimensions in millimeters and handling of large, light-weight parts, the handling time is calculated as follows:

Part girth = Part length + Part width + Part depth

Handling time = Max((0.3 × (Part girth / 25.4) - 4.6), 4)

Common screen frames are 1 inch (25.4 mm) thick, so that the handling time for the screen is:

Screen handling time = Max((0.3 × (1,079.4 / 25.4) - 4.6), 4) = 8.15 sec

Cleaning is assumed to be accomplished by brushing the screen mesh and spray rinsing with water. The time to accomplish the tasks will consist of a tool acquisition time (e.g., brush, hose) and operation time. The general default time for acquisition of tools within easy reach is 3 seconds, and is applicable to a wash station set-up. Brush and rinse operation time will depend on the treatment area. No general area-based guidelines could be found, so we will assume that the operation time per screen side can be estimated using an adaptation of the formula as the total handling time. The calculation for a combination clean and rinse operation for both sides of a screen becomes:

Cleaning time = 4 × (3 + Handling time)

Screen cleaning time = 4 × (3 + 8.15) = 44.6 sec

The emulsion coating is applied with a hand-held trough coater with width equal to the screen width. This allows the emulsion to be applied in one fluid motion from the bottom to the top of the screen. Observations of video recordings of the process indicate that a single coat can be applied to a 1-meter length in approximately 5 seconds. Using 3 seconds for tool acquisition, the time to apply a single coat can be estimated as:

Emulsion application time = 3 + (Screen length / 1,000) × 5

Emulsion application time = 3 + (586 / 1,000) × 5 = 5.93 sec

The number of emulsion coats depends on the desired coating depth. Dupont suggests that fine mesh screens provide a dry print depth for thick film inks of approximately 16 microns. Further reductions in film thickness achieved through calendar rolling of the screen. Kiwo recommends 2 coats of emulsion on the squeegee side of the screen, followed by at least one coat up to as many coats on the print side as necessary to provide the proper coating depth. The number of emulsion coats can be estimated as:

Number of coats = 3 + Max((Coating depth – 16), 0)

Number of coats = 3 + Max((15 – 16), 0) = 3 coats

Screens are air dried for about 1 hour following coating. Consequently, no additional labor time is accumulated for the drying operation. Total emulsion coating time is calculated as:

Emulsion coating time = Number of coats × (Emulsion application time + Handling time)

Emulsion coating time = 3 × (5.93 + 8.15) = 42.24 sec

The emulsion is developed by applying the pattern mask and exposing the coated screen to 4,500-watt light for a period equal to approximately 1 minute per 1 micron of emulsion depth and a minimum of 15 minutes. Assuming approximately 4 seconds to place the mask, the handling time for applying the mask is 10.95 seconds. The required power for the light source can be calculated as:

Exposure power = ((15 + Max((Coating depth – 15), 0) / 60) hrs × 4.5 kW

1 Exposure power cost = (15 / 60) × 4.5 = 1.125 kW

The unexposed emulsion is rinsed from the screen in a manner similar to the cleaning step, air dried, and re-exposed to the light source to harden the emulsion coating on the squeegee side of the screen. Using the cost equations developed previously:

Rinsing time = 2 × (3 + Handling time)

Rinsing time = 2 × (3 + 8.15) = 22.3 sec

Summarizing screen preparation by step:

	100 kW
	Labor Time (sec)
Cleaning	44.60
Coating	42.24
Exposure	10.95
Rinsing	22.30
Post-cure	10.95
Total	131.04

A-14.4.3 Screen Printing

The screen printing operation consists of a part load/unload, which may be manual or robotic, but will be driven by overall part size. Using the handling time formula developed previously, the load/unload time is:

Handling time = Max((0.3 × ((136 + 193 + 1) / 25.4) - 4.6), 4) = 4.0 sec

The time to perform the printing operation is a function of the flood blade speed, which can be estimated to move at 4 times the squeegee speed. Setting L to the squeegee travel length and S to the squeegee speed:

Substrate coating time = (L/S) + (L/4S) = 1.25 × (L/S)

Observations of SOFC screen printing operations suggest that the squeegee speed is approximately 25 mm/sec. Using these values, the time to coat the substrate is:

Substrate coating time = 1.25 × (293 / 25) = 14.65 sec

Total machine time for screen printing is:

Setup time + (Handling time + Coating time) × Number of parts = 0.5 hr + ((4.0 + 14.65) / 3,600) × 107,000 parts = 554.8 hrs

Machine utilization is:

Machine utilization = 554.8 / 6,000 = 9.25%

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

In-house rate = $49.71 / 0.0925 = $537.41

Job shop rate = 1.4 × ($49.71 / 0.65) = $107.07

Assuming one operator per screen printing machine, the machine labor time is equal to the total machine time of 554.8 hours.

A-14.4.4 Ceramic Slurry Drying

Following deposition, the ceramic slurry is dried, usually by means of 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 throughput and the drying time.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler et al. (1978)[21] indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 l/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 l/min.

Previous analysis assumed that the screen printed slurry material was formulated with aqueous components as follows:

- 12 wt% water
- 24 wt% binder (Dow Duramax B-1000/B-1014)
- 1 wt% dispersant

The binder consists of approximately 45% solids. Roughly estimating the volume of liquid per gram of slurry by multiplying the material density by the material weight percent:

$$\text{Liquid density} = (0.12 \times 1.0) + ((0.24 \times 0.55) \times 1.05) + (0.01 \times 1.16) = 0.270 \text{ g/cm}^3$$

The weight of liquid to be removed per unit area is a function of slurry thickness. As with tape casting, we assume a 50% thickness reduction after drying. Using the anode active layer (15 micron green thickness; 30 micron wet thickness) as an example:

$$\text{Liquid removed per area} = 0.270 \text{ g/cm}^3 \times 0.003 \text{ cm} = 0.0008 \text{ g/cm}^2$$

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

$$\text{Drying time} = 0.0008 \text{ g/cm}^2 / 2.0\times10^{-5} \text{ g/cm}^2\text{-sec} = 40.5 \text{ sec} = 0.675 \text{ min}$$

The conveyor speed is a function of part throughput and belt length required to transport the part. Using the results above, the throughput is:

Throughput = 107,000 parts / 554.3 hrs = 193.03 parts/hr

Assuming a 50-mm gap between parts on the belt, the conveyor speed can be calculated as:

Conveyor speed = Belt length per part (mm/part) * Throughput (parts/min)

Conveyor speed = (136 + 50) * (193.03 / 60) = 598.4 mm/min = 0.598 m/min

Infrared heating panels are generally sold with various energy watt densities and in standard sized units and assembled to provide the necessary heating area. Using the Casso Solar Type FB as an example, standard watt densities are 15 and 25 W/in^2 (23 and 39 kW/m^2) with standard width of 12 inches

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

(0.305 m) and lengths in 12-inch increments up to 60 inches (1.524 m). They note 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%.

For a drying time of 0.675 minutes, the required heater area is:

Heater area = Drying time (min) $\times$ Conveyor speed (m/min) $\times$ (Belt length per part (mm) / 1,000)

Heater area = 0.675 $\times$ 0.598 $\times$ (186 / 1,000) = 0.075 m^2

While the heater energy density will be taken as an input, the drying temperatures for the ceramic slurry are fairly moderate (150°C or less), so that the 23 kW/m^2 should be sufficient to maintain the drying area temperature. Using an energy cost of $0.07/kW-hr, the hourly energy cost to power the heaters will be:

Heating energy = 0.075 m^2 $\times$ 23 kW/m^2 = 1.73 kW

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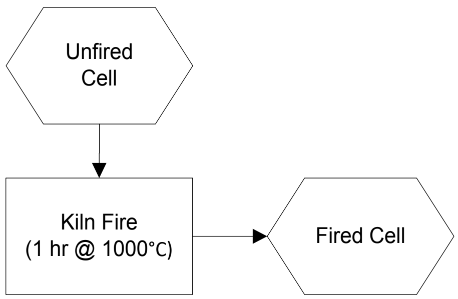
Appendix A-15: SOFC Kiln Firing Process

A-15.1 Model Approach

- Kiln Firing
  - Compute part handling time labor time
  - Compute machine time

A-15.2 Process Flow



A-15.3 Preliminary Analysis

The cells for this analysis are for 6-kW stacks at a production rate of 1,000 stacks per year. The deposition area for the anode will be:

136 mm width × 193 mm length = 262.48 cm^2

The 6-kW stack requires 107 cells, requiring total annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-15.3.1 Kiln Firing

The SOFC process calls for kiln firing at 1,000°C (1,832°F) for 1 hour after the part reaches temperature. The moderate temperatures required allow for the use of a mesh belt furnace to accomplish the kiln firing process.

Large mesh belt furnaces manufactured by AFC-Holcroft feature a 66-inch (167-cm) wide belt, 6-inch (15.24-cm) workspace clearance, and effective load length of 456 inches (1,158 cm) for a total load volume of 2.95×10^6 cm^3. The maximum part thickness following the last screen printing operation is 328 microns (0.0328 cm). Adding 1 cm on all sides for part spacing in the furnace and assuming optimal racking, the total part envelope is:

$$\text{Part envelope} = (13.6 + (2 \times 1.0)) \times (19.3 + (2 \times 1.0)) \times (0.0328 + (2 \times 1.0)) = 675.46 \text{ cm}^3$$

The maximum furnace loading is then:

$$\text{Furnace loading} = 2.95 \times 10^6 \text{ cm}^3 / 675.46 \text{ cm}^3 = 4,368 \text{ parts}$$

The firing schedule is based on the firing schedule suggested in PNNL-22732[22] of:

Segment	Rate/Time	Temp.
Ramp	3°C/min	1,000°C
Hold	1 hr	1,000°C
Ramp	5°C/min	Ambient

Using 25°C as the ambient temperature, the required preheat time is:

$$(1{,}000 – 25)°C / (3°/min) = 325 \text{ min} = 5.42 \text{ hrs}$$

The required cooling time is:

$$(1{,}000 – 25)°C / (5°/min) = 195 \text{ min} = 3.25 \text{ hrs}$$

Therefore, total furnace time is 9.67 hours, making furnace throughput:

Throughput = 4,368 parts / 9.67 hrs = 451 parts/hr

Total machine time to fire the cells is:

Machine time = 107,000 parts / 451 parts/hr = 237.25 hrs

Machine utilization is:

Utilization = 237.25/ 6,000 = 3.95%

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

In-house rate = $53.99 / 0.0395 = $1,366.84

Job shop rate = 1.4 × ($53.99 / 0.65) = $116.29

Part load/unload, which may be manual or robotic, will be driven by overall part size. To determine if a single operator can load and unload parts while the machine is operating, we use the handling time formula adapted from the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software to determine the total load/unload time required per hour of machine time as:

Part handling time = Max((0.3 × ((136 + 193 + 1) / 25.4) - 4.6), 4) × 451 parts/hr = 0.5 hr per hr of machine time

Given that part handling time is a small percentage of the total firing time, we assume one operator is capable of covering three machines, making the labor time:

Machine labor time = 237.25 / 3 = 79.1 hrs

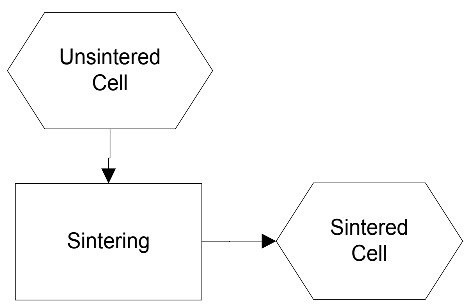
[22] Weimar, M.R., Chick, L.A., Gotthold, D.W., and Whyatt, G.A. 2013. Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems (PNNL-22732). Pacific Northwest National Laboratory, September 2013.

Appendix A-16: SOFC Sintering Process

A-16.1 Model Approach

- Sintering
  - Part handling time labor cost based on part size per Boothroyd Dewhurst, Inc. (BDI) formula and throughput; 4-second minimum
  - Process cost based on furnace energy cost plus standard machine rate

A-16.2 Process Flow



A-16.3 Preliminary Analysis

The cells for this analysis are for a 6-kW stack with anode deposition of:

136 mm width × 193 mm length = 262.48 cm^2

Annual production rate is 1,000 stacks per year. The 6-kW stack requires 107 cells, requiring annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-16.3.1 Sintering Process

The sintering process schedule is based on the bi-layer sintering schedule suggested in PNNL-22732[23] of:

Segment	Rate/Time	Temp.
Ramp	0.5°C/min	190°C
Hold	2 hrs	190°C
Ramp	0.5°C/min	450°C
Hold	1 hr	450°C
Ramp	3°C/min	1,375°C
Hold	1 hr	1,375°C
Ramp	5°C/min	Ambient

[23] Weimar, M.R., Chick, L.A., Gotthold, D.W., and Whyatt, G.A. 2013. Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems (PNNL-22732). Pacific Northwest National Laboratory, September 2013.

Generally, the high sintering temperatures require the use of either pusher, walking beam, or rotary hearth continuous furnaces. A used Surface Combustion rotary hearth furnace supports 60 5-inch × 21-inch (12.7-cm × 53.3-cm) trays with a workspace clearance of 35 inches (88.9 cm), for a total load volume of 3.61×10^6 cm^3. The maximum part thickness following the last screen printing operation is 328 microns (0.0328 cm). Adding 1 cm on all sides for part spacing in the furnace and assuming optimal racking, the total part envelope is:

$$\text{Part envelope} = (18.7 + (2 \times 1.0)) \times (26.8 + (2 \times 1.0)) \times (0.0328 + (2 \times 1.0)) = 675.46\ cm^3$$

The maximum furnace loading is then:

$$\text{Furnace loading} = 3.61 \times 10^6\ cm^3 / 675.46\ cm^3 = 5{,}329 \text{ parts}$$

Using 25°C as the ambient temperature, the required heating times are:

$$(190 – 25)°C / (0.5°/min) = 330 \text{ min} = 5.5 \text{ hrs}$$

$$(450 – 190)°C / (0.5°/min) = 520 \text{ min} = 8.67 \text{ hrs}$$

$$(1{,}375 – 450)°C / (3°/min) = 308 \text{ min} = 5.14 \text{ hrs}$$

The required cooling time is:

$$(1{,}375 – 25)°C / (5°/min) = 270 \text{ min} = 4.5 \text{ hrs}$$

Adding the 4 hours of hold time, the total furnace time is 27.81 hours, making furnace throughput:

$$\text{Throughput} = 5{,}329 \text{ parts} / 27.81 \text{ hrs} = 192 \text{ parts/hr}$$

Total machine time to fire the cells is:

$$\text{Machine time} = 107{,}000 \text{ parts} / 192 \text{ parts/hr} = 557.3 \text{ hrs}$$

Machine utilization is:

$$\text{Utilization} = 557.3 / 6{,}000 = 9.28\%$$

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

$$\text{In-house rate} = \$60.26 / 0.0928 = \$649.35$$

$$\text{Job shop rate} = 1.4 \times (\$60.26 / 0.65) = \$129.79$$

Part load/unload, which may be manual or robotic, will be driven by overall part size. To determine if a single operator can load and unload parts while the machine is operating, we use the handling time formula developed previously, to determine the total load/unload time required per hour or machine time as:

> Part handling time = Max((0.3 $\times$ ((136 + 193 + 1) / 25.4) - 4.6), 4) $\times$ 192 parts/hr = 0.213 hr per hr of machine time

Given that part handling time is a small percentage of total firing time, we assume one operator is capable of covering three machines, making the labor time:

> Machine labor time = 557.3 / 3 = 185.8 hrs

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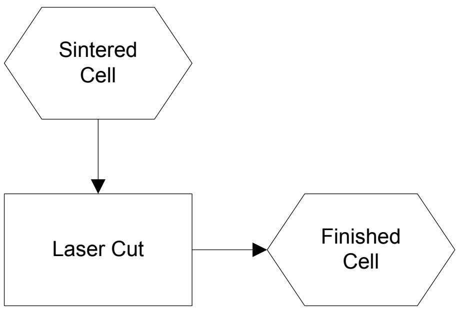
Appendix A-17: SOFC Final Trim Process

A-17.1 Model Approach

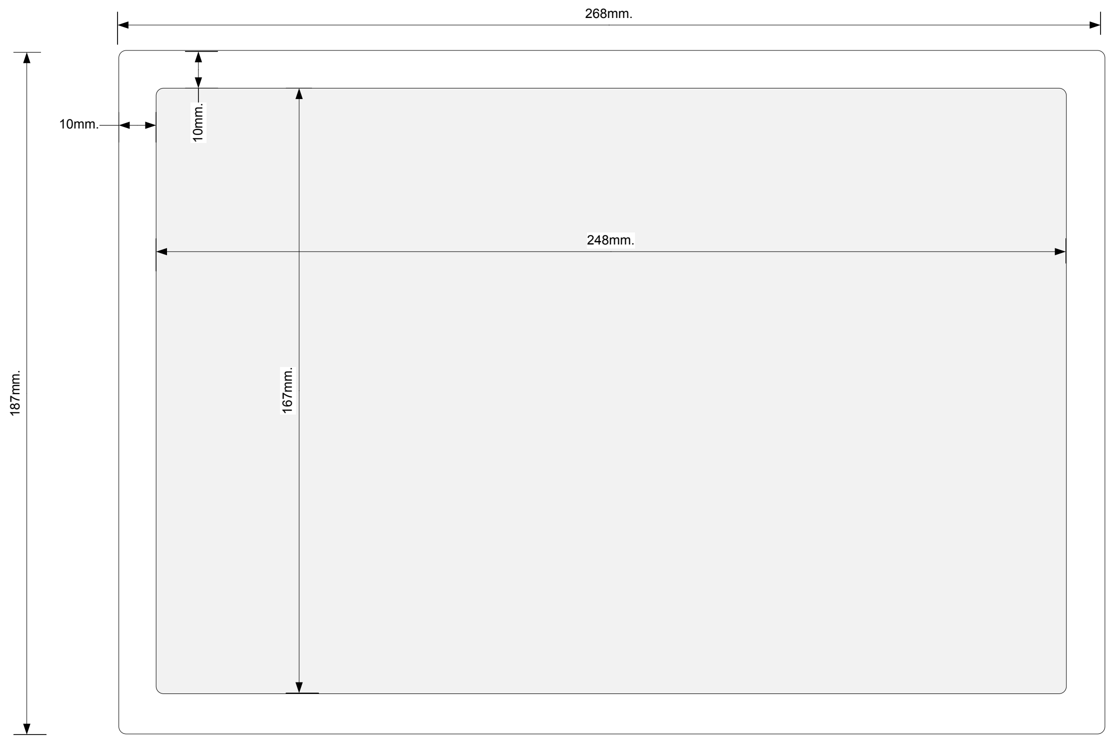
- Laser cut final cell shape

A-17.2 Process Flow



A-17.3 Background

Following sintering, the SOFC cells are laser cut to final dimensions as shown:



A-17.4 Preliminary Analysis

The cells for this analysis are for a 6-kW stack at a production rate of 1,000 stacks per year. The deposition area for the anode will be:

136 mm width × 193 mm length = 262.48 cm^2

The 6-kW stack requires 107 cells, requiring total annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-17.4.1 Laser Cutting Cost

Assuming a single setup operation requiring one operator per batch of parts, the final trim setup time will be 0.5 hour.

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula adapted from the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software, the total handling time is:

Part handling time = Max((0.3 × ((136 + 193 + 0.3) / 25.4) - 4.6), 4) = 4.0 sec/part

The total cutting length for the cell is:

Cutting length = (2 × (136+ 193)) = 658 mm

Linde suggests that laser cutting of 1 mm thick stainless steel be performed using a 1,500-W YAG laser under pure nitrogen flow of 8.0 m^3/hr at a maximum speed of 7.0 m/min (0.117 m/sec). Assuming that the sintered ceramic has similar properties, the time to cut the cells is:

Cutting time = 0.658 m / 0.117 m/sec = 5.62 sec/part

The total machine time required is:

Total machine time = (5.62 + 4) sec/part × 107,000 parts / 3,600 = 285.9 hrs

Machine utilization is:

Utilization = 285.9 / 6,000 = 4.77%

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

In-house rate = $33.81 / 0.0477 = $708.80

Job shop rate = 1.4 × ($33.81 / 0.65) = $72.82

Given that the operator required time for load/unload is nearly the same as the total part processing time, we will assume one operator is capable of operating one machine, making the machine labor hours the same as the machine hours of 285.9.

At a consumption rate of 8.0 m^3/hr, the nitrogen material usage is:

Etching material cost = 8.0 m^3/hr × 5.62 sec/part / 3,600 sec/hr × 107,000 parts = 1,336.3 m^3

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

Material cost = \$0.517/m^3

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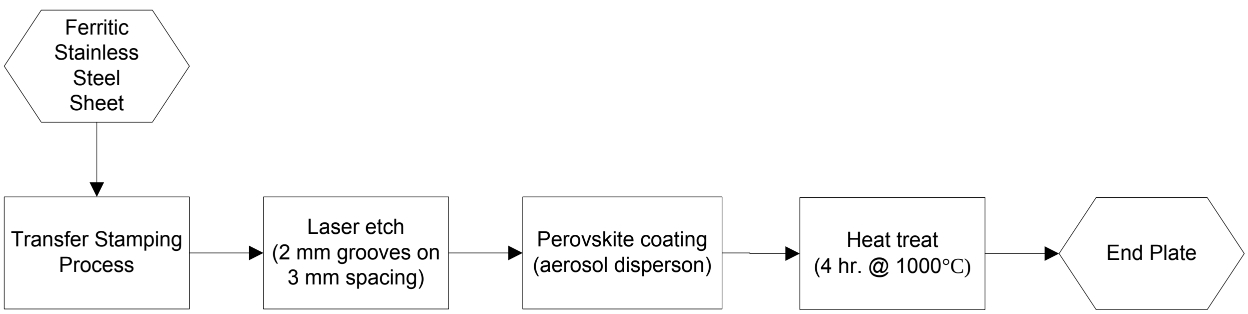
Appendix A-18: SOFC Interconnect Production Process

A-18.1 Model Approach

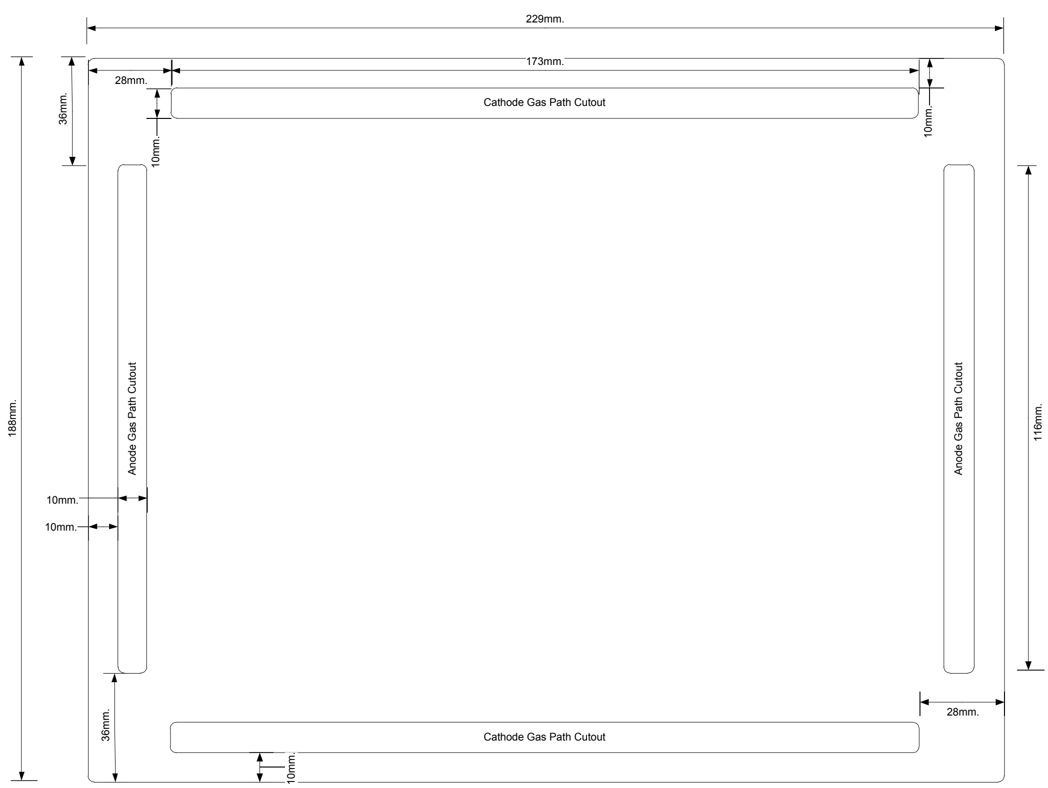
- Ferritic stainless steel stamping operation
- Laser etching operation
- Perovskite coating operation
- Heat treating operation

A-18.2 Process Flow



A-18.3 Background

The interconnect plates are dimensioned as shown:



A-18.4 Preliminary Analysis

The interconnects for this analysis will be working in a 6-kW stack for which the part size is:

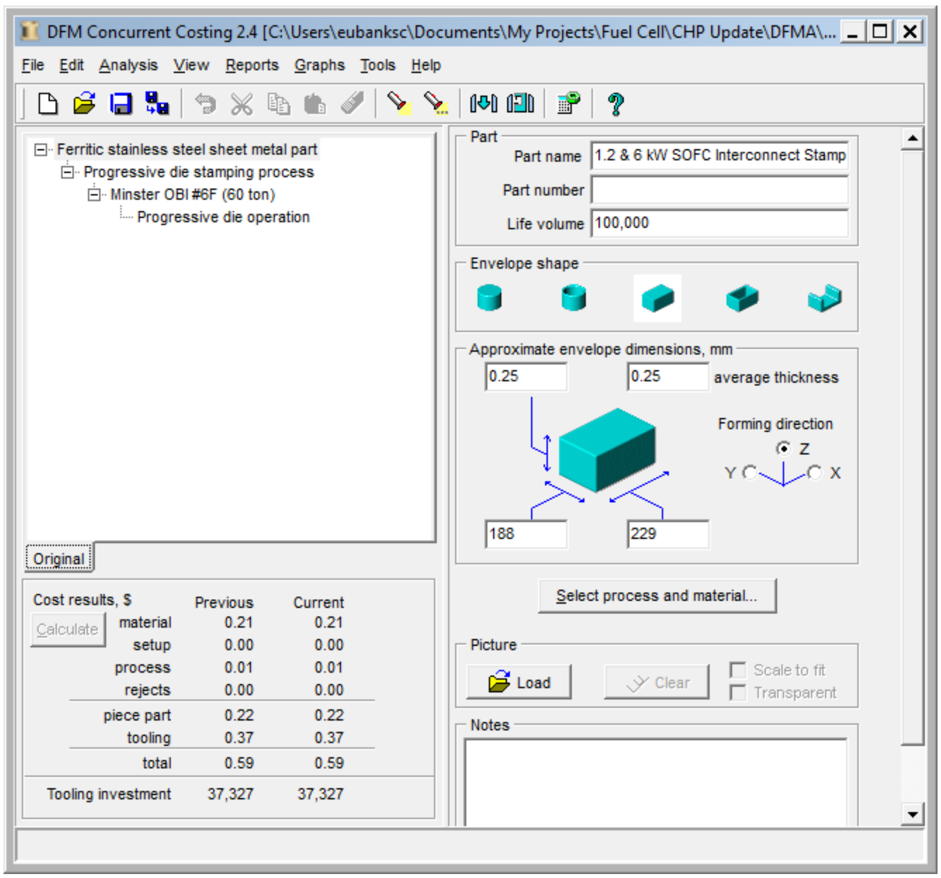
188-mm width × 229 mm length = 430.52 cm^2

The interconnects will be manufactured from 0.25 mm thick ferritic stainless steel (SS-441) plate. The 6-kW stack requires 107 interconnects, so that annual production of 1,000 systems requires annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-18.4.1 Transfer Stamping Processing Cost

The Boothroyd Dewhurst, Inc. (BDI) software provides pre-programmed cost models for the transfer stamping operations used to manufacture the interconnect plate blanks, as shown below



The BDI software estimates a 1-hour machine setup time, and calculates the total manufacturing time for the stamped part as 0.8 sec, making the total machine time for annual production:

Machine time = (0.8 sec/part / 3,600) × 107,000 parts + 1.0 = 24.8 hrs

Machine utilization is:

Utilization = 24.8 / 6,000 = 0.41%

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

In-house rate = \$55.40 / 0.0041 = \$13,512.20

Job shop rate = 1.4 × (\$55.40 / 0.65) = \$119.32

Assuming one full-time operator per machine, the total machine labor time is equal to the machine time of 24.8 hours.

Tooling cost is \$37,327 and is assumed to be capable of producing 400,000 parts. Amortizing over a 5 year life, the total annual tooling cost:

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

where:

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

Annual tooling cost = $\frac{1}{5}$ ((\$37,337) × Roundup((107,000 parts/yr × 5 yrs) / 400,000 parts/tool)) = \$14,934.80

A-18.4.2 Aerosol Coating Processing Cost

Assuming a single setup operation requiring one operator per production run of parts, the setup time will be 0.5 hour.

Part load/unload, which may be manual or robotic, will be driven by overall part size. Because the part will be turned in order to coat both sides, additional time equal to half of the load/unload time will be added. Using the handling time formula developed previously, the total handling time is:

Part handling time = 1.5 × Max((0.3 × ((188 + 229 + 0.25) / 25.4) - 4.6), 4) = 6.0 sec/part

The perovskite coating is deposited via aerosol spray to a depth of 3 microns (0.003 mm) and has a material density of approximately 6.1 g/cm^3. Assuming a 90% spray efficiency, and allowing for 5 mm overspray on the four edges, the total deposited material per coated side is:

Deposited material = 2 × ((18.8 + 0.5) cm × (22.9 + 0.5) cm × 0.0003 cm) = 0.271 cm^3/part

Total coating material usage is:

Coating material usage = 6.1 g/cm^3 × 0.271 cm^3/part × 107,000 parts = 176.9 kg

The material cost before scrap was determined in accordance with Appendix A-2 as:

Material cost = \$223.32/kg

Deposited depth is a function of flow rate, spray width and nozzle speed:

Coating depth = Flow rate (mm^3/sec) / (Spray width (mm) × Nozzle speed (mm/sec))

Spray nozzle manufacturers will generally specify a maximum flow rate associated with a particular nozzle. Therefore, given a flow rate, coated width and coating depth, the nozzle speed is calculated as:

Nozzle speed (mm/sec) = Flow rate (mm^3/sec) / (Spray width (mm) × Coating depth (mm))

Using the SonoTek Flexicoat Impact nozzle system as an example, the maximum precision spray width is approximately 50 mm and maximum nozzle speed of 400 mm/sec. Assuming a maximum coating flow rate of 333 mm^3/sec (20 ml/min), the nozzle speed is:

Nozzle speed = Min(333 / (50 × 0.003), 400) = 400 mm/sec

The time to coat both sides of the interconnect plate, and allowing for 25 mm overspray on the four edges is:

Coating time per part = 2 × ((188 + 50) mm × (229 + 50) mm / (50 mm × 400 mm/sec)) = 6.64 sec/part

Total machine time required for annual production is:

Machine time = (6.64 + 6.0) sec/part / 3,600 × 107,000 parts = 375.7 hrs

Machine utilization is:

Utilization = 375.7 / 6,000 = 6.26%

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

In-house rate = \$31.06 / 0.0626 = \$496.17

Job shop rate = 1.4 × (\$31.06 / 0.65) = \$66.90

Given that the operator required time for load/unload is approximately equal to the total part processing time, we will assume one operator per machine, making the machine labor time equal to the machine time of 375.7 hours.

A-18.4.3 Heat Treating Processing Cost

The interconnect coating process calls for heat treatment at 1,000°C (1,472°F) for 4 hours after the part reaches temperature. Large mesh belt furnaces manufactured by AFC-Holcroft feature a 66-inch (167-cm) wide belt, 6-inch (15.24-cm) workspace clearance, and effective load length of 456 inches (1,158 cm), for a total load volume of 2.95 × 10^6 cm^3. The maximum part thickness following the last screen printing operation is 328 microns (0.0328 cm). Adding 1 cm on all sides for part spacing in the furnace and assuming optimal racking, the total part envelope is:

Part envelope = (18.8 + (2 × 1.0)) × (22.9 + (2 × 1.0)) × (0.025 + (2 × 1.0)) = 1,048.8 cm^3

The maximum furnace loading is then:

Furnace loading = 2.95×10^6 cm^3 / 1,048.8 cm^3 = 2,813 parts

The firing schedule is based on the metallization schedule suggested in PNNL-22732[24] of:

Segment	Rate/Time	Temp.
Ramp	3°C/min	1,000°C
Hold	4 hr	1,000°C
Ramp	5°C/min	Ambient

Using 25°C as the ambient temperature, the required preheat time is:

(1,000 – 25)°C / (3°/min) = 325 min = 5.42 hrs

The required cooling time is:

(1,000 – 25)°C / (5°/min) = 195 min = 3.25 hrs

Therefore, total furnace time is 12.67 hours, making furnace throughput:

Throughput = 2,813 parts / 12.67 hrs = 222 parts/hr

Total machine time to fire the interconnects is:

Machine time = 107,000 parts / 222 parts/hr = 482 hrs

The machine utilization is:

Utilization = 482 / 6,000 = 8.03%

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

In-house rate = \$53.99 / 0.0477 = \$1,131.87

Job shop rate = 1.4 × (\$53.99 / 0.65) = \$116.29

Part load/unload, which may be manual or robotic, will be driven by overall part size. To determine if a single operator can load and unload parts while the machine is operating, we use the handling time formula developed previously, to determine the total load/unload time required per hour or machine time as:

Part handling time = Max((0.3 × ((188 + 229 + 0.28) / 25.4) - 4.6), 4) = 4 sec/part

Total part handling time = (4 sec/part / 3,600) × 222 parts/hr = 0.247 hrs per hr of machine time

[24] Weimar, M.R., Chick, L.A., Gotthold, D.W., and Whyatt, G.A. 2013. Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems (PNNL-22732). Pacific Northwest National Laboratory, September 2013.

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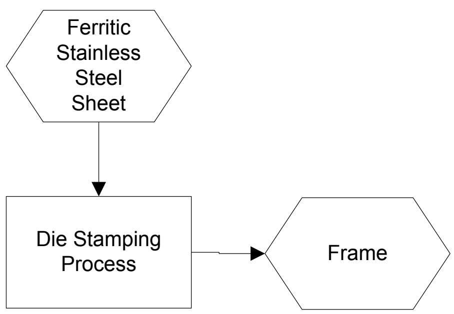
Appendix A-19: SOFC Picture Frame Production Process

A-19.1 Model Approach

- Ferritic stainless steel stamping operation

A-19.2 Process Flow



A-19.3 Background

The SOFC cell contains three frames:

- The anode frame supports the interconnect on the anode side and provides space for the anode mesh
- The picture frame provides space for the cathode side of the cell
- The cathode frame supports the interconnect on the cathode side and provides space for the cathode mesh

The Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software provides pre-programmed cost models for the transfer stamping operations used to manufacture the frames. Labor and machine times will be aggregated to determine the number of presses required and the utilization. Material usage will be aggregated to compute material cost.

A-19.4 Preliminary Analysis

The frames for this analysis will be working in in a 6-kW stack for which the overall part size is:

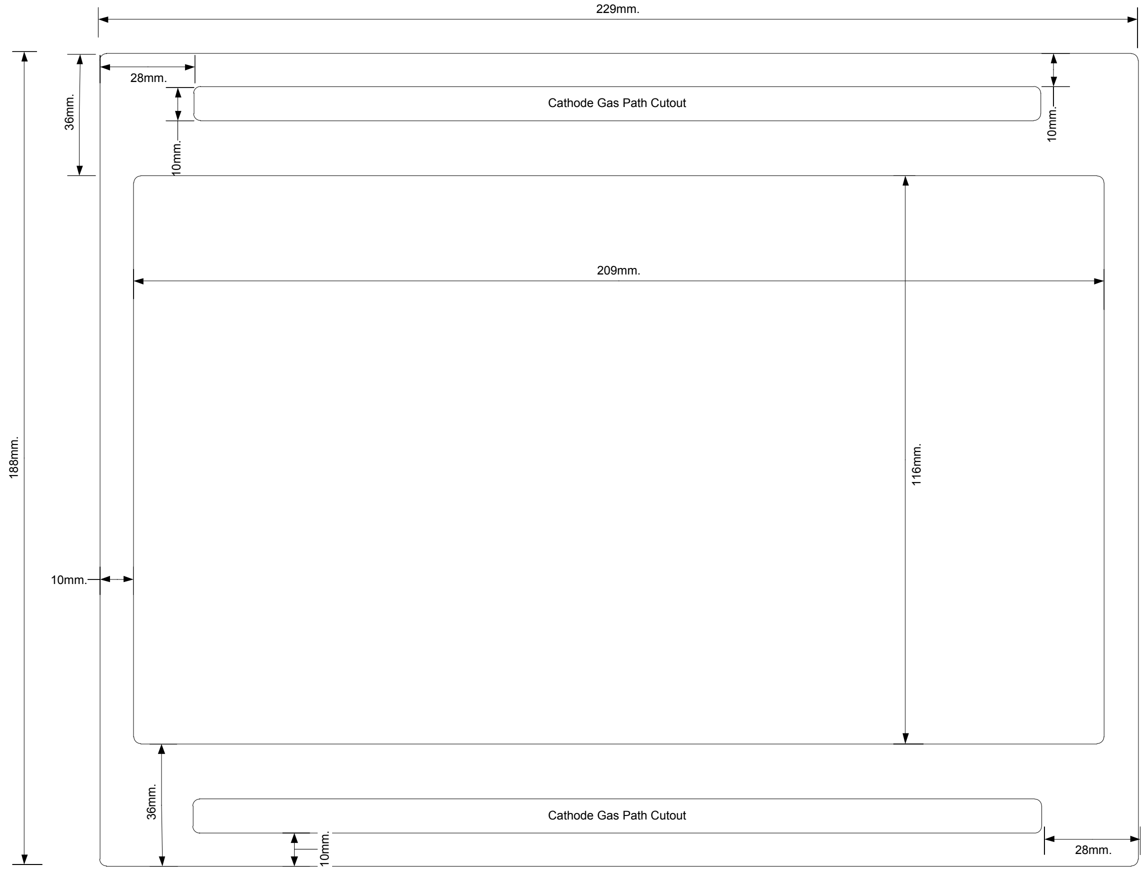
$$188 \text{ mm width} \times 229 \text{ mm length} = 262.48 \text{ cm}^2$$

Machine and labor time will be calculated based on an annual production of 1,000 stacks per year. The 6-kW stack requires 107 of each type of frame, requiring production of:

$$\text{Annual production} = 107 \text{ parts/stack} \times 1{,}000 \text{ stacks} = 107{,}000 \text{ parts/frame}$$

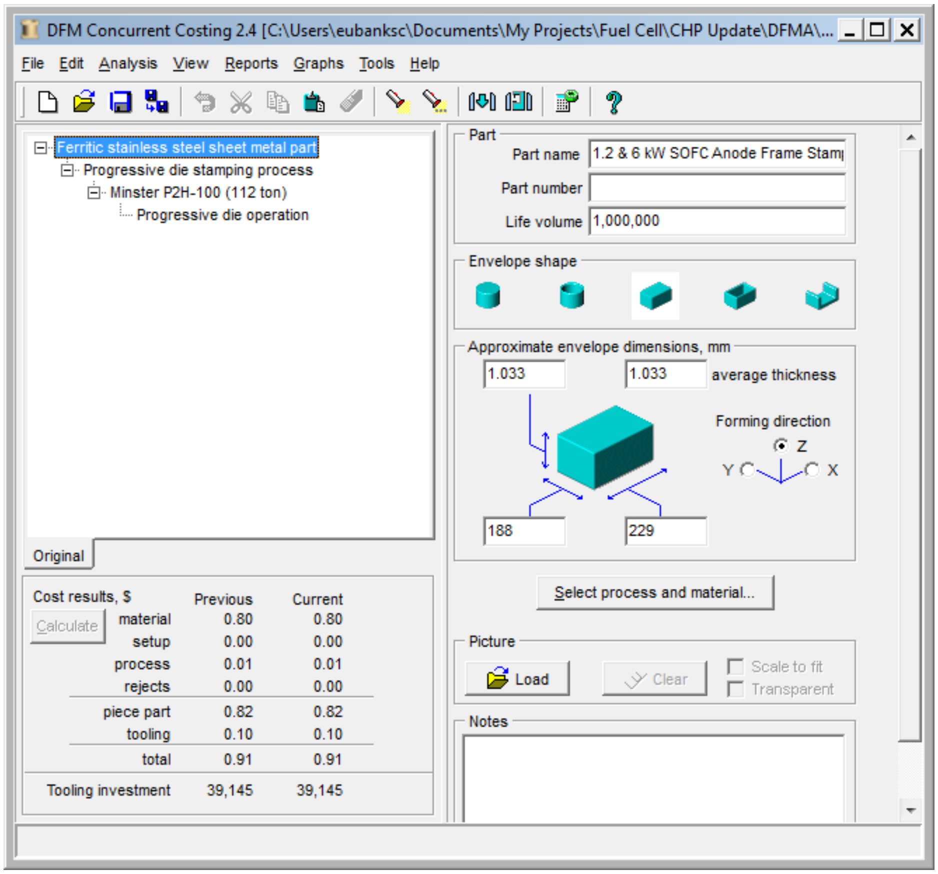
A-19.5 Anode Frame

A-19.5.1 Frame Dimensions



A-19.5.2 Die Stamping Processing Cost

The resulting BDI DFMA software analysis is shown in the following screen shot:



The BDI software estimates a 2-hour machine setup time, and calculates the total manufacturing time for the stamped part as 1.0 sec, making the total machine time for annual production:

$$\text{Machine time} = (1.0 \text{ sec/part} / 3{,}600) \times 107{,}000 \text{ parts} + 2.0 = 31.7 \text{ hrs}$$

Assuming one full-time operator per machine, the total machine labor time is equal to the machine time of 31.7 hours.

Tooling cost is $39,145 and the tool is assumed to be capable of producing 400,000 parts. Amortizing over a 5-year life, the total annual tooling cost is:

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

where:

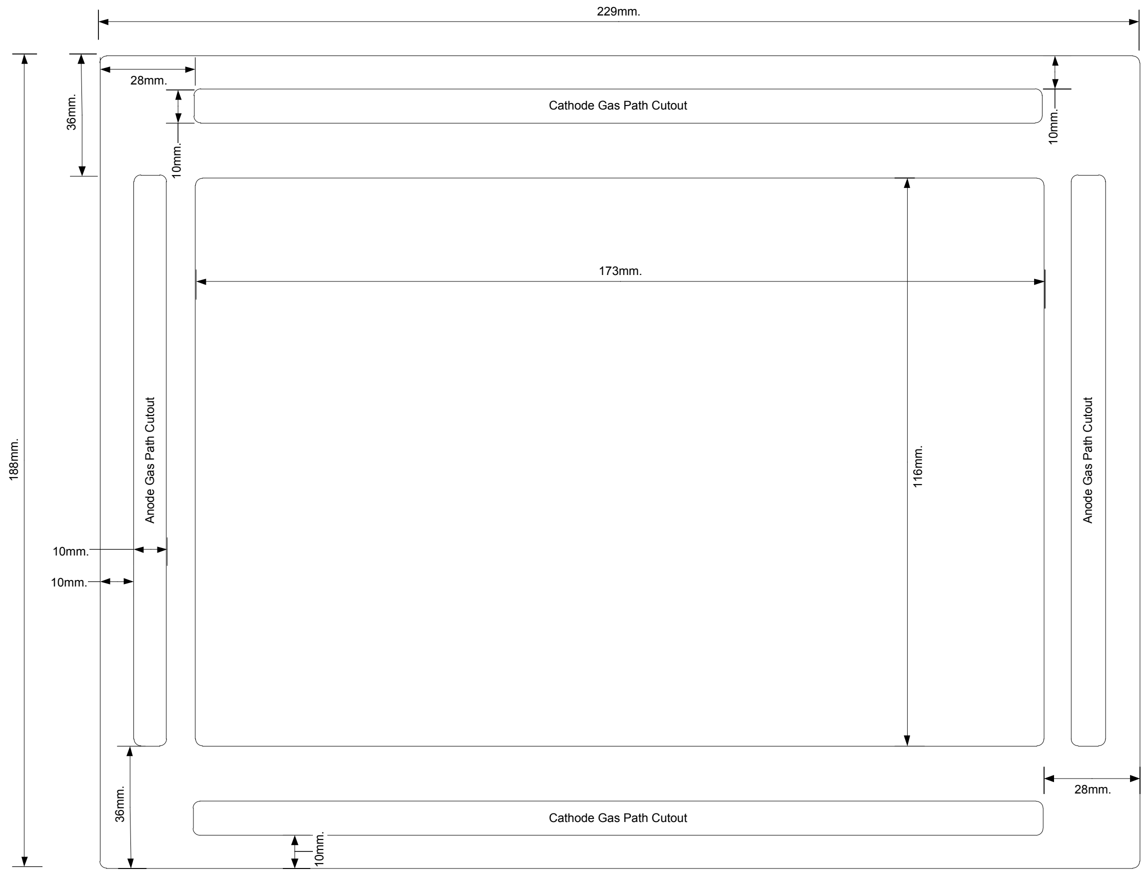
$$\text{Number of tools purchased} = \text{Roundup}(\text{Total production} / \text{Tool life})$$

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

$$\text{Annual tooling cost} = \tfrac{1}{5}\,((\$39{,}145) \times \text{Roundup}((107{,}000 \text{ parts/yr} \times 5 \text{ yrs}) / 400{,}000 \text{ parts/tool})) = \$15{,}658.00$$

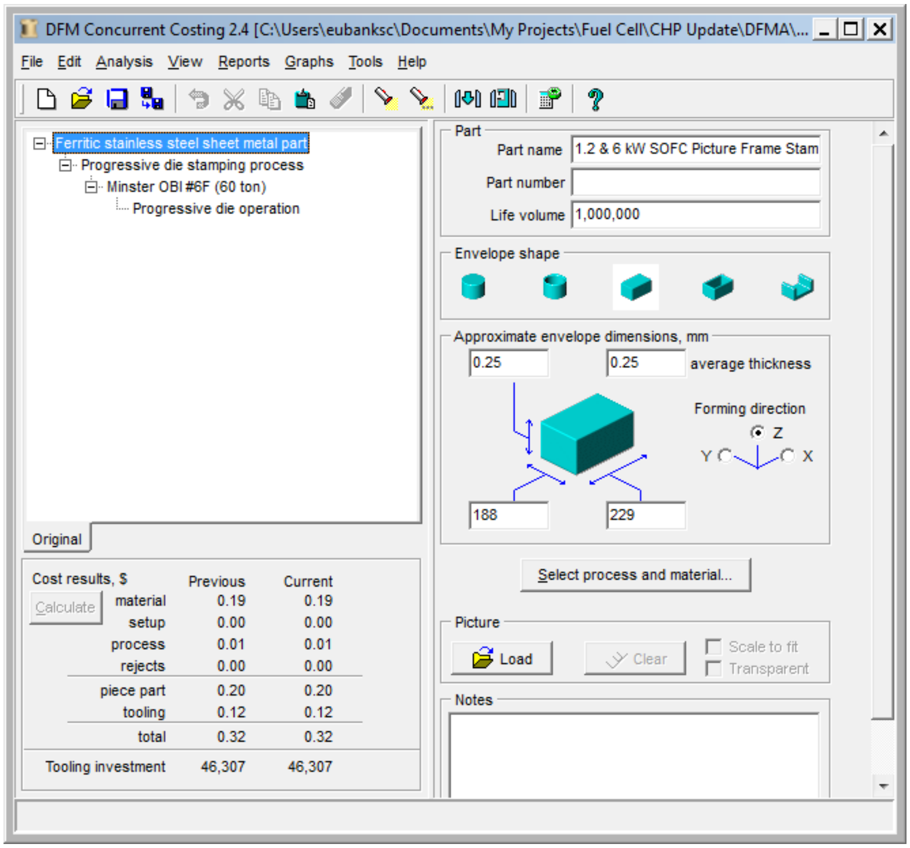
A-19.6 Picture Frame

A-19.6.1 Frame Dimensions



A-19.6.2 Die Stamping Processing Cost

The resulting BDI DFMA software analysis is shown in the following screen shot:



The BDI software estimates a 1-hour machine setup time, and calculates the total manufacturing time for the stamped part as 0.8 sec, making the total machine time for annual production:

Machine time = (0.8 sec/part / 3,600) × 107,000 parts + 1.0 = 24.7 hrs

Assuming one full-time operator per machine, the total machine labor time is equal to the machine time of 24.7 hours.

Tooling cost is $46,307 and is assumed to be capable of producing 400,000 parts. Amortizing over a 5 year life, the total annual tooling cost is:

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

where:

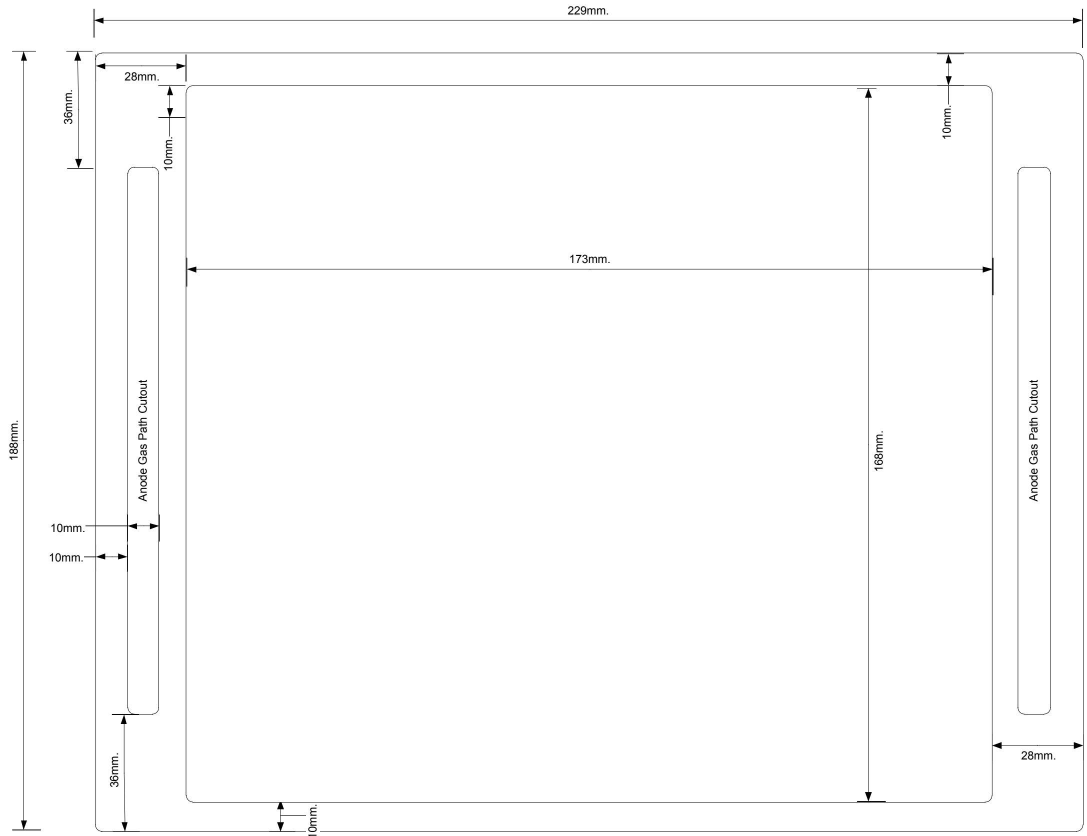
Number of tools purchased = Roundup(Total production / Tool life)

Total production = Annual production × 5

Annual tooling cost = $\frac{1}{5}$ (($46,307) × Roundup((107,000 parts/yr × 5 yrs) / 400,000 parts/tool)) = $18,522.80

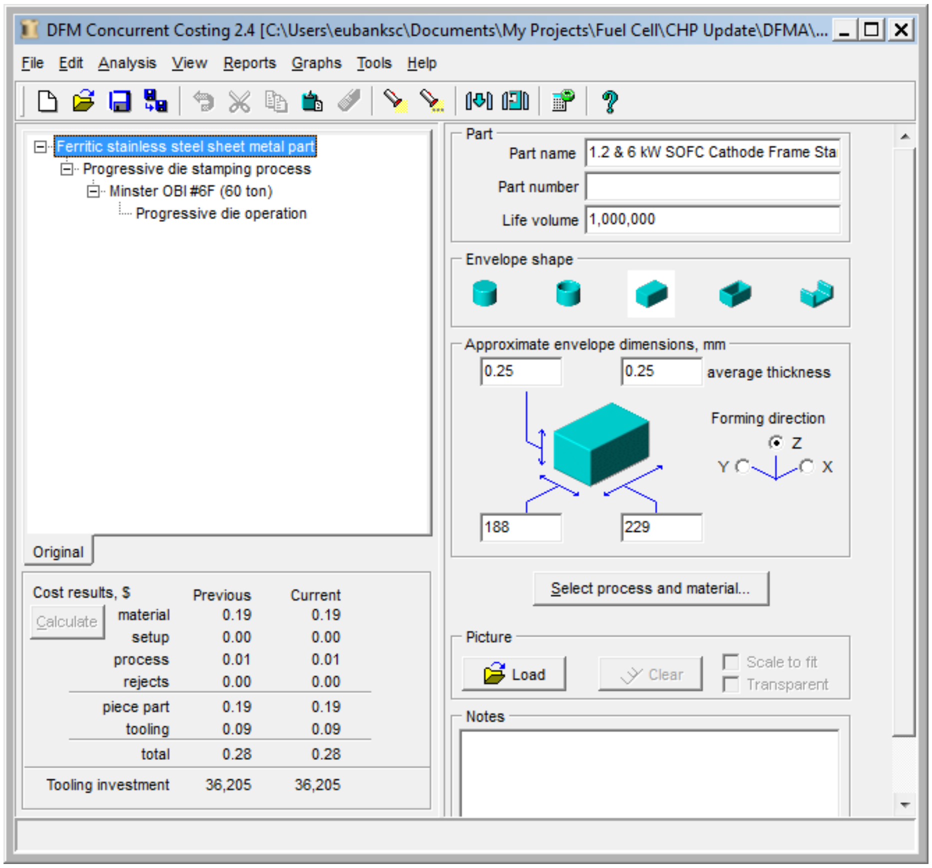
A-19.7 Cathode Frame

A-19.7.1 Frame Dimensions



A-19.7.2 Die Stamping Processing Cost

The resulting BDI DFMA software analysis is shown in the following screen shot:



The BDI software estimates a 1-hour machine setup time, and calculates the total manufacturing time for the stamped part as 0.8 sec, making the total machine time for annual production:

$$\text{Machine time} = (0.8 \text{ sec/part} / 3{,}600) \times 107{,}000 \text{ parts} + 2.0 = 24.7 \text{ hrs}$$

Assuming one full-time operator per machine, the total machine labor time is equal to the machine time of 24.7 hours.

Tooling cost is $36,205 and is assumed to be capable of producing 400,000 parts. Amortizing over a 5-year life, the total annual tooling cost is:

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

where:

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

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

$$\text{Annual tooling cost} = \tfrac{1}{5}\,((\$36{,}205) \times \text{Roundup}((1{,}036{,}000 \text{ parts/yr} \times 5 \text{ yrs}) / 400{,}000 \text{ parts/tool})) = \$14{,}482.00$$

A-19.8 Machine Utilization

Total machine time to produce the three frames is:

Stamping machine time = 31.7 + 24.7 + 24.7 = 81.1 hrs

Machine utilization is:

Utilization = 81.1 / 6,000 = 1.35%

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

In-house rate = \$55.40 / 0.0135 = \$4,103.70

Job shop rate = 1.4 × (\$55.40 / 0.65) = \$119.32

A-19.9 Material Cost

The BDI DFMA software estimated the part weights as:

Anode frame: 0.320 kg

Picture frame: 0.076 kg

Cathode frame: 0.076 kg

Total annual material usage for the three frames is:

Annual material usage = (0.320 + 0. 076 + 0. 076) kg/cell × 107 cells/stack × 1,000 stacks = 50,504 kg

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

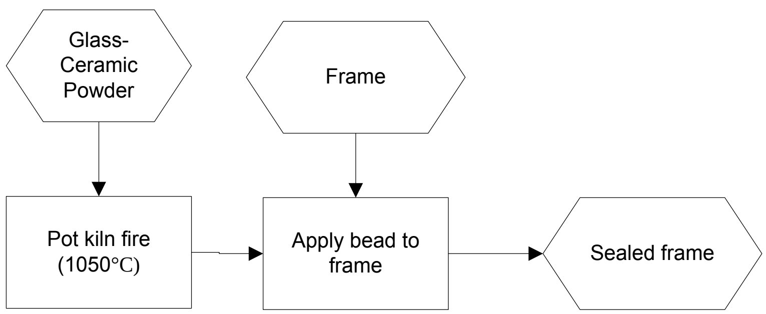
Material cost = \$2.250/kg

Appendix A-20: SOFC Glass-Ceramic Sealant Production Process

A-20.1 Model Approach

- Calculate glass-ceramic sealant batch size
- Calculate glass-ceramic sealant production time
- Calculate glass-ceramic sealant application time

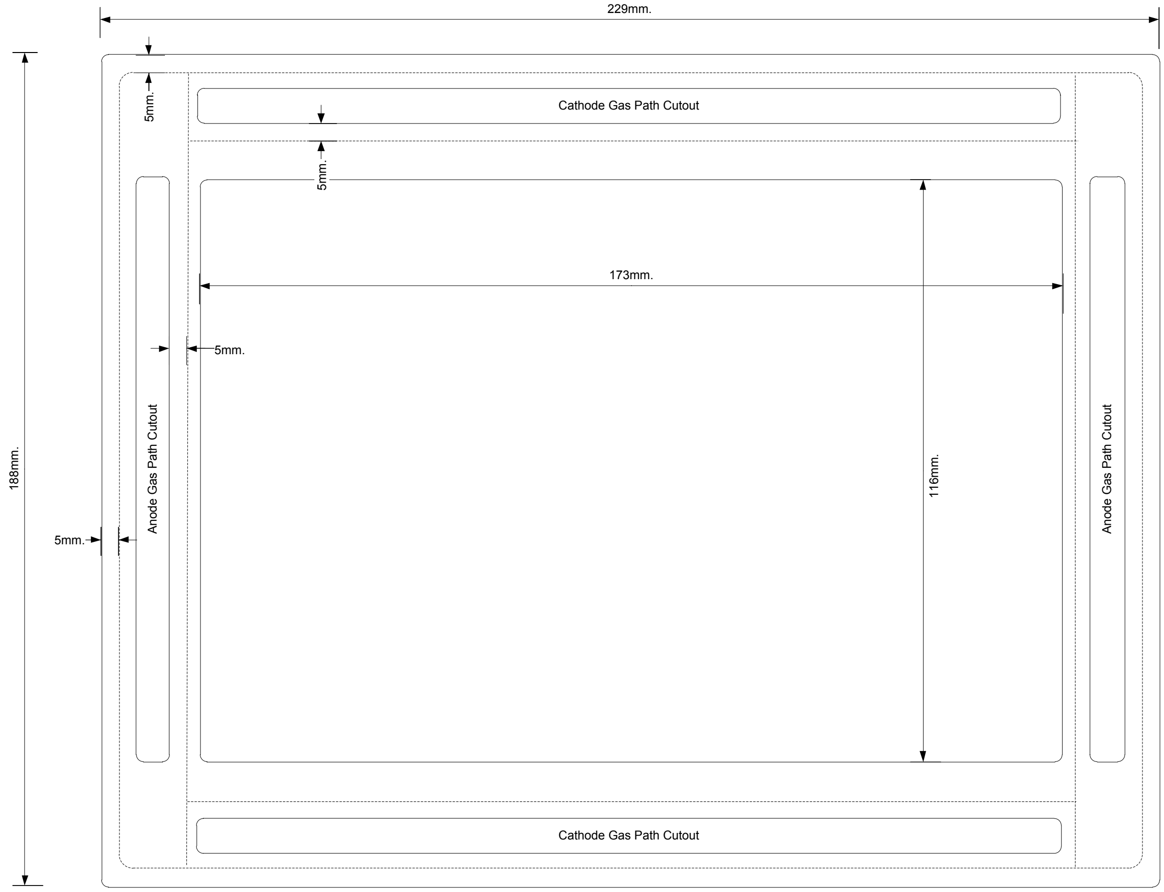
A-20.2 Process Flow



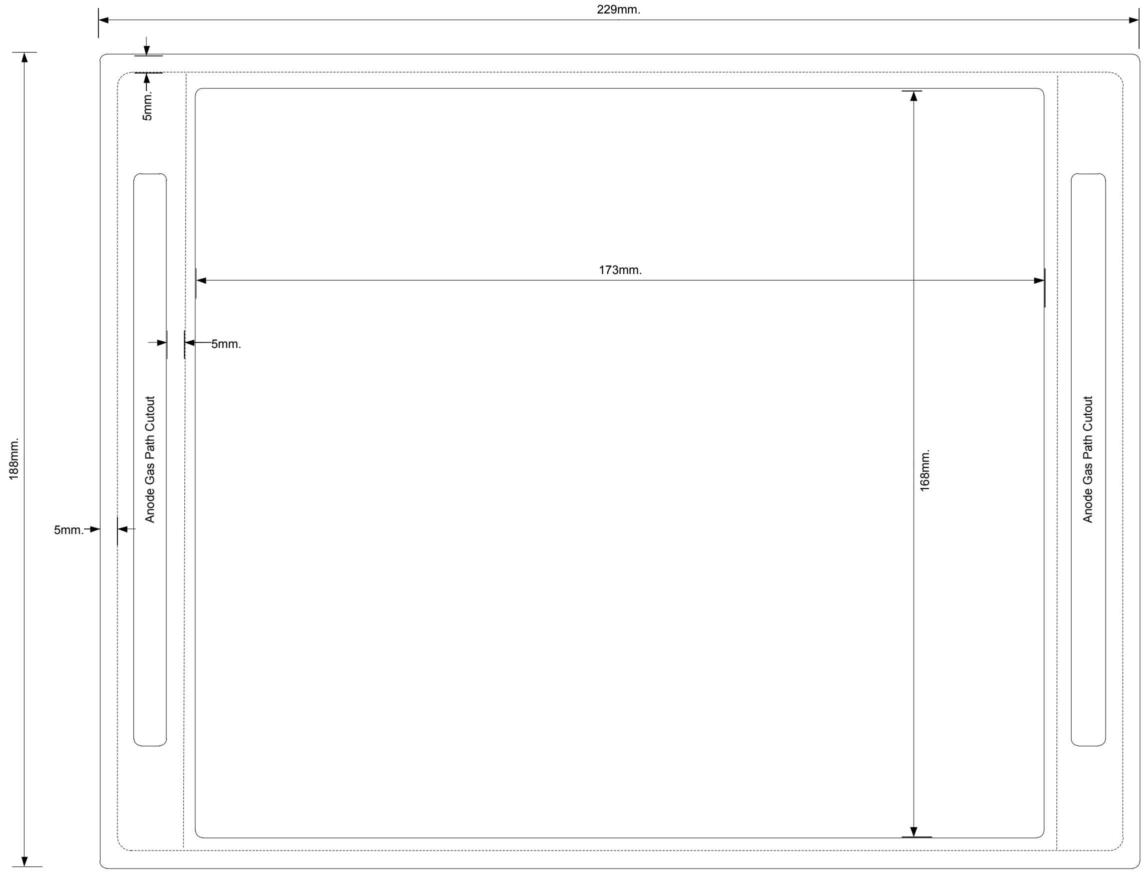
A-20.3 Background

The sealant bead (dashed lines) is applied to the picture frame and cathode frame as shown:

A-20.3.1 Picture Frame



A-20.3.2 Cathode Frame



A-20.4 Preliminary Analysis

Machine and labor time will be calculated based on an annual production of 1,000 6-kW stacks. The 6-kW stack requires 107 of each type of frame.

A-20.4.1 Sealant Material

The sealant will be applied to areas that are 10 mm wide, and needs to fill a gap of about 148 microns (on both sides of the interconnect plates and one side of the picture frame with the same seal length as the cathode side. Assuming a maximum finished seal width of 8 mm, the total seal cross-sectional area is:

Seal cross sectional area = 8 mm wide × 0.148 mm high = 1.184 mm^2

Assuming application in a round bead, the required bead diameter that will yield the same cross-sectional area is:

Seal dispense diameter = 2 × (1.184/п)1/2 = 1.23 mm

The total seal length per side based on the above drawings is:

Picture frame seal length: (4 × (188 – 10)) + (2 × (229 – 10)) + (2 × (229 – 50)) = 1,508 mm

Cathode frame seal length: (4 × (188 – 10)) + (2 × (229 – 10)) = 1,150 mm

The total volume of seal material required per cell (sealing both parts) is:

$1.184 \text{ mm}^2 \times (1{,}508 + 1{,}150) \text{ mm} = 3{,}147 \text{ mm}^3 = 3.147 \text{ cm}^3$

The total sealant batch size (cm^3) for 1,000 stacks is:

$3.147 \text{ cm}^3/\text{cell} \times 107 \text{ cells/stack} \times 1{,}000 \text{ stacks} = 336{,}729 \text{ cm}^3$

A typical sealant is the Ceredyne VIOX V1649 glass ceramic sealant, consisting of 50/50 borosilicate glass (BSG)/lanthanum oxide (LO) by volume. The density of the mixture is:

Sealant density = $(2.23 \text{ g/cm}^3 + 6.51 \text{ g/cm}^3) / 2 = 4.37 \text{ g/cm}^3$

Therefore, the required sealant by weight is:

Sealant weight: $336{,}729 \text{ cm}^3 \times 4.37 \text{ g/cm}^3 / 1{,}000 = 1{,}471.5 \text{ kg}$

The weight of each material in the sealant mixture is:

LO: $(6.51 / 8.74) \times 1{,}471.5 \text{ kg} = 1{,}096.1 \text{ kg}$

BSG: $(2.23 / 8.74) \times 1{,}471.5 \text{ kg} = 375.4 \text{ kg}$

Material costs before scrap were determined in accordance with Appendix A-2 as:

LO material cost = $58.67/kg

BSG material cost = $3.10/kg

To create the paste, the borosilicate glass/lanthanum oxide mixture is fired at 1,050°C in a pot furnace for 3 hours. The Trent PF-1000 17-kW pot furnace with a total pot size of 44,480 cm^3 is capable of holding 145 kg of sealant material at 75% fill volume. At the highest anticipated volume, the 25 kW stack will require annual production 13.4 million cells, requiring about 12.5 times as much material, so this furnace should be sufficient for all anticipated levels of production.

The number of batches is:

Roundup(1,471.5 / 145) = 11

Assuming that one operator can set up a sealant batch in 0.5 hour results in a total furnace machine time of:

Machine time = $(0.5 + 3) \text{ hrs} \times 11 \text{ batches} = 38.5 \text{ hrs}$

Given that the operator required time for batch setup represents a small percentage of the total part processing time, we will assume one operator is capable of operating three machines, making the machine labor hours:

Machine labor hrs = $11 \text{ batches} \times (0.5 + (3.0 / 3)) = 16.5 \text{ hrs}$

A-20.4.2 Sealant Application Cost

Assuming a single setup operation requiring one operator per batch of parts, the sealant application station setup time is 0.5 hour.

Part load/unload (two total part movements), which may be manual or robotic, will be driven by overall part size. Using the handling time formula developed based on the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software, the total handling time for each part is:

Part handling time: Max((0.3 × ((188 + 229 + 0.25) / 25.4) - 4.6), 4) = 4.0 sec/part

The BDI DFMA software tool estimate for the bead application rate of viscous sealants is 2 in/sec (51 mm/sec) with an applicator positioning time of 0.4 seconds. For the picture frame, we assume that the bead is applied to the part perimeter in a single bead, followed by the two beads between the anode gas path and the ceramic cell. Consequently, there will be six total repositionings: move applicator to start of perimeter bead, move applicator to start of each of the four gas path beads, move applicator to second gas path bead, move applicator to home position. The total application time is:

Picture frame application time = 4.0 sec + (6 × 0.4) sec + (1,508 mm / 51 mm/sec) = 35.97 sec/part

For the cathode frame, we assume that the bead is applied to the part perimeter in a single bead, followed by the two beads between the anode gas path and the ceramic cell for four total repositionings. The total application time is:

Cathode frame application time = 4.0 sec + (4 × 0.4) + (1,150 mm / 51 mm/sec) = 28.15 sec/part

Total application time per cell is:

Total application time = 35.97 + 28.15 = 64.12 sec

Total sealant machine time is:

Machine time = 0.5 hr + ((64.12 sec / 3,600) hrs/cell × 107 cells/stack × 1,000 stacks)) = 1,906.3 hrs

Given that the operator required time for load/unload represents a small percentage of the total part processing time, we will assume one operator is capable of operating three sealant machines, making the machine labor hours:

Machine labor hrs = 1,906.3 / 3 = 635.4 hrs

Total sealing station machine time is:

Machine time = 38.5 + 1,906.3 = 1,944.8 hrs

Machine utilization is:

Utilization = 1,944.8 / 6,000 = 32.4%

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

In-house rate = $48.21 / 0.324 = $148.80

Job shop rate = 1.4 × ($48.21 / 0.65) = $103.84

Total machine labor time is:

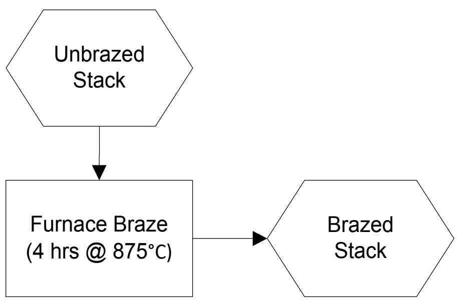
Machine labor hrs = 16.5 + 635.4 = 651.9 hrs

Appendix A-21: SOFC Stack Brazing Process

A-21.1 Model Approach

- Stack Brazing
  - Part handling time labor cost based on part size per Boothroyd Dewhurst, Inc. (BDI) formula and throughput; 4-second minimum
  - Process cost based on oven energy cost plus standard machine rate

A-21.2 Process Flow



A-21.3 Preliminary Analysis

The cells for this analysis are for 6-kW stacks at a production rate of 1,000 stacks per year.

The overall part envelope is bounded by the end plate length and width and the stack height. The 6-kW stack height is estimated based on a thickness of about 2.1 mm per repeat cell, 107 cells per stack, plus 12 mm each for the two end plates. The total stack envelope is estimated as:

$$24.8 \text{ cm width} \times 28.8 \text{ cm length} \times ((0.21*107) + (1.2*2)) \text{ cm high} = 17{,}863 \text{ cm}^3$$

A-21.3.1 Stack Brazing

The brazing schedule is based on the metallization schedule suggested in PNNL-22732[25] of:

Segment	Rate/Time	Temp.
Ramp	3°C/min	600°C
Hold	1 hr	600°C
Ramp	5°C/min	875°C
Hold	4 hrs	875°C
Ramp	5°C/min	750°C
Hold	2 hrs	750°C
Ramp	5°C/min	Ambient

[25] Weimar, M.R., Chick, L.A., Gotthold, D.W., and Whyatt, G.A. 2013. Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems (PNNL-22732). Pacific Northwest National Laboratory, September 2013.

The 6-kW stack dimensions require that the furnace have a workspace clearance of at least 30 cm (11.8 inches), an unusually large size for conveyor-type continuous furnaces. A used Surface Combustion rotary hearth furnace supports 60 5-inch × 21-inch (12.7-cm × 53.3-cm) trays with a workspace clearance of 35 inches (88.9 cm) for a total load volume of 3.61×10^6 cm^3. Allowing 5-cm separation between stacks creates an effective part volume of:

29.8 cm width × 33.9 cm length × 29.9 cm high = 30,205 cm^3

The maximum furnace loading is then:

Furnace loading = Rounddown (3.61×10^6 cm^3 / 30,205 cm^3) = 119 parts

Using 25°C as the ambient temperature, the required heating times are:

(600 – 25)°C / (3.0°/min) = 192 min = 3.2 hrs

(875 – 600)°C / (5.0°/min) = 55 min = 0.917 hrs

The required cooling times are:

(875 – 750)°C / (5.0°/min) = 25 min = 0.417 hrs

(750 – 25)°C / (5.0°/min) = 145 min = 2.417 hrs

Adding the 7 hour hold times, total furnace time is 13.95 hours, making furnace throughput:

Throughput = 119 stacks / 13.95 hrs = 8.53 stacks/hr

Total machine time to fire the cells is:

Machine time = 1,000 stacks / 8.53 stacks/hr = 117.2 hrs

Machine utilization is:

Utilization = 117.2 / 6,000 = 1.95%

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

In-house rate = $60.26 / 0.0195 = $3,090.26

Job shop rate = 1.4 × ($60.26 / 0.65) = $129.79

Part load/unload, which may be manual or robotic, will be driven by overall part size. To determine if a single operator can load and unload parts while the machine is operating, we use the handling time formula adapted from the BDI Design for Manufacture and Assembly (DFMA)® software to determine the total load/unload time required per hour or machine time as:

Part handling time = Max((0.3 × ((248 + 289 + 249) / 25.4) – 4.6), 4) = 4.7 sec

Total part loading time per batch is:

Part loading time = (4.7 / 3,600) * 119 parts = 0.155 hr

Given that part handling time is a small fraction of total firing time, we assume one operator is capable of covering three machines, making the labor time:

Machine labor time = 117.2 / 3 = 39.1 hrs

During the final hold at 750°C, reducing gas (2% hydrogen in nitrogen) is flowed through the anode cavities to reduce the NiO to Ni metal. Using the required testing flow rate for 6-kW stacks of 71.622 l/min:

Total flow rate = 71.622 l/min $\times$ 60 min/hr / 1,000 l/m^3 = 4.297 m^3/hr

During the 2-hour reduction phase, the total reducing gas usage before scrap is:

Nitrogen = (4.297 $\times$ 0.98) m^3/hr $\times$ 2 hrs/stack $\times$ 1,000 stacks = 8,422 m^3

Hydrogen = (4.297 $\times$ 0.02) m^3/hr $\times$ 2 hrs/stack $\times$ 1,000 stacks = 171.9 m^3

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

Nitrogen cost = \$0.517/m^3

Hydrogen cost = \$10.57/m^3

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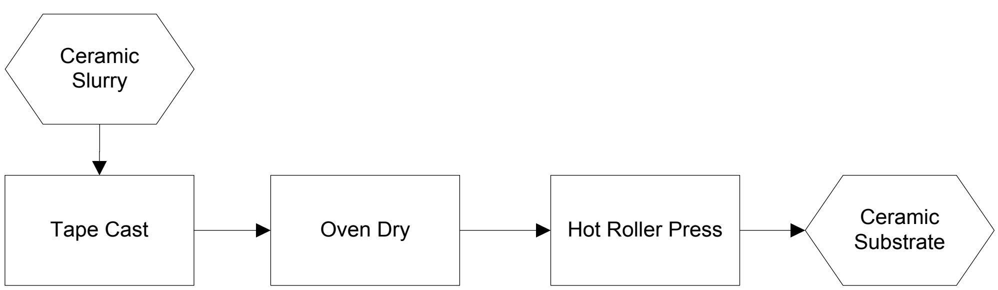
Appendix A-22: SOFC Tape Casting Process

A-22.1 Model Approach

- Tooling Cost
    - Compute tooling cost
- Tape Casting
    - Compute machine time for machine setup
    - Compute material cost for tape casting substrate
    - Compute casting speed/throughput
    - Compute machine and labor time for tape casting operation
- Oven Drying
    - Compute drying time and dryer length
    - Compute radiant heater area
    - Compute heater energy based on energy watt density and dryer area

A-22.2 Process Flow



A-22.3 Background

The total required anode thickness is 500 micron, which will be achieved via hot roller pressing of two 250-micron tapes.

A-22.4 Preliminary Analysis

The cells for this analysis are for a 6-kW system at a production rate of 1,000 stacks per year. The deposition area for the anode will be:

$$136 \text{ mm width} \times 193 \text{ mm length} = 262.48 \text{ cm}^2$$

The 6-kW stack requires 107 cells, requiring total annual production of:

$$\text{Annual production} = 107 \text{ parts/stack} \times 1{,}000 \text{ stacks} = 107{,}000 \text{ parts}$$

A-22.4.1 Cost

In a personal communication with Richard Mistler, co-author of *Tape Casting: Theory and Practice,*[26] he estimates that a doctor blade for this application would cost approximately $2,050 and would "last for years." Using 100,000 parts as a life approximation and amortizing over a 5-year production life, the total annual tooling cost is:

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

where:

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

Annual tooling cost = $\frac{1}{5}$ (($2,050) × Roundup((107,000 parts/yr × 2 tapes/part × 5 yrs) / 100,000 parts/tool)) = $4,510

A-22.4.2 Tape Casting

Since the slurry cost is calculated separately, the material cost will consist of the cost of the tape casting carrier film. The carrier film is usually Mylar or polyethylene. For roll stock in 2 mil thickness, these materials cost approximately $2.00/m^2 in bulk. Assuming that the casting width will be equal to the longest part dimension (i.e., the part length), the required casting length is determined by the part width as:

Carrier length = (136 mm / 1,000) × 107,000 × 2 tapes/part = 29,104 m

Tape casting machine setup consists of loading and threading the casting substrate, and loading the ceramic slurry into the reservoir. Bulk roll stock is available in 1,000-meter lengths so that the number of setups required to run a batch of parts is:

Number of setups = Roundup(29,104 / 1,000) = 30 setups

Allowing 25 mm casting margin on each side, the required minimum roll widths are:

Minimum carrier width = 243 mm

Rolls commonly appear in 6-inch (152.4-mm) incremental widths, requiring a 12-inch (304.8-mm) roll width. The total material required is:

Material required = 0.3048 m × 29,104 m = 8,870.9 m^2

For roll stock in 2-mil thickness, these materials cost approximately $0.315/m^2 in bulk. Material cost was determined in accordance with Appendix A-2 as:

Material cost = $0.878/m^2

[26] Mistler, R.E., and Twiname, E.R. 2000. Wiley – American Ceramic Society. 298 p.

Casting speed is limited by the slurry material properties, since running too fast can result in non-uniform deposition. Tok et al. (1999)[27] plotted experimental data relating maximum green tape thickness to casting speed, which shows a roughly exponential shape. Using the Excel function LOGEST for estimating an exponential curve fit produced the following relationship with maximum 3% error in the range of 150 to 300 microns:

$$\text{Casting speed (mm/sec)} = 157.18 \times 0.987^{\text{Green tape thickness (microns)}}$$

For a green tape thickness of 250 microns, the resulting casting speed is:

$$\text{Casting speed} = 157.18 \times 0.987^{250} = 5.97 \text{ mm/sec} = 0.358 \text{ m/min}$$

Part throughput is calculated as:

Throughput (parts/hr) = Casting speed (m/min) / Part width (m/part) / Tapes/part * 60 min/hr

Throughput = 0.358 / (136 / 1,000) / 2 × 60 = 78.97 parts/hr

The total machine time required to produce 1,000 6-kW stacks is:

Machine time = Setup time + Machine time = (0.5 hr/setup × 30 setups) + (107,000 parts / 78.97 parts/hr) = 1,370 hrs

The number of tape casting machines required is:

Number of machines = Roundup(1,370 / 6,000) = 1 machine

Machine utilization is:

Machine utilization = 1,370 / 6,000 = 22.8%

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

In-house rate = $62.25 / 0.228 = $273.03

Job shop rate = 1.4 × ($62.25 / 0.65) = $134.07

Assuming one operator per casting machine for both setup and operation, the machine labor time is equal to the total machine time of 1,370 hours.

Casting speed is also a function of required drying time and available dryer length. HED® International's PRO-CAST® series features systems ranging in length from 12 to 100 feet (3.66 to 30.5 meters).

A-22.4.3 Ceramic Slurry Drying

Following deposition, the ceramic slurry is dried, usually by means of a tunnel dryer positioned directly after the deposition step. The drying can be done by either radiant or convective heating. For the cost

[27] Tok, A.I.Y., Boey, F.Y.C., Khor, M.K.A. Tape casting of high dielectric ceramic composite substrates for microelectronics applications. *Journal of Materials Processing Technology* 89-90: 508-512.

analysis, we will assume radiant (infrared) heating and compute the cost of drying by determining the required heater area.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler et al. (1978)[28] indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 l/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 l/min.

Previous analysis assumed that the anode slurry material was formulated as follows:

- 26 wt% YSZ (8% mol)
- 37 wt% NiO
- 12 wt% water
- 24 wt% binder (Dow Duramax B-1000/B-1014)
- 1 wt% dispersant

The binder consists of approximately 45% solids. Roughly estimating the volume of liquid per gram of slurry by multiplying the material density by the material weight percent:

$$\text{Liquid density} = (0.12 \times 1.0) + ((0.24 \times 0.55) \times 1.05) + (0.01 \times 1.16) = 0.270 \text{ g/cm}^3$$

The weight of liquid to be removed per unit area is a function of slurry thickness:

$$\text{Liquid removed per area} = 0.270 \text{ g/cm}^3 \times 0.05 \text{ cm} = 0.0135 \text{ g/cm}^2$$

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

$$\text{Drying time} = 0.0135 \text{ g/cm}^2 / 2.0\times10^{-5} \text{ g/cm}^2\text{-sec} = 675 \text{ sec} = 11.25 \text{ min}$$

At a casting speed of 0.358 m/min, the required dryer length is:

$$\text{Dryer length} = 0.358 \text{ m/min} \times 11.25 \text{ min} = 4.03 \text{ meters}$$

Infrared heating panels are generally sold with various energy watt densities and in standard sized units and assembled to provide the necessary heating area. Using the Casso Solar Type FB as an example, standard watt densities are 15 and 25 W/in^2 (23 and 39 kW/m^2) with standard width of 12 inches (0.305 m) and lengths in 12-inch increments up to 60 inches (1.524 m). They note 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%.

The theoretical required heater area is calculated as:

$$\text{Heater area} = \text{Dryer length (meters)} \times (\text{Part width (mm)} / 1{,}000)$$

$$\text{Heater area} = 4.03 \times (268 / 1{,}000) = 1.079 \text{ m}^2$$

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

While the heater energy density will be taken as an input, the drying temperatures for the green tape are fairly moderate (150°C or less), so that the 23 kW/m^2 should be sufficient to maintain the drying area temperature. While researching the tape casting process, the manufacturing specifications for the 1 kW parts were provided to HED International, a manufacturer of coaters, dryers, kilns and furnaces. They recommended their TCM-251M tape casting machine with 12-inch (300-mm) casting width and 25-foot (7.7-meter) casting length with counter-flow heated-air dryer. The total machine power rating is 24 kW, the bulk of which would be consumed by the drying system. This is consistent with our estimate of 25 kW/m^2 × 1.079 m^2 = 27 kW.

A-22.4.4 Anode Roll Pressing

The roll-to-roll pressing operation can be either a semi-continuous process where the material is indexed into a standard heated platen press (see James et al. [2010], Section 4.4.6.1)[29] or by preheating and passing through heated rollers in a calendaring process. For the preliminary analysis we will assume a calendaring process.

A-22.4.1 Setup

Setup consists of loading, threading and aligning the anode tapes 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. Tapes were cast in 1,000-meter lengths totaling 387,464 m, so that the number of setups required is:

Number of setups = Roundup(29,104 / 1,000) / 2 tapes= 15 setups

A-22.4.2 Calendaring

The calendaring process consists of 2 main steps: preheating and rolling. We will assume that the anode layers are brought together and passed through an infrared tunnel oven for preheating. Assuming that the two layers need to reach 500°C, we can estimate the oven dwell time as (noting that 1 W = 1 J/sec):

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

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

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

Energy input = 2.3 W/cm^2 × 262.48 cm^2 × 0.80 = 482.9 W

The cast anode material has a density of approximately 4.6 g/cm^3 and specific heat capacity of 0.590 J/g-°C.

The volume of anode material per part is:

Anode volume = 262.48 cm^2 × 0.05 cm = 13.124 cm^3

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

The heating dwell time for each is:

Anode oven dwell time = (4.6 g/cm^3 × 13.124 cm^3 × 0.590 J/g-°C) × 475°C / 482.9 W = 35.0 sec

For the calendaring process, the layers will be moving together, so the heating time of 35 seconds (0.583 min) is used to determine the required oven length. At a substrate speed of 5 m/min the required heating length is about 2.92 meters, which can be accomplished using eight 12-inch by 36-inch infrared panels (four for each layer).

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

Parts per hour = 300 m/hr / 0.136 m = 2,205.9 parts/hr

Once the material layers are preheated, they are compressed between steel rollers that bond the anode layers together. Total machine time to setup and produce 107,000 parts is:

Machine time = (15 setups × 0.5 hr/setup) + (107,000 parts / 2,205.9 parts/hr) = 56.0 hrs

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

Roundup(56.0 / 6,000) = 1 machine

Machine utilization is:

56.0 / 6,000 = 0.93%

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

In-house rate = $27.79 / 0.0093 = $2,988.17

Job shop rate = 1.4 × ($27.79 / 0.65) = $59.86

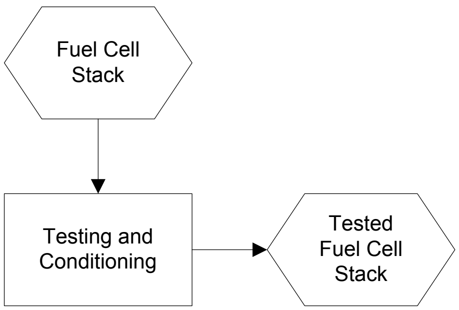
Assuming one operator per casting machine for both setup and operation, the machine labor time is equal to the total machine time of 56 hours.

Appendix A-23: SOFC Testing and Conditioning Process

A-23.1 Model Approach

- Test and condition fuel cell stack

A-23.2 Process Flow



A-23.3 Background

Following assembly, the SOFC stack is tested and conditioned to determine its fitness for installation into a CHP system. The total test time is assumed to be 6 hours, consisting of a 2-hour warm-up at 5% hydrogen (H_2)/95% nitrogen (N_2), a 2-hour test at 50% H_2/50% N_2, and 2-hour cool-down at 100% N_2. Total H_2 consumption for a 6-kW stack at full power is 71.622 l/min. Machine and labor time and material usage will be calculated for production of 1,000 6-kW stacks.

A-23.4 Preliminary Analysis

The mass of 1 mole hydrogen gas (H_2) = 2 grams, so the mass of 22.4 liters (stp) of H_2 is 2 g.

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

Total gas flow rate is:

$$\text{Total flow rate} = 71.622 \text{ l/min} \times 60 \text{ min/hr} / 1{,}000 \text{ l/ m}^3 = 4.297 \text{ m}^3\text{/hr}$$

During the 2-hour warm-up, the total material usage is:

$$\text{Hydrogen: Warm-up material usage} = (4.297 \times 0.05) \text{ m}^3\text{/hr} \times 2 \text{ hrs} = 0.430 \text{ m}^3$$

$$\text{Nitrogen: Warm-up material usage} = (4.297 \times 0.95) \text{ m}^3\text{/hr} \times 2 \text{ hrs} = 8.164 \text{ m}^3$$

During the 2-hour full power test, the total material usage is:

$$\text{Hydrogen: Full power material usage} = (4.297 \times 0.50) \text{ m}^3\text{/hr} \times 2 \text{ hrs} = 4.297 \text{ m}^3$$

$$\text{Nitrogen: Full power material usage} = (4.297 \times 0.50) \text{ m}^3\text{/hr} \times 2 \text{ hrs} = 4.297 \text{ m}^3$$

During the 2-hour cool-down, the total material usage is:

$$\text{Nitrogen: Cool-down material usage} = 4.297 \text{ m}^3\text{/hr} \times 2 \text{ hrs} = 8.594 \text{ m}^3$$

Total material cost for a full test and conditioning cycle of 1,000 stacks is:

Hydrogen: Testing material usage = $(0.430 + 4.297) \times 1{,}000$ stacks = 4,727 m^3

Nitrogen: Testing material usage = $(8.164 + 4.297 + 8.594) \times 1{,}000$ stacks = 21,055 m^3

Material costs we determined in accordance with Appendix A-2 as:

Hydrogen cost = \$10.574/m^3

Nitrogen cost = \$0.517/m^3

We will assume that one operator takes 0.5 hour to for setup and tear-down of each stack on the test stand, and can cover three testing stations, making the total labor time:

Testing labor cost = $(0.5 + (0.33 \times 6)$ hrs/stack$) \times 1{,}000$ stacks = 2,500 hrs

We will assume that each test stand can support three stacks simultaneously, making the total machine time:

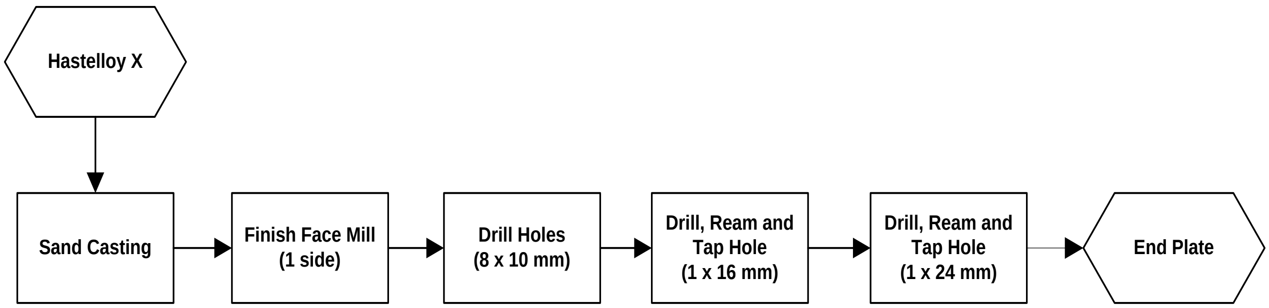
Testing machine time = $(0.5 + 6)$ hrs/stack $\times$ 1,000 stacks / 3 stacks/test stand = 2,167 hrs

Appendix A-24: SOFC End Plate Manufacturing Process

A-24.1 Model Approach

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

A-24.2 Process Flow

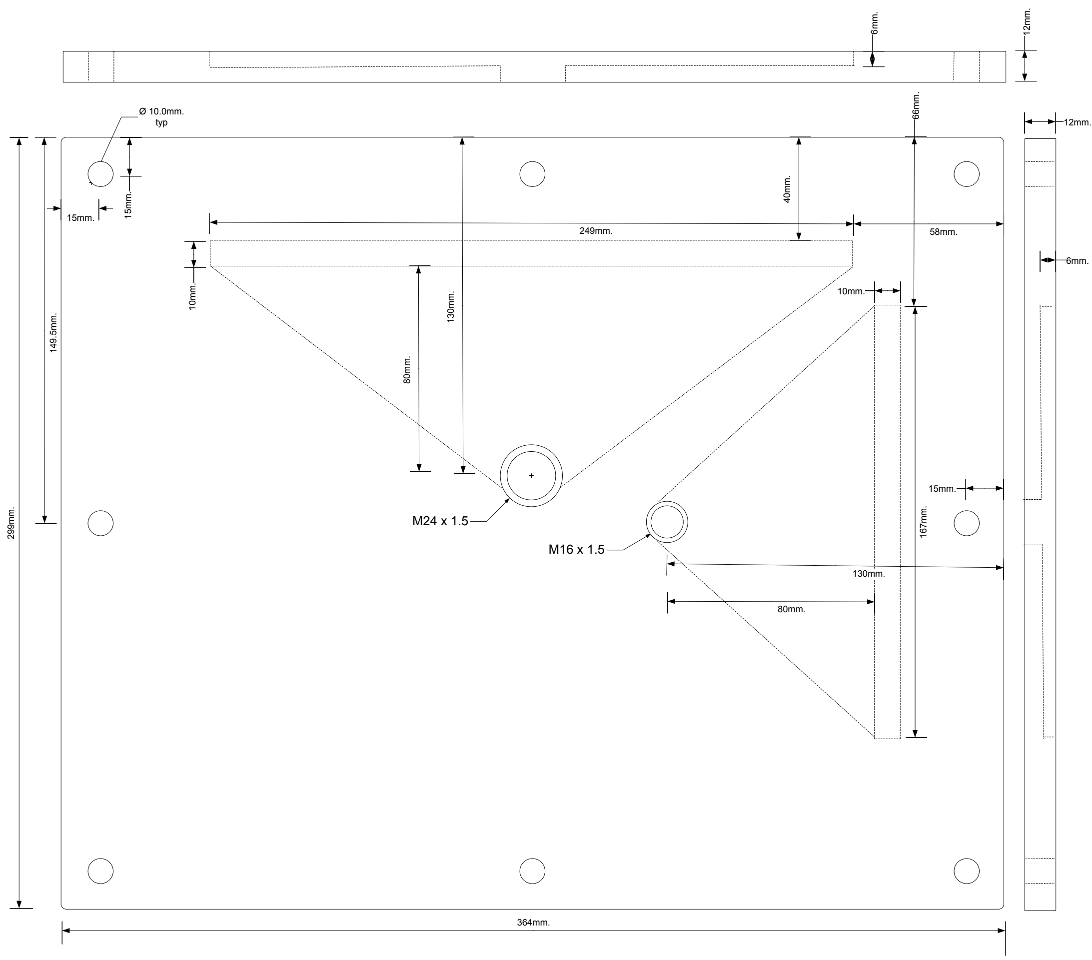


A-24.3 Background

The BDI software provides pre-programmed 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 SOFC end plate was automatic sand casting of A356 cast aluminum to near net shape, followed by finish machining of the stack contact face on a Haas VF-3B vertical machining center, drilling the tie rod holes, and drilling, reaming and tapping the holes for fuel and exhaust.

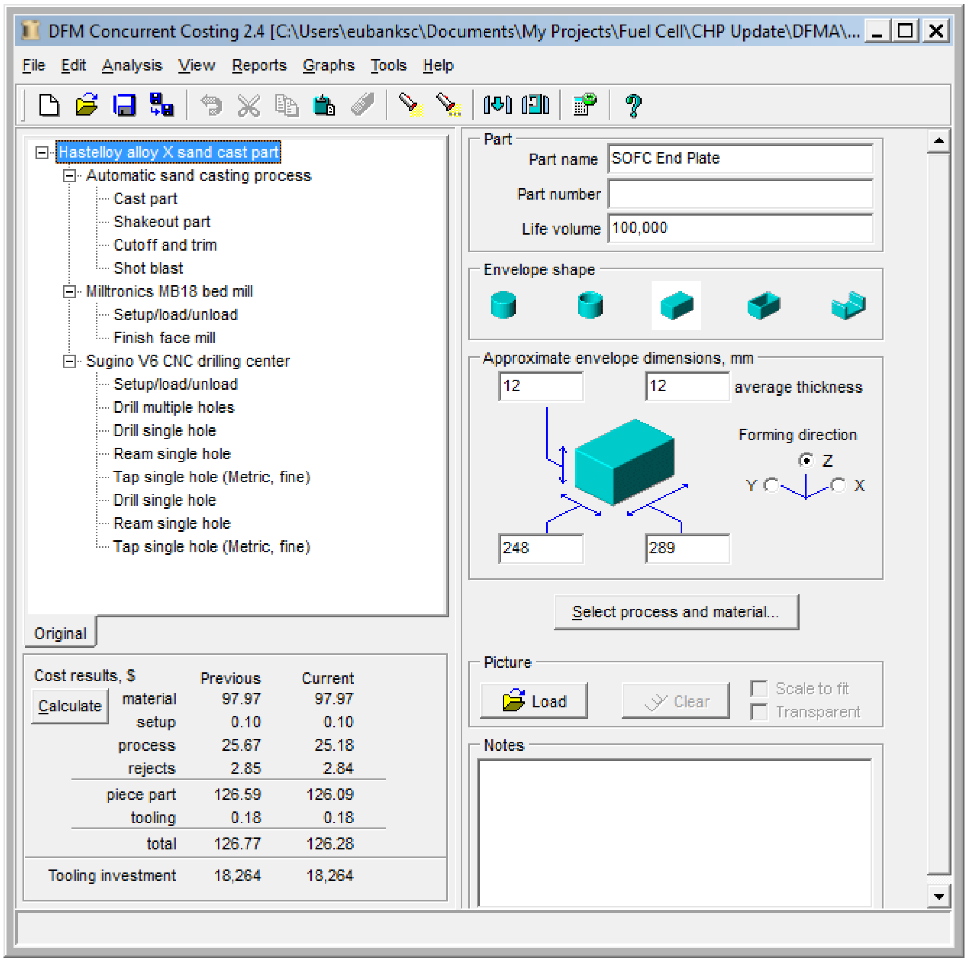
A-24.4 Preliminary Analysis

The end plate features and dimensions are show below:



A-24.5 DFM Software Analysis

A-24.5.1 End Plate



The BDI software estimates a 18.35-hour machine setup time, and calculates the total manufacturing time for the end plates as 1,600 sec, making the total machine time for annual production of 1,000 6-kW systems:

Machine time = (1,600 sec/part / 3,600) $\times$ 2,000 parts + 18.35 = 907.4 hrs

Because total time exceeds available single machine time, machine utilization is:

Utilization = 907.4 / 6,000 = 15.1%

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 = 1,814.8 hours.

Tooling cost is $18,264 and is assumed to be capable of producing 180,000 parts. Amortizing over a 5 year production life, the total annual tooling cost is:

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

where:

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

Total production = Annual production $\times$ 5

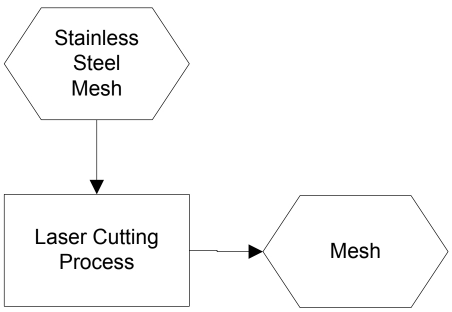
Annual tooling cost = $\frac{1}{5}$ (($18,264) $\times$ Roundup((2,000 parts/yr $\times$ 5 yrs) / 180,000 parts/tool)) = $3,652.80

Appendix A-25: Mesh Production Process

A-25.1 Model Approach

- Stainless steel mesh laser cutting operation

A-25.2 Process Flow



A-25.3 Background

The SOFC cell contains two meshes:

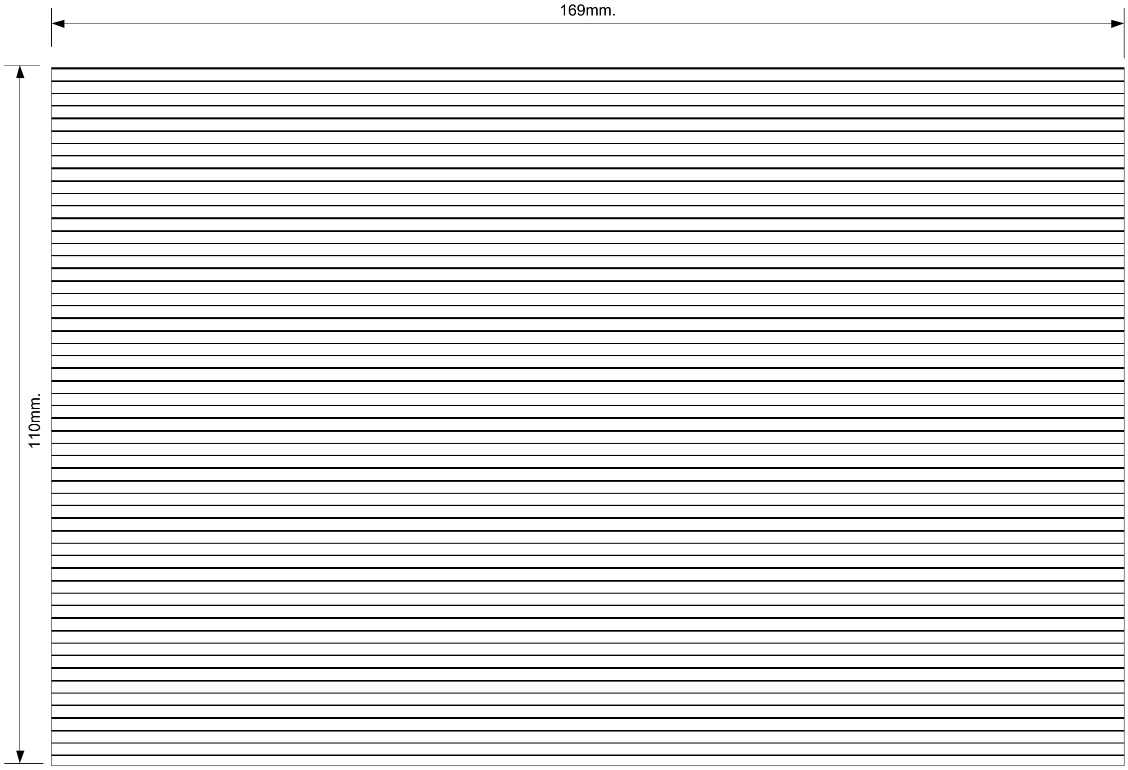
- The anode mesh is 0.5 mm thick and provides directed anode gas flow and electrical contact between the anode contact layer and interconnect
- The cathode mesh is 0.75 mm thick and provides directed cathode gas flow and electrical contact between the cathode contact layer and interconnect

A-25.4 Preliminary Analysis

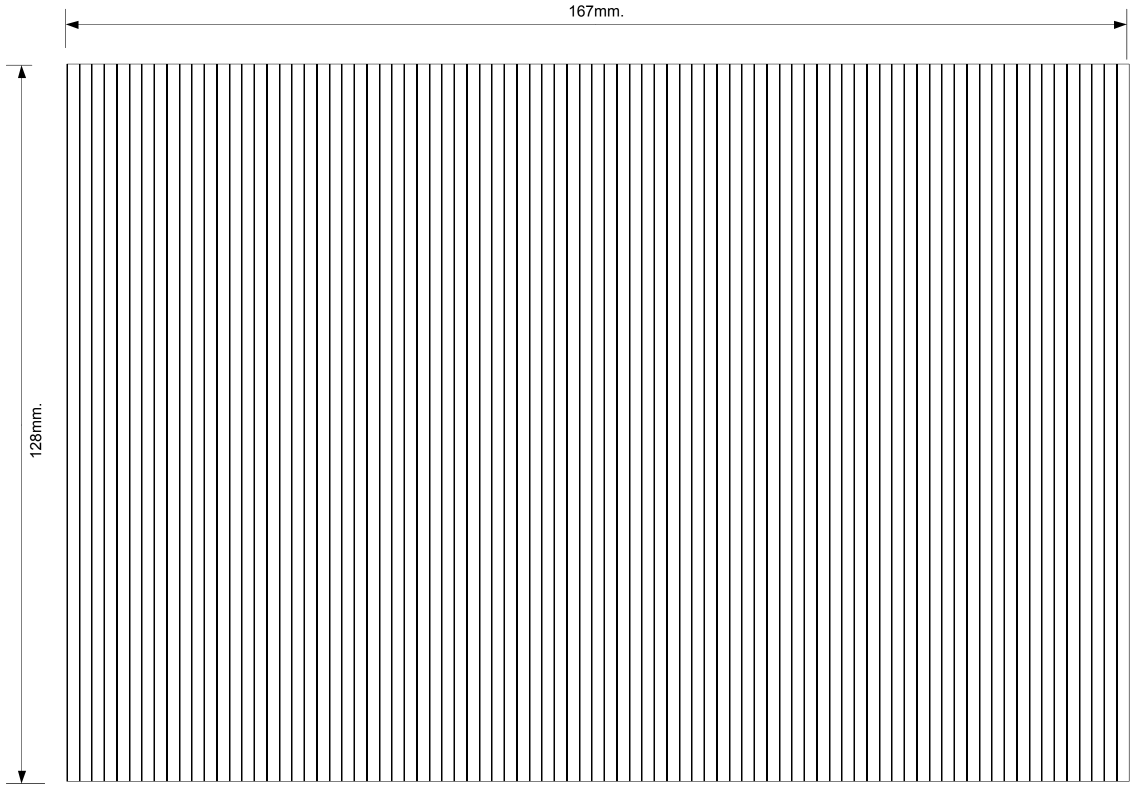
Machine and labor time will be calculated based on an annual production of 1,000 6-kW stacks. The 6-kW stack requires 107 of each type of mesh, requiring production of:

$$\text{Annual production} = 107 \text{ parts/stack} \times 1{,}000 \text{ stacks} = 107{,}000 \text{ parts/mesh}$$

A-25.4.1 Anode Mesh Dimensions



A-25.4.2 Cathode Mesh Dimensions



A-25.4.3 Laser Cutting Cost

Assuming a single setup operation requiring one operator per batch of parts, the laser cutting setup time will be 0.5 hour.

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula adapted from the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software, the total handling time is:

Anode mesh handling time = Max((0.3 × ((110 + 169 + 0.5) / 25.4) - 4.6), 4) = 4.0 sec/part

Cathode mesh handling time = Max((0.3 × ((128 + 167 + 0.75) / 25.4) - 4.6), 4) = 4.0 sec/part

The total cutting length for the meshes is:

Anode mesh cutting length = (2 × (110 + 169)) = 558 mm

Cathode mesh cutting length = (2 × (128 + 167)) = 590 mm

Research suggests that laser cutting of 0.75 mm thick stainless steel can be performed using a 1,500-W YAG laser under pure nitrogen flow of 8.0 m^3/hr at a maximum speed of approximately 15.0 m/min (250 mm/sec). Assuming that the mesh has similar cutting properties as stainless steel plate, the time to cut the mesh is:

Anode mesh cutting time = 558 mm / 250 mm/sec = 2.23 sec/part

Cathode mesh cutting time = 590 mm / 250 mm/sec = 2.36 sec/part

The total machine time required is:

Total machine time = (((2.23 + 4) + (2.36 + 4)) sec/part / 3,600) $\times$ 107 cells/stack $\times$ 1,000 stacks = 381 hrs

Machine utilization is:

Utilization = 381 / 6,000 = 6.36%

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

In-house rate = $33.81 / 0.0636 = $531.60

Job shop rate = 1.4 $\times$ ($33.81 / 0.65) = $72.82

Given that the operator required time for load/unload is about the same as the total part processing time, we will assume one operator per machine, making the machine labor hours equal to 4,153 hours.

At a consumption rate of 8.0 m^3/hr, the nitrogen material usage is:

Material usage = 8.0 m^3/hr $\times$ ((3.20 + 3.23) sec / 3,600) $\times$ 259 cells/stack $\times$ 4,000 stacks = 14,803 m^3

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

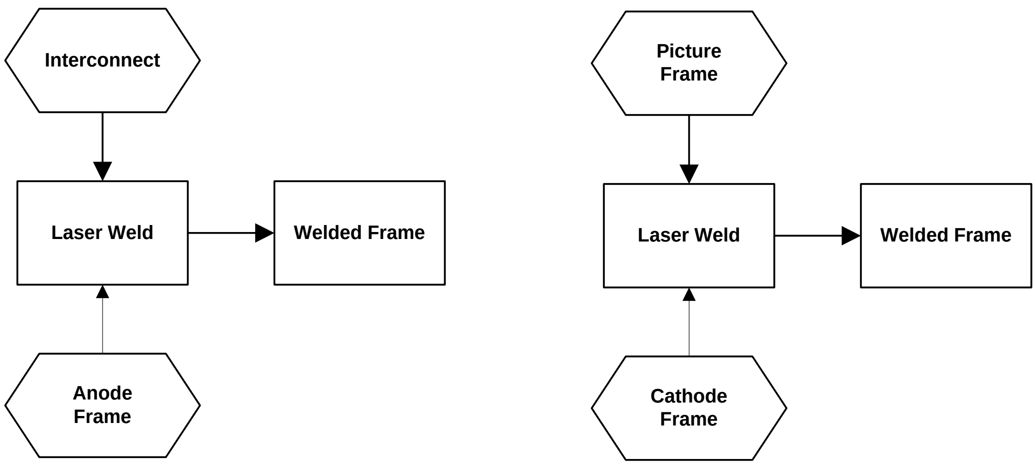
Material cost = $0.423/$m^3$

Appendix A-26: Laser Welding Process

A-26.1 Model Approach

- Laser weld anode frame to interconnect
- Laser weld picture fame to cathode frame

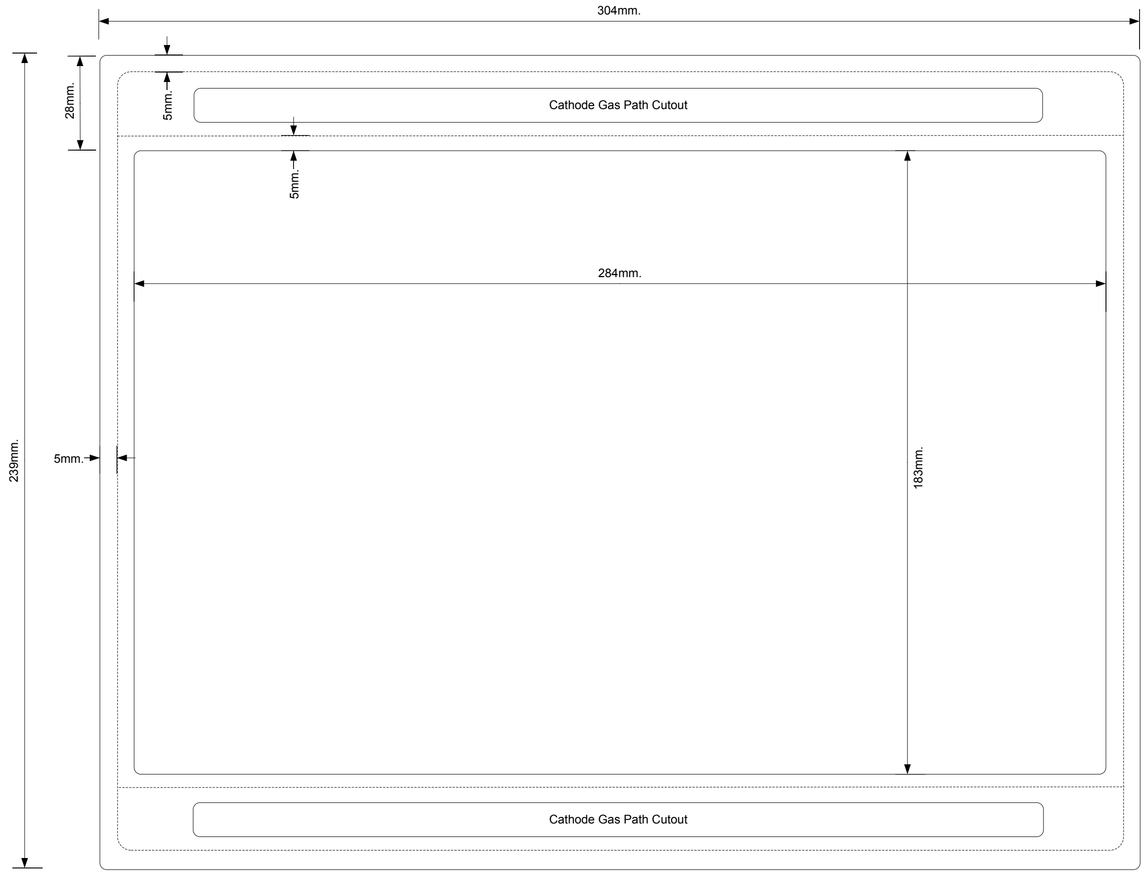
A-26.2 Process Flow



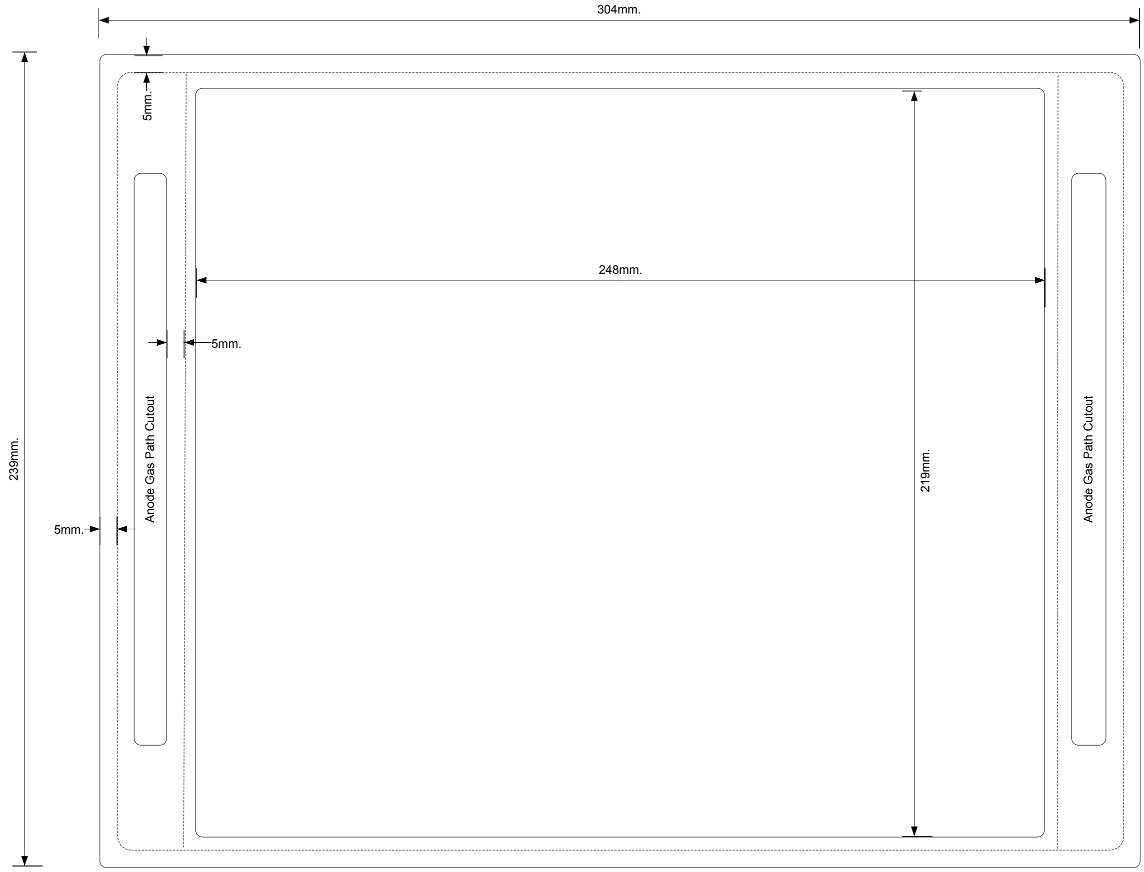
A-26.3 Background

Prior to final assembly and sealing of each SOFC cell, the SOFC frames are laser welded as shown:

A-26.3.1 Anode Frame to Interconnect Welding Path



A-26.3.2 Picture Frame to Cathode Frame Welding Path



A-26.4 Preliminary Analysis

The cells for this analysis are for a 6-kW stack at a production rate of 1,000 stacks per year.

The 6-kW stack requires 107 cells, requiring total annual production of:

Annual production = 107 parts/stack × 1,000 stacks = 107,000 parts

A-26.4.1 Laser Welding Cost

Assuming a single setup operation requiring one operator per batch of parts, the final trim setup time will be 0.5 hour.

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula adapted from the Boothroyd Dewhurst, Inc. (BDI) Design for Manufacture and Assembly (DFMA)® software, the total handling time is:

Part handling time = Max((0.3 × ((188 + 229 + 0.50) / 25.4) - 4.6), 4) = 4.0 sec/part

The total welding length for the frames is:

Anode frame weld length = (2 × (188 – 10)) + (4 × (229 – 10)) = 1,232 mm

Cathode frame weld length = (2 × ((229 – 10) + (4 × (188 – 10)) = 1,150 mm

Dilas suggests that laser welding to a depth of 0.5 mm in stainless steel can be achieved using a 500-W YAG laser at a maximum speed of 6.0 m/min (0.10 m/sec). The time to weld the frames is:

Anode frame weld time = 1.232 m / 0.10 m/sec = 12.32 sec/part

Cathode frame weld time = 1.150 m / 0.10 m/sec = 11.50 sec/part

The total machine time required for welding both sets of frames is:

Total machine time = ((12.32 + 4) + (11.50 + 4)) sec/part × 107,000 parts / 3,600 = 945.8 hrs

Machine utilization is:

Utilization = 945.8 / 6,000 = 15.9%

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

In-house rate = $33.81 / 0.159 = $212.64

Job shop rate = 1.4 × ($33.81 / 0.65) = $72.82

Given that the operator required time for load/unload represents about 34% of the total part processing time, we will assume one operator is capable of operating two machines, making the machine labor hours:

Machine labor hrs = 945.8 / 2 = 472.9 hrs