STRATEGIC ANALYSIS INC

Manufacturing Cost Analysis of Stationary Fuel Cell Systems

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Revision 4

CREATIVE SOLUTIONS FOR TOMORROW'S CHALLENGES

STRATEGIC ANALYSIS INC

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[1] Actual subcontract is with the Alliance for Sustainable Energy, LLC which is the management and operating contractor for NREL.

Table of Abbreviations

AC	alternating current
BOL	beginning of life
BOM	bill of material
BOP	balance of plant
CFCL	Ceramic Fuel Cells Limited (of Australia)
CO	carbon monoxide
DC	direct current
DFMA	Design for Manufacturing and Assembly
DI	de-ionizing
DOE	US Department of Energy
EOL	end of life
ePTFE	expanded polytetrafluoroethylene
FC	fuel cell
FCS	fuel cell system
FP	fuel processor
GDL	gas diffusion layer
HDPE	high density polyethylene
HHV	higher heating value
HT	high temperature
kWe	kilowatts of electricity
LHV	lower heating value
LSCF	lanthanum-strontium-cobalt-ferrite
LT	low temperature
MCO	manganese cobalt oxide
MEA	membrane electrode assembly
Ni-Co	nickel cobalt
Nm^3	normal cubic meters
NREL	National Renewable Energy Laboratory
NSTF	nanostructured thin film
PEM	proton exchange membrane
ppmv	parts per million (by volume)
PROX	preferential oxidation
Pt/Co/Mn	platinum-cobalt-manganese
SMR	steam methane reformer
SOFC	solid oxide fuel cell
SR	steam reforming
TIG	tungsten inert gas
WGS	water gas shift
YSZ	yttrium stabilized zirconia

Table of Contents

1 Executive Summary

1.1 Abstract

This report details efforts to conceptually design and estimate the capital cost of stationary fuel cell systems (FCSs) based on three different fuel cell technologies: low temperature (LT) proton exchange membrane (PEM), high temperature (HT) PEM, and solid oxide fuel cell (SOFC). Each system is configured for operation in combined heat and power (CHP) mode to allow utilization of the system exhaust heat for building heating. Each system's fuel cell (FC) stack, fuel processor (FP) subsystem, and balance of plant (BOP) design and performance parameters are discussed and the methods of cost-modeling each are explained. Cost trends for each FCS and its subsystems are evaluated in terms of the capital costs per unit in dollars per kilowatt-electric ($/kWe) as a function of system installed capacity and system annual production rate. A Design for Manufacturing and Assembly (DFMA) process-based cost estimating methodology is used to derive stack and reactor cost values. Price quotations or estimates based on analogous function components are used to obtain cost estimates for other balance of plant (BOP) components. A 10% cost contingency is added to all systems to reflect non-enumerated costs and components. The marginal cost increase from enhancing an electricity-only FCS (base design) to one that can serve combined heat and power (CHP) applications and/or grid-independent conditions is assessed for each system. Finally, the cost results of all three FCS designs are compared to assess capital cost differences. Systems are cost-modeled with peak electrical capacities of 1 kWe, 5 kWe, 25 kWe, and 100 kWe across annual production rates of 100, 1,000, 10,000, and 50,000 systems per year.

1.2 Summary of System Configurations and Operating Conditions

The cost analysis considers stationary fuel cell power systems suitable for electricity generation for residential or office building power. The systems are configured for combined heat and power (CHP) operation: waste heat from the fuel cell system is available for building heat.

The fuel cell systems (FCS) are examined:

- For three fuel cell technologies (low temperature PEM, high temperature PEM, and solid oxide),
- at four power levels (1, 5, 25, and 100kWe),
- and at four annual manufacturing rates (100, 1,000, 10,000, and 50,000 systems per year).

Although the FCSs vary significantly in technology and system power, they share many of the same configuration characteristics.
These characteristics include:

- Operation
    - operation on natural gas and air
    - design for water-neutral operation using a condenser to capture liquid product water for use in the system
    - produce 110VAC electricity
    - provide waste heat to a building CHP load
    - able to be connected to the external electrical grid that can load follow demands

- Fuel Processing (FP) Subsystem
    - converts NG into a hydrogen-rich reformate gas which is fed to the FC stacks
    - based on Tokyo Gas designs of a highly thermally-integrated concentric-shell reactor which combines the functionality of fuel preheat, raising steam, and steam reforming in one piece of hardware
    - metal monolith catalyst bed for steam reforming (SR), water-gas shift (WGS) (if needed), and preferential oxidation (PROX) (if needed)
    - catalysts applied to monoliths via washcoating
    - catalyst beds sized by assumed space velocities
- Fuel Cell Subsystem
    - operation on NG reformate and air
    - operation at approximately 1.4 atm inlet pressure
- Power Electronics Subsystem (baseline case)
    - contains the system controls, inverters, and sensors for full system operation
    - relies on the grid for system start-up
    - does not contain batteries
- CHP Subsystem
    - uses waste heat from the fuel cell stack and fuel processing sub-system exhaust to heat building water or air
    - includes heat exchangers for this purpose
- Housing and Final System Assembly
    - includes a FCS housing suitable for outdoor installation
    - does not include any cost allowance for system installation in the field
- Cost Margin
    - includes a 10% cost contingency to cover the cost of un-enumerated components
- System Lifetime
    - although system lifetime and cost are related, we treat them as independent variables to allow a cost assessment among FC technologies at different maturity levels.
    - consequently, all systems are oversized by 20% to correspond to future mature FC technologies that only decay 20% in power density over their useful lifetime.

Additionally, technology specific characteristics include:

- Low Temperature (LT) Polymer Electrolyte Membrane (PEM) Fuel Cell
    - planar metallic cell construction
    - stamped stainless steel bipolar plates with an anti-corrosion coating
    - based on a Nafion®-based supported membrane achieving 408 milliwatts per square centimeter (mW/cm^2)at 0.676 volts/cell at 80 degrees Celsius (°C) at 0.4 milligrams (mg) platinum (Pt) catalyst/cm^2 at beginning of life
- High Temperature (HT) PEM Fuel Cell
    - planar metallic cell construction
    - stamped stainless steel bipolar plates with an anti-corrosion coating

    - based on a pyridine-based aromatic polyether membrane achieving 240 mW/cm^2 at 0.6 volts/cell at 160°C at 1.0mgPt/cm^2 at beginning of life
- Solid Oxide Fuel Cell (SOFC)
    - electrolyte supported planar ceramic cell construction based on the NexTech Materials Inc.[2] Flexcell design
    - tape cast ceramic layers
    - nickel –cobalt (Ni-Co) catalyst, lanthanum-strontium-cobalt-ferrite (LSCF) cathode, and yttrium stabilized zirconia (YSZ) electrolyte
    - achieving 291 mW/cm^2 at 0.8 volts/cell at 819°C at beginning of life
- System Efficiency
    - system efficiency among the three technologies is not normalized to a common value
    - rather, each system is designed for operation at its anticipated operating conditions

	LT PEM	**HT PEM**	**SOFC**
Design Cell voltage	0.676 volts/cell	0.6 volts/cell	0.8 volts/cell
Design Power Density	408 mW/cm^2	240 mW/cm^2	291 mW/cm^2
Net Elec. System Efficiency			
Higher Heating Basis	35%	28%	49%
Lower Heating Basis	39%	31%	55%
CHP Heat Load Available (for 25kWe systems)	40 kW$_{thermal}$	56 kW$_{thermal}$	21 kW$_{thermal}$

Figure 1: Summary of System Efficiency

1.3 Summary of Cost Results

The cost analysis yields results detailing the final estimated capital cost of the entire FCS at different annual manufacturing rates and installed[3] capacities for each of three technologies. As shown in Figure 2 through Figure 5, the capital cost per unit of electric output ($/kWe) is seen to decrease dramatically both with increasing system size and increasing system annual production rate.

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[2] http://www.nextechmaterials.com/energy/

[3] Note that "installed capacity" is used to denote the expected maximum electrical generating capacity at which the system is expected to operate. Cost of actual system installation is not included in any of the cost estimates.

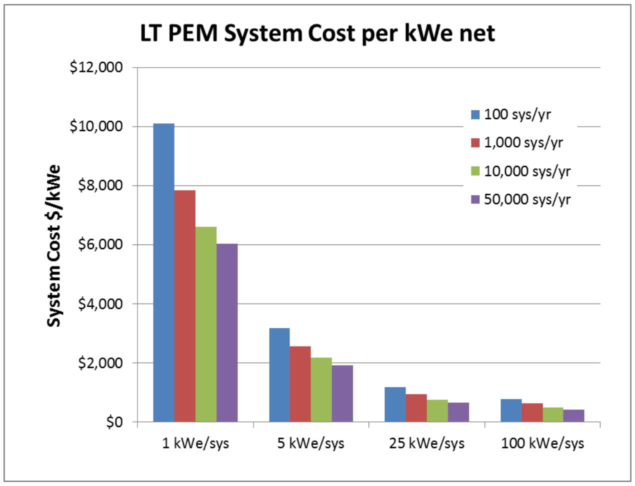

Figure 2: Total LT PEM System Cost Results Across all System Sizes and Production Rates

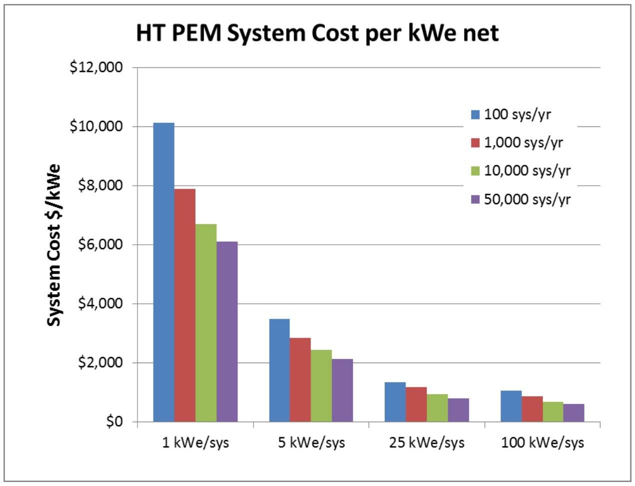

Figure 3: Total HT PEM System Cost Results Across all System Sizes and Production Rates

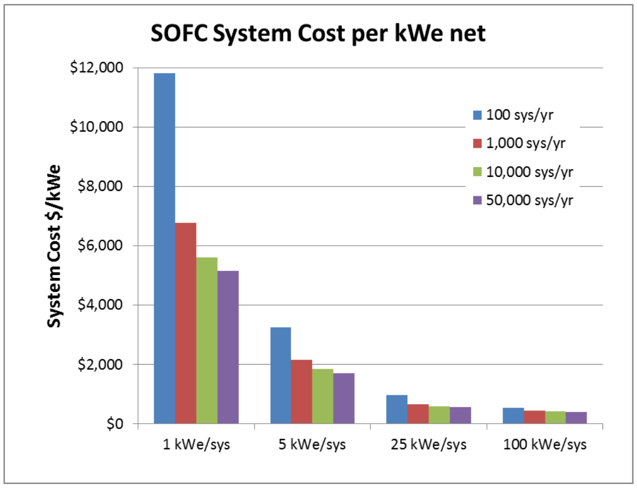

Figure 4: Total SOFC System Cost Results Across all System Sizes and Production Rates

LT PEM Systems	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$10,106	$3,182	$1,180	$771
1,000 sys/yr	$7,854	$2,556	$941	$637
10,000 sys/yr	$6,618	$2,185	$760	$486
50,000 sys/yr	$6,032	$1,935	$658	$428

HT PEM Systems	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$10,130	$3,483	$1,363	$1,062
1,000 sys/yr	$7,895	$2,840	$1,181	$867
10,000 sys/yr	$6,699	$2,448	$941	$680
50,000 sys/yr	$6,101	$2,132	$816	$606

SOFC Systems	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$11,830	$3,264	$981	$532
1,000 sys/yr	$6,786	$2,168	$671	$440
10,000 sys/yr	$5,619	$1,862	$599	$414
50,000 sys/yr	$5,108	$1,709	$570	$402

Figure 5: Summary Table of System Cost Results, $/kWe

Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component. Figure 6 breaks down total system capital costs for the base case SOFC system design (i.e. no CHP or grid independent operation) into six different categories. These categories are:

- fuel processing (FP) subsystem,
- fuel cell (FC) subsystem,
- power electronics subsystem,
- CHP subsystem,
- housing and final assembly, and
- cost margin.

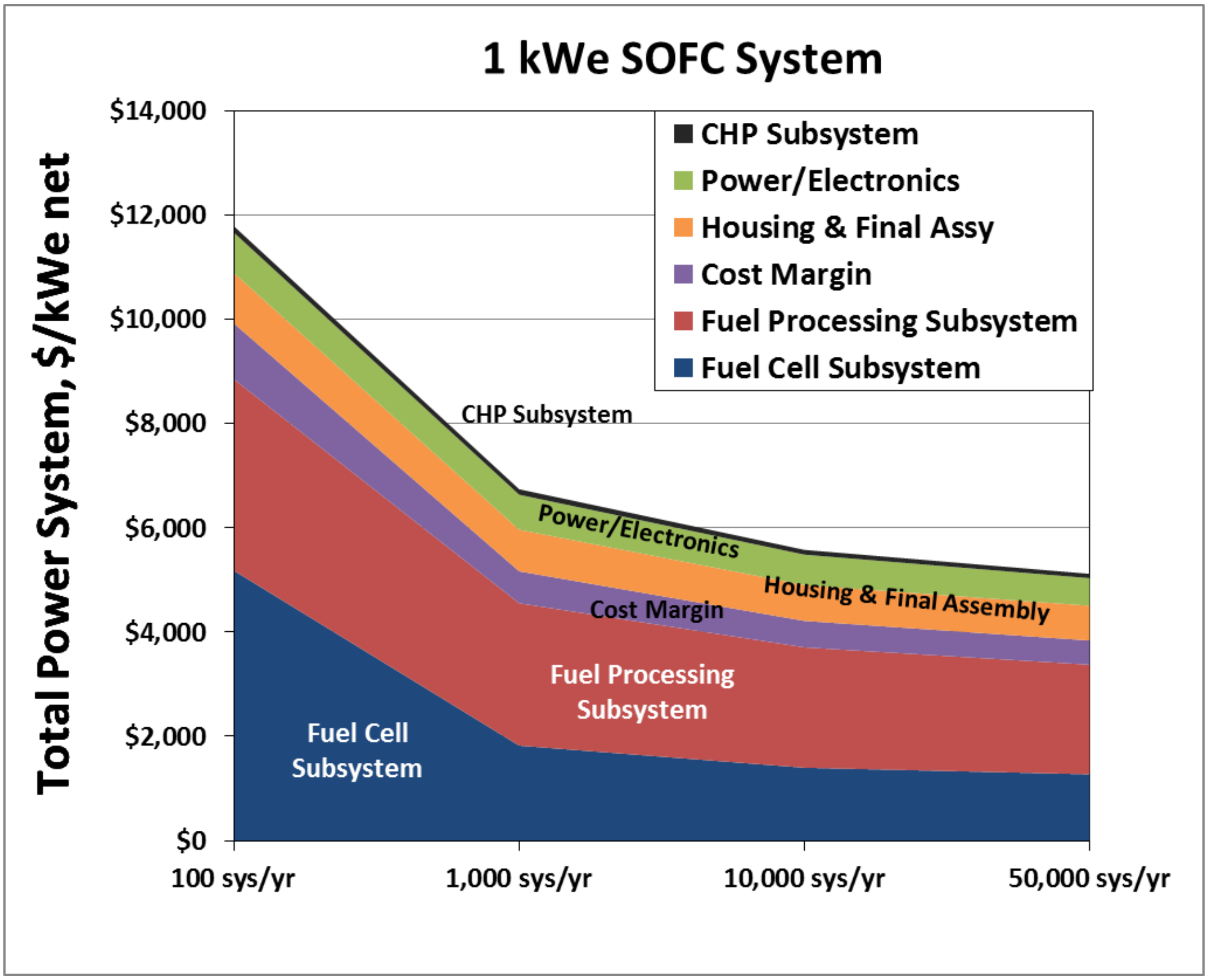

Figure 6: 1 kWe SOFC System Cost Breakdown by Component

As evident from the figure, the greatest contributors to the capital cost are the FP and FC subsystems, together representing 2/3^{rds} to 3/4^{ths} of the total system capital cost. This division is similar to the divisions seen within the other FCS technologies. Model results can indicate a further level of refinement in the breakdown of capital costs, as indicated by Figure 7. This figure shows a capital cost breakdown for the LT PEM system's fuel processing subsystem's BOP. Large contributors to cost such as the natural gas compressor and the condenser are prime candidates for more detailed examination to identify alternate components or operating modes leading to lower cost.

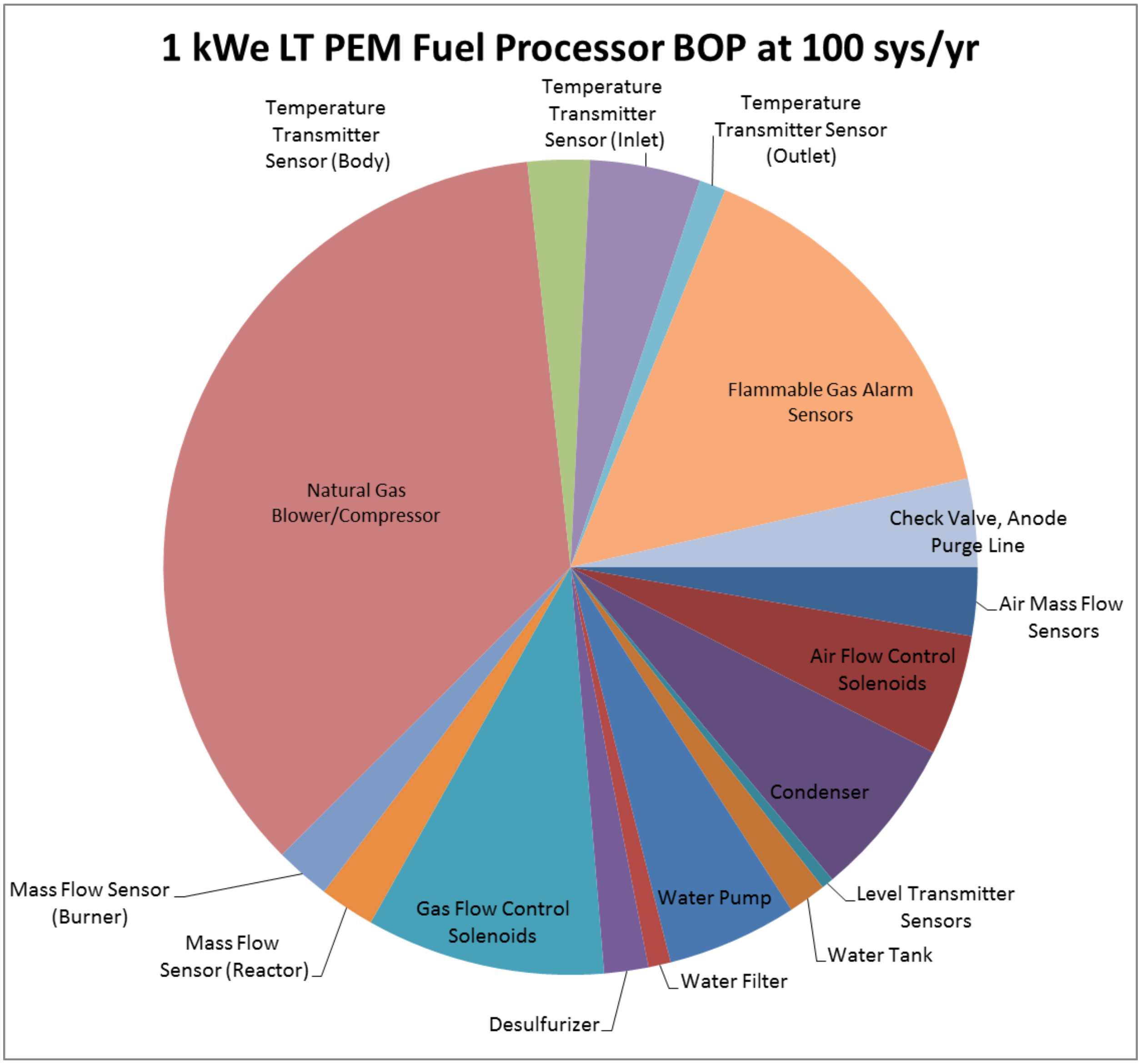

Figure 7: 1 kWe LT System Fuel Processor Subsystem BOP Cost Breakdown

Figure 8 demonstrates that the marginal increase in cost between producing a basic HT PEM system which is not capable of CHP or grid-independent operation and producing a more advanced FCS that is capable of both CHP and grid-independent operation is in fact relatively small, with grid-independent operation capital costs representing 5% to 10% and CHP operation capital costs representing only 2% to 5% of the overall capital cost of such a system. (Please note that these estimates do not include installation costs, which add labor, materials, permitting, and specific site engineering and design costs.)

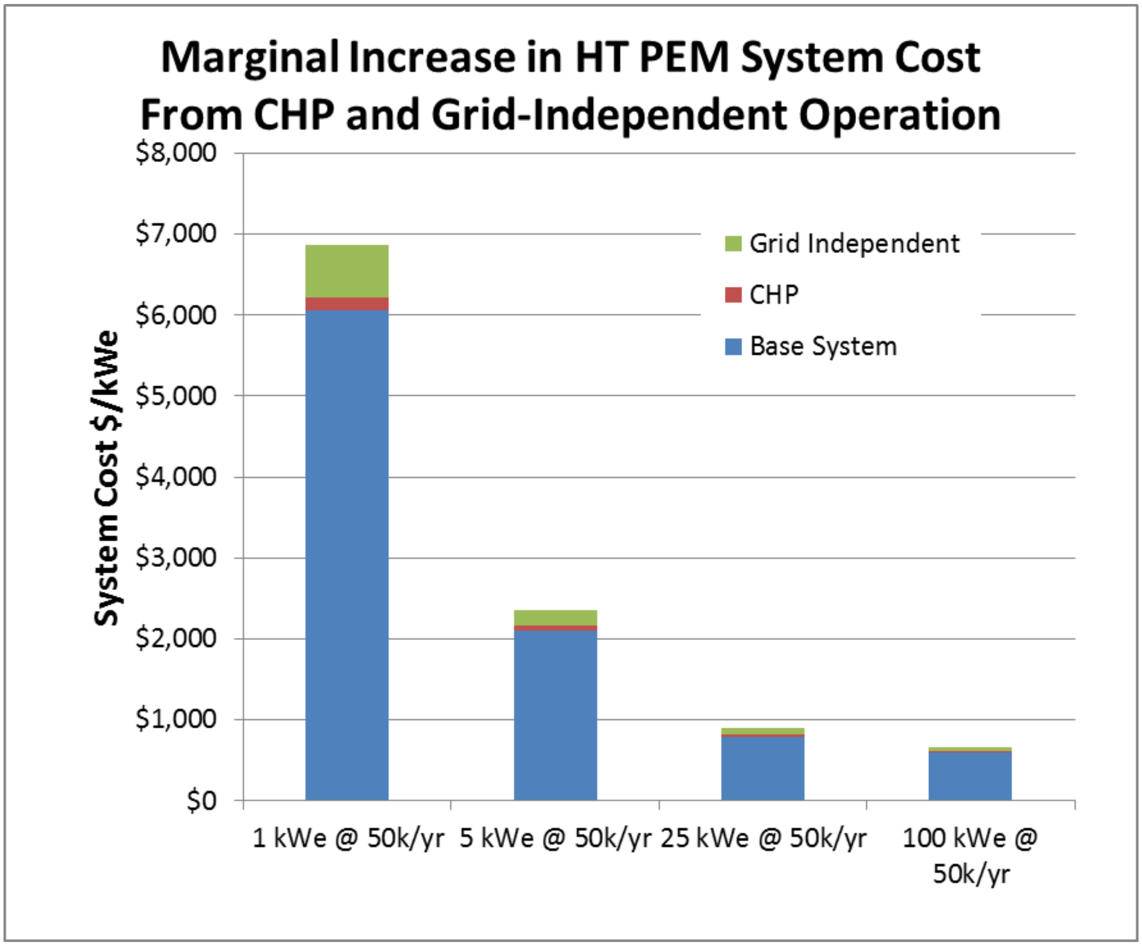

Figure 8: Marginal increase in total HT PEM system cost of CHP and grid-independent operation at highest production rate

Model results indicate that, at the same cumulative global installed capacity, higher power FCSs are expected to have lower per unit capital costs ($/kWe) than lower power FCSs. For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output. This observation is depicted in Figure 9, where for a 10,000 kWe global installed capacity in one year, 100 kWe SOFC systems are 13% of the cost of 1 kWe SOFC systems. This analysis assumes that the FCS electricity and heat will be used with 100% utilization in the buildings that they serve, regardless of system size. In practice, lower power FCSs may experience higher utilizations. Also, the total market volume for lower power FCSs may be larger, allowing for higher production rates.

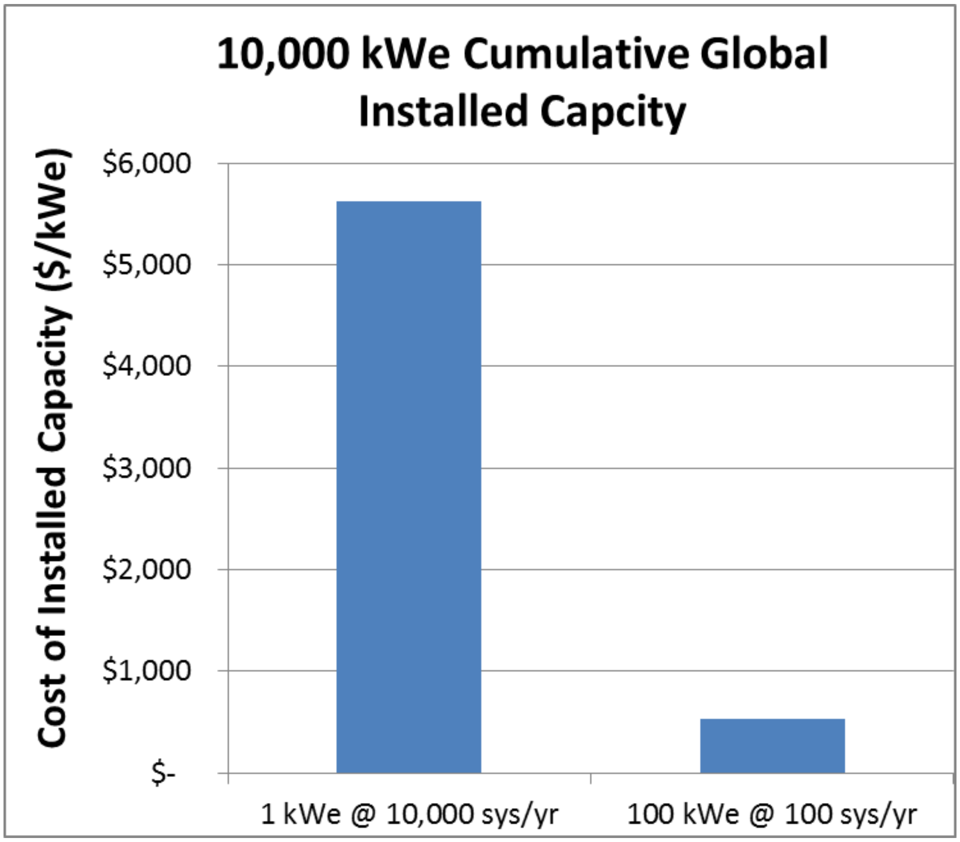

Figure 9: Cost comparison of 1 kWe and 100 kWe SOFC systems for the same cumulative global installed[4] capacity

Additional results include the comparison of fuel cell stack cost to fuel cell subsystem balance of plant at different system sizes. Figure 10 indicates that for a 1 kWe SOFC system, at the highest production rates evaluated (50,000 units/year), the FC BOP is the largest contributor to fuel cell subsystem capital costs. At this FC size and production rate, FC BOP costs are higher than FC stack costs. By contrast, for higher power FCSs, FC stack costs dominate FC subsystem costs. As shown in Figure 11, in the larger 100 kWe SOFC systems, the FC stack costs are the largest contributor to the fuel cell subsystem capital costs

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[4] Note that "installed capacity" is used to denote the expected maximum electrical generating capacity at which the system is expected to operate. Cost of actual system installation is not included in any of the cost estimates.

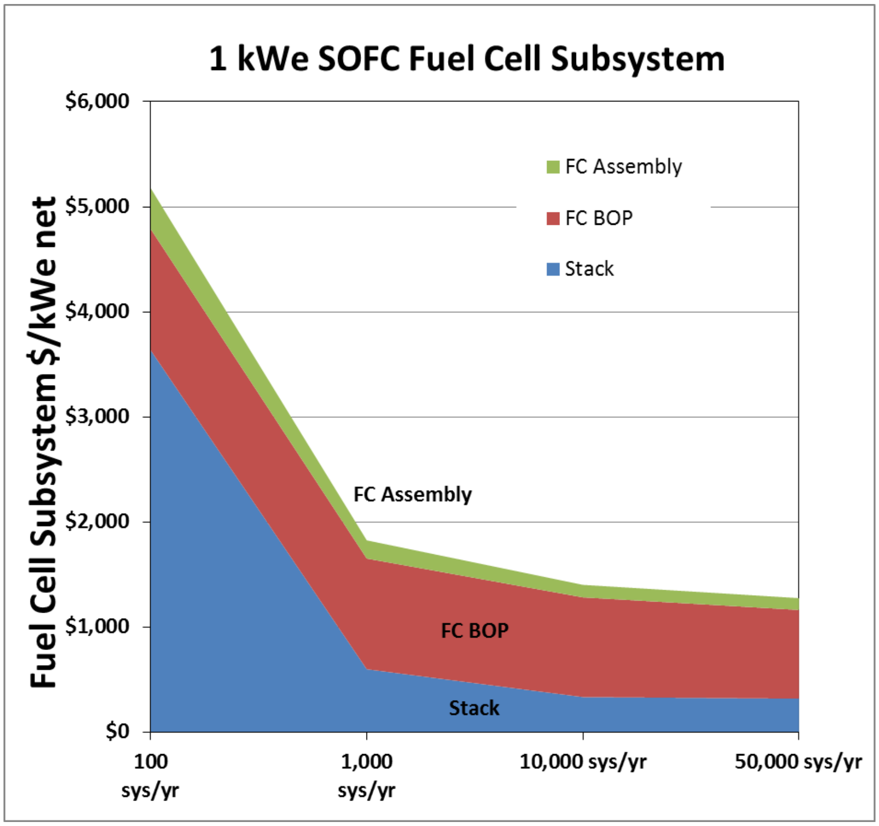

Figure 10: SOFC fuel cell stack subsystem cost breakdown for a 1 kWe system

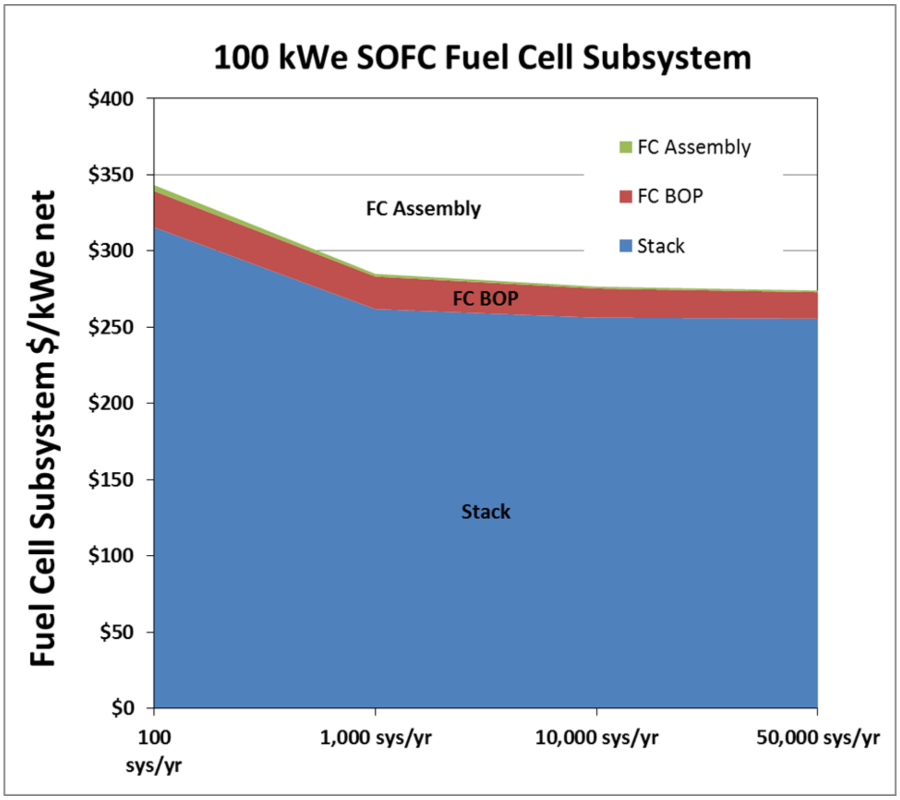

Figure 11: SOFC fuel cell stack subsystem cost breakdown for a 100 kWe system

As shown in Figure 12, at the 100 kWe size, comparison of model results for different technologies indicates that SOFC systems are slightly less expensive than LT PEM and greatly less expensive than HT PEM systems. For a 100 kWe FCS at a production volume of 50,000 units per year, system costs are \$402/kWe for SOFC, \$413/kWe for LT PEM, and \$612/kWe for HT PEM. (Stack power densities assumed in these analyses are 291 mW/cm^2, 408 mW/cm^2, and 240 mW/cm^2, respectively.) According to these data, SOFC systems generally have the lowest capital cost, followed by LT PEM and then HT PEM systems, which can be significantly more expensive. Exceptions include the smallest system (1 kWe) at the lowest production rate (100 systems/year), where the SOFC FCS is dramatically more expensive than either PEM system. (A caveat must be added to these results: PEM cost models used in this comparison have been fine-tuned over the past 15 years,[5,6] whereas the SOFC models have only been developed over the course of one year. The cost advantage of PEM over SOFC observed here may be in part a function of having had more time to iterate on the PEM manufacturing cost models to reduce PEM manufacturing costs.)

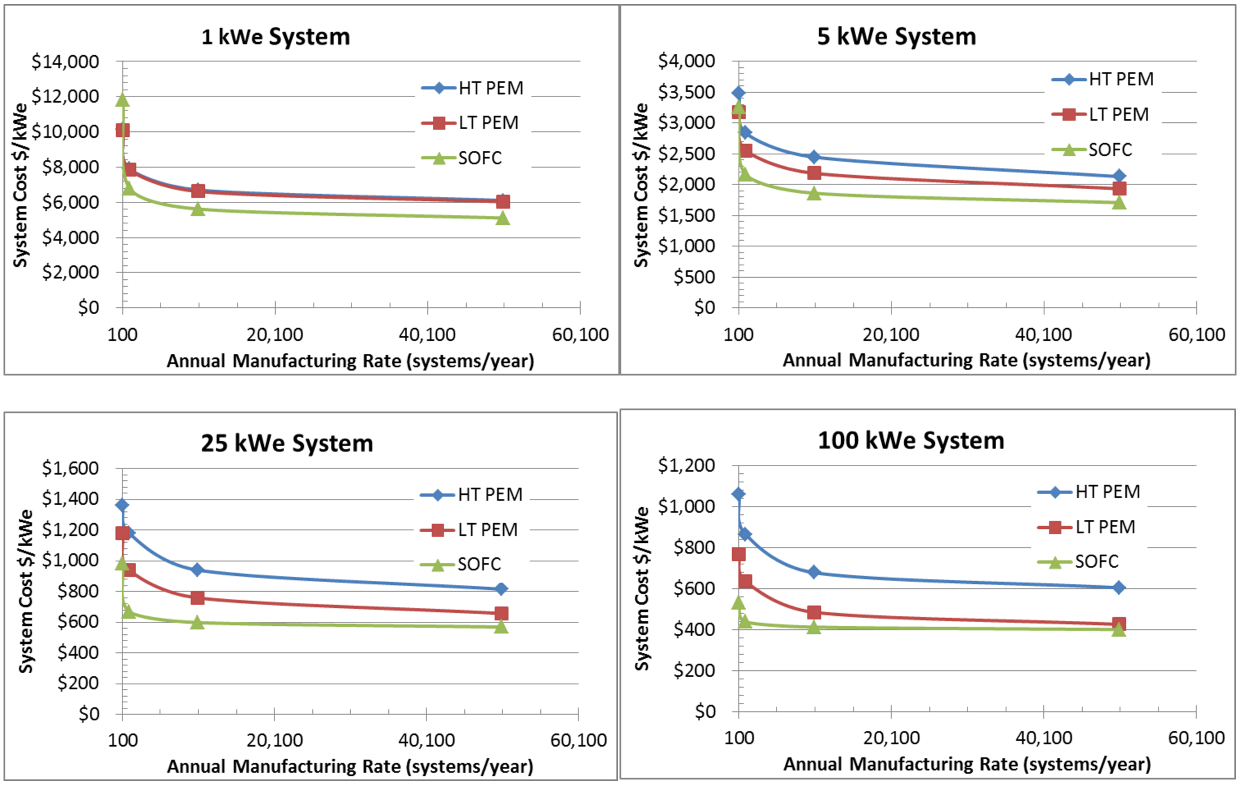

Figure 12: Cost Comparison between Technologies for all Systems

It is further noted that the cost comparisons between fuel cell technologies in this analysis apply only to initial capital cost rather than to life cycle cost. The projected net system electrical efficiency based on higher heating value (HHV) of natural gas of the SOFC FCS (49%) is substantially higher than that of LT

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[5] James, B., Lomax, F., Thomas, S. and Colella, W.G., *PEM Fuel Cell Power System Cost Estimates: Sulfur-Free Gasoline Partial Oxidation and Compressed Direct Hydrogen*, report for the U.S. Department of Energy, 1997.

[6] Kuhn, I., Thomas, S., Lomax, F., James, B. and Colella, W.G., *Fuel Processing Systems for Fuel Cell Vehicles*, report for the U.S. Department of Energy, 1997.

PEM (35%) or HT PEM (28%). While a life-cycle analysis has not been conducted, it is expected that the higher net electrical efficiency of the SOFC system would make those systems even more attractive on a total life cycle cost basis.

The primary findings of this analysis of stationary CHP FCSs relate to the key cost drivers across the range of analysis, from the low power (1 kWe) FCSs to the large (100 kWe) FCSs and from low production (100 systems/year) to higher production rates (50,000 systems/year). Based on the analysis presented here, it was found that for a given cumulative global installed quantity, it is more cost-effective to produce fewer very large systems as compared to a large number of lower power systems. Thus, while both production quantity and system size drove cost down, cost was found to be more sensitive to system size than to production rate. Additional results quantify the relative cost contribution of various subsystems. The greatest contributors to the FCS capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing 1/2 to 3/4$^{\text{ths}}$ of the total system capital cost. Furthermore, model results indicate that the addition of CHP and grid-independent operation adds only about 10% to total system capital costs, compared with a base case design involving no CHP or grid-independent operation. Finally, model results indicate that SOFC system capital costs are expected to be the lowest for most scenarios investigated.

Modeling results for LT PEM, HT PEM, and SOFC systems underscore a few salient points:

- SOFC systems are projected to have the lowest system capital cost of the three technologies examined.
- As system size and system manufacturing rate increase, system cost decreases.
- In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing per kilowatt costs than increasing manufacturing rate over the range of values plotted.
- For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output.
- Across the range of system size levels, the greatest contributors to the capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing half or more of the total system capital cost in all cases.
- The primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.
- The primary cost drivers for the FP BOP may include NG compressors/blowers, water pumps, flammable gas alarm sensors, gas flow control solenoids, pressure regulators, and/or condensers, depending on fuel cell system size and type.

Modeling results for LT PEM CHP systems emphasize several key points:

- Modeling results for FCS capital costs are broadly consistent with manufacturer price values provided by Japan’s Ene Farm program for similar system sizes and production rates if one considers that modeling cost results do not include: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. Further investigation is required for a direct comparison of expected system price.

- The combined cost of the FC and FP subsystems account for greater than 70% of total capital costs.
- For the 1 kWe system, the FP subsystem is relatively more costly than the FC subsystem at all production levels.
- For the 100 kWe system, the FC subsystem is more expensive than the FP subsystem at lower production levels, specifically at 1,000 sys/yr and below.
- For the 1 kWe system, the FP's costs are dominated by the BOP. This modeling result is consistent with the manufacturer test results of Japan's Ene Farm program, which found that a primary cost driver for CHP LT PEM systems was the FP sub-system balance of plant (BOP).
- At higher power levels, the FP BOP component costs decline significantly as a proportion of the total.
- For 1 kWe FCSs, the primary cost drivers for the FP BOP are the natural gas compressor, the flammable gas alarm sensors, and the gas flow control solenoids, in that order.
- For 100 kWe FCSs, the primary cost drivers for the FP BOP are the water pump and the condenser, in that order.
- For 1 kWe FCSs, BOP component costs constitute as much as 70% of FC subsystem costs.
- For 100 kWe FCSs, FC stack costs constitute as much as 80% of FC subsystem costs.
- At both the 1 kWe and 100 kWe size range, fuel cell subsystem assembly costs are estimated to be fairly negligible.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 1% and 3% and for adding grid-independent capability, it is between 10% and 12%.
- For a 100 kWe FCS at 50 k sys/yr, the marginal increase in capital cost from adding either CHP capability or grid-independent capability is not significant (numerical results not shown.)

Modeling results for HT PEM CHP systems emphasize additional important points:

- Modeling results for HT PEM FCS capital costs are broadly consistent with manufacturer values provided via a 2012 DOE deployment program of 5kWe HTPEM systems. Modeling results indicate an unmarked-up manufacturing capital <u>cost</u> of roughly $3,500/kWe for a manufacturing rate of 100 sys/yr. Manufacturer provided capital <u>prices</u> are roughly $13,000/kWe at a similar production rate.[7, 8] The difference between cost and price is significant as the reported modeling cost results do not include: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties;

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[7] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11 and Fig. 5.

[8] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11 and Fig. 5.

advertising; and sales taxes. Further investigation is needed to reconcile cost estimates with manufacturer price.

- For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at all production levels.
- By contrast, for the 100 kWe system, the FC subsystem accounts for between 55% and 65% of capital costs.
- The lower power density of the HTPEM stack results in a large mass and volume of FC stack needed, compared with the LTPEM. At the same time, the HT and LT PEM system designs are very similar, and costs tend to scale with mass and/or volume. As a result, HT PEM stack costs are higher and contribute to a larger percentage of total system costs.
- At the 1 kWe size, BOP costs dominate FP subsystem costs. At the 100 kWe size, fuel processor costs dominate FP subsystem costs.
- For 1 kWe FCSs, the primary cost drivers for the FP BOP are the natural gas compressor, the flammable gas alarm sensors, and the gas flow control solenoids, in that order.
- For 100 kWe FCSs, the primary cost drivers for the FP BOP are the water pump and the condenser, in that order.
- At low power (1 kWe), the FP subsystem cost is dominated by the FP BOP components.
- At high power (100 kWe), the FC stack cost dominates the total system cost.
- At 1 kWe, FC BOP component costs constitute 60% or more of FC subsystem costs.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 3% and 4% and for adding grid-independent capability, it is between 7% and 11%.

Modeling results for SOFC CHP systems underscore some additional key points:

- Modeling results for SOFC capital costs are broadly consistent with manufacturer values provided by Ceramic Fuel Cells Limited (CFCL) of Australia. Modeling results indicate a unmarked-up manufacturing cost of roughly $11,830/kWe for a manufacturing rate of about 100 sys/yr for 1kWe systems. Manufacturer provided capital prices are roughly $22,000/kWe at a similar production rate.[9, 10] Modeling cost results do not include: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. Further investigation is needed to reconcile cost estimates with manufacturer price.
- For the 1 kWe and 100 kWe system sizes, the FC and FP subsystems combined account for the majority of FCS capital costs, about 60% of total capital costs at a minimum.

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[9] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11 and Fig. 5.

[10] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11 and Fig. 5.

- For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at production levels of 1,000 sys/yr and above. By contrast, for the 100 kWe system, the FC subsystem contributes about 65% to total cost.
- For the 1 kWe and 100 kWe systems, the fuel processing subsystem costs are dominated by the FP BOP.
- At low power (1kWe), at production rates above 1,000 sys/yr, the FP subsystem cost is dominated by the BOP components.
- At 100 kWe, FC stack costs constitute over 90% of FC subsystem costs.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 2% and 3% and for adding grid-independent capability, it is between 11% and 13% of the base cost.

2 Introduction

2.1 Project Motivation

Stationary applications for FCSs are an active and growing area of FC product development. Numerous companies already have preliminary products on the market for a variety of sizes and applications[11] and research continues into the full range of uses for stationary systems.[12] To better assess the potential usefulness and market-worthiness of the stationary FCS concept, this work describes a "Design for Manufacturing and Assembly" (DFMA)[13]-style analysis of the cost to manufacture a series of stationary FCSs. Because there is a broad range of applications and fuel cell technologies under the "stationary" umbrella, it is useful to examine the relative cost impact of systems based on several fuel cell technologies at different installed capacities, as well as applications such as CHP and grid-independent operation. Finally, the impact of annual production rate on the cost of all systems is examined to assess the difference between a nascent and a mature product manufacturing base.

2.2 System Summary

The stationary FCSs modeled in this report include four major functional subsystems. The first is the fuel processor (FP) subsystem which includes a steam reforming reactor external to the fuel cell stack that converts natural gas (NG) into a hydrogen-rich reformate gas for the fuel cells. This subsystem draws heavily on an interpretation of a Ballard Power Systems integrated steam reformer concept reactor based on patents by Tokyo Gas. The reactor has a highly thermally-integrated concentric shell design which combines the functionality of fuel preheating, raising steam, and steam reforming. These shells contain metal monolith catalyst beds for steam reforming, water-gas shift (WGS), and preferential oxidation (PROX) reactions but are adapted for the specific needs of each fuel cell technology. (For more details on the breakdown of the FCSs into various subsystems, see Section 4.1.1. For more details on FP subsystem design for each system technology, see Sections 4.1.2.7 and 4.4.)

After the FP subsystem processes the NG fuel into reformate, the reformate is fed into the FC stack. The stack performance parameters are highly dependent on the stack technology (Low Temperature (LT) Polymer Electrolyte Membrane (PEM), High Temperature (HT) PEM, or Solid Oxide Fuel Cell (SOFC)), but all stacks are sized appropriately to yield the desired system net peak electrical capacity (1 kWe, 5kWe, 25 kWe, or 100 kWe) given the stack's power density, efficiency, and parasitic electrical loads. Stack anode and cathode exhaust gas is then fed back into the FP subsystem via a burner assembly, which combusts unreacted fuel to provide heat for the steam reforming reaction. Finally, the burner exhaust gas is fed through a series of heat exchangers, first to extract a combined heat and power (CHP) load and then to condense out product water for feeding back into the reactor inlet.

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[11] See e.g. UTC Power PureCell http://www.utcpower.com/products/purecell400, FuelCell Energy http://www.fuelcellenergy.com/products.php, and Bloom Energy http://www.bloomenergy.com/fuel-cell/energy-server/.

[12] Colella, W.G., *Network Design Optimization of Fuel Cell Systems and Distributed Energy Devices*, Sandia Report, Sandia National Laboratories, Albuquerque, New Mexico 87185, SAND2010-5071, July 2010.

[13] Boothroyd, G., P. Dewhurst, and W. Knight. "Product Design for Manufacture and Assembly, Second Edition," 2002.

The LT PEM stacks consist of coated and stamped stainless steel bipolar plates, a Nafion® membrane on an expanded polytetrafluoroethylene (ePTFE) support, and 3M Inc. nanostructured thin film (NSTF) platinum-cobalt-manganese (Pt/Co/Mn) catalyst based on automotive design. For the HT PEM stacks, a pyridine-based aromatic polyether membrane is used in place of the Nafion®. An NSTF catalyst layer is also assumed used but with a higher Pt loading. Other design details remain unchanged. The SOFC stack is an electrolyte supported planar thin film cast ceramic with nickel –cobalt (Ni-Co) catalyst, lanthanum-strontium-cobalt-ferrite (LSCF) cathode, and yttrium stabilized zirconia (YSZ) electrolyte. The overall stack construction is based on a design by NexTech Materials, Inc. For more details on FC stack subsystem design for each system technology, see Section 4.3.

The third major subsystem is the thermal management subsystem for CHP operation and includes the additional heat exchangers required to provide CHP heat to the building space heating and service water loads. This subsystem is counted separately to assess the cost impact of configuring a system for CHP operation versus a system that does not supply CHP. The CHP subsystem is configured differently for different system sizes and is discussed in Section 4.1.2.9.

The final major functional subsystem is the Power Electronics subsystem. This subsystem includes all of the equipment and parts required to convert the stack direct current (DC) power into alternating current (AC), regulate the AC power supplied by the system, and provide power to peripherals. The baseline system is configured for grid-dependent operation, but a grid-independent case is also examined to assess the cost impact of grid-independent operation. The grid-independent system configuration includes batteries for start-up and transient management. For more information on the Power Electronics subsystem, see Section 4.1.2.11.

2.3 Structure of Report

Cost modeling results are limited in their utility without a clear description of the system being modeled, the assumptions underlying the model itself, and the methodology used to reach the conclusions. Thus, this report gives detailed explanations and definitions of the analyzed systems. Because there is a great amount of detail to be specified, description is done in several tiers. First, the general costing methodology is explained, from system conceptual design to cost modeling of all components. Then an overview is given describing the features, subsystems, and design elements which are common to all three FCS technologies. Once the commonalities are described, this report then provides a description of the unique aspects of each FCS on a subsystem-by-subsystem basis. After system description is complete, cost results are given for each FCS, again at the subsystem level.

3 Methodology

The cost model relies upon a DFMA-style methodology to determine the cost to manufacture several stationary system designs at varied rates of production. The methodology consists of three major steps:

1. System Conceptual Design,
2. System Physical Design, and
3. Cost Modeling.

3.1 System Conceptual Design

The main purpose of the system conceptual design phase is to develop a valid thermodynamic model of a physical system. In this phase, design requirements are identified and performance parameters are determined. Design requirements include considerations such as system technology (LT PEM, HT PEM, or SOFC), system peak rated net electrical output (1, 5, 25, and 100 kWe for each technology), whether to allow for CHP operation or grid-independent operation, input fuel composition, water neutrality, and so forth (see Section 4.1.2 for more discussion of system design requirements). Once these design requirements are identified, a conceptual system can be laid out which satisfies the requirements.

For each system technology, detailed designs are developed for the four main FCS subsystems: the FC subsystem, the FP subsystem, the electrical management subsystem, and the CHP subsystem (for more detail on the terminology of the breakdown into various subsystems, see Section 4.1.1). The entire FCS is modeled within Aspen HYSYS^{TM} chemical engineering process plant modeling software to determine performance parameters such as net system electrical efficiency, flow rates, temperatures, and pressures. Net system electrical efficiency [ε] is defined as the net alternating current (AC) electrical power produced by the FCS [P_{AC}] (including electricity supplied from the FC stack and any energy storage minus electricity drawn internally by ancillary loads such as pumps and compressors) divided by the energy input to the system based on the higher heating value[14] (HHV) of the NG fuel consumed by the system, where $\dot{m}_{NG}$ is the mass flow rate of natural gas (see Equation 1).

$$\varepsilon = \frac{P_{AC}}{(HHV_{NG}\ \dot{m}_{NG})} \tag{1}$$

As part of the conceptual design phase, system diagrams are produced which identify all material flows and system components (see Sections 4.1 and 4.2 for system diagrams and a detailed explanation of system design). Reference to existing FCSs is made to assure the performance parameters are consistent with expected values for systems with similar performance and operational goals. The system conceptual design also facilitates the next stage, system physical design, by identifying all required system components and their physical constraints, for example mass flow quantities, operating temperatures, and heat exchanger area.

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[14] Efficiency of stationary power systems are typically assessed on the basis of the fuel's higher heating value (HHV) capacity whereas automotive power systems are typically assessed on the basis of lower heating value (LHV). Efficiency assessments within this document are reported both ways for maximum clarity and to facilitate comparisons to other systems.

3.2 System Physical Design

A main purpose of the system physical design phase is to develop detailed bills of materials (BOMs) for all major system and subsystem components. With the system conceptual design in hand, it becomes possible to define the system physical design. For standardized components such as compressors, blowers, sensors, heat exchangers, piping, etc. (common in the BOP), it is sufficient to use the required performance parameters to obtain an appropriate quote for each piece of equipment. For integral components for which a full DFMA-style analysis will be performed, the system physical design step involves determining the full physical embodiment of the system, including materials, geometry, and manufacturing methods. Design for this step is supplemented by assistance from industry partners and previous design work. For example, the fuel processor subsystem design is based upon an integrated reactor designed by Tokyo Gas. For the LT and HT PEM FCSs, fuel cell subsystem designs are based upon prior work on automotive PEM subsystems, adapted for the new requirements identified in the previous step. The physical design for the SOFC stack was based upon the FlexCell SOFC system by NexTech Materials Inc.

3.3 Cost Modeling

Once the physical embodiment has been determined, costs can be modeled. There are two levels of detail in cost modeling. The first and more detailed level corresponds to the core system components, while the second and less-detailed level corresponds to standardized components common in the system BOP.

3.3.1 Core System Components

DFMA is a costing methodology developed by Boothroyd-Dewhurst, Inc. and used by hundreds of companies worldwide. For this project, the standard DFMA techniques were blended with detailed knowledge of industry standards and best practices, application of new materials, technology, or manufacturing ideas, and Strategic Analysis, Inc.'s own cost modeling software, innovative ideas, and practical common sense. For the core system components, the estimated cost [C_{Est}] is the sum of materials cost [C_{Mat}], manufacturing cost [C_{Man}], tooling cost [C_{Tool}], and assembly cost [C_{Assy}] (see Equation 2).

$$C_{Est} = C_{Mat} + C_{Man} + C_{Tool} + C_{Assy} \qquad (2)$$

To determine materials cost [C_{Mat}], the system physical design is used to determine the amount of required raw materials to manufacture each individual part. The material, geometry, and manufacturing method are identified for every component. From this information, it is possible to take into account material wastage because of flash, scrap, or defects.

For the manufacturing cost component [C_{Man}], a process train is defined for construction of all of the individual parts necessary for the system. Based upon the capital cost of the manufacturing equipment in the process train, as well as the production rate of that equipment, a machine rate is computed for that process. The machine rate [R_M] is the cost per unit time ($/min) of operating the machinery to produce a fixed quantity of parts in a fixed time (see Equation 3). It depends on the following variables: total capital cost [C_{Cap}], the annual capital recovery factor [F_{Cap}], the multiplicative factor applied to the total capital cost to account for installation and delivery of the machinery onto the factory floor [F_{Inst}], the annual maintenance cost factor as a fraction of capital cost [F_{Maint}], annual miscellaneous expense factor as a fraction of capital cost [F_{Misc}], the total annual runtime [T_R], the total annual setup time [T_S], the electrical utility energy cost [C_P], the process power usage [P], fully loaded labor cost [C_L], and the number of simultaneous laborers required for the process train [L]. The values assumed for these factors are displayed in Figure 13 below.

$$R_M = C_{Cap}\frac{(F_{Inst}F_{Cap} + F_{Maint} + F_{Misc})}{T_R + T_S} + C_P P + C_L L \tag{3}$$

Financial Input Parameter	Units/Values	Description
Process Train/Equipment Capital Cost [C_{Cap}]	$	Varies by process train
Discount Rate [R_I]	10%	Discount rate used to determine annual amount for repayment of capital
Installation Factor [F_{Inst}]	1.4	Multiplier of equipment capital cost to allow for delivery and installation of equipment at manufacturing plant
Lifetime [T_L]	15 years	Varies with equipment
Corporate Income Tax [R_T]	38.9%	35% federal, 6% state. Increases annual costs to reflect tax payments
Annual Maintenance / Spares [F_{Maint}]	6% of cap cost	Annual cost
Annual Misc. Expenses [F_{Misc}]	12% of cap cost	Annual cost
Electricity [P]		Power at $0.08/kWh

Figure 13: Table of Input Assumptions for Cost Modeling Calculations

Annual maintenance cost is the annual cost of maintenance and spare parts for the machinery and is expressed as a percentage of total capital cost. Annual miscellaneous expenses represent various additional contingent expenses and, like maintenance cost, are modeled as a fixed percentage of total capital cost. The annual capital recovery payment is the annual payment required to finance the capital cost of the equipment; it considers repayment of the initial purchase price as well as the time value of money and the tax rate. The annual capital recovery factor [F_{Cap}] is determined via a net present value[15] calculation over the equipment lifetime [T_L] based on corporate income tax rate [R_{Tax}] and discount rate [R_I] (see Equation 4).

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[15] Ross, S., Westerfield, R., Jaffe, J., Jordan, B.D., *Corporate Finance: Core Principles and Application* (New York, NY: McGraw-Hill, 2010).

$$F_{Cap} = \frac{\frac{R_I(1+R_I)^{T_L}}{(1+R_I)^{T_L}-1} - \frac{R_{Tax}}{T_L}}{1-R_{Tax}} \qquad (4)$$

The total manufacturing cost for a process train is then simply the product of the machine rate and the operating runtime [T_R] and setup time [T_S] required for the process train to produce the relevant number of parts (see Equation 5).

$$C_{Man} = R_M(T_R + T_S) \qquad (5)$$

One advantage of performing the manufacturing cost calculations in this way is that it allows comparison of manufacturing cost of identical process trains at different utilizations. A process train at low utilization will have a much higher machine rate—and a correspondingly higher cost per part—when compared to the same process train at high utilization due to the same capital outlay being amortized over fewer parts. This methodology automatically takes this difference into account when comparing manufacturing costs of the same system at different annual production rates.

In some cases, the calculated in-house machine rate from above is compared to a separately-computed "job shop" machine rate, based on the same process train but at a fixed minimum utilization of 37%.[16] At low production rates, it can be more cost-effective to send out parts for manufacture at machine shops, even after machine shop markup is taken into account.

The cost of expendable tooling [C_{Tool}] such as dies and molds is traditionally computed as a separate cost item. The capital cost of the expendable tooling is estimated and then is divided by the number of parts made by the tooling over its expected useful life. It some instances, particularly at low annual production rate, the tool has such a high cycle lifetime that it could be used for many years of production. However, since the design lifetime is likely to be only a few years, the expendable tooling lifetime is limited to a maximum of 3 years.

The final cost component modeled at this level is the cost of assembly of the system after part manufacture [C_{Assy}]. This process often includes assembly of the core components themselves and assembly of the entire system including standardized and core components as two separate assembly steps. The cost methodology for assembly is very similar to the rest of the manufacturing process train and is based upon modeled assembly times [T_{Assy}] for various parts (see Equations 6 and 7). Similar to the discussion above, a machine rate for the assembly train [R_{Assy}] is computed based on the capital cost of the installation workstation [C_{Cap}], factors for workstation installation [F_{Inst}], capital recovery [F_{Cap}], maintenance [F_{Maint}], and miscellaneous expenses [F_{Misc}], power consumption [C_P] and labor use [C_L], and associated cost rates for power [P] and labor [L]. These variables are defined in the same way as the equivalent variables in the general machine rate equation discussed above.

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[16] Based upon 2010 median single shift utilization of 65% for machine shops converted to 14-hour two-shift work days (0.65 x 8 hours / 14 hours) http://www.mmsonline.com/articles/see-how-you-stack-up

$$R_{Assy} = C_{Cap}\frac{F_{Inst}F_{Cap} + F_{Maint} + F_{Misc}}{\sum T_{Assy}} + C_P P + C_L L \tag{6}$$

$$C_{Assy} = R_{Assy}\sum T_{Assy} \tag{7}$$

For this effort, full DFMA manufacturing analyses were performed on the reactor component of the FP subsystem (see Section 4.1.2.7 for details on the reactor manufacturing process train) and on the stack component of the FC subsystem (see Section 4.3.1 for details on the stack manufacturing process train).

3.3.2 Balance of Plant Components

For standardized system components, it is less important to obtain a full physical and manufacturing process train specification. A less intensive cost analysis can be performed. For these standardized components, quotes are obtained for suitable parts according to the process parameters. To model the effect of price reductions when ordering large quantities, a learning curve formula is used which reduces the price by a fixed factor for every doubling of annual order quantity. This approach is based on standard experience curve theory[17,18] but alters the base from "cumulative production quantity" to "annual order quantity". This learning curve formula thus determines the price [P_Q] at a desired annual production quantity [Q] given the initial quotation price [P_I] at an initial quantity [Q_I] and an assumed learning curve reduction factor [F_{LC}] (see Equation 8).

$$P_Q = P_I F_{LC}^{\left(\frac{\ln\left(\frac{Q}{Q_I}\right)}{\ln 2}\right)} \tag{8}$$

When available, quotations at differing quantities are used to calculate an appropriate learning curve reduction factor for the part by taking P_Q and Q to be the values taken the second quotation and solving Equation 8 for F_{LC} . In this way, two quotations at two different combinations of price and quantity are used to further specify equation variables. Otherwise, a default value is used.

3.3.3 Cost Factors Included in Analysis

The analysis explicitly includes fixed factory expenses such as equipment depreciation, tooling amortization, utilities, and maintenance as well as variable direct costs such as materials and labor. However, because this analysis is intended to model manufacturing costs, a number of components that contribute to the original equipment manufacturer (OEM) price are explicitly not included in the modeling. The following costs are not included in this analysis: profit and markup, one-time costs such as non-recurring research, design, and engineering, general and administrative (G&A) costs, warranties, advertising, and sales taxes. Figure 14 represents this division as a diagram.

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[17] Wright, T.P., Factors Affecting the Cost of Airplanes, Journal of Aeronautical Sciences, 3(4) (1936): 122-128.

[18] "Statistical Methods for Learning Curves and Cost Analysis", *Matthew S. Goldberg and Anduin E. Touw, ISBN:1-877640-18-2. Available from: https://online.informs.org/informsssa/ecssashop.show_category?p_category_id=TOPICS*

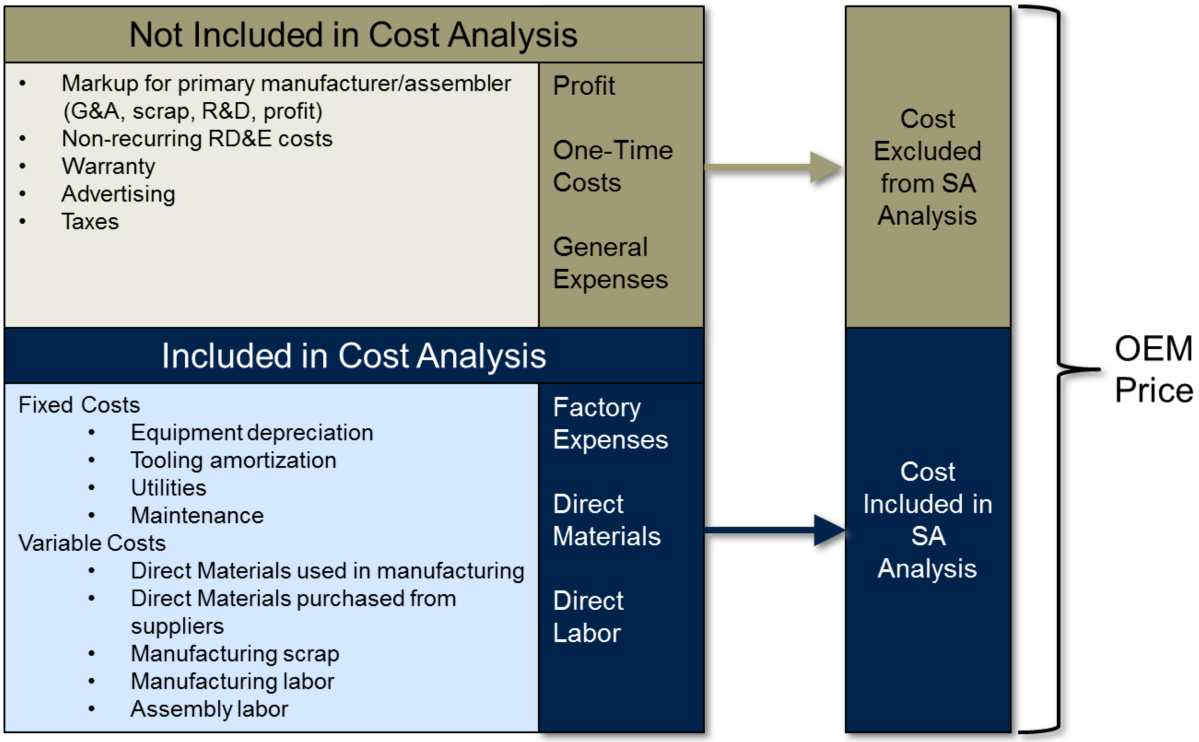

Figure 14: Cost Factors Included and Excluded from Analysis

3.3.4 Iteration

To reduce costs and optimize system performance, changes at all stages of the modeling and design process are constantly considered as the system conceptual design, system physical design, and manufacturing cost models are developed. Additionally, feedback from industry is continuously incorporated into this work. Thus, the three-step methodology is constantly iterated upon. New design approaches and physical system embodiments are continually examined, and the cost model refined, with the primary aim of reducing manufacturing costs.

4 System Design, Performance, and Manufacturing Details

This section describes the assumptions regarding system design, performance, and manufacturing that underlie the cost analysis. It begins by giving an overview of the design assumptions that are common among all three FCS technologies. Next it provides full design and manufacturing specifications for each FCS technology on a subsystem-by-subsystem basis.

4.1 System Overview

From a top-level perspective, all three FCSs are based on the same general design concept and operate in a similar manner. Natural gas (NG) fuel and water are pumped into the reactor for conversion into hydrogen-rich reformate. Conversion occurs due to the SMR reaction, optionally assisted by WGS and PROX (system-dependent). Heat for the SMR conversion is provided by oxidation of unconsumed fuel and air from the FC stack anode and cathode exhaust streams, supplemented by providing additional NG fuel as needed. The reformate is fed into the fuel cell stack, where it is converted into DC electricity and heat. If the stack is actively cooled, a coolant system removes heat from the stack and makes it available to the CHP system. The stack exhaust streams are burned to provide reactor heat and then flow into the CHP system, which includes a condenser to capture product water and achieve overall water-neutral system operation.

4.1.1 Breakdown of Subsystems

The overall system design includes four functional subsystems and six primary cost categories. Of those four subsystems, several are broken down further into subsystem components. The four functional subsystems and their subsystem components are:

- Fuel Cell Subsystem
    - Stack: FC stack including its assembly
    - FC BOP: peripheral components associated with the FC subsystem, including controls
    - Assembly: integration of the stack with the BOP components
- Fuel Processing Subsystem
    - Fuel processing Reactor: integrated reactor device that performs the fuel and air preheating, reforming, and other fuel processing reactions. Also includes reactor assembly
    - FP BOP: peripheral components associated with the FP subsystem, including controls
    - Assembly: integration of the reactor with the BOP components
- Power Electronics Subsystem: components required for power regulation and system control, including voltage regulation, overall system control, and batteries (if grid-independent operation is being analyzed)
- CHP Subsystem: components required for use of system waste heat as heat supply for building use.

In addition to these four functional subsystems, two additional cost contributors make up the full set of six cost categories.

- Housing and Final System Assembly: assembly of all subsystem components and BOP components inside a general system housing
- Cost Margin: a 10% cost markup is applied to cover non-enumerated components or processes. Adding a margin follows judicious cost estimation practice, particularly in preliminary costing exercises.

4.1.2 Common Design and Cost Assumptions

4.1.2.1 Power levels and Manufacturing Rates

For each of the three FCS technologies examined, systems were modeled at maximum installed electrical capacities of 1 kWe, 5 kWe, 25 kWe, and 100 kWe. In most cases the differences between different peak capacities are manifested by progressively increasing size in the relevant part or subsystem design, e.g. stack area and cell count (see Section 4.3.1) or reactor dimensions (see Sections 4.1.2.7 and 4.4.1). In some cases, however, an increase in system peak capacity necessitated a discrete change in system design, e.g. multiple reactors for 100 kWe systems (see Sections 4.1.2.7 and 4.4.1).

These system size-dependent design differences will always be discussed in the relevant section or sections below.

In addition to the three modeled technologies at four different system sizes, the manufacturing process was modeled at four different annual system production rates: 100, 1,000, 10,000, and 50,000 systems per year. This allows an analysis of the effect of economies of scale in manufacturing on each FCS size and design. As production rates increase from a low value of 100 systems per year to a high value of 50,000 systems per year, capital equipment utilization increases dramatically. In some cases, equipment or methods that are well-suited to high production are not economical at low production, and vise-versa. Thus, manufacturing process may change for the same design over the range of production rates, e.g. from a manual process to an automated process. Production rate-dependent manufacturing process differences will always be discussed in the relevant section or sections below.

4.1.2.2 Gross Power vs. Net Power

Although energy and mass models of each system were generated in the chemical engineering simulation software HYSYS^{TM}, there is an insufficient basis to assess gross power differences between the three technologies. All three technologies are expected to operate at approximately the same stack pressure (6psig) and thus are expected to have similar parasitic loads. Consequently, to avoid disparate treatment without valid basis of discernment, a standard addition equal to 5% of net power is added to all systems to represent the sum of all parasitic power loads (blowers, pumps, sensors, system controllers, etc.).

4.1.2.3 System Efficiency

System efficiencies between the three FC technologies are not standardized. Instead, a reasonable stack operating point is selected for each technology based on consideration of each technologies strengths and weaknesses (primarily polarization performance and power density), and the resulting system efficiency is computed. For instance, SOFC systems are able to achieve reasonable power density at high cell voltage, leading to the possibility of a high system efficiency at a reasonable capital cost. In contrast, HT PEM systems have a generally lower polarization performance leading to selection of a lower system efficiency operating point to reduce stack cost.

While cell voltages, operating conditions, and mass and heat balances differ between fuel cell technologies, there are several assumptions affecting system efficiency which are applied uniformly to all systems:

- Parasitic load: 5% of gross power (see section **Error! Reference source not found.**).
- AC /DC Inverter: 93% efficiency.

4.1.2.4 Air Supply

Air is supplied to the stack(s) via a regenerative air blower. Costs are projected based a pair of proprietary estimates at 10,000/year production rate and and assumed 0.97 learning curve factor: $540 for a blower suitable for a 25 kWe system and $300 for a blower suitable for a 1 kWe system. These quotes include the full system and controller. In addition to the blower, the air supply system includes an air mass flow sensor, an air filter and housing, and the requisite ducting for air flow. The cost of the air mass flow sensor is based upon a Cardone Reman Mass Air Flow Sensor which costs $59 at 10,000/year with a 0.97 learning curve factor. The air filter and housing is based on a part which costs $20 for a 1 kWe system and $90 for a 100 kWe system, both at 10,000/year with a 0.97 learning curve factor. For the ducting, a comparison analysis was conducted against the 80 kW automotive system. A cost representing $122 for an 80 kWe system at 100k/year with a 0.2 exponential scaling factor on system size and a 0.97 learning curve factor was determined to most closely reflect the automotive results for this part. The components comprising the air supply are all considered BOP components of the FC Subsystem.

4.1.2.5 Fuel and Water Supply

Fuel and water supply components are considered to be part of the FP Subsystem BOP items, and the price scaling is based on the same basic equipment for all three system technologies. The fuel supply system included in the system cost depends upon the fuel supply assumed for the system. For 1 kWe and 5 kWe systems, a residential installation is assumed with a 1 psig NG supply pressure. Thus, a NG compressor is required for those system sizes to boost to the approximate 6 psig operating pressure. The base cost of the NG compressor is $1300 for 1 kWe PEM system at 10/year with a learning curve of 0.96. The $1300 base cost consists of $500 for the compressor, $300 for the motor, and another $500 for the controller based on proprietary conversations with fuel cell system experts. The cost is scaled according to system size by an exponent of 0.5, and in the case of the SOFC system is also scaled according to cathode air stoichiometry and system efficiency, to capture the difference in air and fuel flows in the SOFC system. For 25 and 100 kWe systems, a commercial installation is assumed with a 15 psig NG supply pressure. For these systems only a pressure regulator is required since the NG supply pressure exceeds the 6 psig system operating pressure. The 25 kWe system uses a $220 pressure regulator, while the 100 kWe system uses a cost of $369. Both costs are obtained from FLOMEC quotes for single, 10k, and 50k purchases quantities. A learning curve factor of 0.99 is used.

The water supply system is based on pumps of two distinct designs. The first pump, suitable for 1 kWe and 5 kWe systems, is based upon Thomas-Magnete price quotation of $188 for a single unit, with an assumed learning curve factor of 0.96. In the 1 kWe system, a single pump in used while in the 5 kWe system two are used in parallel. The pump used in the 25 kWe and 100 kWe systems is based on a Flight Works, Inc. price quote of $799 with a learning curve of 0.96. One pump is used in the 25 kWe systems, while the 100 kWe systems use four (one per reactor). Included in the water supply systems in addition to the pumps are a tank, a water level sensor, and a demineralized water filter. For the tanks, one price was obtained for 1 kWe, 5 kWe, and 25 kWe systems while a second was used for the 100 kWe system. Tank pricing was based on quotations from Grainger. The smaller tank was $30 and the larger $53, both for 10,000/year and with a learning curve of 0.93. The level sensors cost $20 and the filter cost $37, both at a quantity of 1 with a learning curve factor of 0.96. Each system has a single level sensor. The 1 kWe and 5 kWe systems both have a single filter, while the 25 kWe system has two and the 100 kWe system has eight.

4.1.2.6 Desulfurization System

The desulfurization system is based on an analysis of SulfaTrap passive sulfur adsorbent by TDA Research, Inc.[19] This adsorbent system can achieve a weight capacity of up to 2.35%, resulting in bed volumes 30 times smaller than traditional activated carbon adsorbents. However, a sulfur adsorption of 1% wt (sulfur/adsorbent) is assumed in the cost analysis based on worst case operating conditions (45°C wet NG). Sulfur concentration in the NG is assumed to be 2.57 ppmv. The adsorbent is housed in a high density polyethylene (HDPE) canister of 12.7cm diameter and a length varying between ~12 cm (at 1kWe) to ~24cm (at 100kWe). A single canister is used for 1kWe systems and four canisters in parallel are used for 100kWe systems. Canister replacement frequency is estimated at once per year for 1kWe systems and monthly for 100kWe systems. While total annual absorbent costs are computed, only the cost of a single set of desulfurization canisters is included in the tabulated capital cost. The adsorbent can be regenerated and does not parasitically adsorb hydrocarbons. Cost is estimated to range from $24-$10 per pound, depending on production scale, with an estimated final cost of $4.71 / 1,000 Nm^3 of NG processed.

4.1.2.7 Fuel Processor

The reactor component of the FP subsystem represents an interpretation of an existing Ballard Power Systems design which was in turn based upon patents by Tokyo Gas.[20,21] The fuel processing reactor consists of several metal cylinders which create annular flow fields for fuel and exhaust flow, as well as promote heat transfer between different flows. In the basic operation, fuel and water flow into their respective inlet ports and follow a spiral path through dedicated feed coils. Heat transfers into the inlet fluids from the burner zone on one side and the reformate exit stream on the other, raising the temperature of both fluids and converting the water to steam. The steam and natural gas are forced through the mixing plate, a flat plate filled with many small holes designed to promote turbulence and mixing as the fuel and steam pass through. At this point the fuel/steam mixture enters the steam methane reforming (SMR) catalyst zone. This zone is situated closest to the internal tail gas burner, and as a result the incoming fluid is heated quickly to SMR reaction temperature (at least 650 °C). The tail gas burner takes in anode and cathode exhaust and burns it to provide heat and energy for the endothermic SMR reaction. Burner exhaust gas flows out and is recaptured or used as a CHP heat source.

From the SMR zone at the bottom of the reactor cylinder, the reacted reformate rises through the outer shell and passes through two additional catalyst zones. The first zone contains the water-gas shift (WGS) catalyst and performs the necessary reactions to convert carbon monoxide (CO) into hydrogen. The second contains preferential oxidation (PROX) catalyst and an air feed tube to provide oxygen for the PROX reaction. Air is introduced to the reformate stream immediately prior to the air mixing plate, which like the fuel/steam mixing plate, forces flow through many small holes to promote turbulent

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[19] Alptekin , Gökhan O., "Sorbents for Desulfurization of Natural Gas, LPG and Transportation Fuels," Sixth annual SECA Workshop, April 21, 2004.

[20] Komiya, J., et al., "Single-Pipe Cylinder-Type Reformer." US Patent 7,037,472, issued May 2, 2006.

[21] Miura, T., et al., "Cylindrical Steam Reforming Unit." US Patent 7,182,921, issued February 27, 2007.

mixing of reformate and air. After PROX, the reformate flows out of the reactor and into the downstream system components.

Figure 15 below shows a diagram of the full reactor design (not to scale).

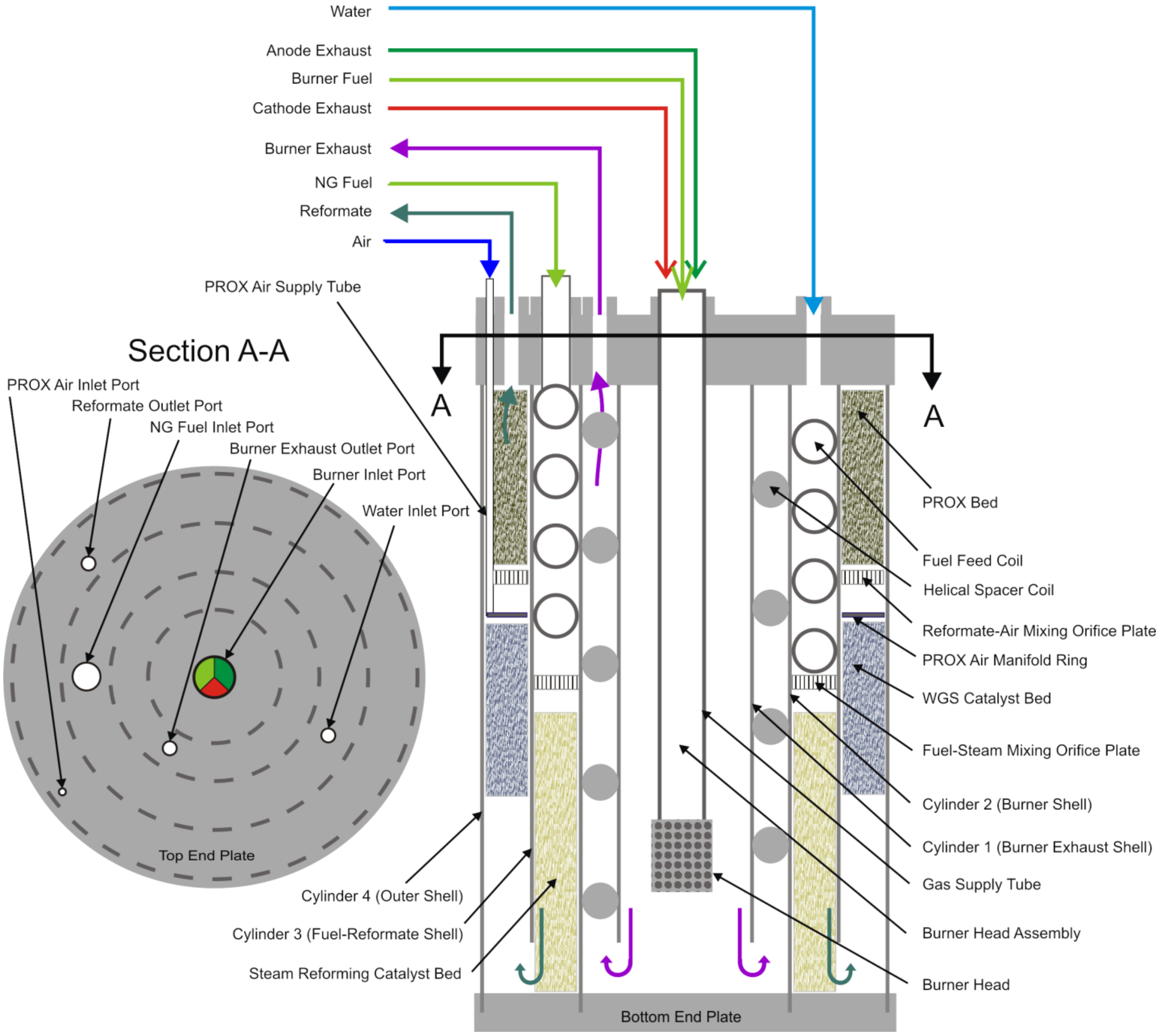

Figure 15: Reactor Diagram

The reactor is designed to be modular to allow for multiple scale-up alternatives. Sizing is derived from gas-hourly space velocity (GHSV) data and modeling provided by Ballard.[22] The 1 kWe system reactor is based upon the operating conditions of the current prototype. The 5 kWe system is based upon a single reactor running at modeled future expected conditions of the system. For the 25 kWe system, reactor volume was increased by increasing total diameter by a factor of 2.5 and by doubling reactor length. Finally, the 100 kWe system makes use of the modular aspect to include 2 or 4 reactors at the 25 kWe

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[22] Personal communication with Pat Hearn, Ballard Power Systems.

scale. See Section 4.4 for further discussion of reactor scaling and modularity for the three system types.

Note that the above description most accurately describes the reactors used in the LT and HT PEM FCS; the reactor for the SOFC system is configured and sized slightly differently. As further described in section 4.4.1.3, the SOFC FCS employs some internal reforming within the SOFC stack. Consequently the SMR reactor is used primarily for start-up and to provide a moderately hydrogen rich NG stream to the stack for ease of reaction. Because only a 25% reforming reaction is assumed to be conducted within the reactor, reactor space velocity is nominally multiplied by four and the sizing of the SOFC reactor accordingly adjusted.

The cylindrical reactor's manufacturing methods are modeled as follows. The inner two of the reactor's four annular cylinder surfaces are formed from pre-cut sheets of 35 mil Inconel 625, an alloy chosen for its superior corrosion resistance at elevated temperatures. The outer two cylinders, which do not reach temperatures as high as the cylinders immediately adjacent to the burner and reactor zones, are made from 35 mil 316 stainless steel. The sheets are rolled by a slip rolling machine and welded together with an integrated tungsten inert gas (TIG) welder. The cylinders are then annealed for 20 minutes at 820 °C in a large batch furnace. The burner assembly is constructed from a nested pair of Inconel tubes through which anode and cathode exhaust separately flow. At the exit point of the tubes is a ceramic mixing plate to force the anode and cathode exhaust streams together. Finally, a pair of high temperature wires provides an electric arc to ignite the stream. The metal monoliths that occupy the interior annular spaces between nested cylinders are formed from 2 mil FeCrAlloy® (Iron/Chromium) sheets, heat treated to create microscopic porosity[23], processed through a fin forming machine[24] (15 fins per inch) and then die cut into the appropriate shapes. For systems which require WGS or PROX catalysts, the monoliths corresponding to those reaction regions in the reactor are washcoated with catalyst[25]. The washcoating process involves coating and drying several layers of catalyst and solvent slurry, followed by a one hour calcining at 600°C in air. The calcining step drives out the solvent and oxidizes the binder, firmly entrenching the catalyst on the surface of the monolith. The WGS catalyst is modeled as 3% Pt on alumina and the PROX catalyst is 1% Pt on alumina. For systems which do not require either WGS or PROX, the uncatalyzed monoliths are still included in the reactor design because they promote heat transfer between different reactor flow zones. The SMR monolith is washcoated in a 2% Pt on alumina catalyst for all systems. For more information on which systems make use of which reactions and why, see Section 4.4.1 below. (The reactor for the SOFC system has a slightly different geometry which is described in section 4.4.1.3.)

The assembly of the reactor system consists of five stations, each with a series of subtasks with associated processing times. For these systems, assembly is assumed to be performed by human laborers rather than robots. In the first three stations, individual cylinder shells are tack-welded with

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[23] Heat treatment modeled as ten minutes at 1200°C in air.

[24] Fin forming machine modeled as a $300,000 initial price with a $110,000 rebuild cost after 5 years of service. Line speed is 0.15 meters/minute.

[25] Modeled as a gamma alumina support with loading of 0.106 grams alumina per cm^3 of monolith. (Consistent with a 40 micron layer thickness.) Active metal catalyst is 1-3% (as specified) as a fraction of alumina mass.

metal monoliths and other required items such as the fuel feed coil, helical spacer coil, and mixing plate. The three cylinder assemblies are then induction brazed onto the top endplate along with the burner assembly, to create a single annular reactor assembly. In the final step, the reactor bottom endplate is laser welded onto the assembly. The total assembly time is approximately 15 minutes per reactor, and this time does not vary appreciably with reactor size.

4.1.2.8 Stack Degradation

In general, FC stack cost and lifetime are interdependent: for a given degradation rate, stack lifetime can be increased at the expense of increased cost through system oversizing. For the purposes of this analysis and to accommodate DOE objectives, it is desirable to treat stack cost and stack lifetime as independent variables. By doing so, stack costs are compared as if the systems have equivalent expected lifetime degradations (in this analysis, ~17%) thereby revealing any intrinsic cost differences that otherwise would be overwhelmed by the effects of high-stack-degradation/short-lifetime. Simultaneously, this approach explicitly recognizes that degradation rates can be (and are) different for different technologies, resulting in stacks which reach their final useful lifetime more quickly or slowly (see Figure 16). Thus the reader is able to both discern cost differences from materials/design/operating point while separately noting the cost impact of stack lifetime.

To achieve this, the lifetime of the FC stacks for all three technologies was defined as degradation to 83% of starting performance,[26] with the end-of-life (EOL) conditions being the system design conditions. Thus each system is oversized[27] by 20% to allow for full rated power at end of life (EOL), regardless of whether the stack technology generally experiences fast degradation rates (e.g. HT PEM) or slow degradation rates (e.g. LT PEM). Under this scheme, stack lifetime is a function of degradation rate but the FCS cost may be calculated without specifying that lifetime. Figure 16 displays a range of degradation rates and their corresponding stack lifetimes (based on our definition of EOL occurring at 83% of initial performance).

Degradation Rate (% of initial value per 1000 hours)	Lifetime (years)
0.95%	2
0.63%	3
0.38%	5
0.19%	10

Figure 16: Degradation Rate and Corresponding Lifetime for FC Stacks

Prior to full degradation to EOL conditions, the stacks operate at higher voltage and lower current density, resulting in higher-efficiency operation at beginning-of-life (BOL) conditions.

4.1.2.9 CHP Operation

For CHP operation, the FCS waste heat is utilized to provide building hot water and climate control. The base systems are configured for CHP operation by default. To allow for assessment of the marginal cost increase from assuming CHP operation, the CHP-specific components are separated out into their own cost subsystem.

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[26] More specifically, EOL is defined as the point when power density drops to 83% of initial power density at a specified design cell voltage.

[27] This is achieved by increasing membrane active area by 20% above that dictated by design conditions.

The three different system technologies produce varying amounts of waste heat suitable for CHP use. Based on computation for 25 kWe systems, the thermal load transferred to the CHP loop is: 40 kW thermal for the LT PEM system, 56 kW thermal for the HT PEM system, and 21 kW thermal for the SOFC system. The lower amount of CHP heat available for SOFC is a result of higher system electrical efficiency[28] and the relatively high air stoichiometry assumed (2.5x). It should be noted that CHP heat may have low utilization within the building, and thus this CHP heat may often be wasted. Thus an overall system efficiency based on combining electrical and CHP heat outputs may be misleadingly high. Section 5 contains further discussion.

For service water heating, a hydronic heating system with a 60°C water supply temperature is assumed for all systems. For space heating, an air heating system with a 23°C supply temperature is assumed for small offices and residential buildings, while large offices are assumed to use a hydronic space heating system with an 82°C supply temperature. Figure 17 below indicates further system details for each FCS size.

FCS Size	**1 kWe**	**5 kWe**	**25 kWe**	**100 kWe**
Building Application Type	Small Office / Residential	Small or Large Office	Large Office	Large Office
Service Water Heating System Type	Hydronic	Hydronic	Hydronic	Hydronic
Service Water Heating Supply Temp	60 °C	60 °C	60 °C	60 °C
Service Water Heating % Of Building Heat Demand	28%	13%	13%	13%
Space Heating System Type	Air	Hydronic	Hydronic	Hydronic
Space Heating System Supply Temp	23 °C	82 °C	82 °C	82 °C
Space Heating System Return Temp	22 °C	30 °C	30 °C	30 °C
Space Heating % of Building Heat Demand	72%	87%	87%	87%
Space Heating Reformer Exhaust Hx Type	gas/gas	gas/liquid	gas/liquid	gas/liquid

Figure 17: CHP System Details

In addition to the CHP heat exchangers, all systems are configured with an additional condenser for water recovery when CHP heat service is not required.

4.1.2.10 System Housing

The system housing analysis assumes a single housing unit for the entire FCS. The housing is powder coated metal with a NEMA 4 or greater specification for protection from elements and with ports for cooling air. Quotes were obtained for three sizes of Eldon Multi-Flex single door enclosures with side panels, 4” plinths, shelving, air fan and filter, and rain hoods for all ports. An analysis of these price quotes allowed a correlation between enclosure interior volume and enclosure cost. Required enclosure volume was determined from computed stack and reactor dimensions. The reactor was assumed to occupy 1/3 of the total volume of the FP subsystem. Likewise, the FC stack was assumed to occupy 1/3 of the total volume of the FC subsystem. The FP and FC subsystems were further assumed

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[28] More input energy is being converted to electricity, so less is available as waste heat for CHP.

to occupy 1/2 of the total FCS volume. Thus the total system volume is assumed to be 6 times the combined volume of the stack and the reactor. This value is scaled according to the calculated volume relationship to achieve a base cost, which is further modified by a 95.54% learning curve deduced from enclosure quotes at various sales volumes.

4.1.2.11 Grid-Dependent vs. Grid-Independent Operation

By default, the base FCS is configured to be grid-dependent for both startup and transient operation. This allows a very simple circuit design for the power electronics subsystem. In the baseline system, peripheral loads are powered from the grid for start-up and the FCS electric load is fed through a diode and an inverter to supply a net AC power load to the building[29]. See Figure 18 for a diagram of the baseline system.

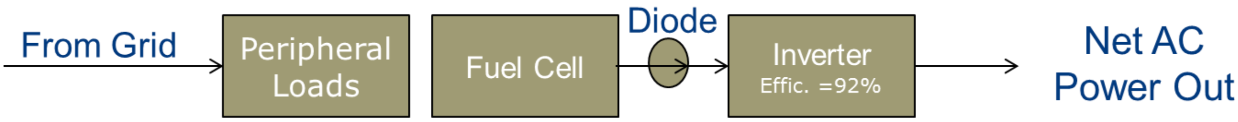

Figure 18: Electric System Design for Baseline, Grid-Dependent System

The AC/DC inverter is based upon two different models. For the 1 kWe systems, the inverter cost is based upon a PowerBright model #ML2300-24 inverter quote for $150 at 100 units. For the 5, 25, and 100 kWe systems, a larger PowerBright inverter #PW6500 is used as $600 for a quantity of 100. The cost for this is further scaled at a 0.1 exponent with system size. Both inverters use a learning curve of 0.96. The system diode for 1, 5, and 25 kWe is based upon a cost of $79 for a quantity of 100 and a learning curve of 0.97. The 100 kWe diode is twice as costly.

To evaluate the marginal cost impact of grid-independent operation, a second electrical system was designed for full grid independence. This system provides for running peripheral loads directly off of power supplied by the FCS (DC for 1-25 kWe and AC for 100 kWe) as well as batteries for both start-up and transient management. Figure 19 represents a diagram of this system.

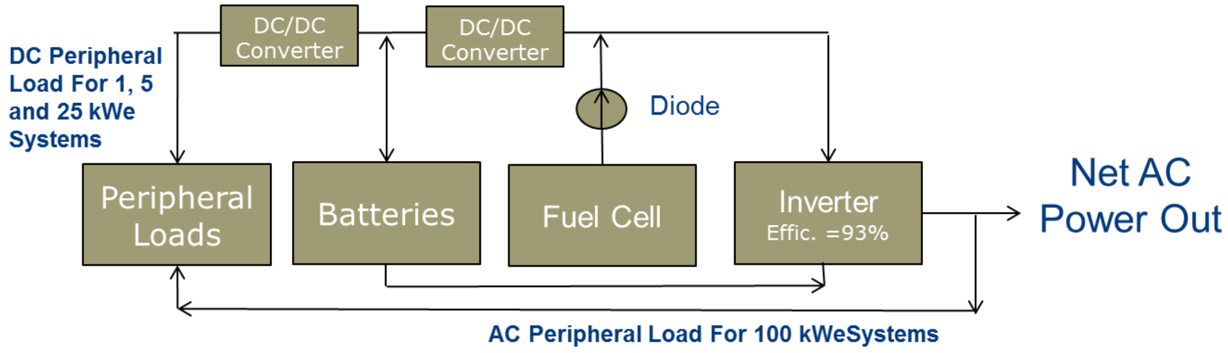

Figure 19: Electric System Design for Grid-Independent System

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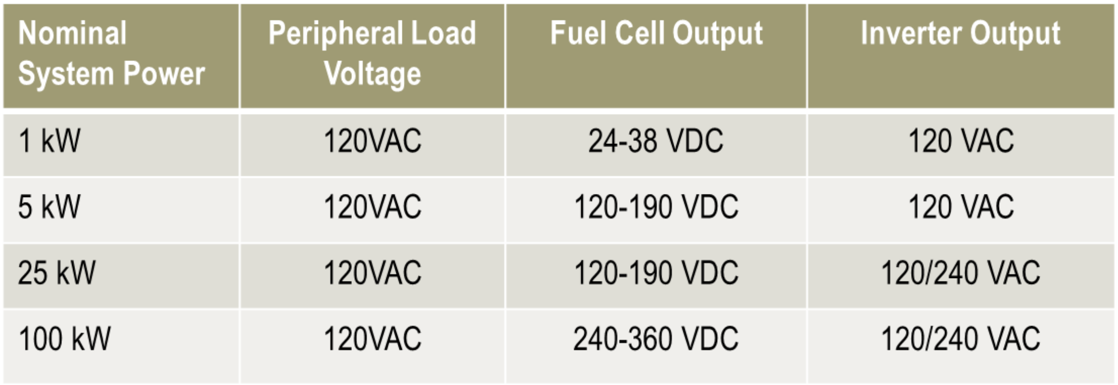
[29] We describe this as grid-dependent operation because it requires AC power from the grid for system startup. Once operational, the system does not need power from the grid but may benefit from grid connection to during transient load changes. Analysis of transient loads is beyond the scope of this analysis.

The DC/DC converter for 1 and 5 kWe systems is based on Power Stream Part # PST-APS45 with a cost of $306 in single quantity, while the converter for 25 and 100 kWe systems is based on Power Stream Part # PST-APS220-30 with a cost of $416 in single quantity. The learning curve is 0.98.

The battery subsystem consists of a combination of lead-acid batteries (for sustained power during startup) and Li-ion batteries (for transient response). The lead-acid startup batteries are sized to provide 30 minutes of 10% rated-power while the FCS starts up. A lead acid battery cost of $315/kWh is used for all systems. The Li-ion transient batteries are sized to provide full rated-power for up to 10 seconds at a time for load leveling during normal system operation. A Li-ion battery cost of $500/kWh is used for all systems and is consistent with performance specifications of 1770W/kg and 85Wh/kg derived from personal communications with battery supplier A123.

Common system voltage levels are shown in Figure 20 below. All systems used an DC to AC inverter efficiency of 92%.



Nominal System Power	Peripheral Load Voltage	Fuel Cell Output	Inverter Output
1 kW	120VAC	24-38 VDC	120 VAC
5 kW	120VAC	120-190 VDC	120 VAC
25 kW	120VAC	120-190 VDC	120/240 VAC
100 kW	120VAC	240-360 VDC	120/240 VAC

Figure 20: Common System Voltages

4.2 System Schematics

While the basic system design remains constant between the three system technologies, differences in stack operating temperatures lead to different flow temperatures, which in turn lead to differing heat exchange and fluid flow requirements.

4.2.1 LT PEM

The flow schematic for the low temperature PEM FCS is shown in Figure 21 below. The schematics are fundamentally the same for all power levels considered.

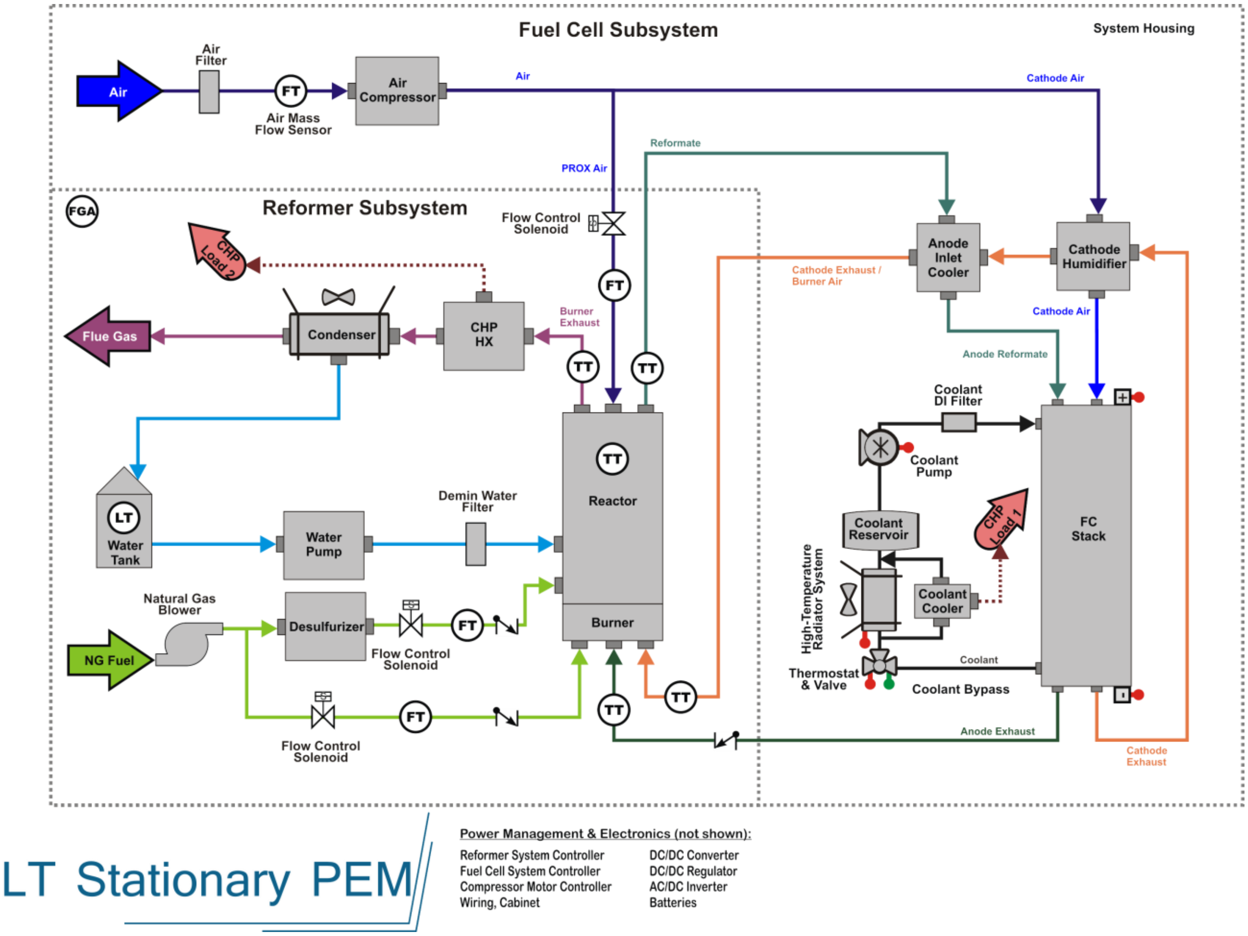


Figure 21: LT PEM System Diagram

4.2.2 HT PEM

The flow schematic for the high temperature PEM FCS is shown in Figure 22 below. The schematics are fundamentally the same for all power levels considered.

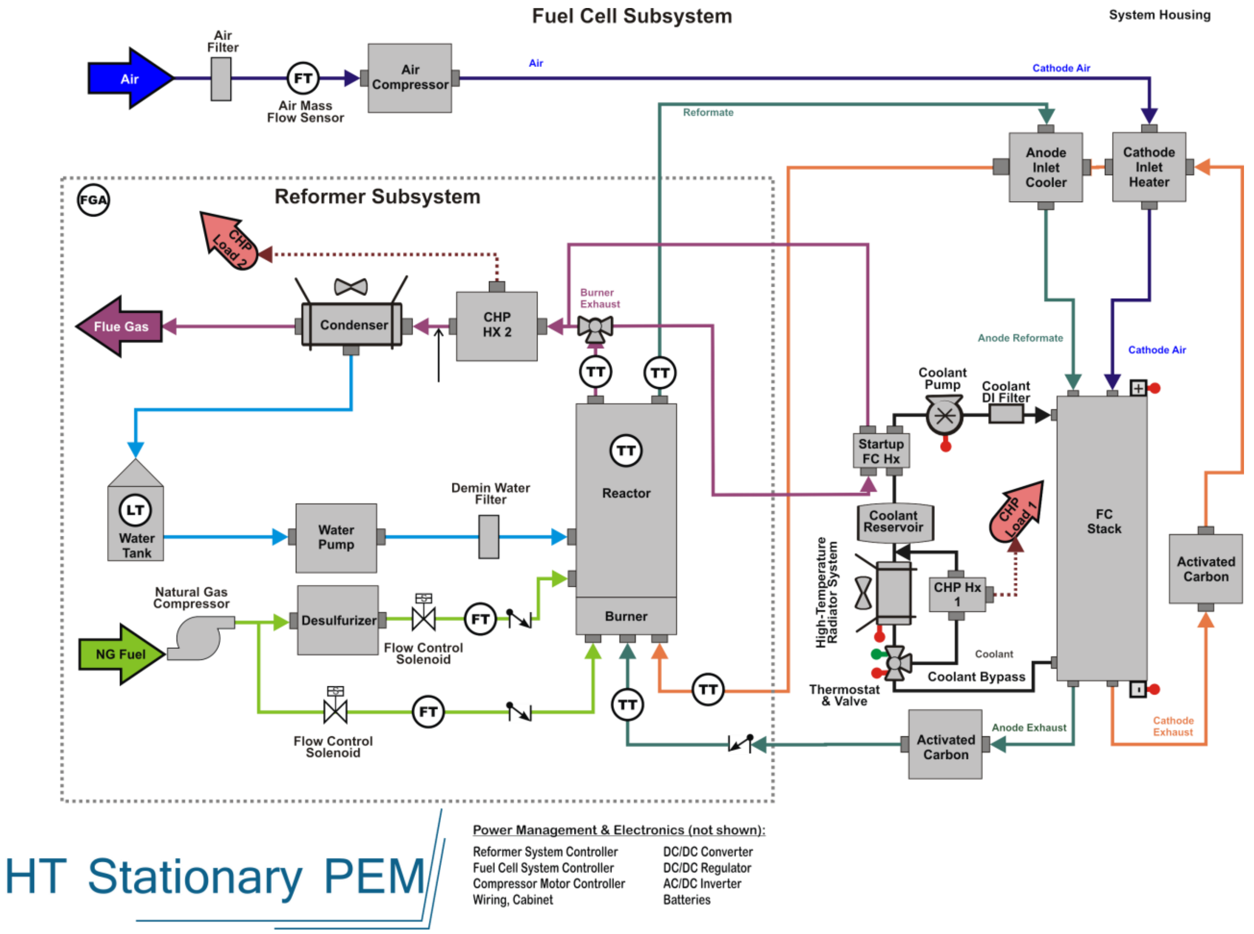


Figure 22: HT PEM System Diagram

4.2.3 SOFC

The flow schematic for the SOFC FCS is shown in Figure 23 below. The schematics are fundamentally the same for all power levels considered.

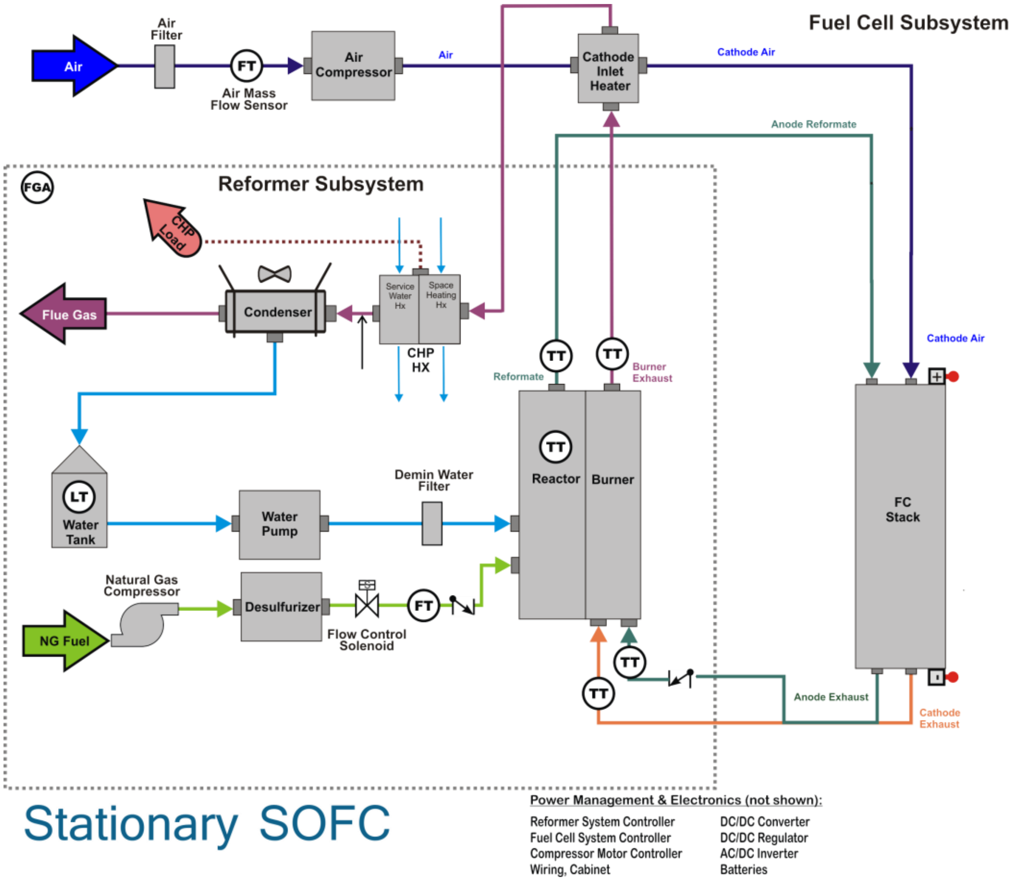


Figure 23: SOFC System Diagram

4.3 Fuel Cell Subsystem

The FC subsystem consists primarily of the FC stack itself and the BOP components associated with the operation of the stack. For the three technology systems, the FC stack is the subsystem that varies the most from system to system.

4.3.1 Fuel Cell Stack

At the most basic level, the FC stack portion of the subsystem consists of a stack based upon specific electrochemistry, materials, and operating conditions. All stacks have cathode and anode inlets into which air and reformate flow, respectively, and corresponding outlets for cathode and anode exhaust streams. The PEM stacks also have liquid coolant inlet and exit flows. All other FC stack subsystem components—blowers, pumps, sensors, piping, valves, etc.—are considered part of the FC BOP.

4.3.1.1 LT PEM Stack Parameters

The physical design and cost analysis of the stationary LT PEM stack is modeled on the author's past work on automobile PEM stacks.[30,31] In most respects, LT PEM stationary and automotive stacks are

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[30] James, B., J. Kalinosky, and K. Baum, "Mass Production Cost Estimation for Direct H2 PEM Fuel Cell Systems for Automotive Applications: 2010 Update," September 30 2010.

[31] James, B., "Fuel Cell Transportation Cost Analysis, Preliminary Results," *United States (U.S.) Department of Energy (DOE) Fuel Cell Technology (FCT) Program Annual Merit Review*, Washington, D.C., May 17th, 2012.

expected to function and be constructed in very similar fashions. However some differences are expected: different flow geometries, different pressure drops and optimal operating pressures, auto systems are typically run harder (i.e. at a lower cell voltage point), and auto systems are typically optimized for high power density whereas stationary systems are optimized for longevity/reliability. The stationary LT PEM stacks in this analysis nominally operate at 80 °C and use a Nafion®[32] membrane supported on expanded polytetrafluoroethylene ePTFE. A nanostructured thin film (NSTF) catalyst layer, (developed by 3M for automotive stack applications[33]) is assumed[34]. The gas diffusion layer (GDL) is based on a macroporous, non-woven, carbon layer[35,36] on which a microporous layer is applied. Stack performance is based on a W.L. Gore report[37] for reformate/air operation with 0.4mgPt/cm^2 and is generally consistent with a recent 2010 representative operating point from Ballard[38]. The bipolar plates are stamped stainless steel with a proprietary Treadstone Technologies Inc. anti-corrosion coating[39]. The membrane electrode assembly (MEA) is contained and sealed via frame gaskets, while the bipolar plates are laser welded to form coolant channels for a water-based coolant. Additional stack design operating conditions are summarized in Figure 24 below. As noted earlier, the stack is sized based on these operating conditions but has its active area increased by 20% to account for performance degradation over the stack lifetime. Consequently, these operating conditions are only experienced by the stack at the end of its life. At all other times, a higher cell voltage and lower power density are achieved.

Parameter	**Value**
Operating Temperature[40]	80 °C
Power Density	408 mW/cm^2
Cell Voltage	0.676 V/cell
Operating Pressure	~1.4 atm

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[32] Nafion® is a sulfonated tetrafluoroethylene based fluoropolymer-copolymer discovered and produced by Dupont.

[33] "Nanostructured Thin Film Electrocatalysts - Current Status and Future Potential," Mark K. Debe, Radoslav T. Atanasoski and Andrew J. Steinbach, *ECS Trans.* 2011, Volume 41, Issue 1, Pages 937-954, doi: 10.1149/1.3635628

[34] NSTF catalyst technology is the only practical extended high surface area shown to generally achieve the performance, cost, and durability requirements for LT PEM vehicle applications. Application to stationary applications is not known to the authors but is expected to require further development to re-optimize the catalyst/substrate to achieve high performance at higher catalyst loading. The cost of NSTF catalyst application was extensively examined by the author's past work on automotive fuel cell system cost analysis. Thus applying NSTF methods to the stationary system provides a convenient basis for cost analysis.

[35] GDL's for the LT PEM systems are modeled on GDL's for automotive fuel cell systems. While differences are expected given the different operating conditions, they are not expected to have an appreciable cost impact.

[36] "Reduction in Fabrication Costs of Gas Diffusion Layers", Jason Morgan, Ballard Material Products, presented at the 2011 DOE Hydrogen and Vehicle Technology Annual Merit Review & Peer Evaluation Meeting, 12 May 2011, Washington DC.

[37] "The Effect of Reformate on PEM Fuel Cell Performance", Mahesh Murthy, W.L. Gore & Associates, 2002 AIChE Spring National Meeting, New Orleans, LA, 10-14 March 2002. Data from Figure 1.

[38] "Influence of System Architecture in Achieving Low Cost and Efficient PEM Fuel Cell Systems," Greg Jackson and Ian Young (University of Maryland); Pat Hearn, Chris Tesluk, Bahman Habibzadeh, Maxim Lyubovsky, Atul Bhargav (Ballard Power Systems), Fuel Cell Seminar, 20 October 2010. Data from slide 23.

[39] Details of the materials and manufacturing process for the Treadstone coating were transmitted to the authors under a non-disclosure agreement. Consequently, the resulting cost is reported but not the proprietary details.

[40] Operating temperature is defined as the stack cathode exit temperature.

Cathode Stoichiometry	1.8
Fuel Utilization	77%
Platinum Loading	0.4 mgPt/cm^2
System Efficiency (HHV)	31%
System Efficiency (LHV)	35%

Figure 24: Summary of Design Parameters for LT PEM Stack

4.3.1.2 HT PEM Stack Parameters

The HT PEM stack is based upon the LT PEM stack, but with several changes for HT operation. The HT PEM membrane is based on Advent Technologies pyridine-based aromatic polyether chemistry operating at 160°C. A nanostructured thin film (NSTF) catalyst layer (developed by 3M for automotive stack applications[41]) is assumed[42] for the HT PEM system. The GDL is based on a macroporous, non-woven, carbon layer[43] on which a microporous layer is applied. Stack performance is based on specifications in an Advent Technologies patent[44] and is generally consistent with a recent 2010 representative operating point from Ballard[45]. Like the LT system, it features a planar design with stamped stainless steel bipolar plates and a Treadstone Technologies anti-corrosion coating[46]. The MEA is sealed with frame gaskets. The bipolar plates are laser welded to form coolant channels, through which an oil-based coolant may flow. Figure 25 lists the relevant operating parameters for the HT system. Like the LT PEM stack, the HT stack is sized based on these design conditions but is oversized by 20%.

Parameter	**Value**
Operating Temperature[47]	160 °C
Power Density	240 mW/cm^2
Cell Voltage	0.6 V/cell
Operating Pressure	~1.4 atm
Cathode Stoichiometry	2
Fuel Utilization	83%
Platinum Loading	1 mgPt/cm^2
System Efficiency (HHV)	30.5%
System Efficiency (LHV)	34%

Figure 25: Summary of Design Parameters for HT PEM Stack

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[41] "Nanostructured Thin Film Electrocatalysts - Current Status and Future Potential," Mark K. Debe, Radoslav T. Atanasoski and Andrew J. Steinbach, *ECS Trans.* 2011, Volume 41, Issue 1, Pages 937-954, doi: 10.1149/1.3635628

[42] NSTF catalyst technology is typically associated with LT PEM for automotive application. It is an extrapolation to apply it to stationary applications (that operate on reformate, typically have higher metal loadings, and demand longer lifetimes). It is a further extrapolation to apply NSTF to HT PEM systems (operating at 160°C vs. the LT PEM typical value of 80°C). However, it is felt that NSTF for stationary HT PEM is a reasonable assumption for cost estimation purposes.

[43] The HT PEM GDL is modeled identically to the LT PEM GDL. While differences in optimized systems would exist, they are expected to be of minimal cost impact.

[44] US Patent 7,842,733 B2, Gourdoupi et al., Advent Technologies SA, 30 November 2010. Data from Figure 6(B).

[45] "Influence of System Architecture in Achieving Low Cost and Efficient PEM Fuel Cell Systems," Greg Jackson and Ian Young (University of Maryland); Pat Hearn, Chris Tesluk, Bahman Habibzadeh, Maxim Lyubovsky, Atul Bhargav (Ballard Power Systems), Fuel Cell Seminar, 20 October 2010. Data from slide 23.

[46] The Treadstone Technologies anti-corrosion coating application methodology is similar between LT PEM and HT PEM coatings, but differ in choice of materials.

[47] Operating temperature is defined as the stack cathode exit temperature.

4.3.1.3 SOFC Stack Parameters

The SOFC stack design and manufacturing process were based on technical details provided by NexTech Materials for their FlexCell SOFC cell design[48]. The stack consists of an anode-supported planar design with tape casted ceramic cells. Each repeat unit is composed of a four layer architecture:

(1) The anode current collector and seal,
(2) an electrolyte-supported active cell (a layer containing the anode, the electrolyte, and the cathode),
(3) the cathode current collector and seal, and
(4) the interconnect.

A schematic diagram of the stack repeat components is shown in Figure 26, while key operating parameters are summarized in Figure 27. Stack performance is based on an approximate average from several sources: Fuel Cell Energy[49,50], Ceramic Fuel Cell Limited[51], and NexTech[52,53]. Like the other stack technologies, the SOFC stack is sized based on these design conditions but is oversized by 20%.

While the LT and HT PEM systems assume that 100% of natural gas reforming occurs in the fuel processing reactor, the SOFC system assumes 25% reforming in the reactor and the remaining 75% to be internally reformed in the SOFC stack. Internal reforming of natural gas happens spontaneously at the ~800°C stack temperature in the presence of nickel catalyst. Internal reforming is beneficial since it both reduces the size of the FP reactor and provides an SMR endotherm which lowers stack temperature. Excess cathode air is used to remove the remaining heat and achieve the target stack exit temperature.

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[48] NexTech Materials, Ltd., *Validation of Novel Planar Cell Design for MW-Scale SOFC Power Systems: Final Technical Report*, December 31, 2011.

[49] “Progress in SECA Coal-Based Program”, Hossein Ghezel-Ayagh, Fuel Cell Energy Inc., 12th Annual SECA Workshop, Pittsburgh, PA, 26-28 July 2011. Data from slide 21.

[50] “Progress in SECA Coal-Based Program”, Hossein Ghezel-Ayagh, Fuel Cell Energy Inc., 12th Annual SECA Workshop, Pittsburgh, PA, 26-28 July 2011. Data from slide 13.

[51] “Ultra High Efficient Power Generation with BlueGen in an Increasing Renewable Energy World”, Karl Foger, Ceramic Fuel Cells Ltd., FC Expo 2012, Tokyo, 2 March 2012. Data from slide 17.

[52] “Validation of Novel Planar Cell Design for Megawatt-Scale SOFC Power Systems”, M.J. Day, NexTech Materials, 12th Annual SECA Workshop, Pittsburgh, PA, 28 July 2011. Data from slide 10.

[53] “Validation of Novel Planar Cell Design for Megawatt-Scale SOFC Power Systems”, M.J. Day, NexTech Materials, 12th Annual SECA Workshop, Pittsburgh, PA, 28 July 2011. Data from slide 16.

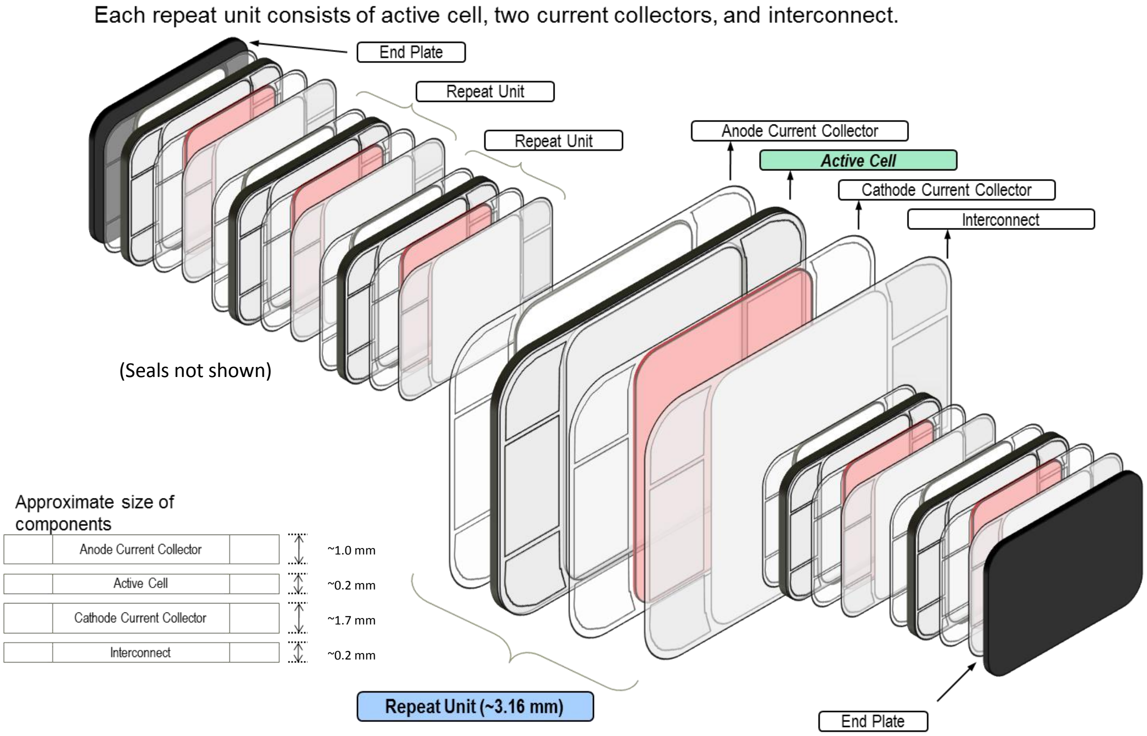

Figure 26: Schematic of SOFC Stack Construction

Parameter	Value
Operating Temperature[54]	819 °C
Power Density	291 mW/cm^2
Cell Voltage	0.8 V/cell
Operating Pressure	~1.4 atm
Cathode Stoich	2.5
Fuel Utilization	80%
System Efficiency (HHV)	49%
System Efficiency (LHV)	55%

Figure 27: Summary of Parameters for SOFC Stack

The design and manufacturing steps of the SOFC stack closely follows those of the NexTech Flexcell stack. The active cell includes a ceramic substrate (made of electrolyte material) which provides the structural support for the electrically-active components. The substrate is designed to handle the high operating temperatures in the cell and is tape cast from an yttria-stabilized zirconia (YSZ) slurry. Hexagonal holes are subsequently laser cut into the substrate for later introduction of anode catalyst. The electrolyte is also tape-cast from a different YSZ recipe, and is isostatically pressed with the much thicker substrate as a long sheet. At this point, the tape-cast rolls are cut into sheets and sintered into solid ceramic. The anode layer of nickel cobalt (Ni-Co) catalyst is spray deposited onto the sheet, which

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[54] Operating temperature is defined as the cathode exhaust gas temperature.

is then annealed in a furnace. Next, a cathode layer of lanthanum-strontium-cobalt-ferrite (LSCF) is screen-printed onto the opposite side of the sheet, and the sheet is annealed again. Finally, the sheets are laser-cut into their cell shape, and the active cell layer is complete.

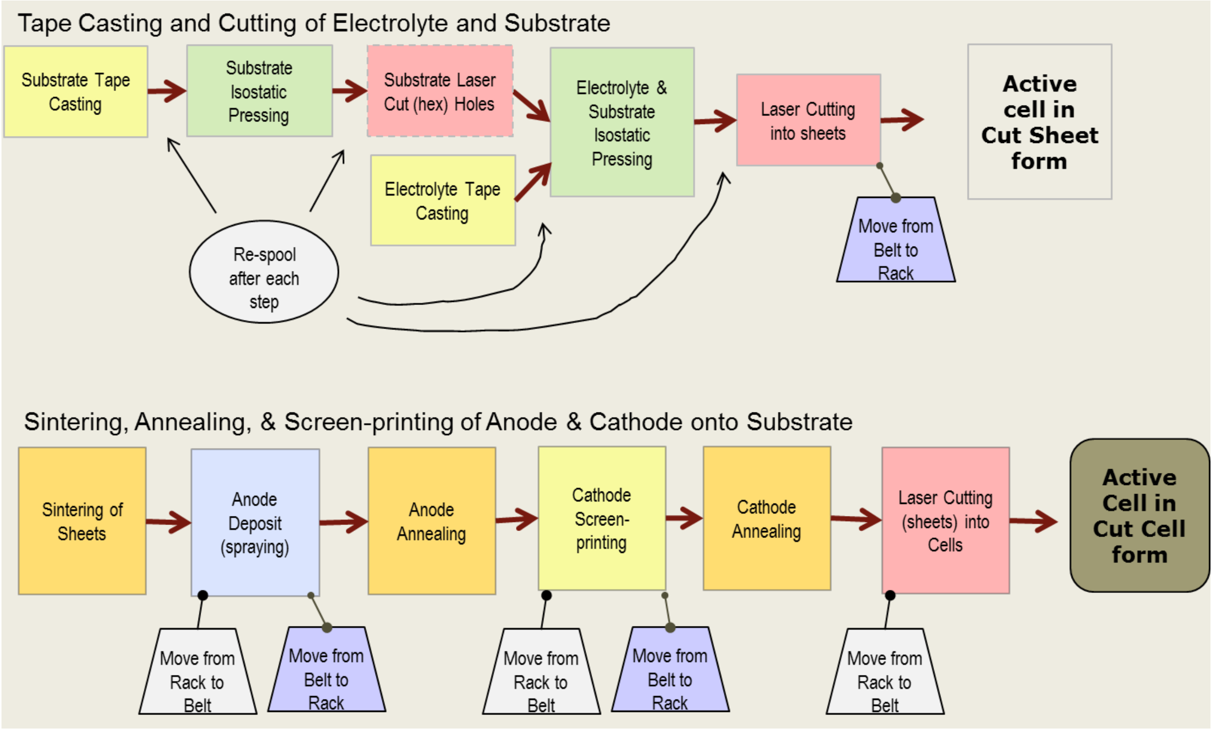

Figure 28: Manufacturing Process Train for SOFC Active Cells

Ceramic seals form the physical support structure for the anode and cathode current collectors, and are tape-casted from similar YSZ slurries at different thicknesses, stamped into appropriate shapes, and sintered at high temperature. The anode current collector is made from nickel foam which is stamped into shape and washcoated with nickel oxide catalyst. The cathode current collector is made from expanded metal mesh stainless steel which is stamped into shape and sprayed with a manganese cobalt oxide (MCO) to inhibit oxidation. Finally, the interconnect is a thin sheet of expanded metal mesh stainless steel, which is also stamped into shape and sprayed with a layer of MCO.

The fuel stack consists of several of these four layer repeated units. The number of repeated units depends on the desired electrical efficiency and electrical power output of the fuel cell stack, which determines its size. Our cost model assumes a high degree of automation in the manufacturing process (see Figure 28 and Figure 29 above). Because of the large number of part processing and handling steps—many individual parts are repeatedly cut, stamped, sprayed, and annealed—the complexity of the process train is a large contributor to part cost, especially at lower manufacturing rates. It is anticipated that a simpler stack design requiring fewer annealing[55] and part handling steps would further reduce manufacturing cost of the SOFC stack.

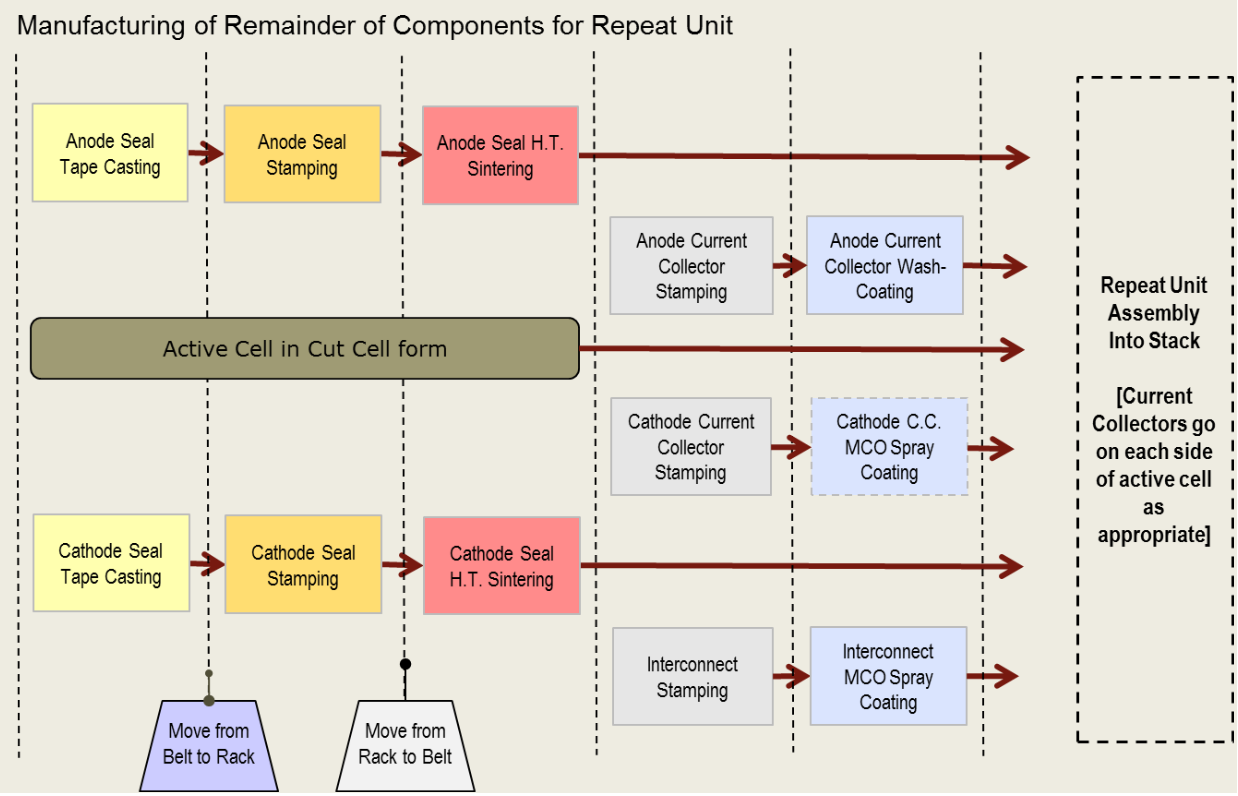

Figure 29: Manufacturing Process Train for SOFC Repeat Unit

4.3.2 Fuel Cell Balance of Plant

4.3.2.1 Common FC BOP Parts

In addition to the air supply system discussed in Section 4.1.2.2 above, the FC Subsystem BOPs for the three systems share a number of other common parts. They are briefly described below. There is one of each part per system unless otherwise noted. These parts comprise the entirety of the FC BOP for all

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[55] Versa Power Systems reports that they co-fire all layers of their SOFC cells in a single sintering step. "Cell and Stack Development at Versa Power Systems," Brian Borglum, 10th Annual SECA Workshop, Pittsburgh, PA, 15 July 2009.

FC BOP Component	Cost and Scaling Relationship	Cost Basis
Pressure transducer	$80 per part at 10,000/year, 0.95 learning curve factor.	AST 4000 Pressure sensor http://www.astsensors.com/files/pdf/AST4000-OEM-pressure-transducer.pdf
Over-pressure cutoff valve	$23 per part at 10,000/year, 0.95 learning curve factor	Grainger Air Pressure Switch http://www.grainger.com/Grainger/items/3FHX3?Pid=search#
Hydrogen purge valve	$23 per part at 10,000/year, 0.95 learning curve factor	Estimate based on ACDelco 214-641 Vapor Canister Purge Valve
Hydrogen piping	$96 for an 80 kWe system at 100k/year with a 0.1 exponential scaling factor on system size and a 0.97 learning curve factor	based on a comparison analysis against the 80 kW automotive system.
System controller	$82.50 for 500k/year	Cost based on rough DFMA-like analysis (analogous to method in automotive analysis) with a 25% vendor markup.
Current sensor (2 per system)	$10 for a 1 kWe system at 10,000/year with a 0.5 exponential scaling and a 0.95 learning curve	Engineering estimate.
Voltage sensor	$8 for a 1 kWe system at 10,000/year with a 0.5 exponential scaling and a 0.95 learning curve.	Rough Estimate based on a small Hall Effect sensor in series with a resistor
Fasteners	Set to be 40% of the calculated cost of wiring and piping BOP items, including wiring, cathode ducting, hydrogen piping, and any coolant piping, if applicable	Engineering estimate.

Figure 30: Cost, Scaling, and Basis for Common FC BOP Parts

systems with the exception of coolant systems for LT and HT PEM. Because the coolant systems operate at different temperatures, they are slightly different and will be discussed in their own sections below. The SOFC FC BOP consists of only the common parts.

4.3.2.2 Unique LT PEM BOP Components

The LT PEM system uses a 60°C water-based coolant loop modeled on automotive cooling systems. In addition to standard automotive components (radiator and fan, coolant reservoir, coolant pump, thermostat and bypass valve) the system also includes a de-ionizing (DI) filter[56] to remove metallic contaminants from the coolant and a CHP coolant heat exchanger to allow heat transfer to the building heat loop.

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[56] A DI filter is needed to remove ions from the coolant that would impart electrical conductivity to the fluid and short circuit the fuel cell. The DI filter is based on a simple plastic canister filled with a commercial DI resin.

4.3.2.3 Unique HT PEM BOP Components

The HT PEM system uses a 160°C oil-based coolant loop similar to that used in the LT PEM system. Additionally, activated carbon bed are used on both the cathode and anode stack exhaust streams to capture fugitive phosphoric acid from the stack and prevent it from migrating downstream to foul the catalyst are create acidic conditions.

4.3.2.4 Unique SOFC BOP Components

As discussed above, the SOFC FC BOP does not include any components outside of the common components.

4.3.3 Fuel Cell Subsystem Assembly

For all three systems, FC Subsystem assembly cost is based on number of BOP components and assumed assembly times for each of the various components. Components are split into major, minor, and piping components, with each having an associated placement time and fixation time. Piping components also have bending time, welding time, and threading time. With a total assembly time calculated, it is possible to determine a machine rate cost based on the cost of labor and the cost of an assembly station, giving a final cost contribution of the assembly step.

4.4 Fuel Processor Subsystem

4.4.1 Reactor

4.4.1.1 LT PEM

For the LT PEM FCS, all three reaction zones of the reactor are used with the monoliths for steam reforming (SR), WGS, and PROX each being wash-coated with their corresponding catalyst. This is necessary due to the sensitive nature of the LT PEM membrane: even low amounts of carbon monoxide (CO) in the anode inlet stream (<5ppm) would lead to poisoning of the anode catalyst. The combination of WGS and PROX processes ensures that reformate CO content is reduced as low as possible. PROX operation requires the full set of PROX-related parts to be included in the reactor, including catalyst, air inlet port and feed tube, and the PROX air mixing plate.

	1 kWe System	5 kWe System	25 kWe System	100 kWe System
Reactor Outer Diameter (cm)	9	12	23	23
Reactor Height (cm)	20	48	104	104
Reactor Volume (L)	1.2	5.4	41.5	41.5

Figure 31: Table of Reactor Dimensions for LT PEM System

4.4.1.2 HT PEM

The 160°C operating temperature of the HT PEM system imparts a higher degree of CO tolerance compared to the cooler running LT PEM system. Consequently, the HT PEM system does not make use of the PROX reaction, but still includes a WGS catalyst monolith. By removing the PROX from the design, it is possible to eliminate any reactor components specific to the PROX operation. This includes not only the PROX catalyst, but also the air feed tube and inlet port and the PROX air mixing plate.

	1 kWe System	5 kWe System	25 kWe System	100 kWe System
Reactor Outer Diameter (cm)	9	12	23	23
Reactor Height (cm)	20	48	104	104
Reactor Volume (L)	1.2	5.4	41.5	41.5

Figure 32: Table of Reactor Dimensions for HT PEM System

4.4.1.3 SOFC

The reactor for the SOFC system, like the HT PEM reactor, lacks the parts associated with the PROX reaction (PROX catalyst, air feed tube, inlet port, mixing plate) and also eliminates the WGS reaction components.

The SOFC reactor has additional deviations from the base reactor design. In order to have a higher reformate exit temperature (~600°C), the reformate exit port is positioned on the side of the reactor, towards the bottom, rather than at the top of the reactor. A solid baffle is placed above the exit port, blocking the reformate gas from filling the empty cavity above. This space, which would ordinarily contain monoliths for WGS and PROX, is thus a gas-filled void for thermal standoff.

For a given system size, the SOFC reactor is much smaller than the reactor for either PEM system. This is because, unlike the HT and LT reactors, which strive to reform as much NG as operating conditions will allow, the SOFC reactor only converts 25% of the NG to hydrogen using the SMR reaction. The rest of the reaction is assumed to occur as internal reforming in the SOFC stack. Because of the reduced size of reactors, it is possible to reduce the number of reactors required in the FP Subsystem for the 100 kWe SOFC system. This subsystem, like the others, has but one reactor. This allows significant cost savings not only in reactor materials and manufacturing, but through the elimination of redundant BOP components.

	1 kWe System	5 kWe System	25 kWe System	100 kWe System
Reactor Outer Diameter (cm)	9	12	23	23
Reactor Height (cm)	10	14	22	65
Reactor Volume (L)	0.6	1.6	8.9	25.7

Figure 33: Table of Reactor Dimensions for SOFC System

4.4.2 Fuel Processor Balance of Plant

4.4.2.1 Common FP BOP Parts

In addition to the fuel and water supply systems discussed in Section 4.1.2.5, several other components are common in the FP Subsystem BOP across all three systems. They are briefly described below. There is one part per system unless otherwise noted.

- Gas flow control solenoid: $180 for 1/year with a learning curve of 0.98, based on quote for a Bosch Natural Gas Injector Part # 0280158821 from Five O Motor Sports at a quantity of 400 units. LT and HT PEM systems have two per reactor (eight total for 100 kWe systems), one for the primary NG fuel feed and one for the additional NG fuel feed to the burner. SOFC systems lack the burner fuel line and only need one solenoid per reactor, for the primary fuel line.

- NG mass flow sensor: $59 for 10,000/year with a learning curve of 0.98, based on quote for a Jet Performance 69147 Powr-Flo Part # 69147. Like the gas flow control solenoids above, LT and HT PEM systems have two per reactor, one for the primary fuel feed line and a second for the burner fuel feed line. SOFC systems have one per reactor.
- Temperature Sensor: All systems have temperature sensors to monitor the reactor body temperature as well as all reactor inlet and outlet stream temperatures. Each application has a different sensor part and price quote depending on application and probe type. The reactor body temperature sensor is a Love RTD sensor Part # RTD-646 quote obtained from Grainger for $112 as single quantity. The inlet temperature sensor is an Omega sensor Part # RP-20-2-100-1/8-2-E-T, with a single-quantity manufacturer's quote of $60. There are two of these per reactor. Finally the reactor outlet temperature sensor is a Dwyer sensor Part # TE-IBN-D0844-14, with a single-quantity quote of $22. As with the inlet sensor, there are two of these per reactor. The learning curve factor for all temperature sensors is 0.96.
- Flammable Gas Alarm Sensor: This critical component is represented by a McMaster Carr price quote of $640 at a quantity of one with a 0.96 learning curve factor.
- Check Valve: Each input to the reactor features a check valve, thus there are three per reactor in the LT and HT PEM systems and two per reactor in the SOFC system. The check valves are Plast-O-Matic Part # CkM050V-PV with single quantity quotes from J. O. Galloup Company of $37 and a learning curve factor of 0.99.

4.4.3 Fuel Processing Reactor Assembly

The FP reactor is specifically designed for low cost and ease of assembly. The relatively small size and light weight of the individual components facilitate manual handling and assembly on custom workstation jigs. Reactor assembly is modeled as taking place at five custom workstations:

Station 1: Burner Exhaust Shell Attachments
Station 2: Burner Shell Attachments
Station 3: Fuel-Reformate Shell Attachments
Station 4: Induction Brazing of Top Head Assembly
Station 5: Laser Welding of Bottom Assembly

Only three primary pieces of equipment are required: laser welder to affix the bottom plate to the cylinder shells, a tack welder to temporarily hold parts in position, and an induction brazing unit to braze the top head to the cylinder shells. Process step times for part acquisition, part placement, processing, and part removal are summed at each station. Capital cost of each station is assessed and utilization rates and number of parallel workstations to achieve full annual production is computed.

Assembly of the FP BOP components with the reactor is separately tabulated via a simplified method. The number of major system components, minor system components, fluid hose segments, and individual wiring harness are summed and then multiplied by their corresponding placement and fixation time. This time total is then added to the expected fluid pipe assembly time which is determined by multiplying the total number of pipe segments by representative number of pipe bends per segment, time per bend, pipe segment placement time, welds per pipe, and weld time.

5 Performance Results

While the focus of this report is on a cost assessment, system cost is meaningless without a clear picture of the systems being analyzed. Consequently system level performance is summarized in Figure 34 on both the basis of net electrical efficiency and the amount of CHP heat produced. As previously discussed, the systems are not normalized to a common system electrical efficiency: rather the systems are designed to take advantage of their strengths with the resulting system efficiency computed from that design. Performance differences based on power level are not recognized in the analysis, although future iterations of this work could incorporate such distinctions.

All systems are configured for combined heat and power (CHP) operation. Because they have varying levels of electrical system efficiency, they also have varying level of waste heat available for the CHP load. Building heating loads vary[57] and may not always have sufficient thermal demand to absorb FCS waste heat. However, for purposes of this analysis, we assume a building heat load is always available to absorb available FCS waste heat

We define the overall system (heat + electric) efficiency as:

$$Overall\ System\ Efficiency = \frac{(Net\ System\ kWelectric + Captured^{58}\ Waste\ Heat\ kWthermal)}{(HHV_{NG}\ \dot{m}_{NG})}$$

An analysis of building thermal loads suggests that even low quality waste heat (~30°C) is useful in a well-designed CHP system. Consequently, all three systems technologies are able to achieve a high system overall efficiency. Given the complexity of building loads, seasonal fluctuations, and types of applications, a detailed analysis is beyond the scope of this work. Thus, instead of reporting a computing system overall efficiency, we assign a 90% overall efficiency to all systems and compute available CHP waste heat accordingly[59].

	LT PEM	HT PEM	SOFC
Design Cell voltage	0.676 volts/cell	0.6 volts/cell	0.8 volts/cell
Design Power Density	408 mW/cm^2	240 mW/cm^2	291 mW/cm^2
Net Elec. System Efficiency Higher Heating Basis Lower Heating Basis	 35% 39%	 27.7% 31%	 49% 55%
Assumed Overall System Efficiency (HHV)	90%	90%	90%
CHP Heat Load Available (for 25kWe systems)	40 kW$_{thermal}$	56kW$_{thermal}$	21 kW$_{thermal}$

Figure 34: Summary of System Level Performance

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[57] "Examining the integration of fuel cell systems into buildings through simulation", Whitney G. Colella, Viraj Srivastava, Pacific Northwest National Laboratory, Proceedings of the ASME 2012 6th International Conference on Energy Sustainability & 10th Fuel Cell Science, Engineering and Technology Conference, July 23-26, 2012, San Diego, CA, ESFuelCell2012-91474.

[58] We define captured waste heat as the thermal load transferred into the CHP loop. Thus, captured waste heat is a function of the FCS waste heat flow, the CHP HX, and the temperature requirements of the CHP load.

[59] Overall system efficiency was computed from Hysys™ simulations and >=90% was achieved for all technologies. However, it was judged that there was insufficient modeling detail to reliably discern between the technologies, so a common estimate of 90% overall system efficiency was used.

6 Cost Results

The cost analysis yields results detailing the final estimated capital cost of entire fuel cell power systems, at different annual manufacturing rates and installed capacities. Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component.

Modeling results for LT PEM, HT PEM, and SOFC systems underscore a few salient points:

- SOFC systems are projected to have the lowest system capital cost of the three technologies examined.
- As system size and system manufacturing rate increase, system cost decreases.
- In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing costs per kilowatt than increasing manufacturing rate over the range of values plotted.
- For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output.
- Across the range of system size levels, the greatest contributors to the capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing half or more of the total system capital cost in all cases.
  The primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.
- The primary cost drivers for the FP BOP may include NG compressors/blowers, water pumps, flammable gas alarm sensors, gas flow control solenoids, pressure regulators, and/or condensers, depending on fuel cell system size and type.

A substantial quantity of cost results are generated from the analysis since there are three technologies, four system power levels, and four annual manufacturing rates (plus the lower level costs associated with the six major subsystems and the individual components of each subsystem). Consequently, to aid in the analysis of these data, graphical data (column and pie charts) are presented in this section, and tabular detailed information are presented in the report appendices. Furthermore, only the "corners" of the data range (i.e. the lowest (1kWe) and highest (100kWe) power levels and the lowest (100 systems/year) and highest (50k systems/year) manufacturing rates) are graphically displayed to illustrate trends without overwhelming the reader with repetitive charts. Data for all systems is contained in the appendices.

6.1 LT PEM Costs

6.1.1 LT PEM System Costs

Figure 35 and Figure **36** display the final results for the LT PEM system broken down by system size and manufacturing rate. As shown in the figures, the capital cost per unit of electric output ($/kWe) is seen to decrease dramatically both with increasing system size and increasing system annual production rate. As system size and system manufacturing rate increase, system cost decreases. In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing costs than increasing manufacturing rate over the range of values plotted. In comparing an increase in system size of 100 fold (moving from 1 kWe to 100 kWe) and an increase in manufacturing rate of 100 fold (moving from 100 systems per year to 10,000 systems per year), there is a greater reduction in system capital cost from increasing system size (an average decrease of 93% over the range of plotted values) than from increasing manufacturing rate (an average decrease of only 35%). (Plotted values do not show the effect of a change in manufacturing rate between producing 1 system per year and 100 systems per year.)

Model results indicate that, at the same cumulative global installed capacity, higher power FCSs are expected to have lower per unit capital costs ($/kWe) than lower power FCSs. For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output. This observation is shown in Figure 35 and Figure 36. For example, for a 10,000 kWe global installed capacity in one year, 100 kWe systems are 12% of the cost of 1 kWe systems ($771/kWe vs. $6,618/kWe). For a 50,000 kWe global installed capacity in one year, 5 kWe systems are 34% of the cost of 1 kWe systems ($2,185/kWe vs. $6,032/kWe). For a 250,000 kWe global installed capacity in one year, 25 kWe systems are 39% of the cost of 5 kWe systems ($760/kWe vs. $1,935/kWe). This analysis implicitly assumes that the FCS electricity and heat will be used with 100% utilization in the buildings that they serve, regardless of system size. In practice, lower power FCSs may experiencedfferent utilizations[60,61]. Also, the total market volume for lower power FCSs may be larger, allowing for higher production rates.

It can be informative to compare modeled values with current manufacturer values. The ENE Farm Program has deployed several thousand ~1 kWe LT PEM CHP systems in Japanese homes since 2005. [62] The combined capital and installation costs for these systems are roughly $43,000/kWe for Toshiba Inc. LTPEM CHP systems, $40,000/kWe for JX Oil & Energy Inc. LTPEM CHP systems, and $30,000/kWe for Panasonic Inc. LTPEM CHP systems at production rates of several thousand 1 kWe units per year.[63, 64] For a 2011 and 2012 deployment program of 5 kWe HTPEM CHP systems in the U.S., installation costs were approximately 20% of combined capital and installation costs. [65, 66] Applying this ratio, the capital

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[60] Colella, W.G. and Srivastava, V., 2012, "Examining the Integration of Fuel Cell Systems Into Buildings Through Simulation," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91474. PNNL-SA-87066.

[61] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709.

[62] ASME Fuel Cell Conference 2011, Keynote Presentation by ToHo Gas Company.

[63] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11.

[64] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11.

[65] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 5.

costs alone for the LT PEM CHP systems from Japan may be estimated as roughly 20% less, or $34,000/kWe for Toshiba Inc. systems, $32,000/kWe for the JX Oil & Energy Inc. systems, and $24,000/kWe for the Panasonic Inc. systems. For comparison, modeling results indicate a cost range of roughly $7,800/kWe to $6,600/kWe over the 1,000 sys/yr to 10,000 sys/yr range, respectively. These modeling results and manufacturer values are consistent if one considers that this modeling work does not consider any of these costs: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. These costs can increase total capital costs by a factor of three or four at low production levels. In particular, non-recurring R&D costs are significant.

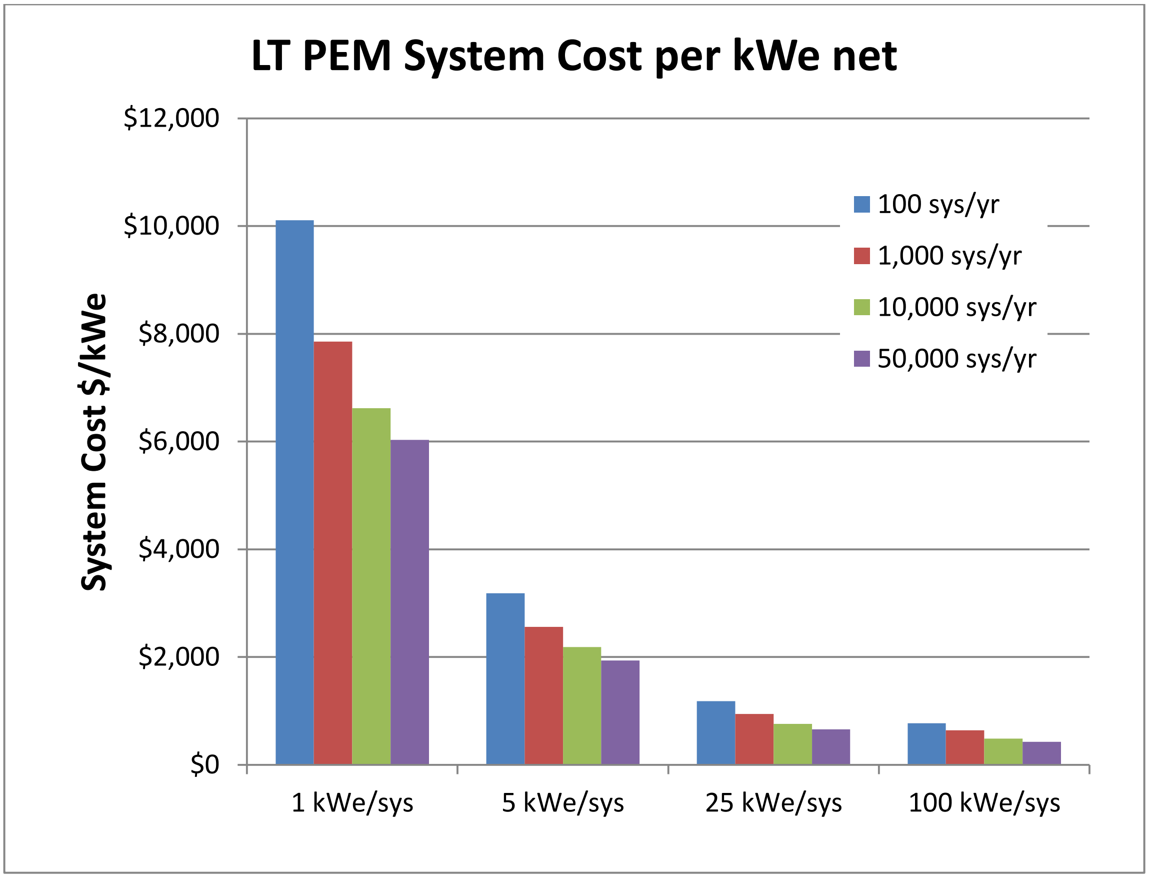

Figure 35: Cost Results for LT PEM System

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[66] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 5.

	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$10,106	$3,182	$1,180	$771
1,000 sys/yr	$7,854	$2,556	$941	$637
10,000 sys/yr	$6,618	$2,185	$760	$486
50,000 sys/yr	$6,032	$1,935	$658	$428

Figure 36**: Table of Cost Results for LT PEM System, $/kWe**

6.1.2 LT PEM System Costs as a Function of Subsystem and Component Costs

Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component. Figure 37 and Figure 38 display the breakdown of total system capital costs as a function of the costs of the six major subsystems for the 1 kWe and 100 kWe system sizes. These six categories are CHP subsystem (which includes the exhaust gas heat exchanger/condenser), housing and final assembly, power electronics subsystem, cost margin, fuel processing subsystem, and fuel cell subsystem. At both size levels, the FC and FP subsystems combined account for the majority of FCS capital costs, about 70% of total capital costs at a minimum. For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at all production levels. By contrast, for the 100 kWe system, model results indicate that the FC subsystem is more expensive than the FP subsystem at lower production levels, specifically at 1,000 sys/yr and below. At manufacturing rates of 1,000 sys/yr and below, the FC subsystem accounts for about one half or more of capital costs. At higher manufacturing rates above 1,000 sys/yr, the FP subsystem costs begin to dominate over FC subsystem costs as the primary cost driver.

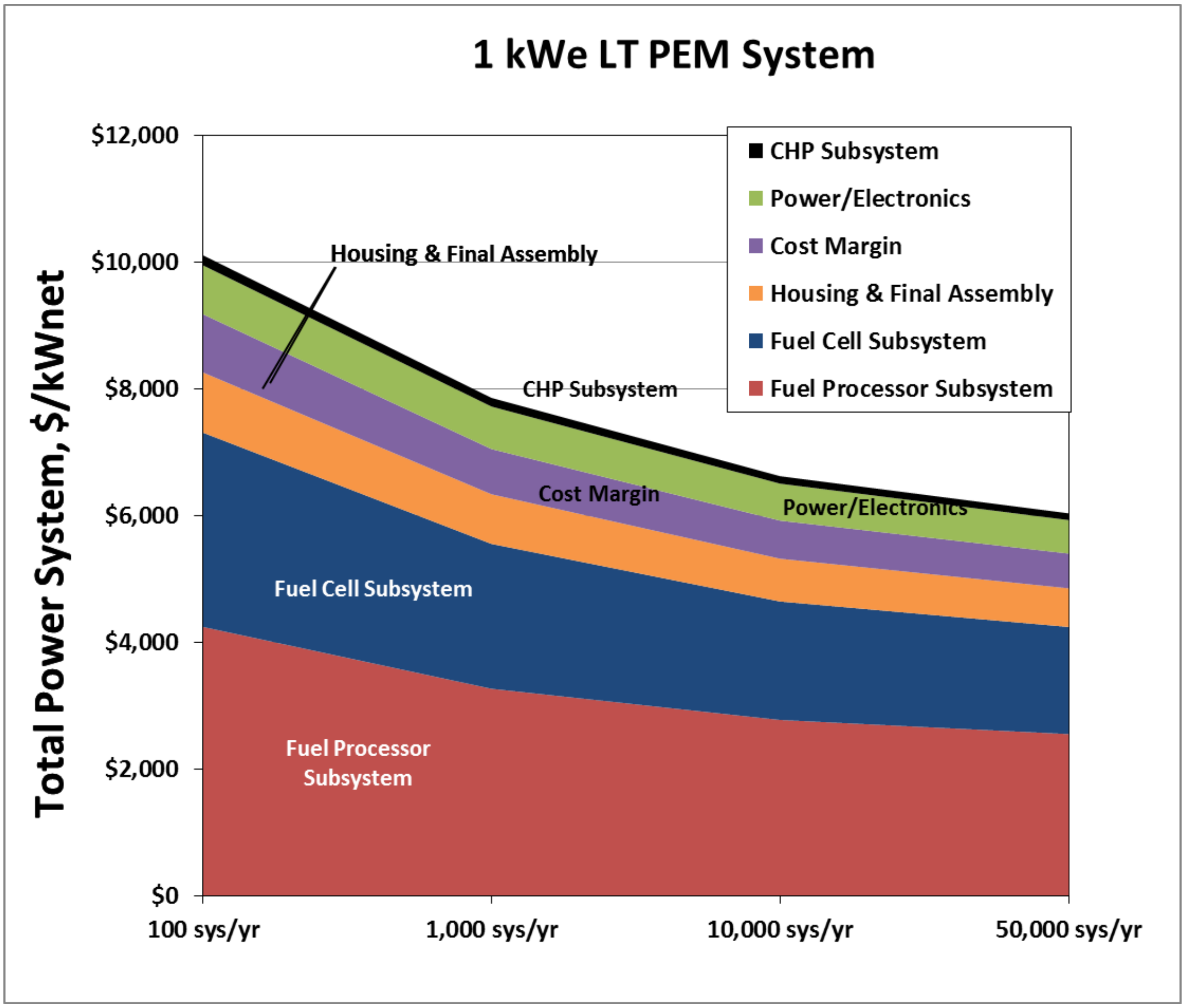

Figure 37: 1 kWe LT PEM System Cost Breakdown by Component

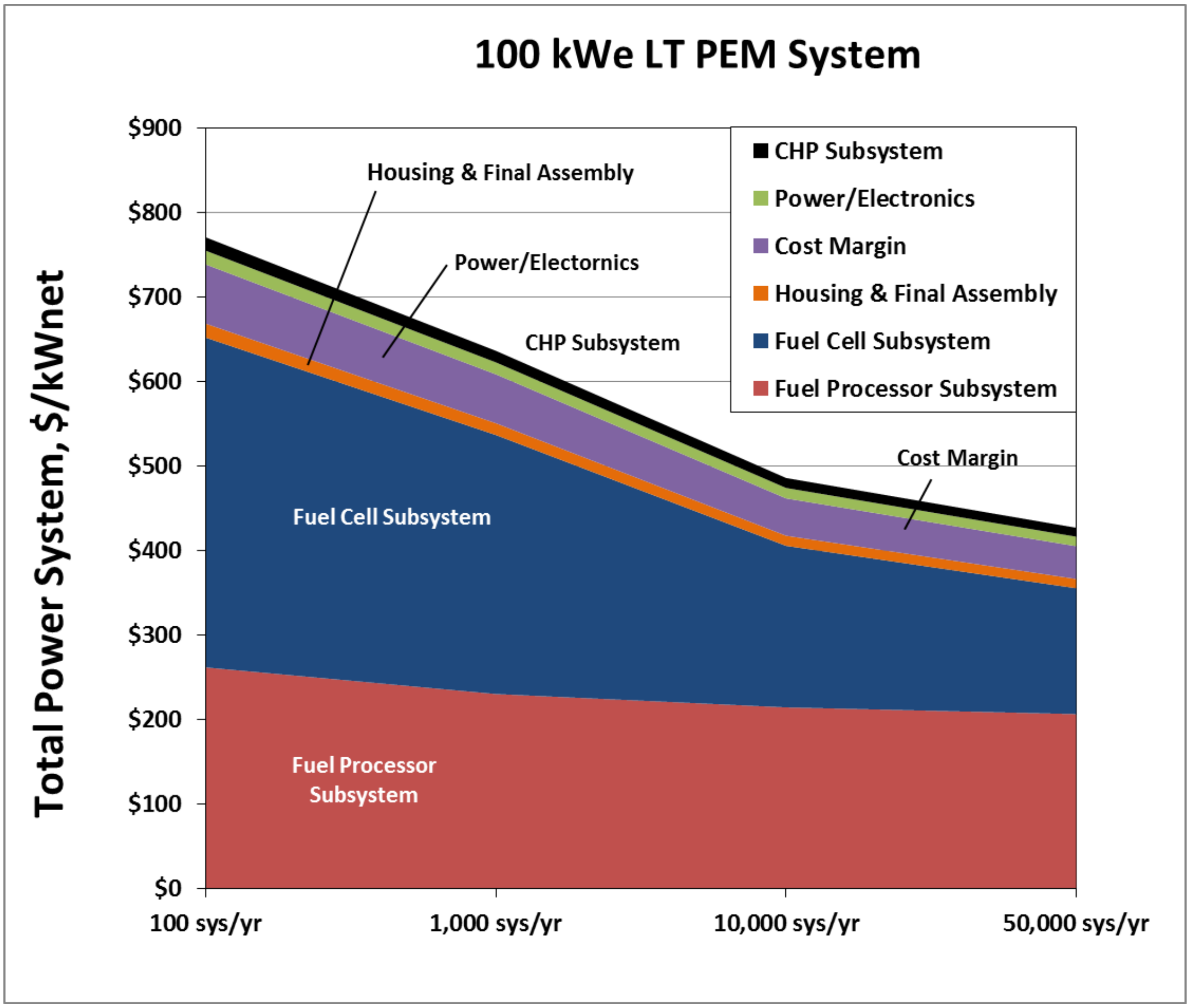

Figure 38: 100 kWe LT PEM System Cost Breakdown by Component

6.1.3 LT PEM FP Subsystem Costs

Figure 39 and Figure 40 show a breakdown of the fuel processor subsystem costs. For the 1 kWe system, the FP's costs are dominated by the BOP. This modeling result is consistent with the manufacturer test results of the Ene Farm program, which tested thousands of 1 kWe LT PEM CHP systems throughout Japanese homes, and found that a primary cost driver was the fuel processing sub-system balance of plant (BOP).[67] The Ene Farm program significantly reduced LT PEM CHP costs by focusing development efforts on the FP BOP and by finding better ways to out-source FP BOP standard components.[68]

In contrast to the 1 kWe system, for the 100kWe system, the FP's costs are dominated by the fuel processor, composed of a steam reformer (SR), water gas shift (WGS) reactors, and preferential

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[67] ASME Fuel Cell Conference 2011, Keynote Presentation by ToHo Gas Company.

[68] ASME Fuel Cell Conference 2011, Keynote Presentation by ToHo Gas Company.

oxidation unit (PROX). At higher power levels, the FP BOP component costs decline significantly as a proportion of the total. FP BOP component costs scale well with increasing system size. For example, BOP component costs decrease from about $3,000/kWe for a 1 kWe system to only $100/kWe for a 100 kWe system at a production rate of 100 sys/year.

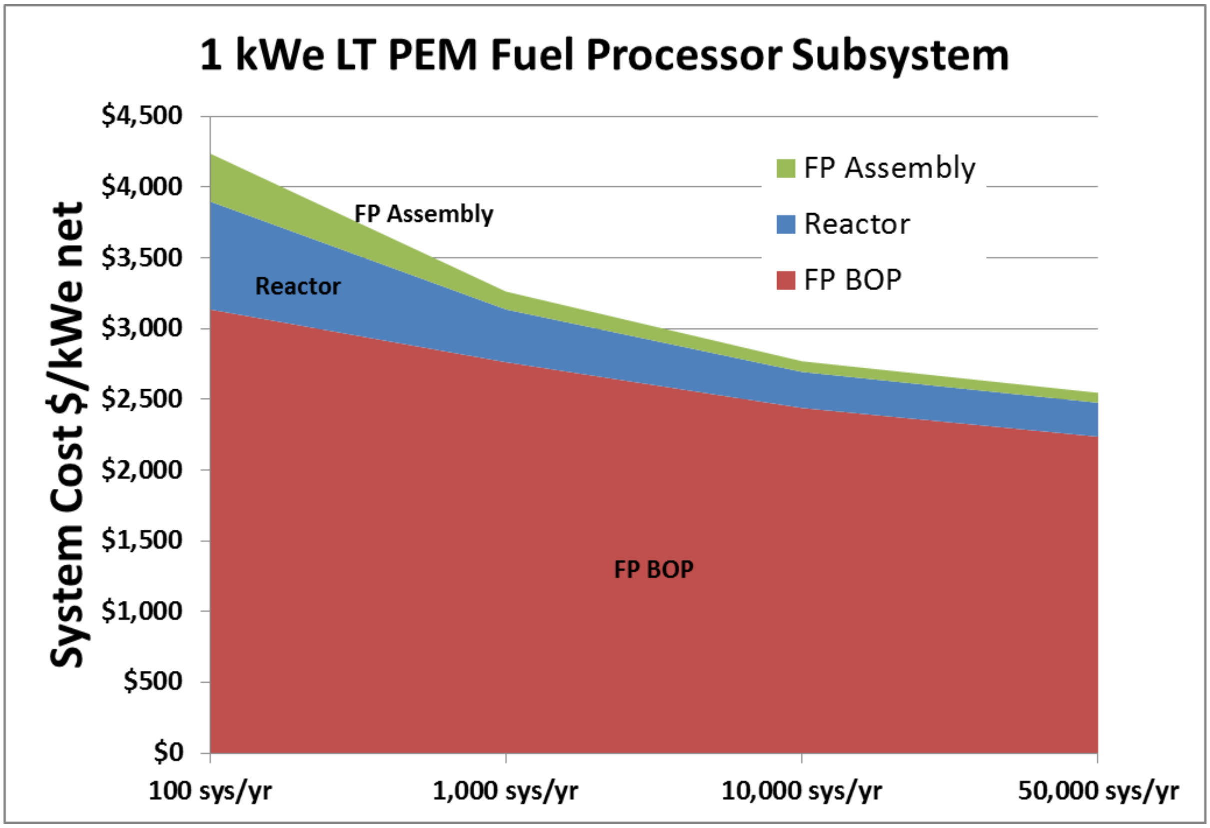

Figure 39: 1 kWe LT PEM FP Subsystem Cost Breakdown

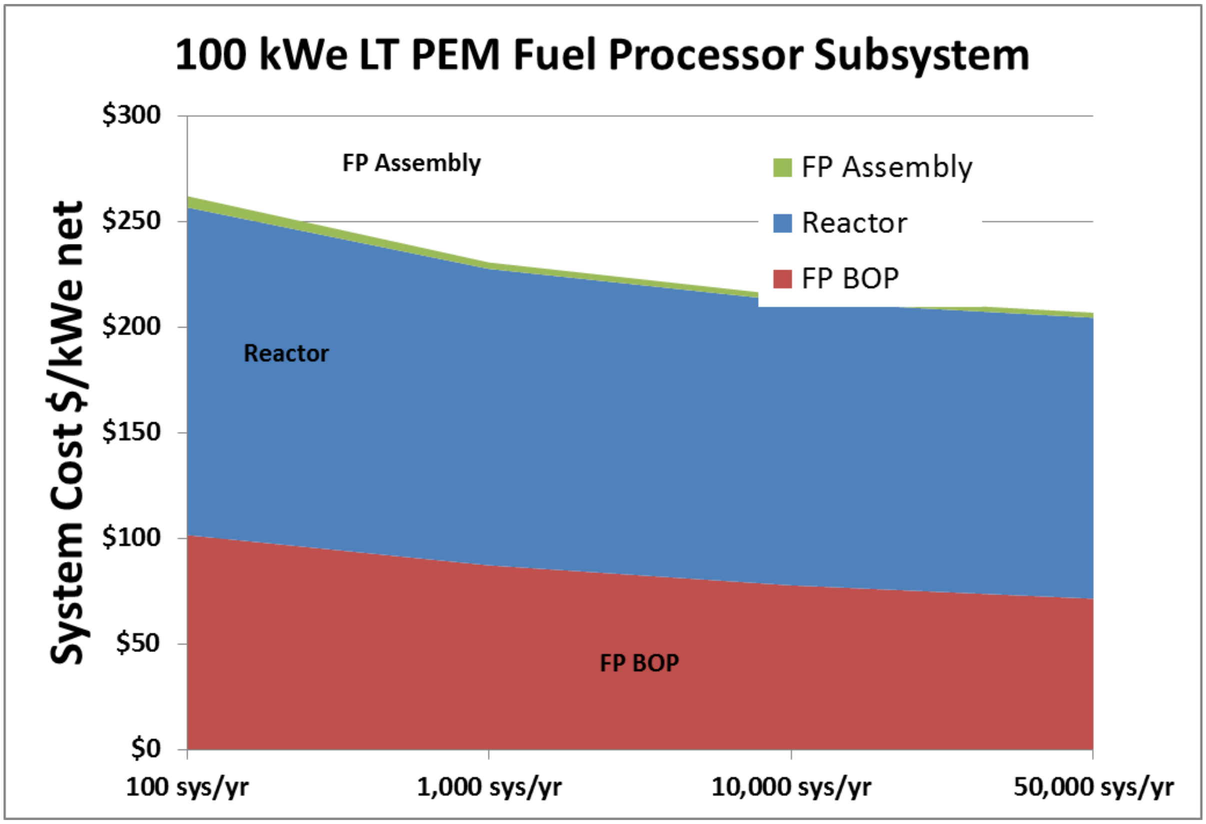

Figure 40: 100 kWe LT PEM FP Subsystem Cost Breakdown

Figure 41 through Figure 44 display the relative cost contributions of the various FP BOP components for 1kWe and 100kWe systems, at production levels of 100 sys/yr and 50,000 sys/yr (i.e. the "four corners" of the analysis). In comparing all four figures, results indicate that the primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.

At the 1 kWe rating, the primary cost driver for the FP BOP is the natural gas compressor. As previously detailed, a natural gas compressor is needed for only the 1 and 5 kWe systems based on assumed NG inlet pressure, for the system designs chosen here. At the 1 kWe rating, the next more important cost drivers for the FP BOP are the flammable gas alarm sensors followed by the gas flow control solenoids.

At the 100 kWe rating, the primary cost driver for the FP BOP is the water pump, for supplying water to the steam reforming and water gas shift reactions. The next more important FP BOP cost driver is the condenser at the outlet of the FCS exhaust gases, which is needed for condensing gaseous water in the exhaust into liquid water, which is then recycled within the system to the upstream steam reforming and water gas shift reactions. A condenser is needed to achieve "neutral system water balance,"[69] such that no additional water needs to be added to the system from an external source. For example, prior

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[69] O'Hayre, R., Cha, S.W., Colella, W.G., Prinz, F.B., *Fuel Cell Fundamentals*, 1st edition (John Wiley & Sons, Inc.: Hoboken, NJ, 2006), ISBN-13 978-0-471-74148-0, p. 285.

modeling work[70,71] indicates that to achieve neutral or positive system water balance on a particular design of a 5 kWe LT PEM FCS, the condenser outlet temperature would need to be below 65 °C.

Manufacturers may be able to obviate the need for some of this equipment or reduce equipment cost through innovative system design choices.

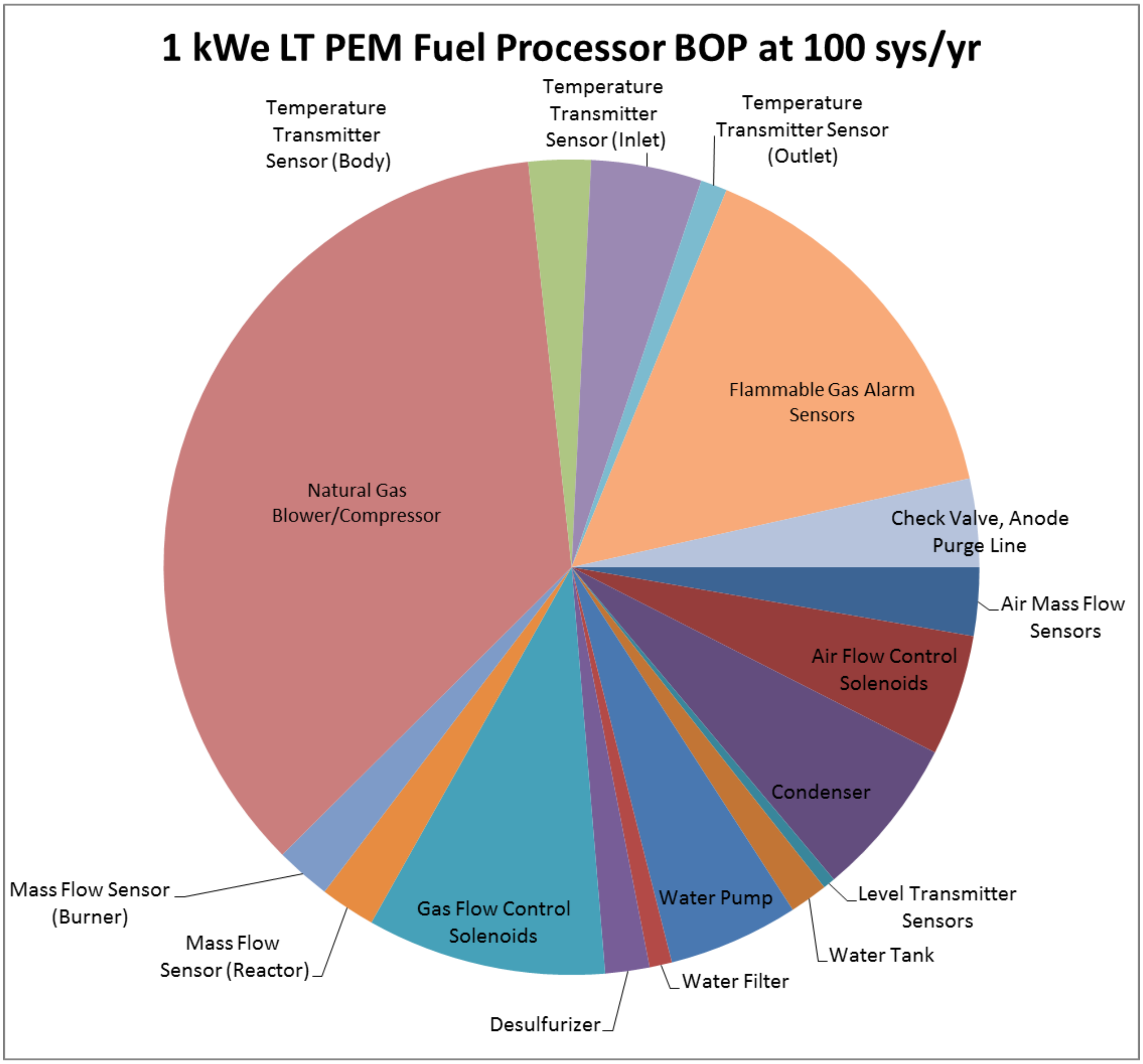

Figure 41: 1 kWe LT PEM FP BOP Pie Chart @ 100 Systems per Year

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[70] Colella, W.G. “Modelling Results for the Thermal Management Sub-System of a Combined Heat and Power (CHP) Fuel Cell System (FCS),” *Journal of Power Sources*, 118, 129-49, May 2003.

[71] Colella, W.G. *Combined Heat and Power Fuel Cell Systems*, Doctoral Thesis Dissertation, Department of Engineering Sciences, Oxford University, Oxford, UK, 2004.

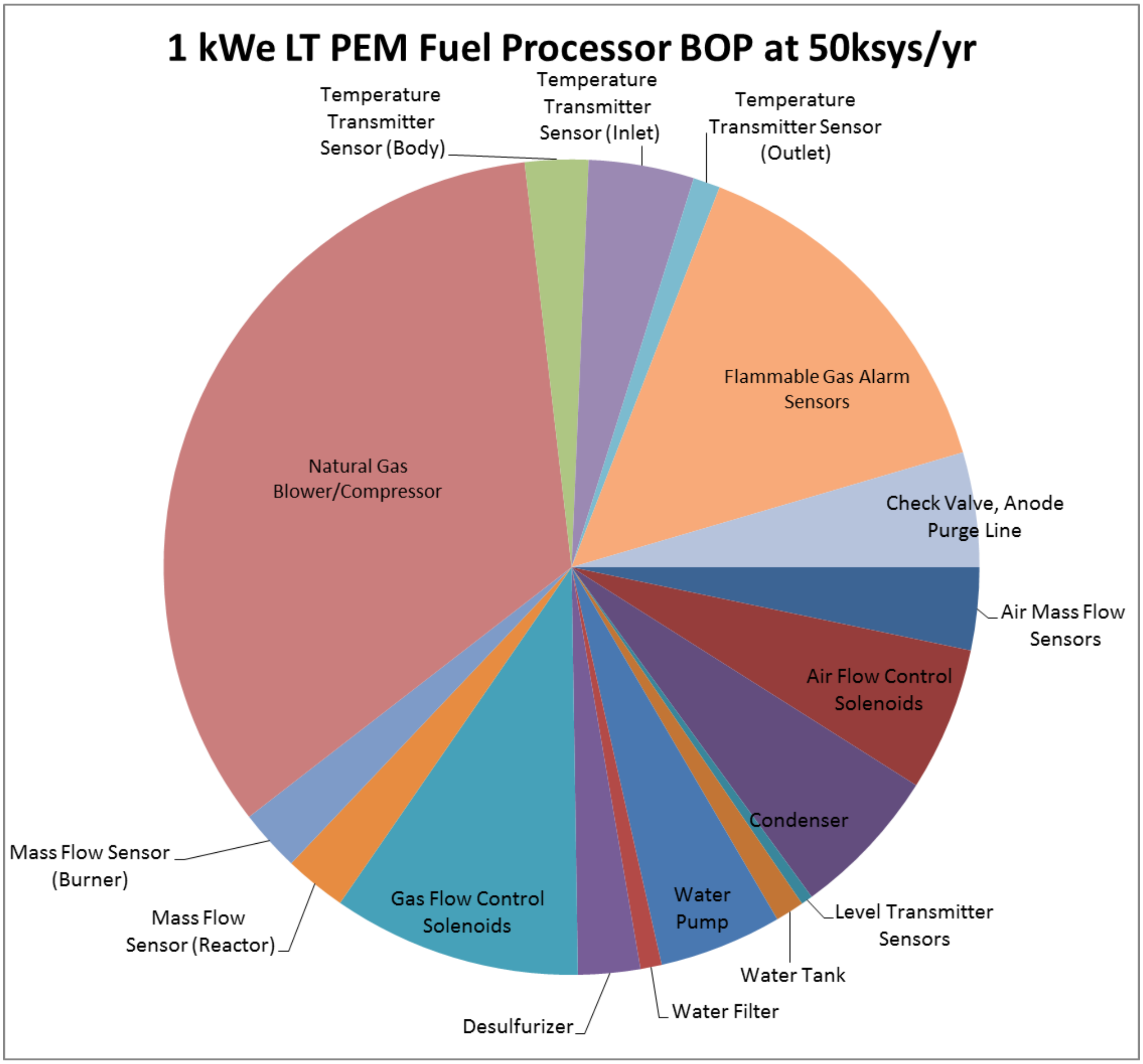

Figure 42: 1 kWe LT PEM FP BOP Pie Chart @ 50k Systems per Year

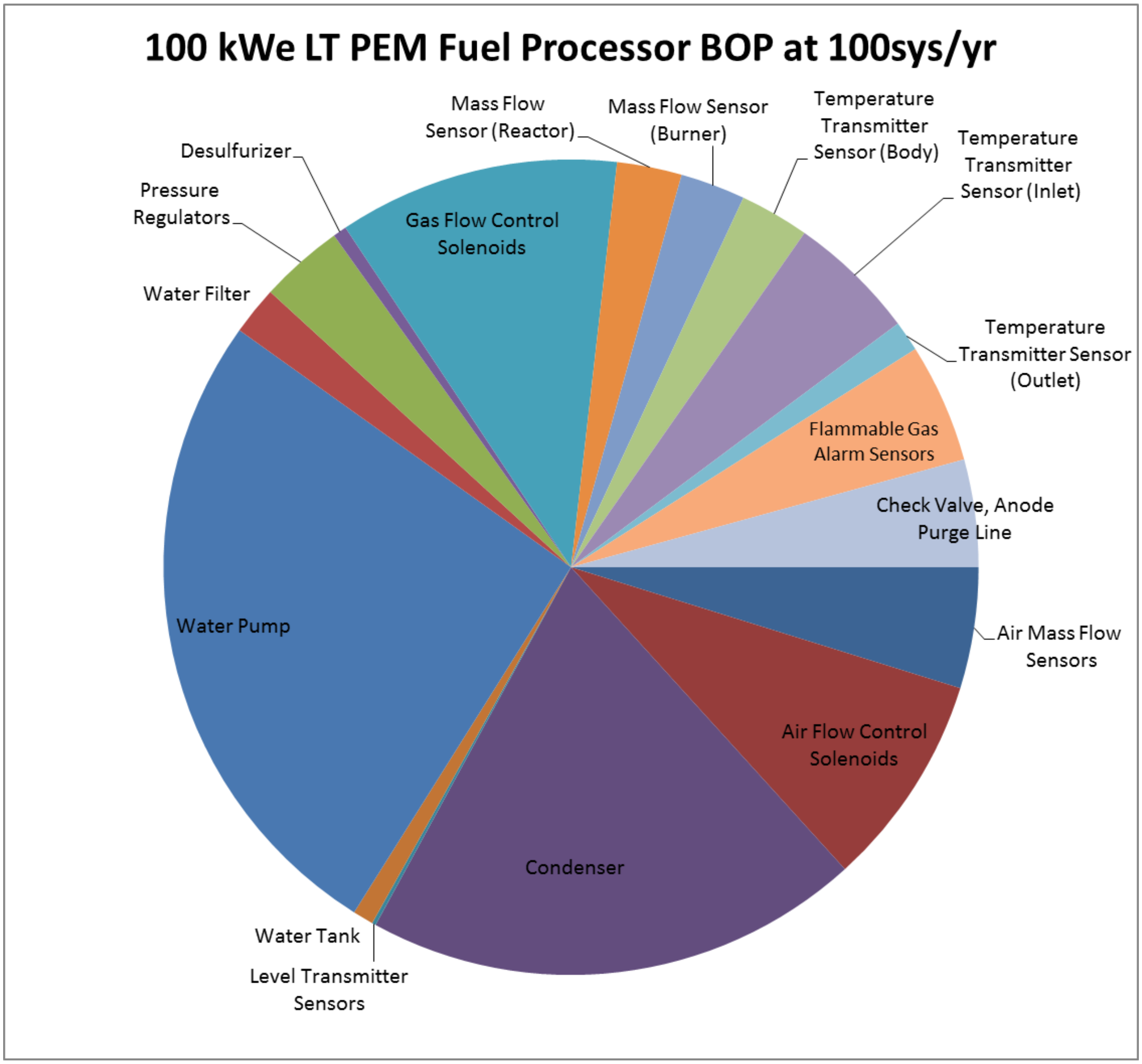

Figure 43: 100 kWe LT PEM FP BOP Pie Chart @ 100 Systems per Year

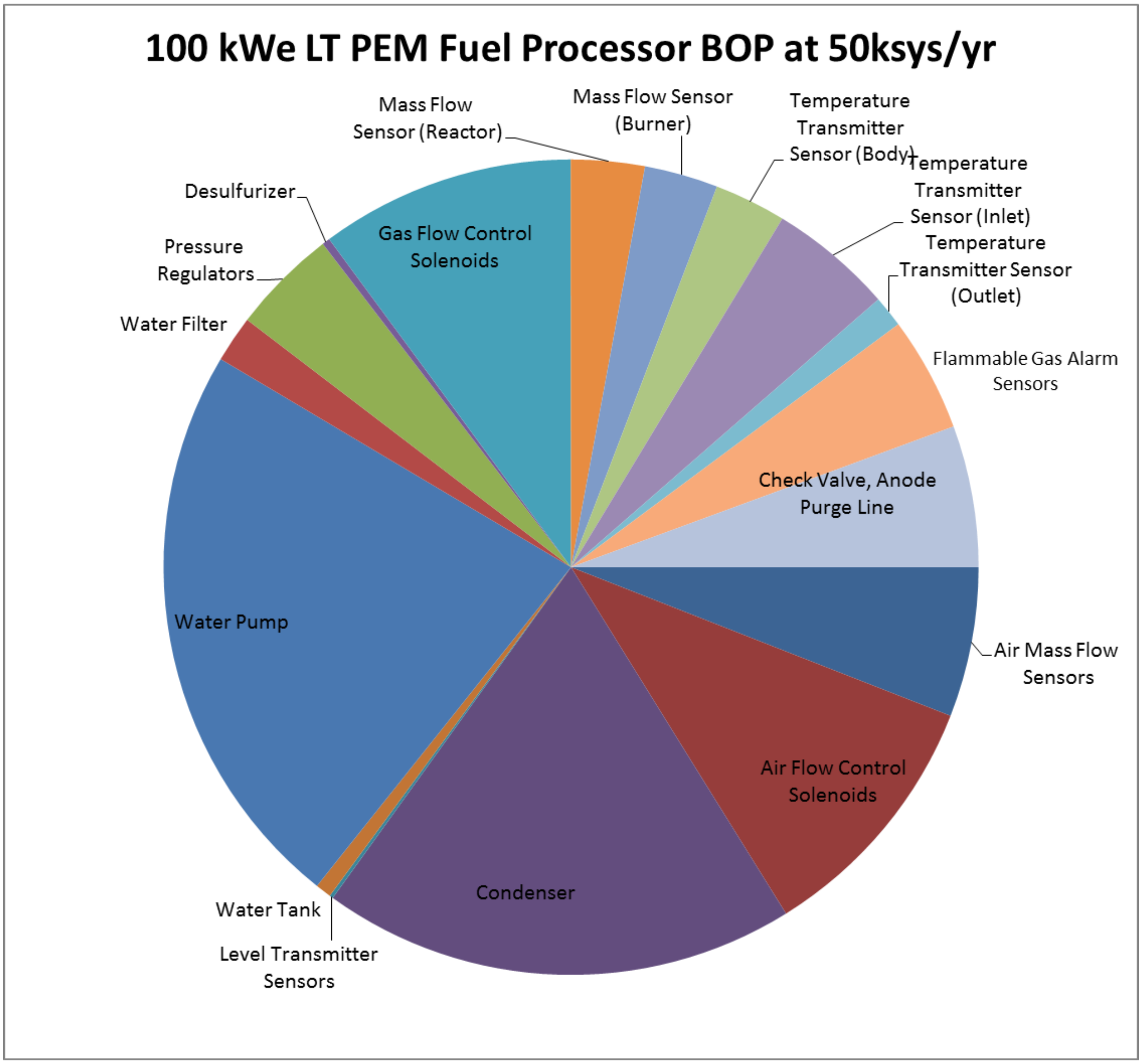

Figure 44: 100 kWe LT PEM FP BOP Pie Chart @ 50k Systems per Year

6.1.4 LT PEM FC Subsystem Costs

Figure 45 and Figure 46 display the breakdown of costs within the fuel cell subsystem by FC assembly, FC BOP, and FC stack. As observed with the FP subsystem, at low power (1kWe), the subsystem cost is dominated by the BOP components. At 1 kWe, BOP component costs constitute as much as 70% of FC subsystem costs. At high power (100kWe), the FC stack cost dominates. At 100 kWe, FC stack costs constitute as much as 80% of FC subsystem costs. Fuel cell subsystem assembly costs include the costs of the assembly of the BOP components and the costs of assembly of the BOP with FC stack. These costs are fairly negligible. (Assembly of the fuel cell stack is included within stack cost.)

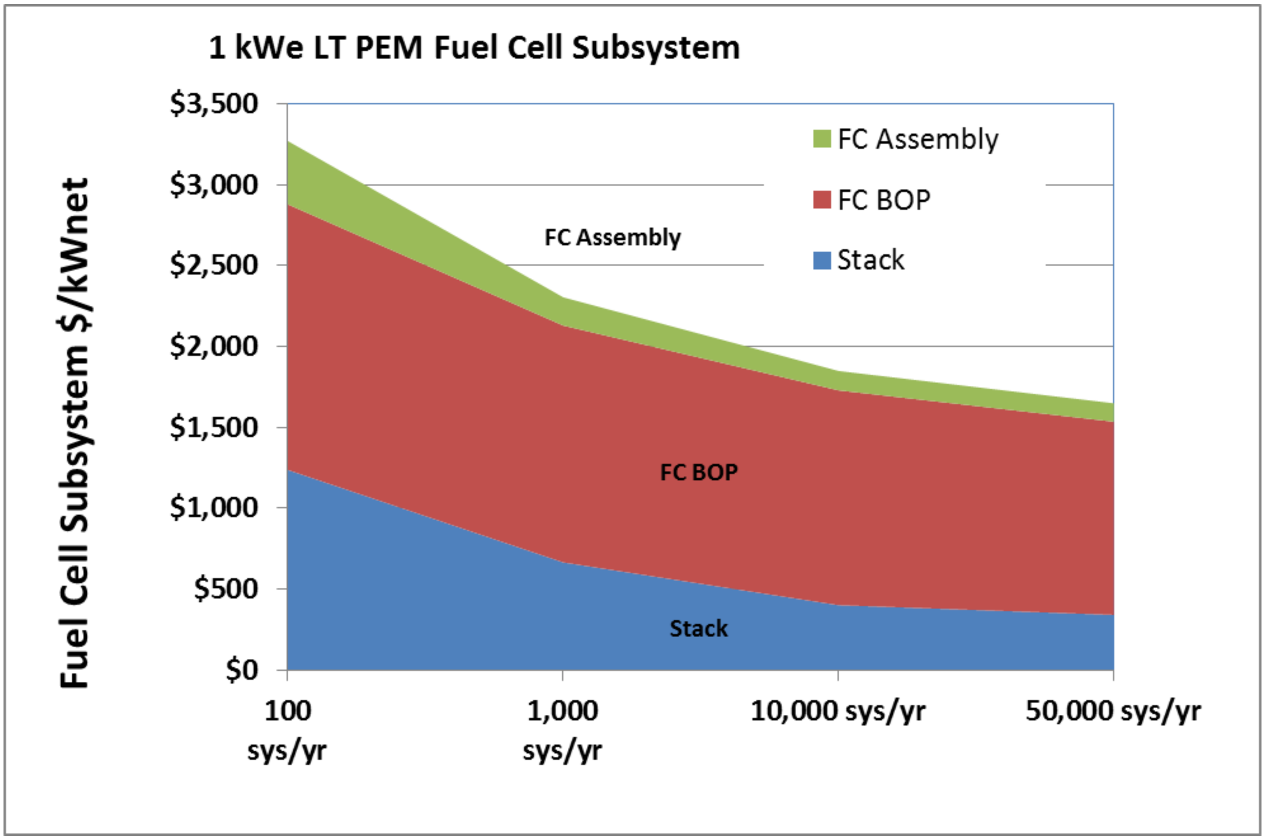

Figure 45: 1 kWe LT PEM FC Subsystem Cost Breakdown

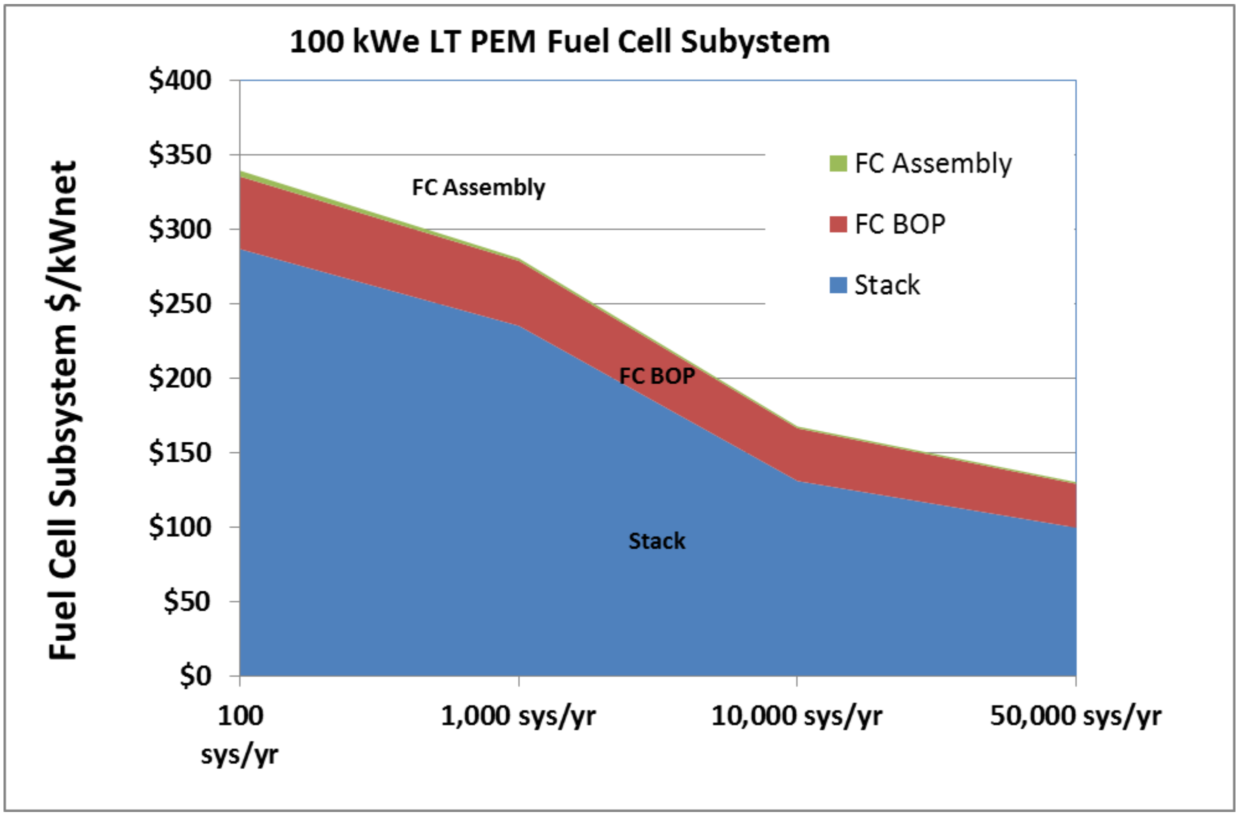

Figure 46: 100 kWe LT PEM FC Subsystem Cost Breakdown

6.1.5 LT PEM CHP and Grid-Independent Costs

Results also indicate the incremental cost of adding on either CHP capability or grid-independent capability. Figure 47 displays the baseline system cost[72] and the incremental cost of adding on CHP capability and the incremental cost of adding on grid-independent capability. The incremental cost of adding on a CHP capability includes the capital cost of additional heat exchangers needed for conveying anode and/or cathode off-gas heat to a building's heating system. Heat exchanger inlet/outlet temperatures are based on prior modeling work[73] on integrating CHP FCSs into large and small office commercial building systems. The incremental cost of adding on grid-independent capability includes the cost of additional power electronics and battery components. Results indicate that the marginal increase in cost between producing a basic system that is not capable of CHP and producing a more advanced FCS that is capable of CHP is in fact quite small: CHP capital costs represent only 1% to 2% of the overall capital cost of such a system. Results also indicate that the marginal increase in cost between producing a basic system that is not capable of grid-independent operation and producing a

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[72] Please note that the "baseline system" shown in the "Marginal Increase in System Cost from CHP and Grid-Independent Operation" figures is different from the "baseline system" referred to throughout the rest of the report. Throughout the rest of the report, the baseline system includes all components needed for CHP operation but does not include additional components needed for grid-independent operation.

[73] Colella, W.G. and Srivastava, V., 2012, "Examining the Integration of Fuel Cell Systems Into Buildings Through Simulation," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91474. PNNL-SA-87066.

more advanced FCS that is capable of grid-independent operation is significant: grid-independent capital costs represent between 9% and 10% of the overall capital cost of such a system. For example, at 50k sys/yr, for a 1 kWe FCS, this amounts to an increase in cost of about $600/kWe. In summary, for a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 1% and 3% and for adding grid-independent capability, it is between 10% and 12% of the base cost. By contrast, for a 100 kWe FCS at 50 k sys/yr, the marginal increase in capital cost from adding either CHP capability or grid-independent capability is not significant (numerical results not shown.)

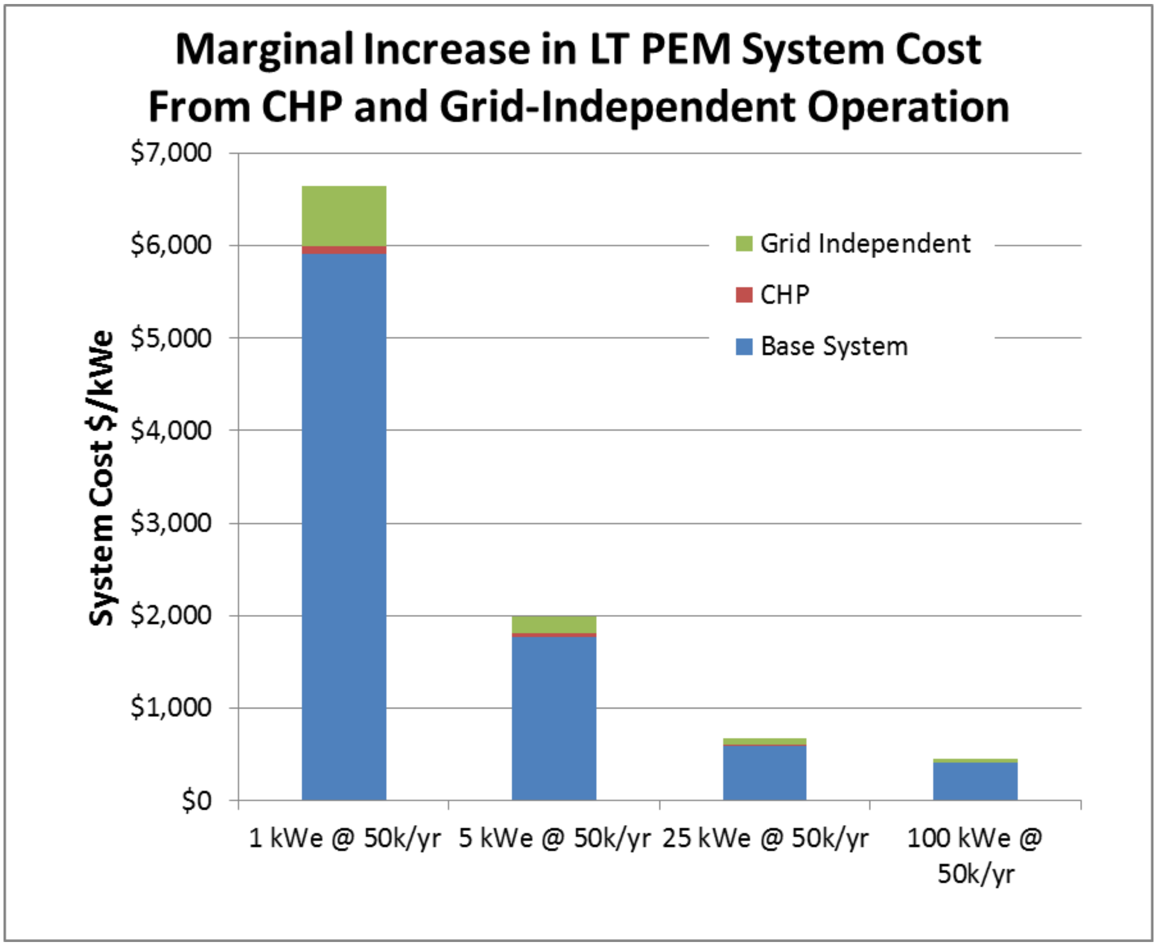

Figure 47: Marginal Increase in LT PEM System Cost from CHP and Grid-Independent Operation

6.2 HT PEM Costs

6.2.1 HT PEM System Costs

Figure 48 and Figure 49 display the final results for the HT PEM system broken down by system size and manufacturing rate. As shown in the figures, the capital cost per unit of electric output ($/kWe) is seen to decrease dramatically both with increasing system size and increasing system annual production rate. As system size and system manufacturing rate increase, system cost decreases. In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing costs than increasing manufacturing rate over the range of values plotted. In comparing an increase in system size of 100 fold (moving from 1 kWe to 100 kWe) and an increase in manufacturing rate of 100 fold (moving from 100 systems per year to 10,000 systems per year), there is a greater reduction in system capital cost from increasing system size (an average decrease of 90% over the range of plotted values) than from increasing manufacturing rate (an average decrease of only 33%). (Plotted values do not show the effect of a change in manufacturing rate between producing 1 system per year and 100 systems per year.)

Model results indicate that, at the same cumulative global installed capacity, higher power FCSs are expected to have lower per unit capital costs ($/kWe) than lower power FCSs. This observation is shown in Figure 48 and Figure 49. For example, for a 10,000 kWe global installed capacity in one year, 100 kWe systems are 16% of the cost of 1 kWe systems ($1,062/kWe vs. $6,699/kWe). For a 50,000 kWe global installed capacity in one year, 5 kWe systems are 40% of the cost of 1 kWe systems ($2,448/kWe vs. $6,101/kWe). For a 250,000 kWe global installed capacity in one year, 25 kWe systems are 44% of the cost of 5 kWe systems ($941/kWe vs. $2,132/kWe).

It can be informative to compare modeled values with current manufacturer values. The U.S. Department of Energy recently sponsored the deployment of fifteen 5 kWe HT PEM CHP FCSs.[74, 75] According to data supplied by the manufacturer (ClearEdge Power Inc.), the combined capital and installation costs for their CE5 systems are roughly $16,000/kWe: the capital costs alone are roughly $13,000/kWe.[76, 77] These costs refer to a global installed capacity of less than 200 systems, and an annual production rate of less than 100 systems per year. For comparison, modeling results indicate a cost of roughly $3,500/kWe for a manufacturing rate of 100 sys/yr. These modeling results and manufacturer values are consistent if one considers that this modeling work does not consider any of these costs: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; G&A costs; warranties; advertising; and sales taxes.

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[74] Dillon, H.E. and Colella, W.G., 2012, "Independent Analysis of Real-Time, Measured Performance Data from Micro-Cogenerative Fuel Cell Systems Installed in Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86987.

[75] Dillon, H.E and Colella, W.G., 2012, "Real-Time Measured Performance of Micro Combined Heat and Power Fuel Cell Systems Independently Evaluated in the Field," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91470. PNNL-SA-86752.

[76] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11 and Fig. 5.

[77] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11 and Fig. 5.

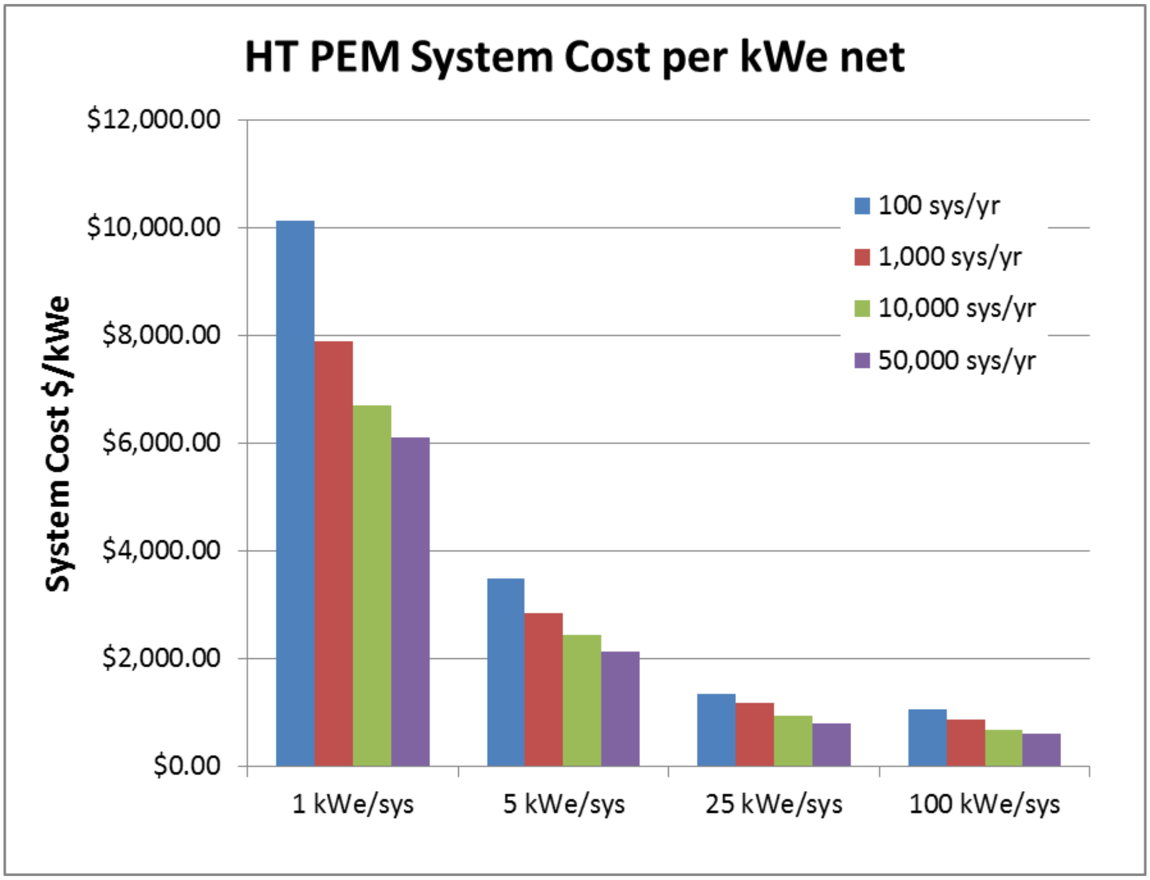

Figure 48: Cost Results for HT PEM System

	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$10,130	$3,483	$1,363	$1,062
1,000 sys/yr	$7,895	$2,840	$1,181	$867
10,000 sys/yr	$6,699	$2,448	$941	$680
50,000 sys/yr	$6,101	$2,132	$816	$606

Figure 49: Table of Cost Results for HT PEM System, $/kWe

6.2.2 HT PEM System Costs as a Function of Subsystem and Component Costs

Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component. Figure 50 and Figure 51 below display the breakdown of these costs according to the six major cost subsystems for the 1 kWe and 100 kWe system sizes. As evident from the figures, at both size levels, the greatest contributors to the capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing 65% or more of the total system capital cost. For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at all production levels. At the 1kWe power level, the FC and FP subsystems are of similar magnitude. By contrast, for the 100 kWe system, model results indicate that the FC subsystem is more expensive than the FP subsystem at all production levels. For the 100 kWe system, the FC subsystem accounts for between 55% and 65% of capital costs.

A comparison of HT and LT PEM cost results underscores that HT PEM stacks are expected to be more costly than LT PEM stacks, and therefore contribute a larger percentage to total system costs. The HT PEM system has a lower power density and therefore requires a larger stack. At the same time, the HT and LT PEM system mechanical designs are very similar, and costs tend to scale with mass and/or volume. Because a larger mass and volume of stack is needed for the HT PEM, the HT PEM stack is relatively more expensive than the LT PEM stack, and the HT PEM stack cost contributes more to total system costs, for the same power rating and manufacturing rate. (Additionally, the HT PEM stack has higher Pt catalyst loading per unit active area, tending to make it higher cost even at the same power density.) For example, for a 100 kWe system, at a manufacturing rate of 100 sys/yr, the FC stack cost is about 50% of the total capital cost in the LT PEM system and about 60% of the total capital cost in the HT PEM system.

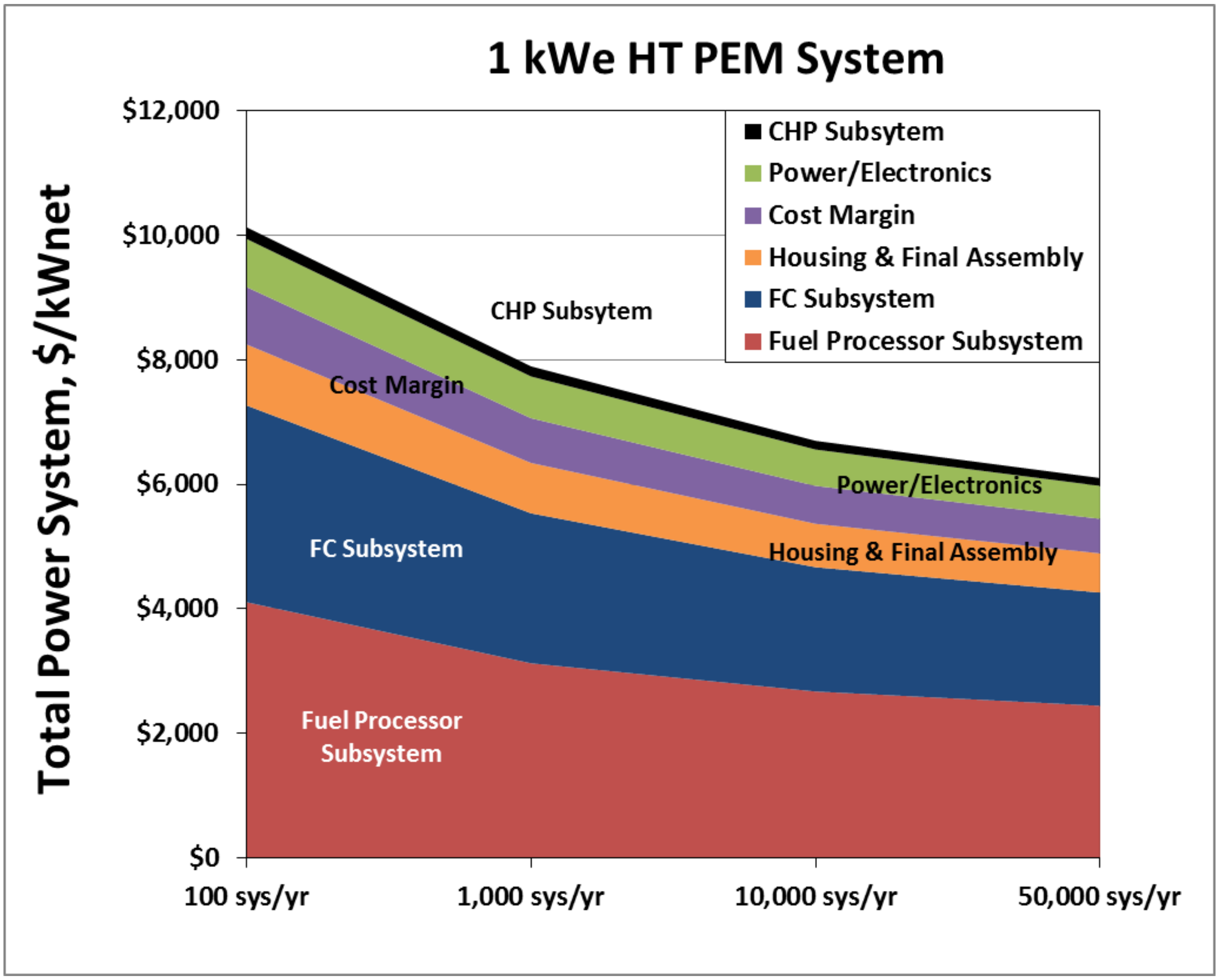

Figure 50: 1 kWe HT PEM System Cost Breakdown by Component

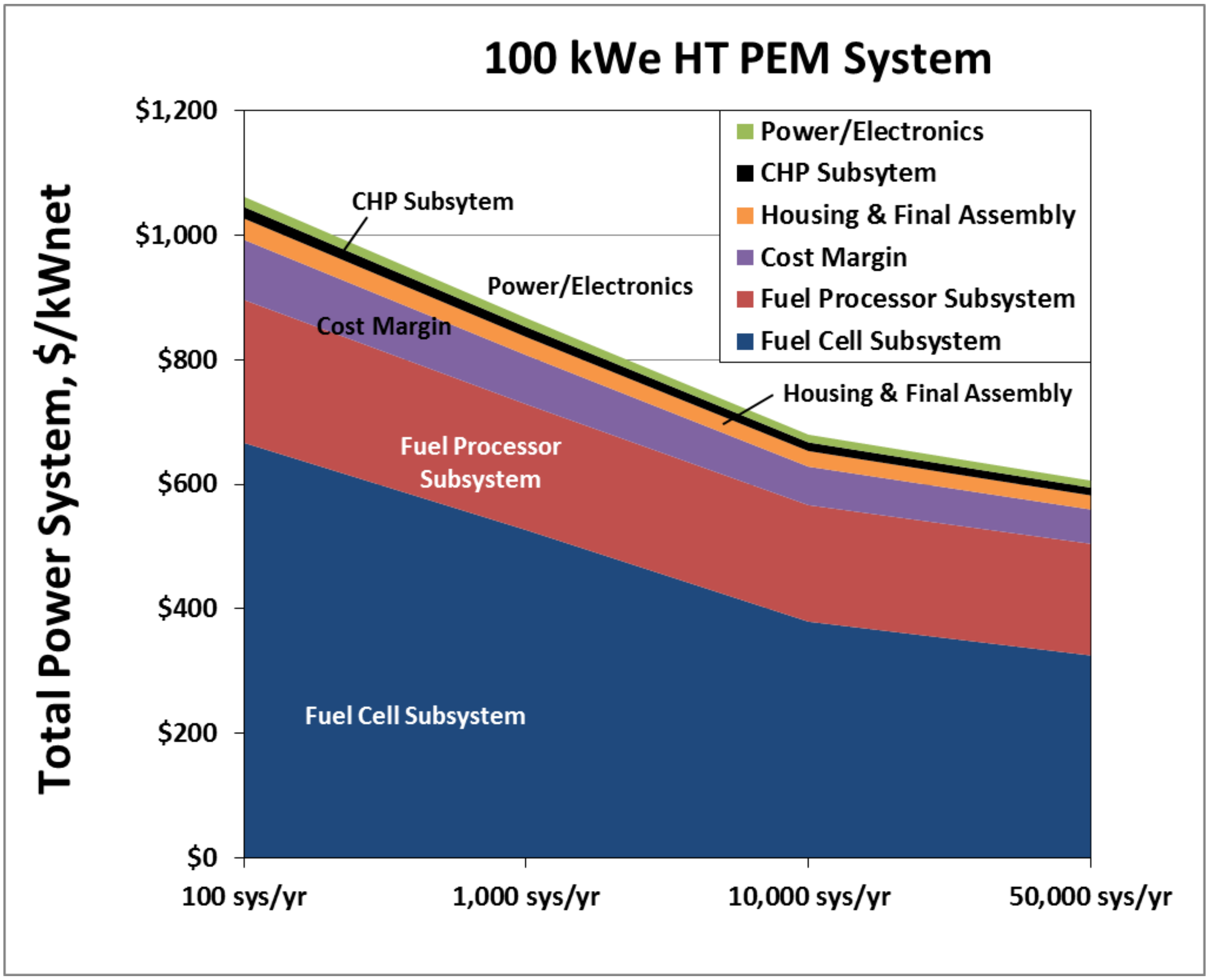

Figure 51: 100 kWe HT PEM System Cost Breakdown by Component

6.2.3 HT PEM FP Subsystem Costs

Model results can indicate a further level of refinement in the breakdown of capital costs, as indicated by Figure 52 and Figure 53. These figures display the HT PEM fuel processor cost breakdown for 1kWe and 100kWe, respectively. As previously observed in the LT PEM FP subsystem, BOP costs dominate subsystem cost at the 1kWe scale and are slightly less than half the cost at 100kWe scale. In contrast to the 1 kWe system, for the 100kWe system, the FP's costs are dominated by the fuel processor.

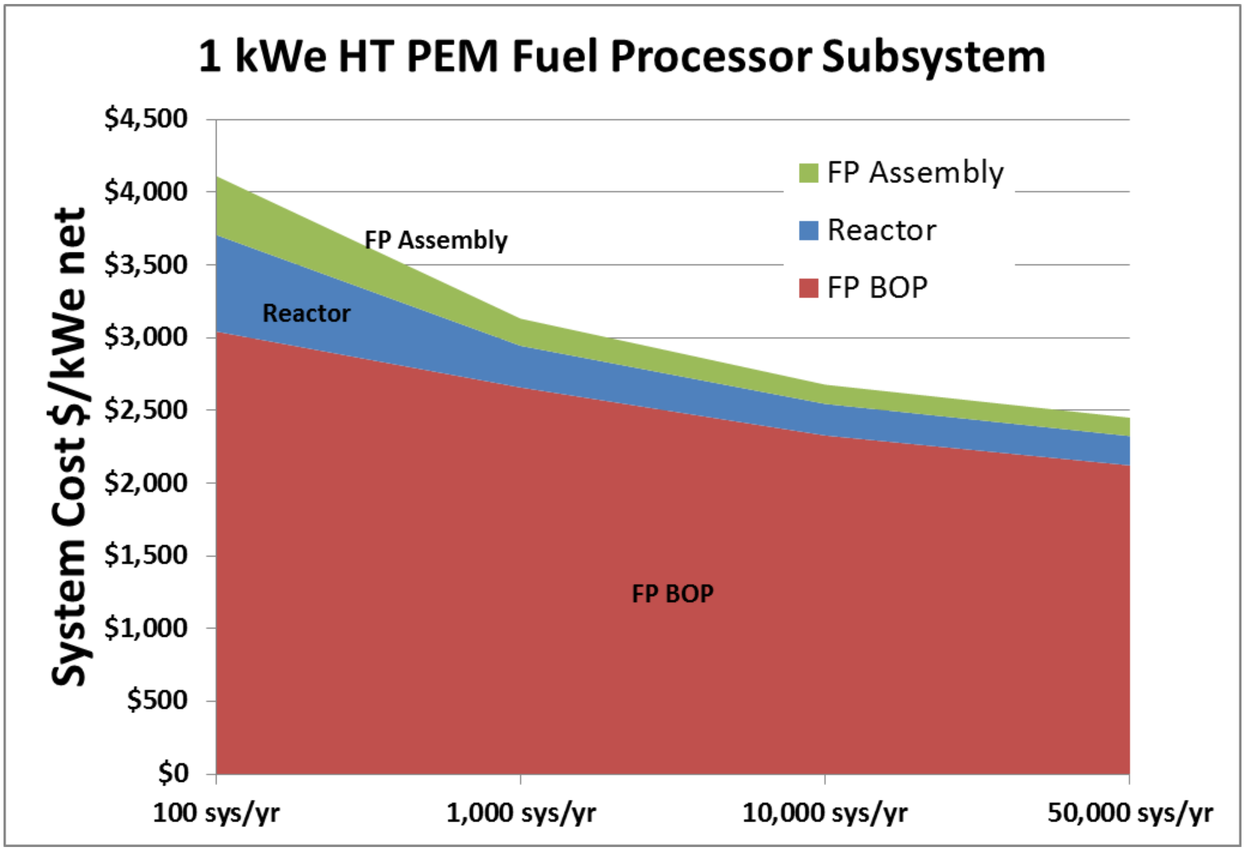

Figure 52: 1 kWe HT PEM FP Subsystem Cost Breakdown

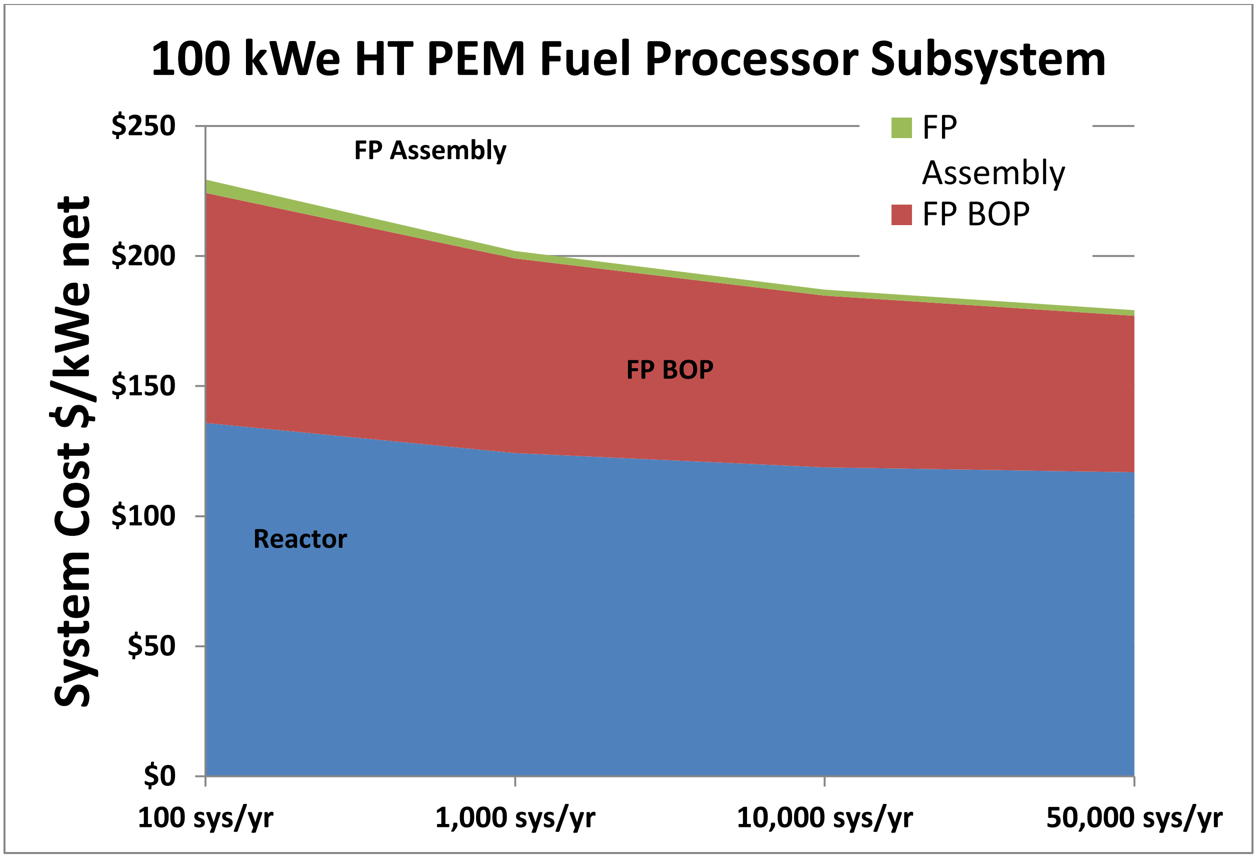

Figure 53: 100 kWe HT PEM FP Subsystem Cost Breakdown

Figure 54 through Figure 57 display the cost breakdown of the components within the FP BOP category for the four "corner" cases in the analysis: the lowest (1kWe) and highest (100kWe) system powers, and the lowest (100 system/year) and highest (50,000 system/year) manufacturing rates. Although not shown, the intermediate systems following the expected trends established by an examination of these four "corner" cases. In comparing all four figures, results indicate that the primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.

At the 1 kWe rating, the primary cost driver for the FP BOP is the natural gas compressor. As previously detailed, a natural gas compressor is needed for only the 1 and 5 kWe systems based on assumed NG inlet pressure, for the system designs chosen here. At the 1 kWe rating, the next more important cost drivers for the FP BOP are the flammable gas alarm sensors followed by the gas flow control solenoids.

By contrast, at the 100 kWe rating, the primary cost drivers for the FP BOP are the water pump and the condenser.

NG compressors/blowers, water pumps, flammable gas alarm sensors, gas flow control solenoids, and condensers are all significant cost elements, depending on system size. Manufacturers may be able to obviate the need for some of this equipment or reduce equipment cost through innovative system design choices.

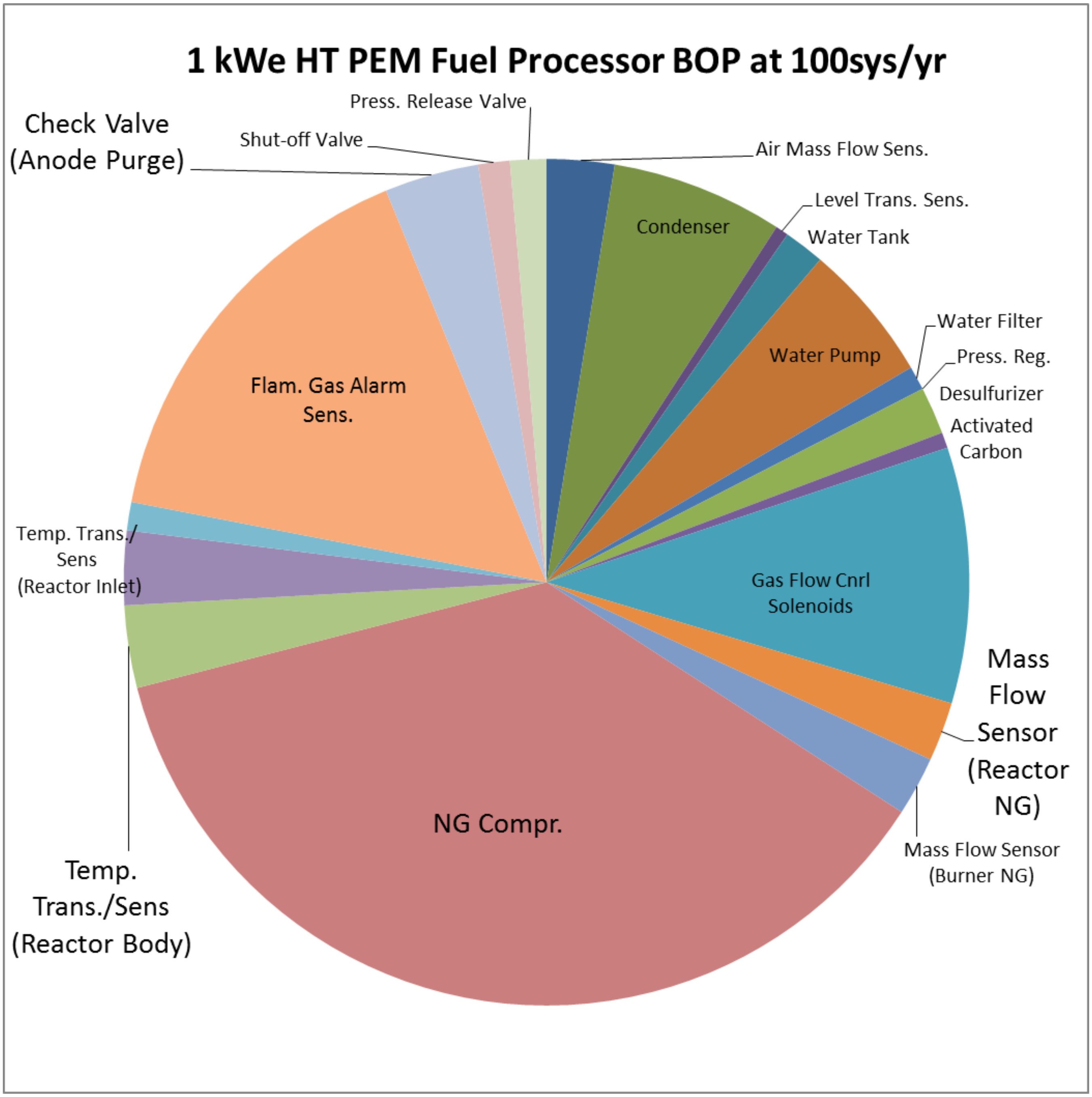

Figure 54: 1 kWe HT PEM FP BOP Pie Chart @ 100 Systems per Year

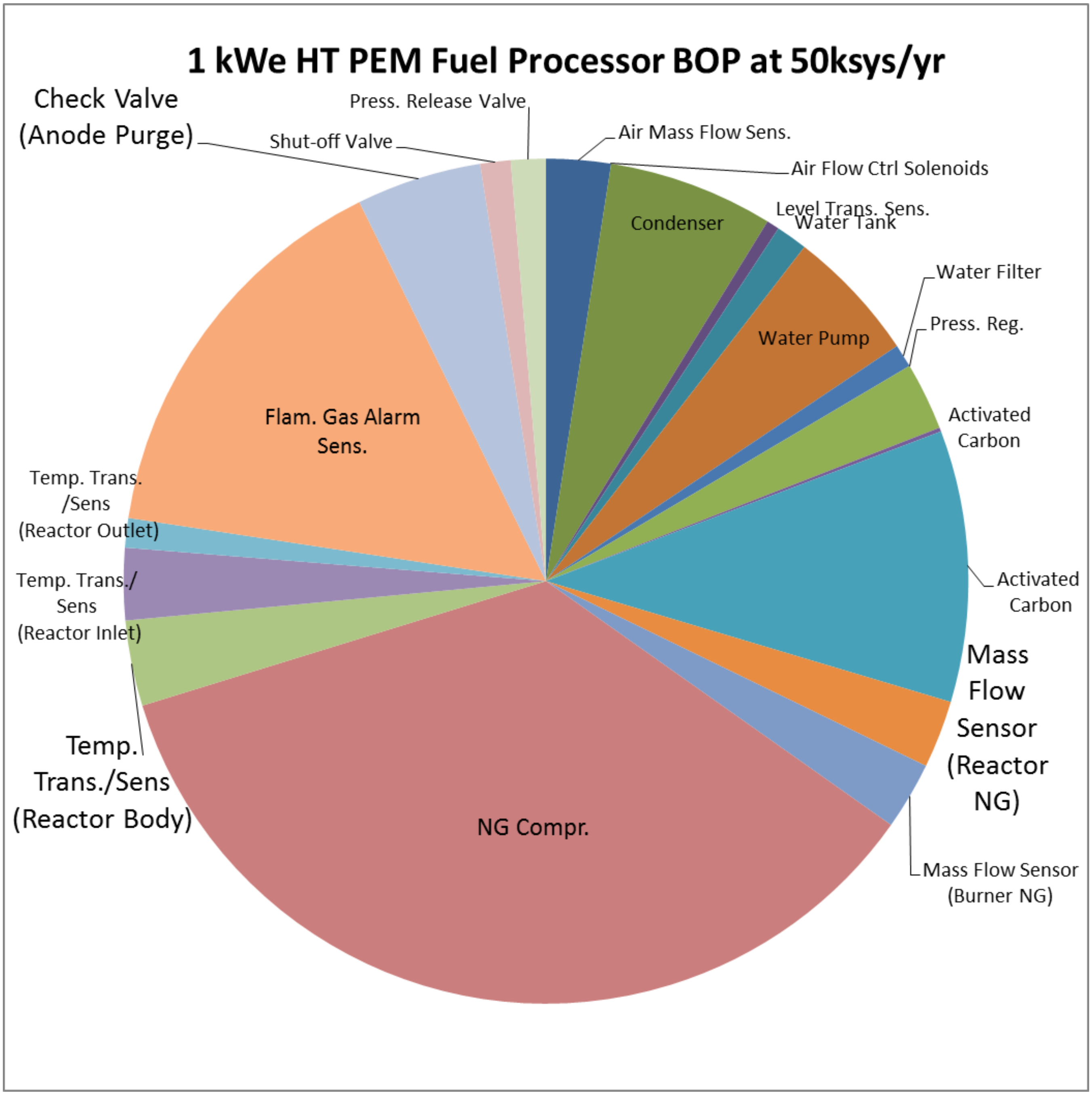

Figure 55: 1 kWe HT PEM FP BOP Pie Chart @ 50k Systems per Year

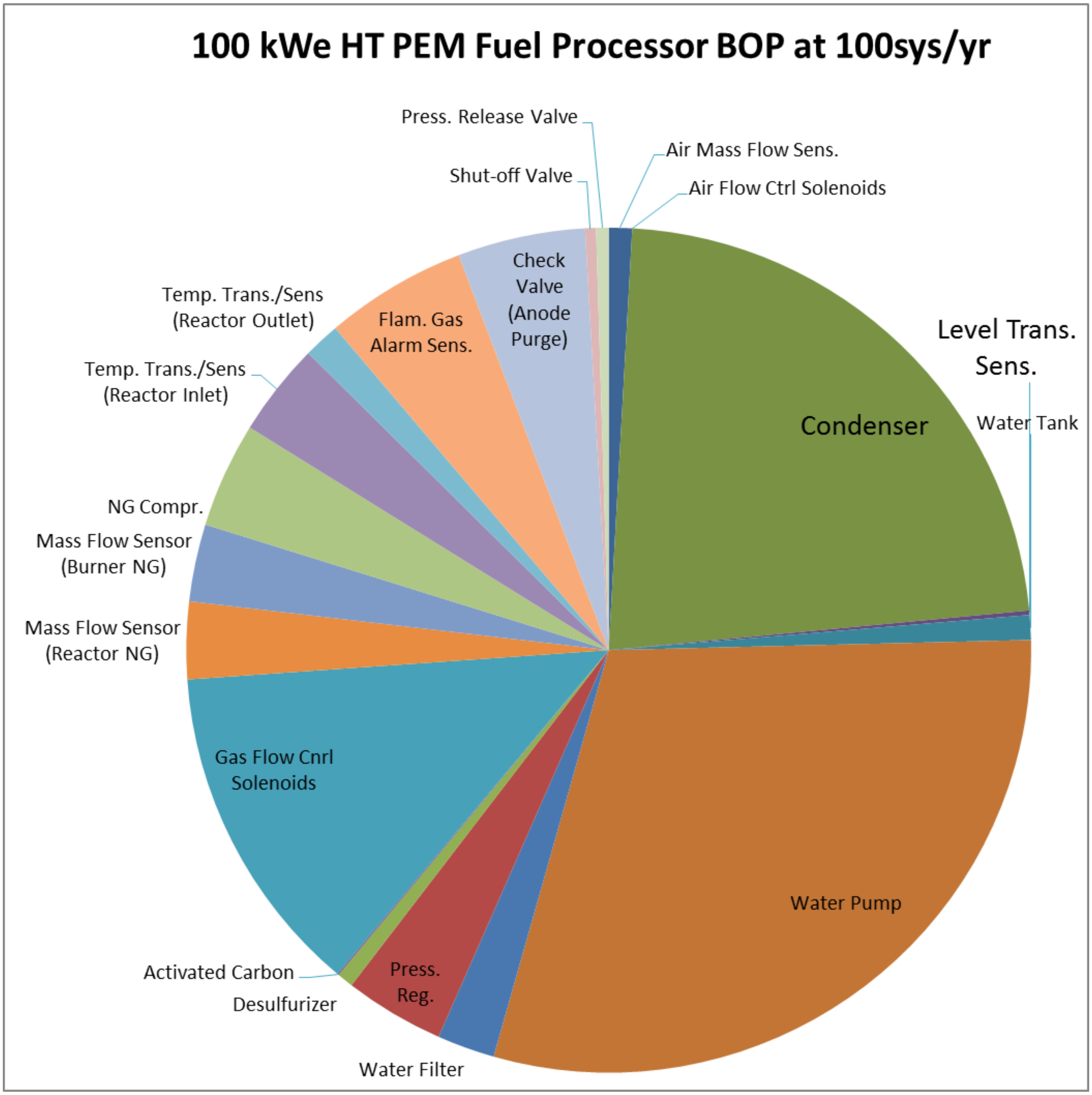

Figure 56: 100 kWe HT PEM FP BOP Pie Chart @ 100 Systems per Year

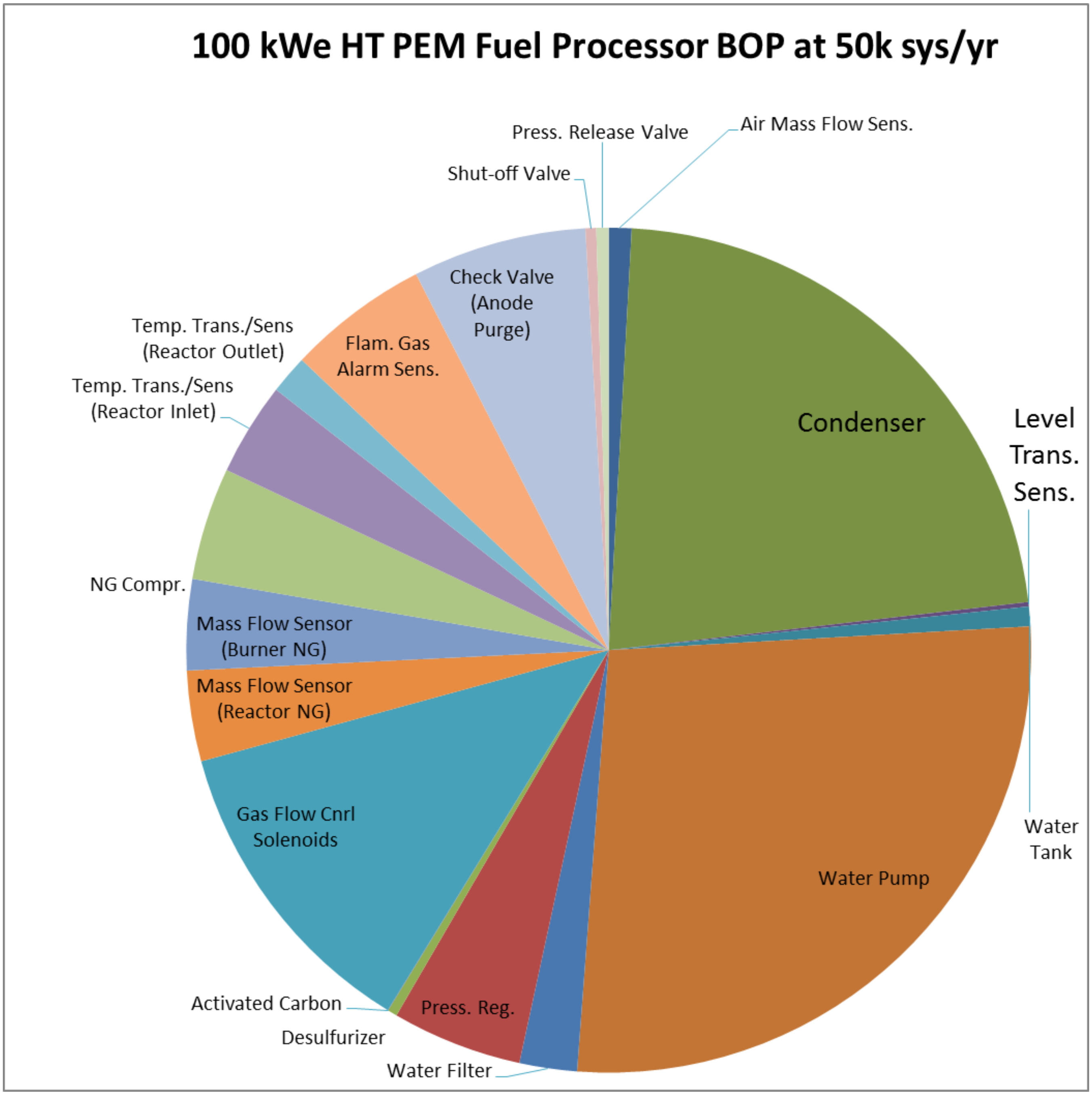

Figure 57: 100 kWe HT PEM FP BOP Pie Chart @ 50k Systems per Year

6.2.4 HT PEM FC Subsystem Costs

Figure 58 and Figure 59 display the breakdown of costs within the HT PEM FC subsystem by FC assembly, FC BOP, and FC stack for 1kWe and 100kWe systems, respectively. As observed with the FP subsystem, at low power (1kWe), the subsystem cost is dominated by the BOP components. At 1 kWe, BOP component costs constitute 60% or more of FC subsystem costs. At high power (100kWe), the FC stack cost dominates. At 100 kWe, FC stack costs constitute over 90% of FC subsystem costs. Due to the

HT PEM's relatively low power density, the stack is a significant cost element at all powers levels and manufacturing rates. Fuel cell subsystem assembly costs are fairly negligible.

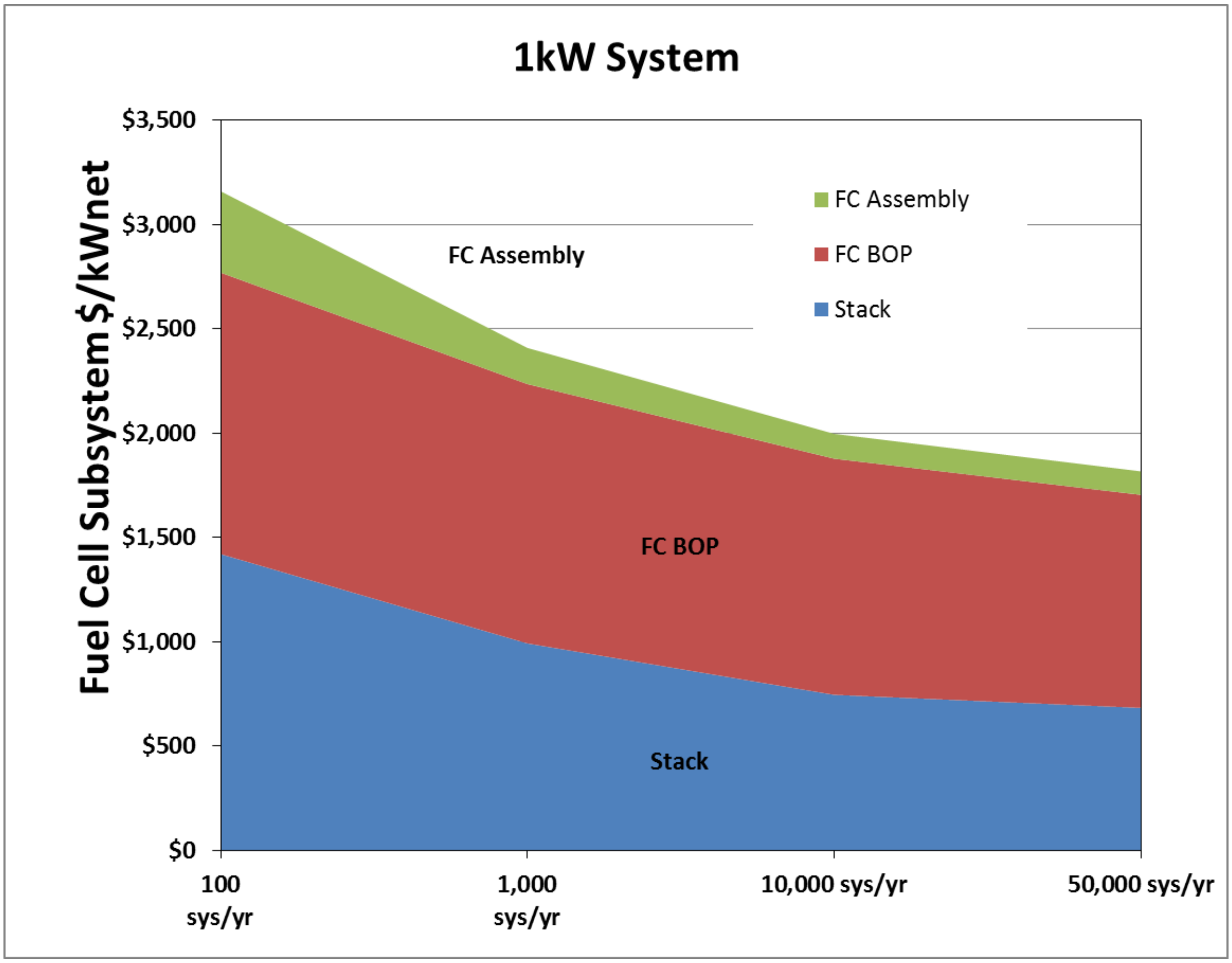

Figure 58: 1 kWe HT PEM FC Subsystem Cost Breakdown

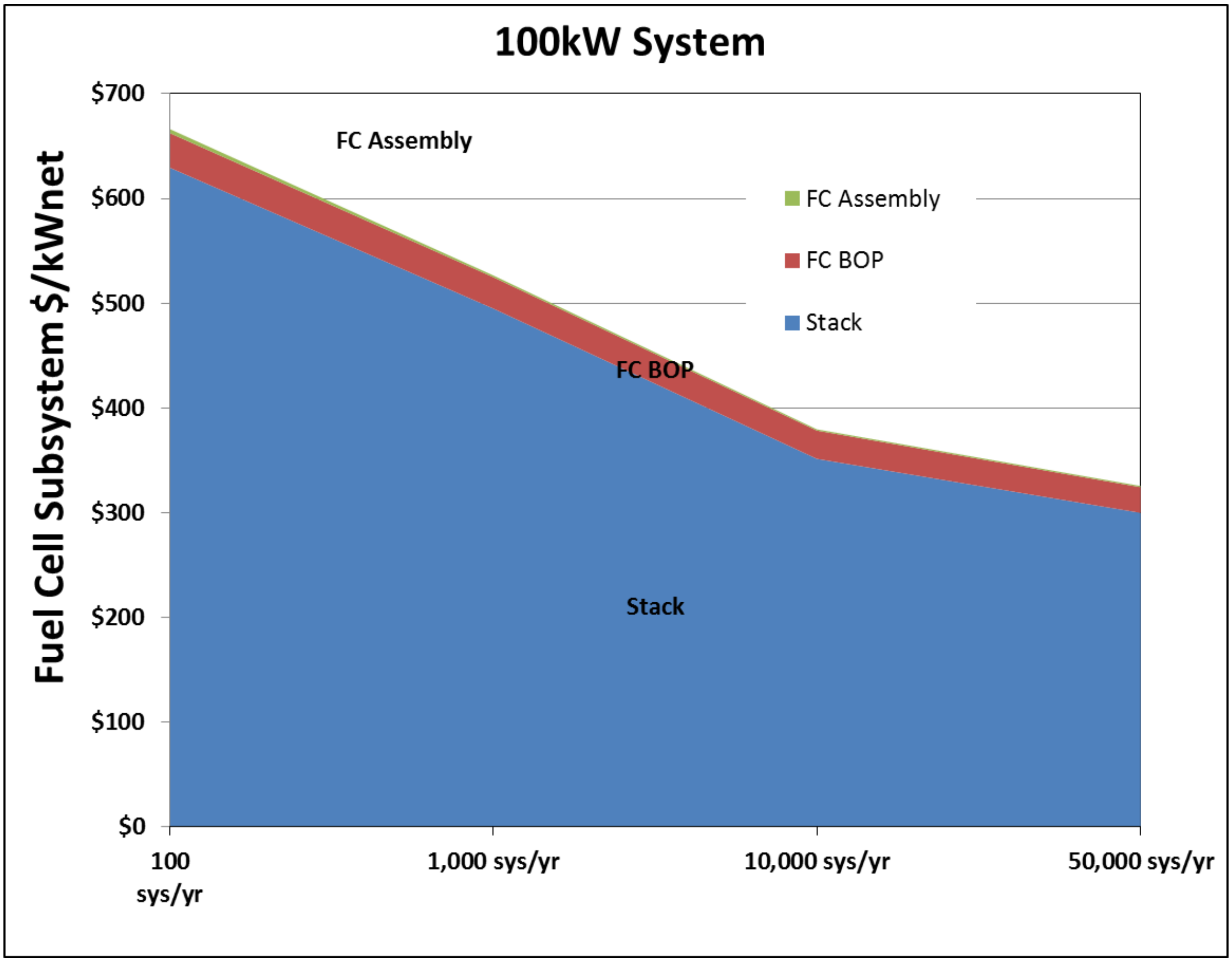

Figure 59: 100 kWe HT PEM FC Subsystem Cost Breakdown

6.2.5 HT PEM CHP and Power Electronics Subsystem Costs

Results also indicate the incremental cost of adding on either CHP capability or grid-independent capability. Figure 60 displays the baseline system cost[78] and the incremental cost of adding on CHP capability and the incremental cost of adding on grid-independent capability. The incremental cost of adding on a CHP capability includes the capital cost of additional heat exchangers needed for conveying anode and/or cathode off-gas heat to a building's heating system. Heat exchanger temperature input/output values are based on prior modeling work[79] on integrating CHP FCSs into large and small office commercial building systems. The incremental cost of adding on grid-independent capability includes the cost of additional power electronics and battery components. Results indicate that the marginal increase in cost between producing a basic system that is not capable of CHP and producing a more advanced FCS that is capable of CHP is in fact quite small: CHP capital costs represent only 2% to

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[78] Please note that the "baseline system" shown in the "Marginal Increase in System Cost from CHP and Grid-Independent Operation" figures is different from the "baseline system" referred to throughout the rest of the report. Throughout the rest of the report, the baseline system includes all components needed for CHP operation but does not include additional components needed for grid-independent operation.

[79] Colella, W.G. and Srivastava, V., 2012, "Examining the Integration of Fuel Cell Systems Into Buildings Through Simulation," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91474. PNNL-SA-87066.

4% of the overall capital cost of such a system. Results also indicate that the marginal increase in cost between producing a basic system that is not capable of grid-independent operation and producing a more advanced FCS that is capable of grid-independent operation is significant: grid-independent capital costs represent between 7% and 9% of the overall capital cost of such a system. For example, at 50k sys/yr, for a 1 kWe FCS, this amounts to an increase in cost of about $600/kWe. In summary, for a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 3% and 4% and for adding grid-independent capability, it is between 7% and 11% of the base cost.

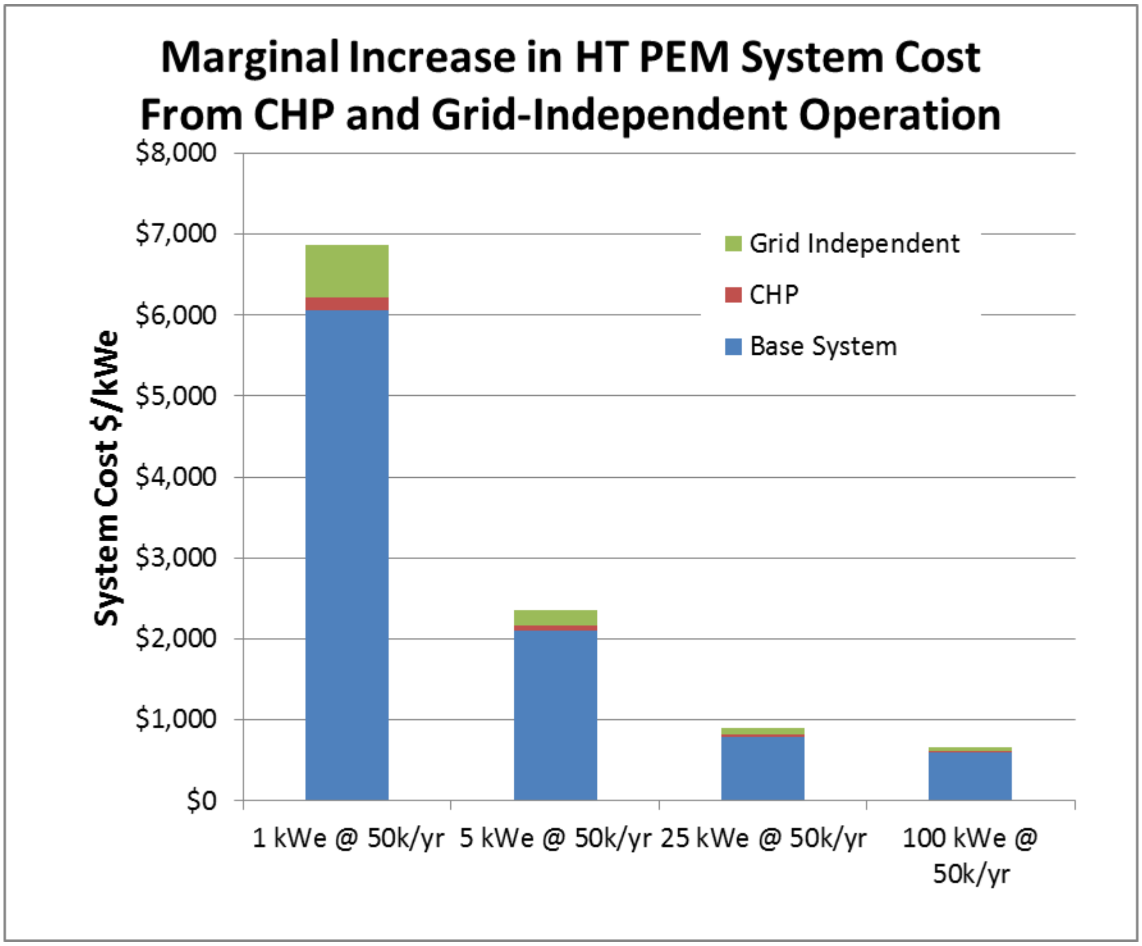

Figure 60: Marginal Increase in HT PEM System Cost from CHP and Grid-Independent Operation

6.3 SOFC Costs

6.3.1 SOFC System Costs

Figure 61 and Figure 62 display the final results for the SOFC system broken down by system size and manufacturing rate. As shown in the figures, the capital cost per unit of electric output ($/kWe) is seen to decrease dramatically both with increasing system size and increasing system annual production rate. As system size and system manufacturing rate increase, system cost decreases. In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing costs than increasing manufacturing rate over the range of values plotted. In comparing an increase in system size of 100 fold (moving from 1 kWe to 100 kWe) and an increase in manufacturing rate of 100 fold (moving from 100 systems per year to 10,000 systems per year), there is a greater reduction in system capital cost from increasing system size (an average decrease of 93% over the range of plotted values) than from increasing manufacturing rate (an average decrease of only 39%). (Plotted values do not show the effect of a change in manufacturing rate between producing 1 system per year and 100 systems per year.)

At the same cumulative global installed capacity, higher power FCSs are expected to have lower per unit capital costs ($/kWe) than lower power FCSs. This observation is shown in Figure 61 and Figure 62. For example, for a 10,000 kWe global installed capacity in one year, 100 kWe systems are 9% of the cost of 1 kWe systems ($532/kWe vs. $5,619/kWe). For a 50,000 kWe global installed capacity in one year, 5 kWe systems are 36% of the cost of 1 kWe systems ($1,862/kWe vs. $5,108 /kWe). For a 250,000 kWe global installed capacity in one year, 25 kWe systems are 35% of the cost of 5 kWe systems ($599/kWe vs. $1,709/kWe).

It can be informative to compare modeled values with current manufacturer values. Ceramic Fuel Cells Limited (CFCL) of Australia has deployed over a hundred ~1 kWe SOFC CHP systems, called the BlueGen system, primarily in buildings in Australia and Europe. [80] The combined capital and installation costs for these systems are roughly $27,000/kWe.[81, 82] Applying a similar assumption as previously discussed (i.e. that installation costs are 20% of this total [83, 84]), the uninstalled purchase price for the CFCL 1 kWe SOFC CHP systems may be estimated as roughly 20% less, or $22,000/kWe. For comparison, modeling results indicate a cost of roughly $11,830/kWe at the 100 sys/yr production rate. These modeling results and manufacturer values are broadly consistent if one considers the contributors to total cost that the modeling work does not include and also the difference between cost and manufacturer price.

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[80] ASME Fuel Cell Conference 2011, Keynote Presentation by ToHo Gas Company.

[81] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11.

[82] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11.

[83] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 5.

[84] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 5.

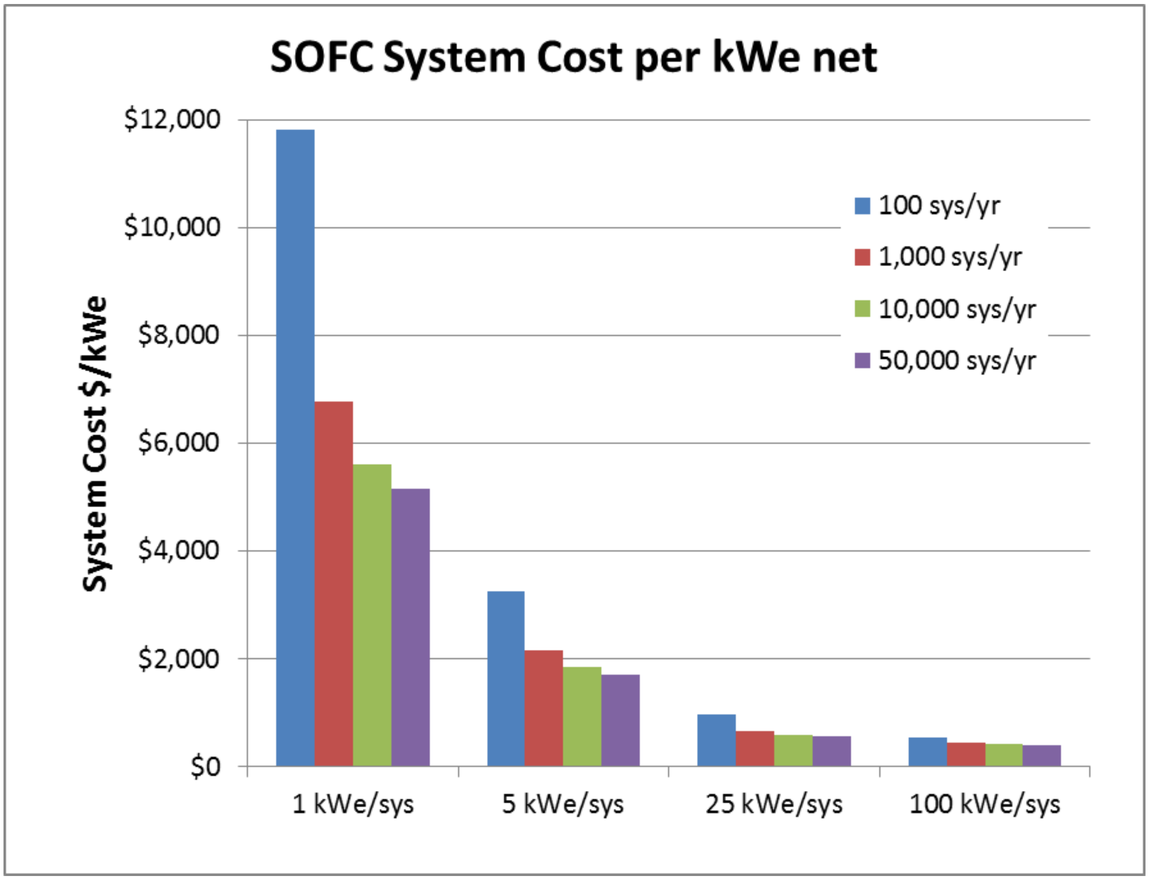

Figure 61: Cost Results for SOFC System

	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	$11,830	$3,264	$981	$532
1,000 sys/yr	$6,786	$2,168	$671	$440
10,000 sys/yr	$5,619	$1,862	$599	$414
50,000 sys/yr	$5,108	$1,709	$570	$402

Figure 62: Table of Cost Results for SOFC System, $/kWe

6.3.2 SOFC System Costs as a Function of Subsystem and Component Costs

Results also indicate the proportion of capital cost attributable to each subsystem and subsystem component. Figure 63 and Figure 64 display the breakdown of total system capital costs as a function of the costs of the six major subsystems for the 1 kWe and 100 kWe system sizes. At both size levels, the FC and FP subsystems combined account for the majority of FCS capital costs, about 60% of total capital costs at a minimum. For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at production levels of 1,000 sys/yr and above. By contrast, for the 100 kWe system, model results indicate that the FC subsystem is more expensive than the FP subsystem at all production levels. At the 100kWe power level, the FC subsystem contributes about 65% to total cost. (For comparison, in the 100 kWe HT PEM system, the FC subsystem also is a large cost contributor due to low HT PEM stack power density.)

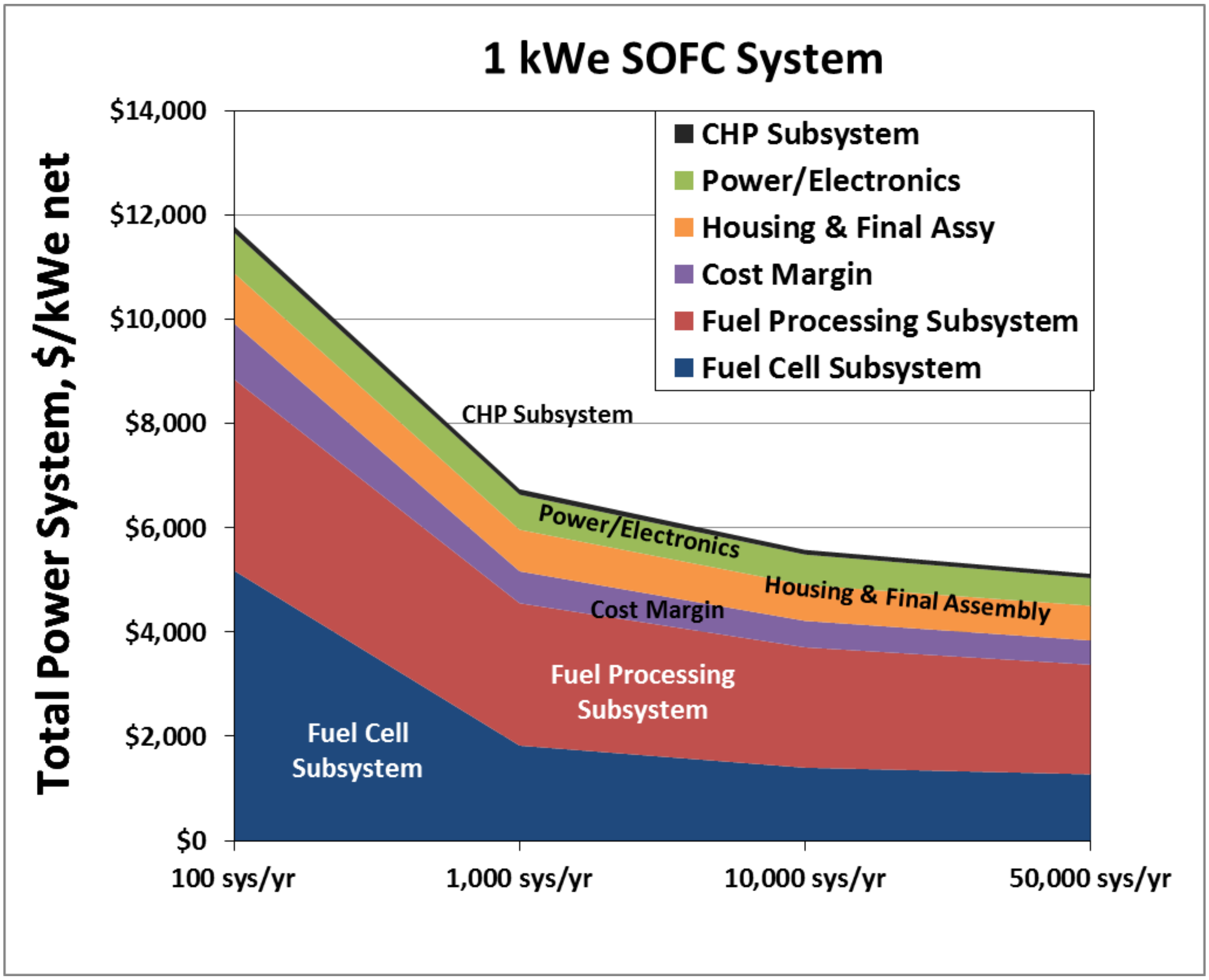

Figure 63: 1 kWe SOFC System Cost Breakdown by Component

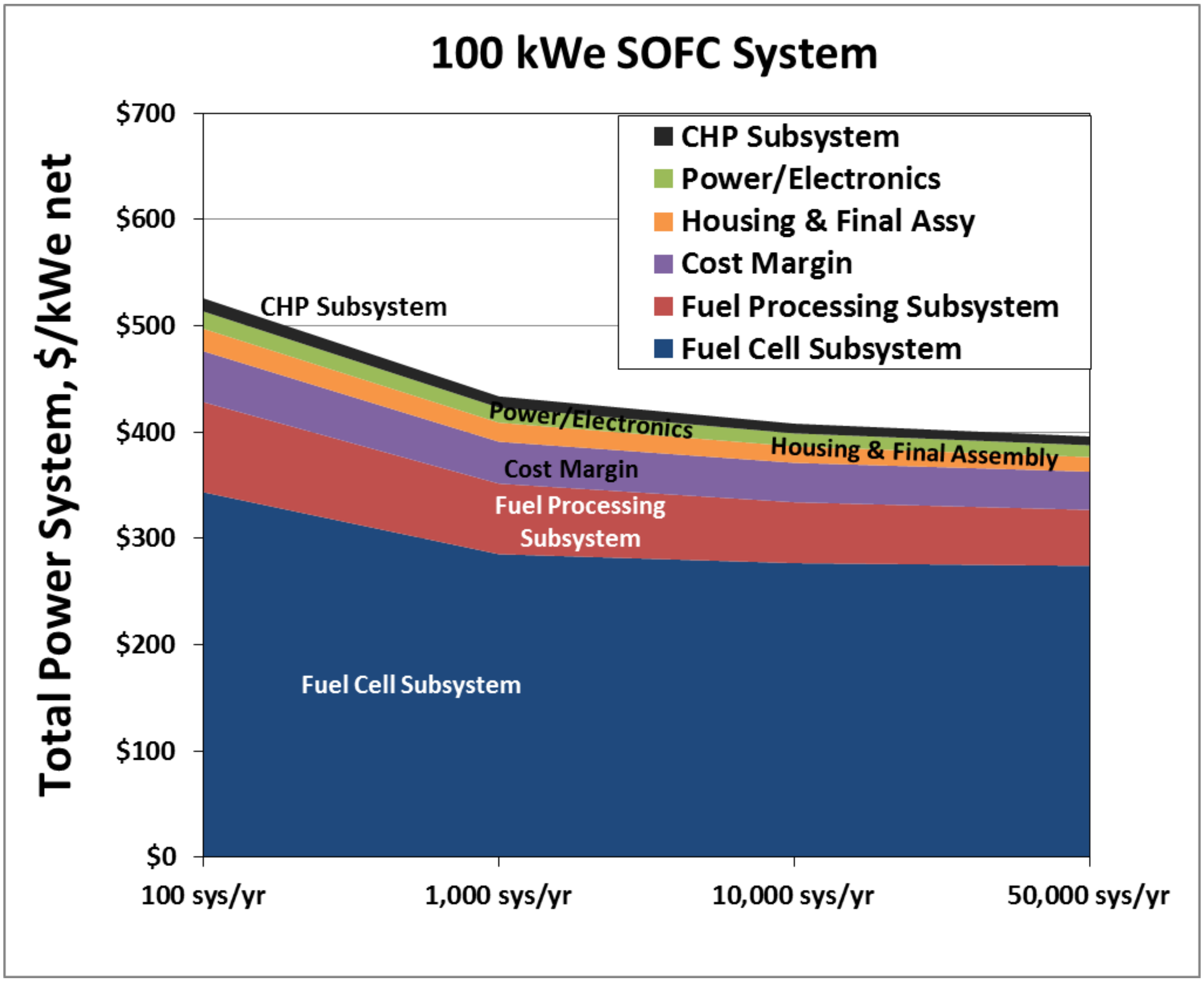

Figure 64: 100 kWe SOFC System Cost Breakdown by Component

6.3.3 SOFC FP Subsystem Results

Figure 65 and Figure 66 show a breakdown of the fuel processor subsystem costs. For the 1 kWe and 100 kWe systems, the FP's costs are dominated by the BOP. At both size levels, the fuel processor's contribution to the total FP subsystem costs is relatively low.

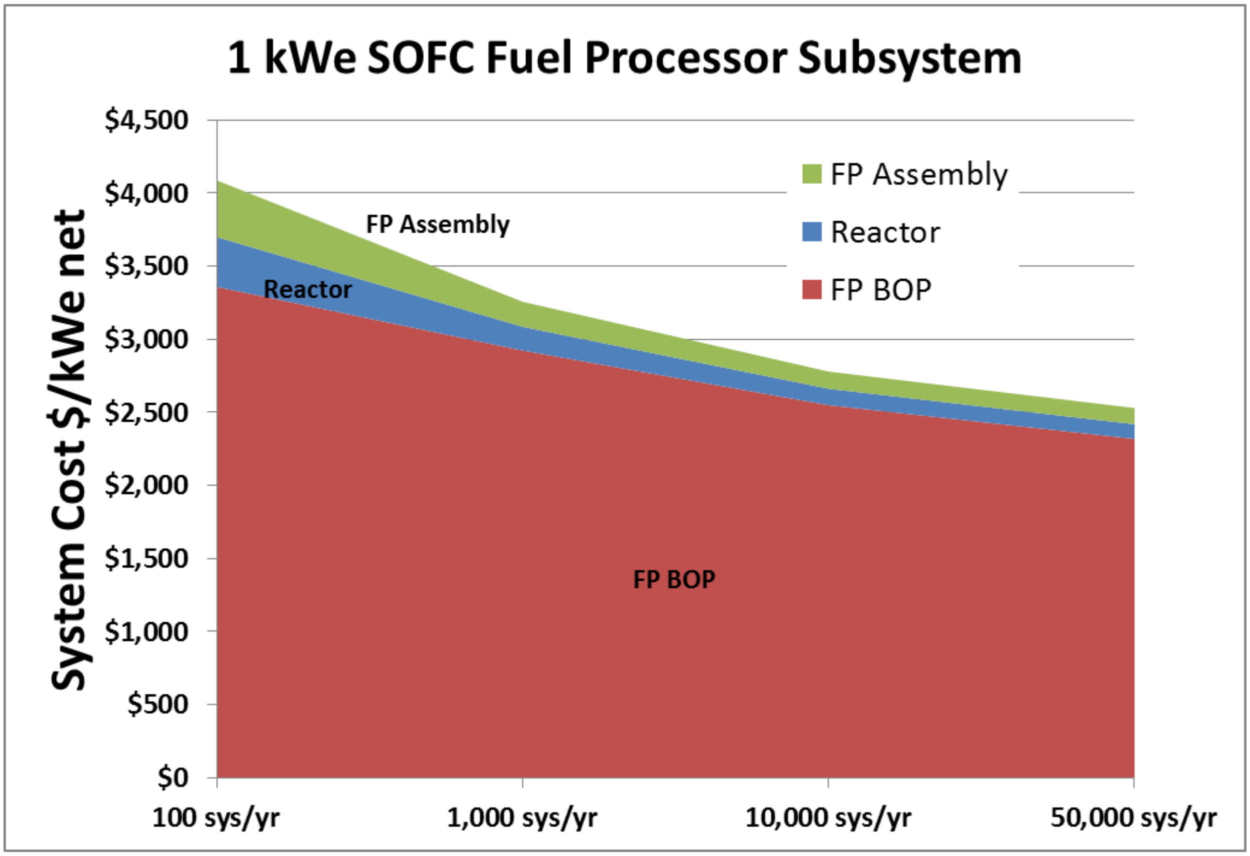

Figure 65: 1 kWe SOFC FP Subsystem Cost Breakdown

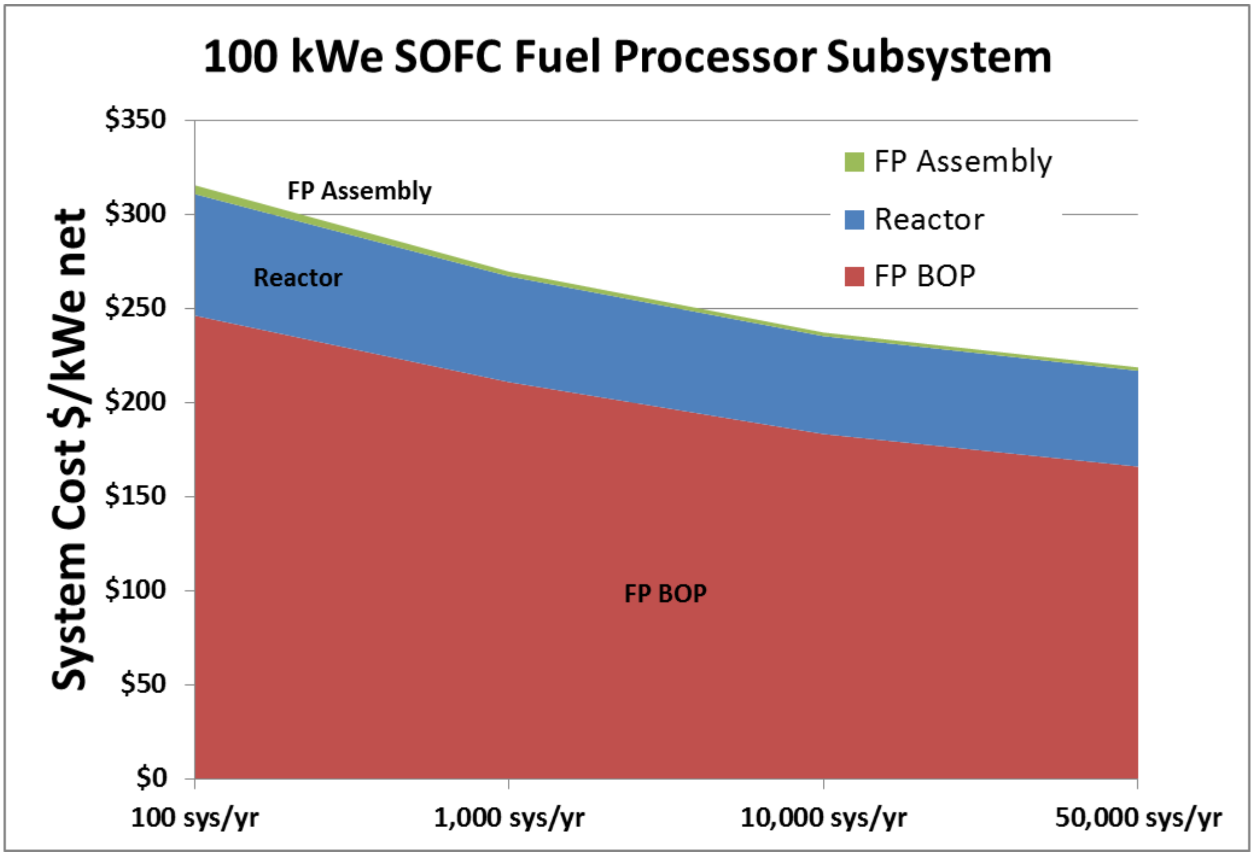

Figure 66: 100 kWe SOFC FP Subsystem Cost Breakdown

Figure 66 through Figure 70 display the relative cost contributions of the various FP BOP components for 1kWe and 100kWe systems, at production levels of 100 sys/yr and 50,000 sys/yr. In comparing all four figures, results indicate that the primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.

At the 1 kWe rating, the primary cost driver for the FP BOP is the natural gas compressor. As previously detailed, a natural gas compressor is needed for only the 1 and 5 kWe systems based on assumed NG inlet pressure, for the system designs chosen here. At the 1 kWe rating, the next more important cost drivers for the FP BOP are the flammable gas alarm sensors followed by the gas flow control solenoids and condenser. For both high and low manufacturing rates at the 1kWe power level, the NG compressor and the flammable gas detection are major cost contributors since these components do not scale down very well in power.

By contrast, at the 100 kWe rating, the primary cost drivers for the FP BOP are the water pump, the condenser, the flammable gas alarm sensor, and the pressure regulator, in that order. The condenser has a larger cost for the SOFC system than it does for the LT or HT PEM systems due to the high volume of exhaust gas made necessary to cool the SOFC stacks. Optimization of system cost through exploration of alternate flow geometries[85] should be further pursued.

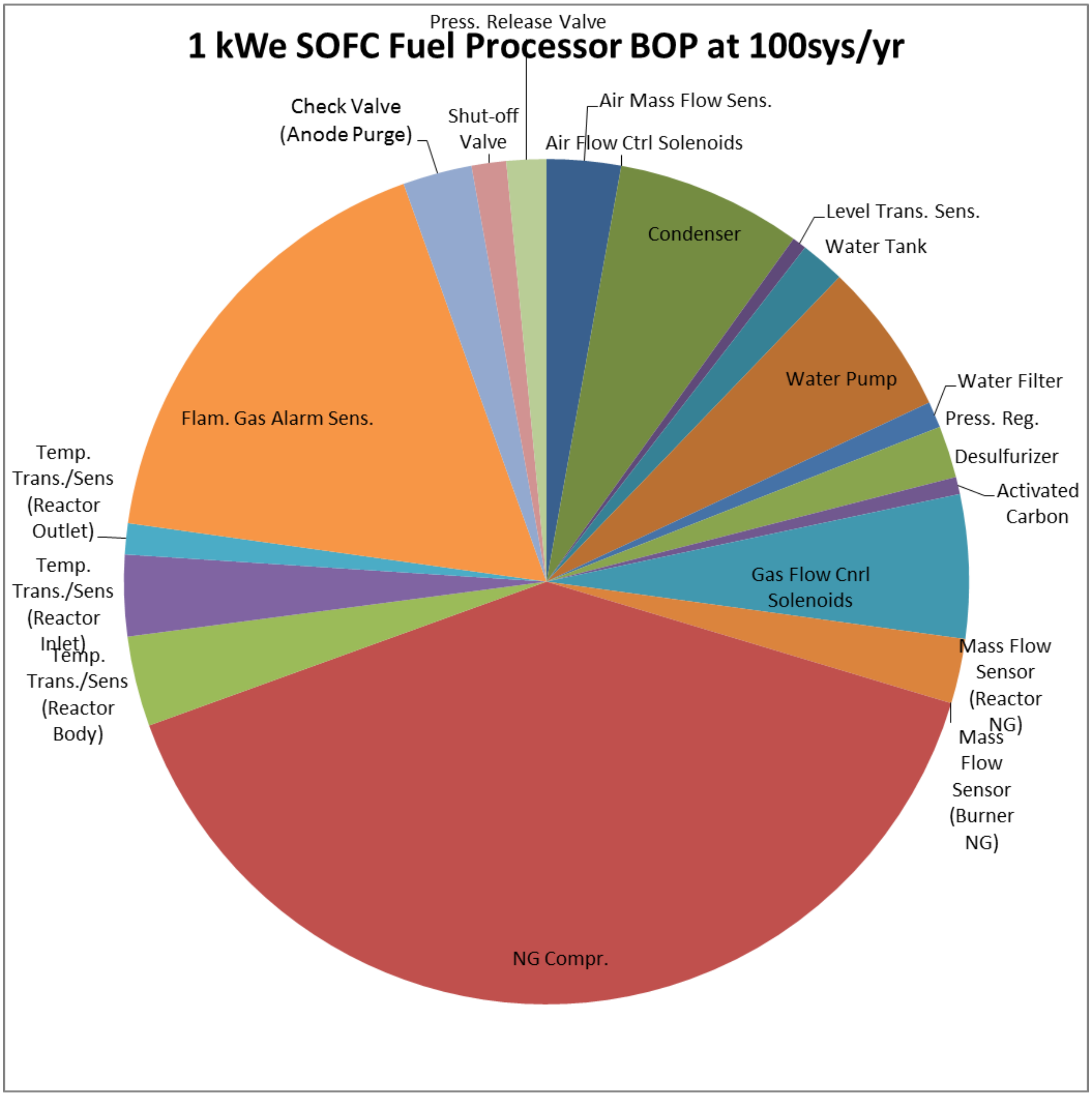

Figure 67: 1 kWe SOFC FP BOP Pie Chart @ 100 Systems per Year

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[85] Instead of using cathode exhaust as the oxidant stream for the SR burner, Ballard Power uses a separate dedicated air stream for the burner. This has the advantage of allowing less nitrogen dilution in the burner exhaust, thereby raising the condenser flow dew point, and allowing a physically smaller (and cheaper) condenser.

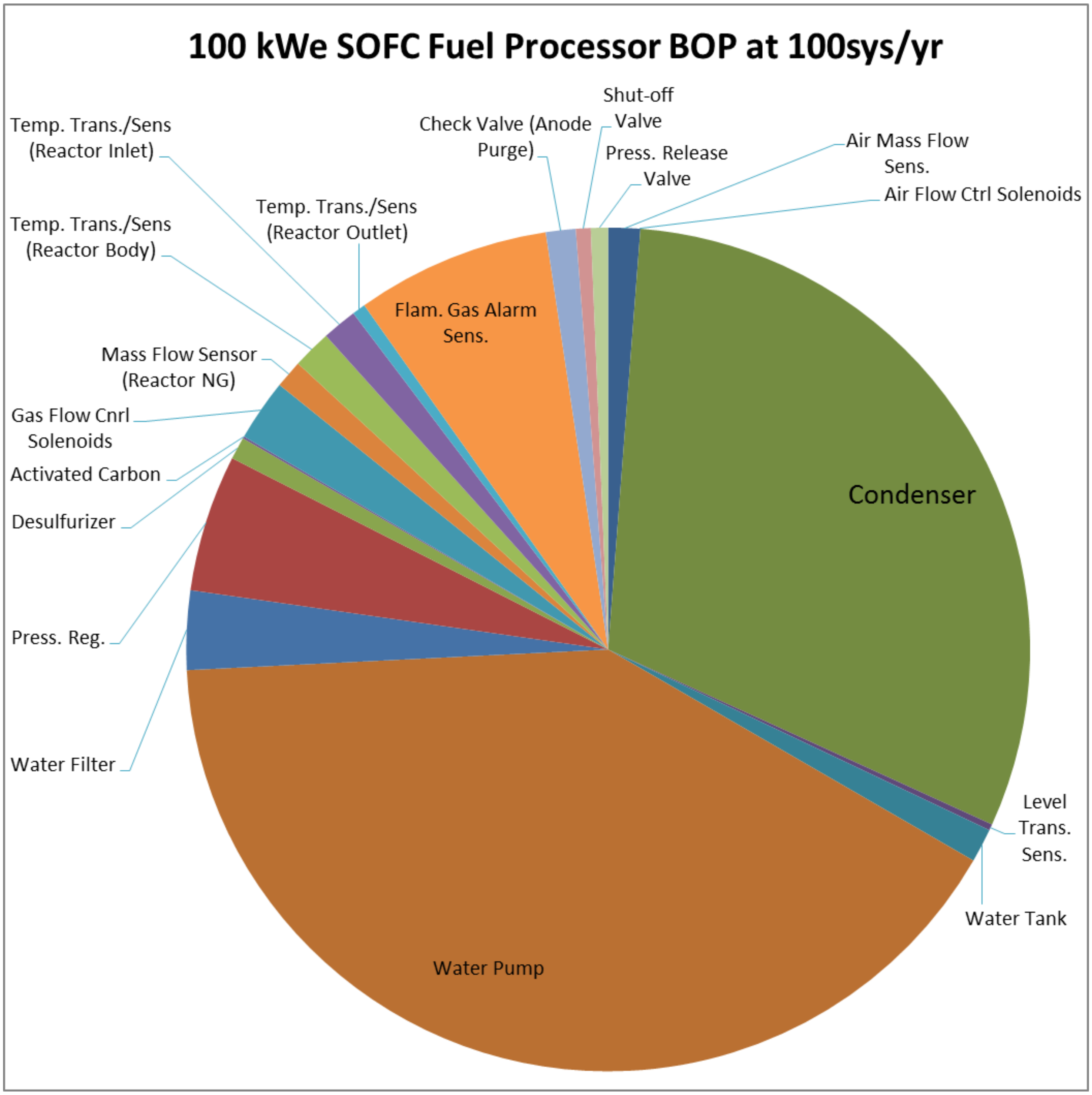

Figure 68: 100 kWe SOFC FP BOP Pie Chart @ 100 Systems per Year

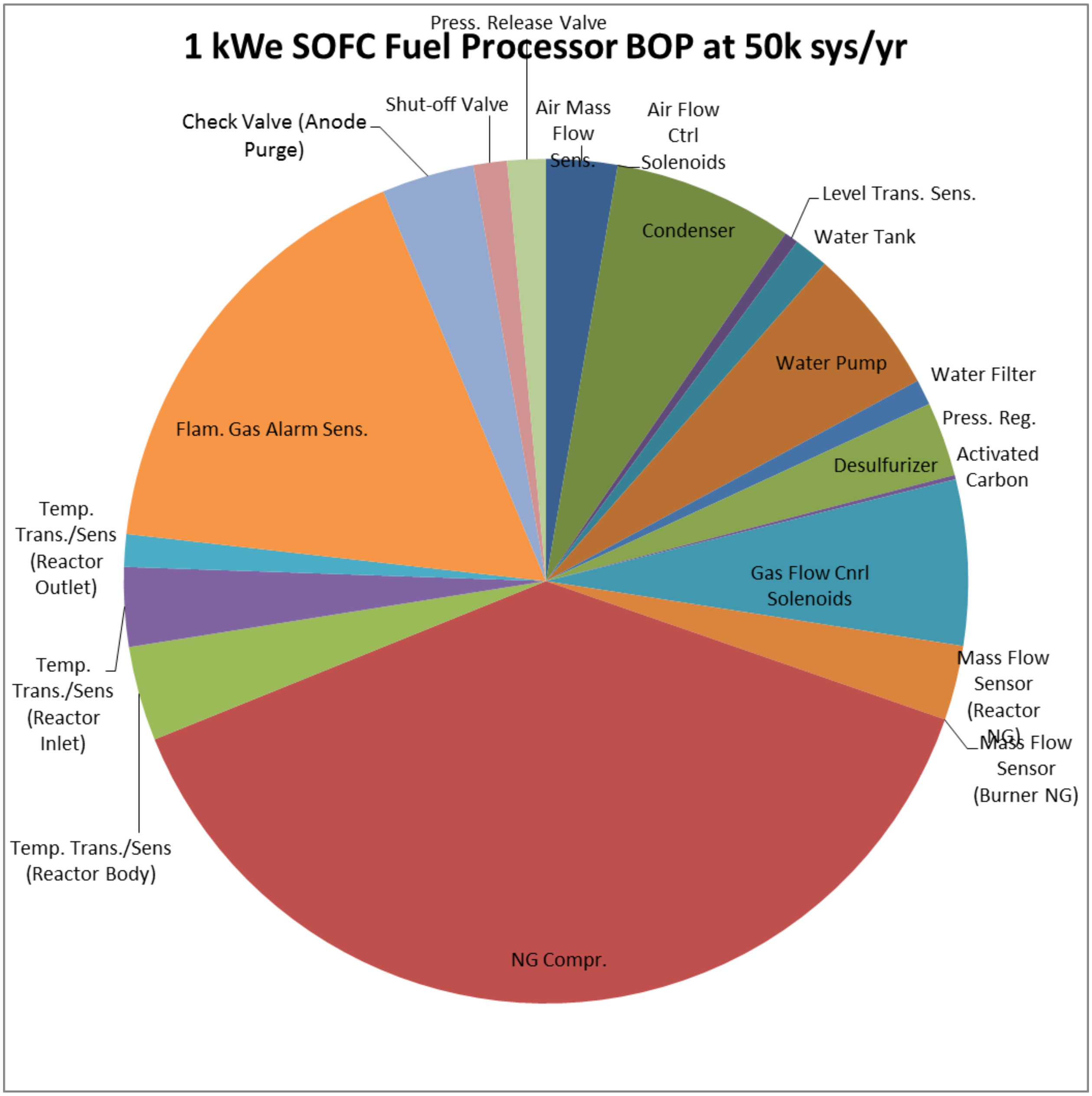

Figure 69: 1 kWe SOFC FP BOP Pie Chart @ 50k Systems per Year

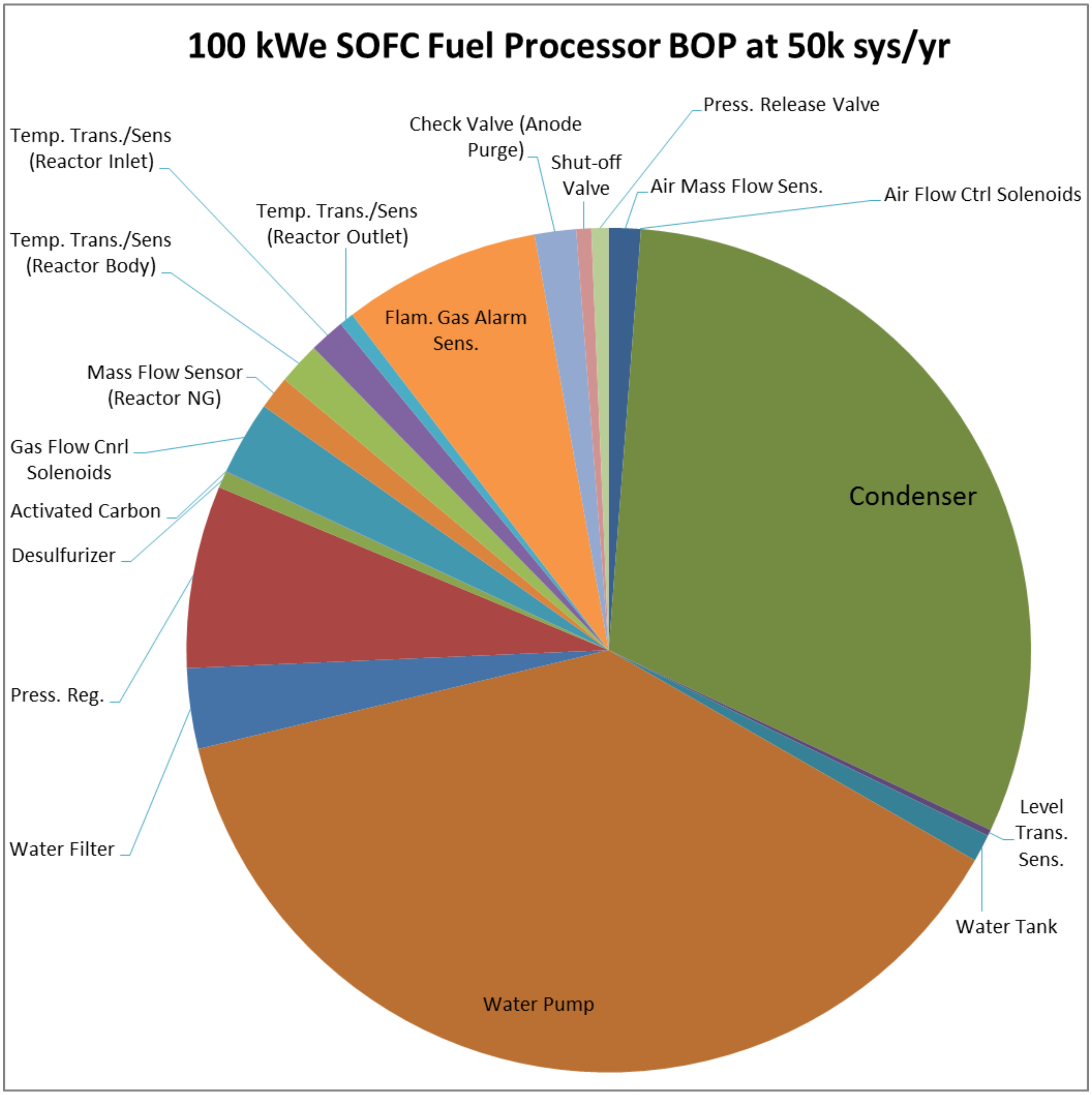

Figure 70: 100 kWe SOFC FP BOP Pie Chart @ 50k Systems per Year

6.3.4 SOFC FC Subsystem Costs

Figure 71 and Figure 72 display the breakdown of costs within the fuel cell subsystem by FC assembly, FC BOP, and FC stack. At low power (1kWe), at production rates above 1,000 sys/yr, the subsystem cost is dominated by the BOP components. At high power (100kWe), the FC stack cost dominates. At 100 kWe, FC stack costs constitute over 90% of FC subsystem costs. Fuel cell subsystem assembly costs are fairly negligible.

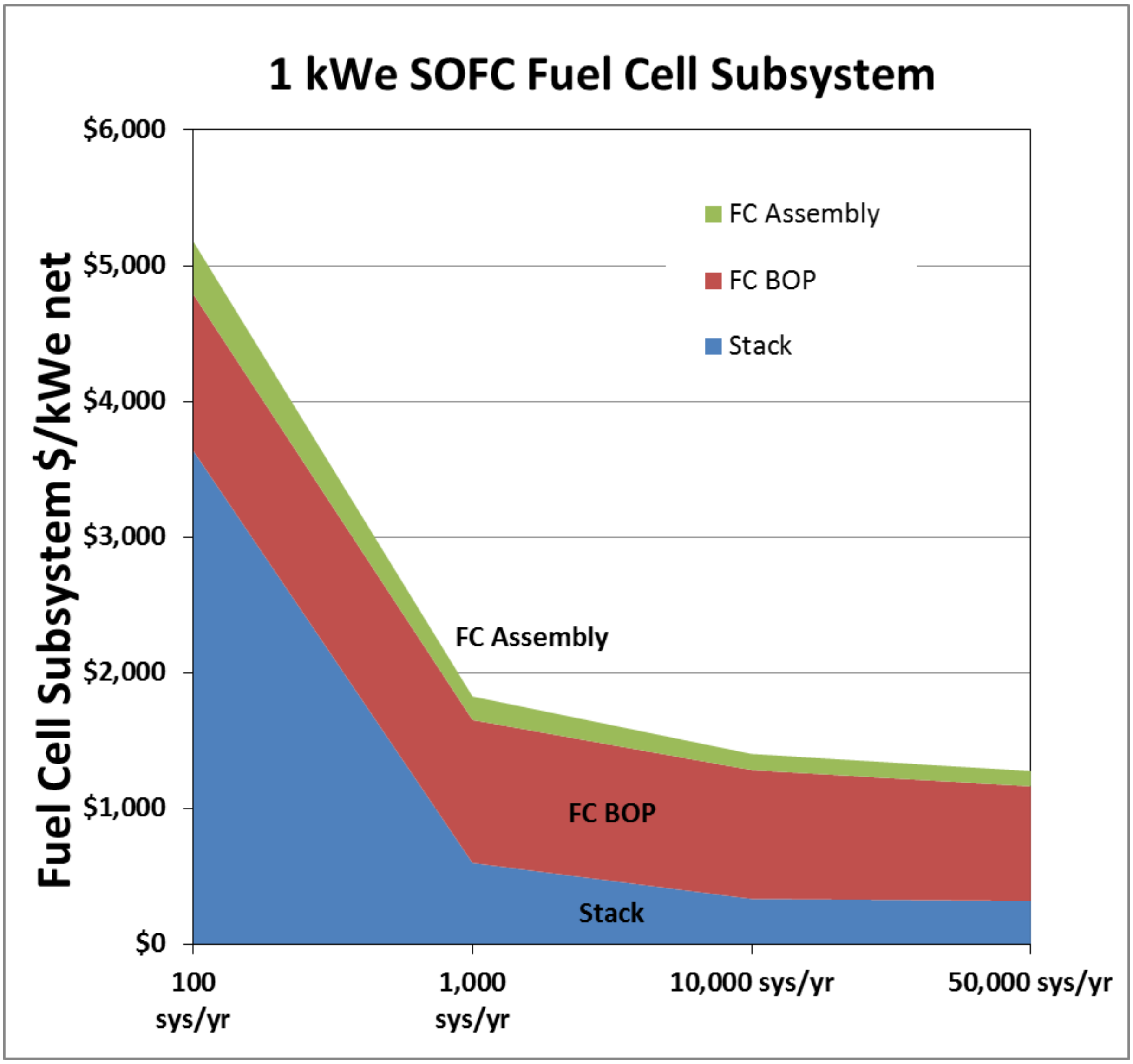

Figure 71: 100 kWe SOFC FC Subsystem Cost Breakdown

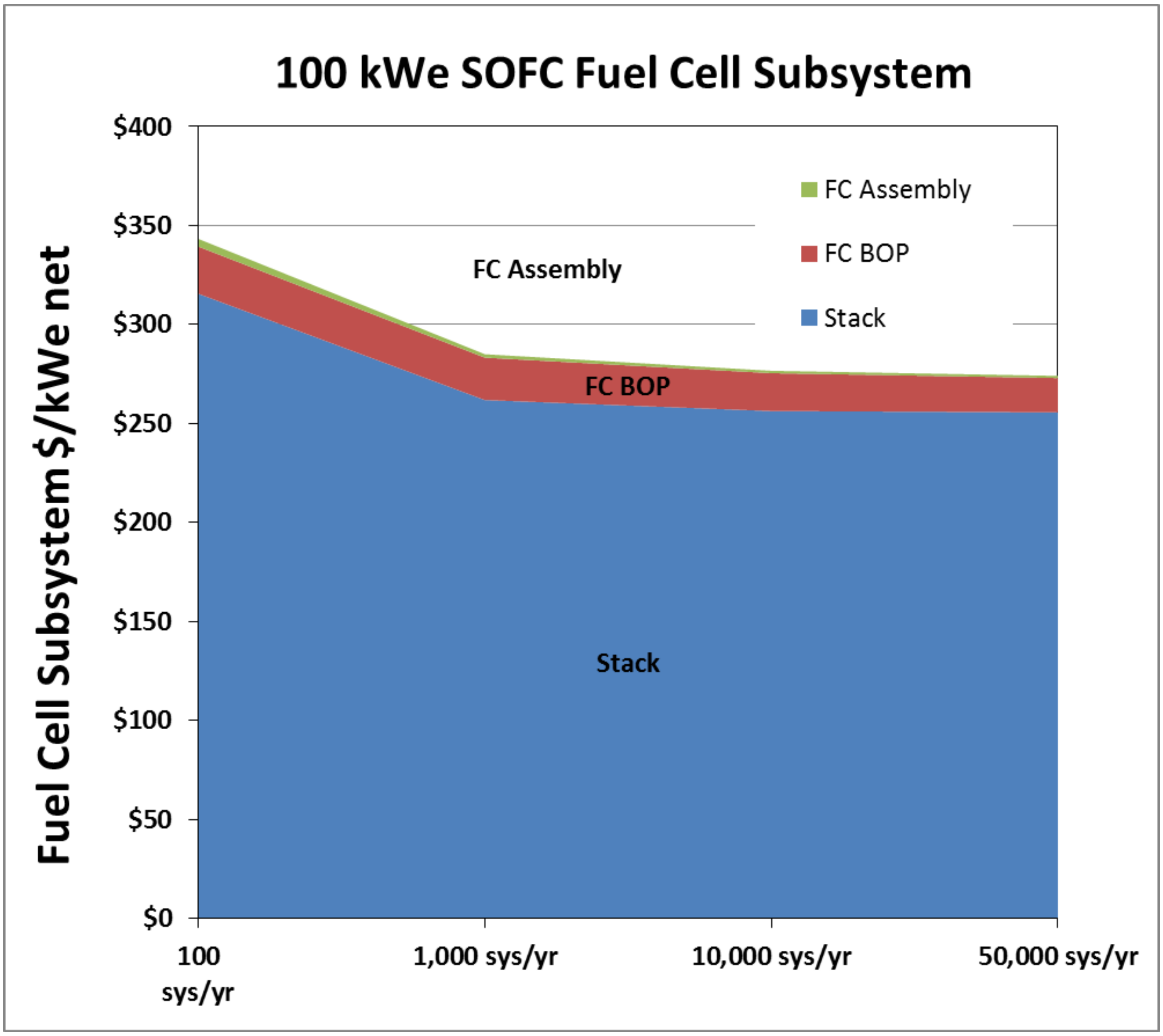

Figure 72: 100 kWe SOFC FC Subsystem Cost Breakdown

6.3.5 SOFC CHP and Power Electronics Subsystem Costs

Results also indicate the incremental cost of adding on either CHP capability or grid-independent capability. Figure 73 displays the baseline system cost[86] and the incremental cost of adding on CHP capability and the incremental cost of adding on grid-independent capability. The incremental cost of adding on a CHP capability includes the capital cost of additional heat exchangers needed for conveying anode and/or cathode off-gas heat to a building's heating system. Heat exchanger inlet/outlet

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[86] Please note that the "baseline system" shown in the "Marginal Increase in System Cost from CHP and Grid-Independent Operation" figures is different from the "baseline system" referred to throughout the rest of the report. Throughout the rest of the report, the baseline system includes all components needed for CHP operation but does not include additional components needed for grid-independent operation.

temperatures are based on prior modeling work[87] on integrating CHP FCSs into large and small office commercial building systems. The incremental cost of adding on grid-independent capability includes the cost of additional power electronics and battery components. Results indicate that the marginal increase in cost between producing a basic system that is not capable of CHP and producing a more advanced FCS that is capable of CHP is in fact quite small: CHP capital costs represent only 1% to 3% of the overall capital cost of such a system. Results also indicate that the marginal increase in cost between producing a basic system that is not capable of grid-independent operation and producing a more advanced FCS that is capable of grid-independent operation is more significant: grid-independent capital costs represent between 10% and 11% of the overall capital cost of such a system. For example, at 50k sys/yr, for a 1 kWe FCS, this amounts to an increase in cost of about $600/kWe. In summary, for a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 2% and 3% and for adding grid-independent capability, it is between 11% and 13% of the base cost. By contrast, for a 100 kWe FCS at 50 k sys/yr, the marginal increase in capital cost from adding either CHP capability or grid-independent capability is not significant (numerical results not shown.)

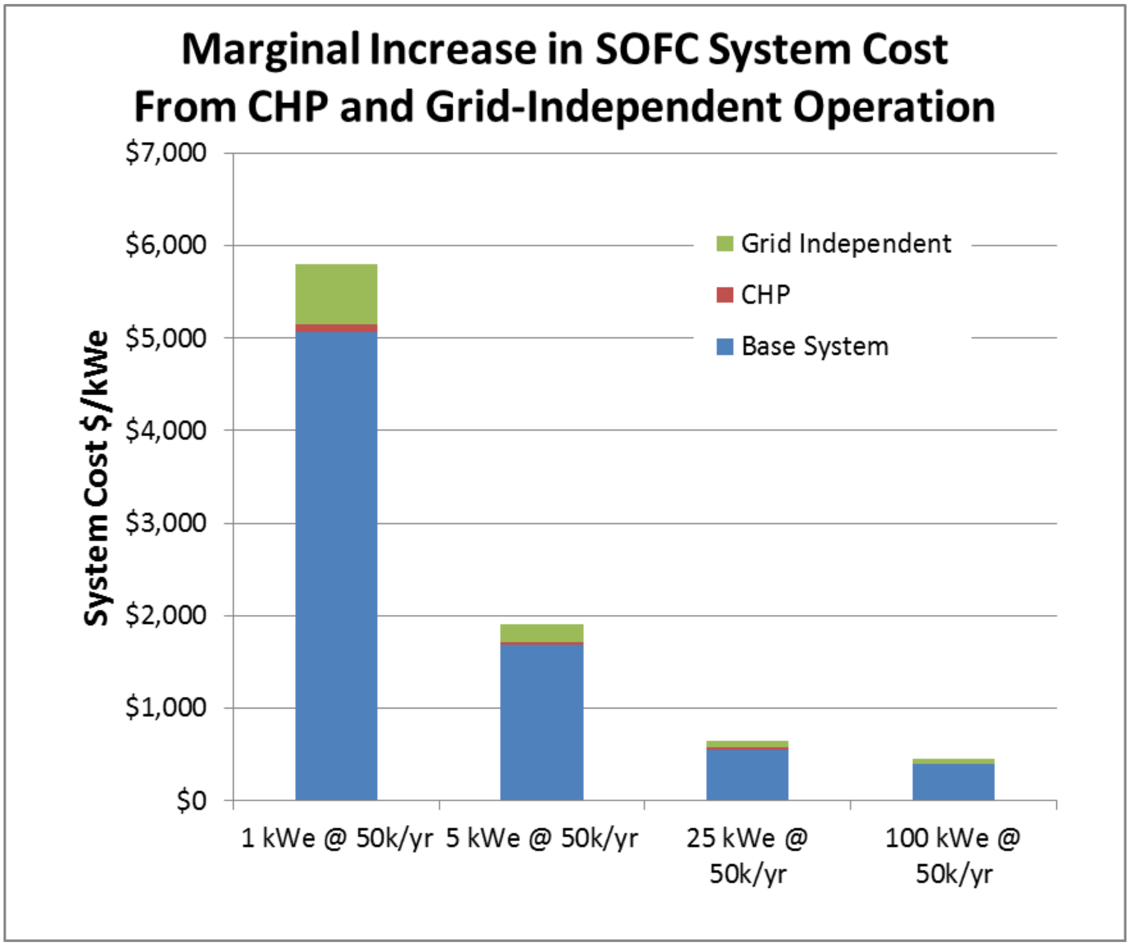

Figure 73: Marginal Increase in SOFC System Cost from CHP and Grid-Independent Operation

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[87] Colella, W.G. and Srivastava, V., 2012, "Examining the Integration of Fuel Cell Systems Into Buildings Through Simulation," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91474. PNNL-SA-87066.

6.4 Cost Results Comparisons by Fuel Cell System Type

Figure 74 through Figure 77 display the overall system cost comparisons of all three FC technology at each system power level (1 kWe, 5kWe, 25kWe, and 100kWe). For all four power levels, system cost is observed to decrease with annual manufacturing rate and to have a very steep slope at around 3,000 systems/year and a nearly flat slope at greater than 10,000 systems/year. The "knee" in the curves is around 3,000-5,000 systems per year for all systems. However, additional data points in this "knee" region are needed to better establish the exact location. Furthermore, examination of the SOFC curves suggests that the "knee" in the curve might be very sharp. An exact reason or explanation for a very sharp change in slope is not well understood.

In general, SOFC systems are projected to have the lowest system capital cost of the three technologies examined. The only exceptions to this occur at the 100 system/year manufacturing rates (at 1 and 5kWe system power) where SOFC is slightly higher cost. It is also noted that at the other end of the spectrum (50k systems/year at 100kW system power), SOFC and LT PEM system costs are nearly identical in cost. In general, SOFC tends to be modestly (<15%) less expensive than LT PEM, and HT PEM tends to be the most expensive.

A caveat must be added to these results: LT PEM cost models used in this comparison have been fine-tuned over the past 15 years[88,89] whereas the SOFC and HT PEM models have only been developed over the course of this project. The relative cost competitiveness of LT PEM with SOFC may be in part a function of having had more time to refine the LT PEM manufacturing cost models and systems designs to reduce LT PEM manufacturing costs.

It is further noted that the cost comparisons between fuel cell technologies in this analysis apply only to initial capital cost rather than to life cycle cost. The projected net system electrical efficiency based on higher heating value (HHV) of natural gas of the SOFC FCS (49%) is substantially higher than that of LT PEM (35%) or HT PEM (28%). While a life-cycle analysis has not been conducted, it is possible that the higher net electrical efficiency of the SOFC system may prove to be a more important discriminator between the FC technologies than capital cost.

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[88] James, B., Lomax, F., Thomas, S. and Colella, W.G., *PEM Fuel Cell Power System Cost Estimates: Sulfur-Free Gasoline Partial Oxidation and Compressed Direct Hydrogen*, report for the U.S. Department of Energy, 1997.

[89] Kuhn, I., Thomas, S., Lomax, F., James, B. and Colella, W.G., *Fuel Processing Systems for Fuel Cell Vehicles*, report for the U.S. Department of Energy, 1997.

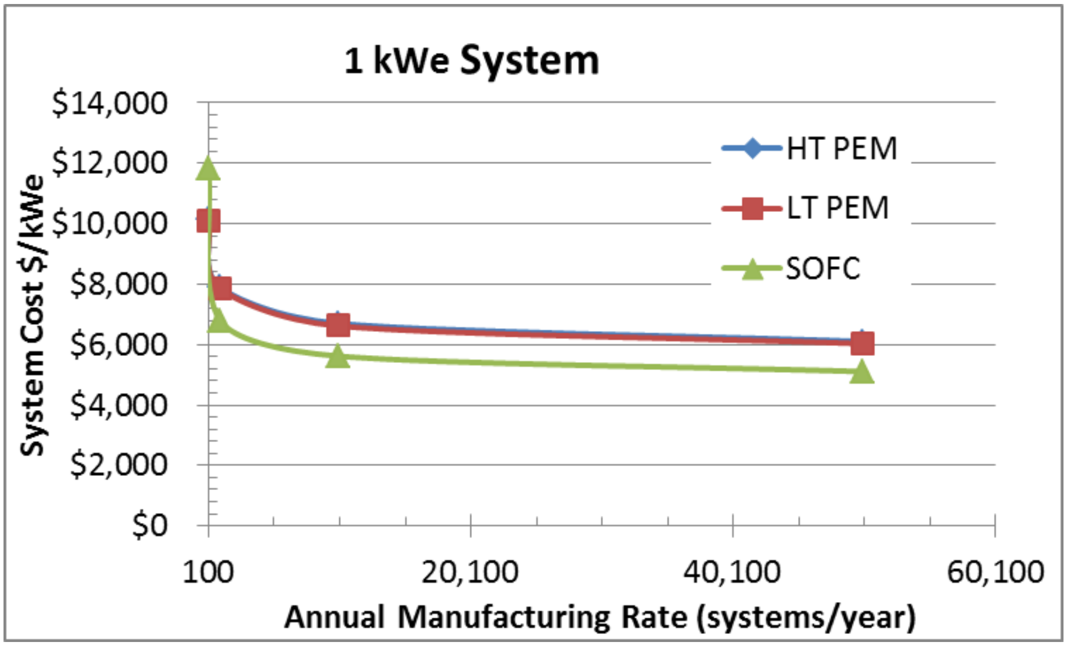

Figure 74: Cost Comparison between Technologies for 1 kWe Systems

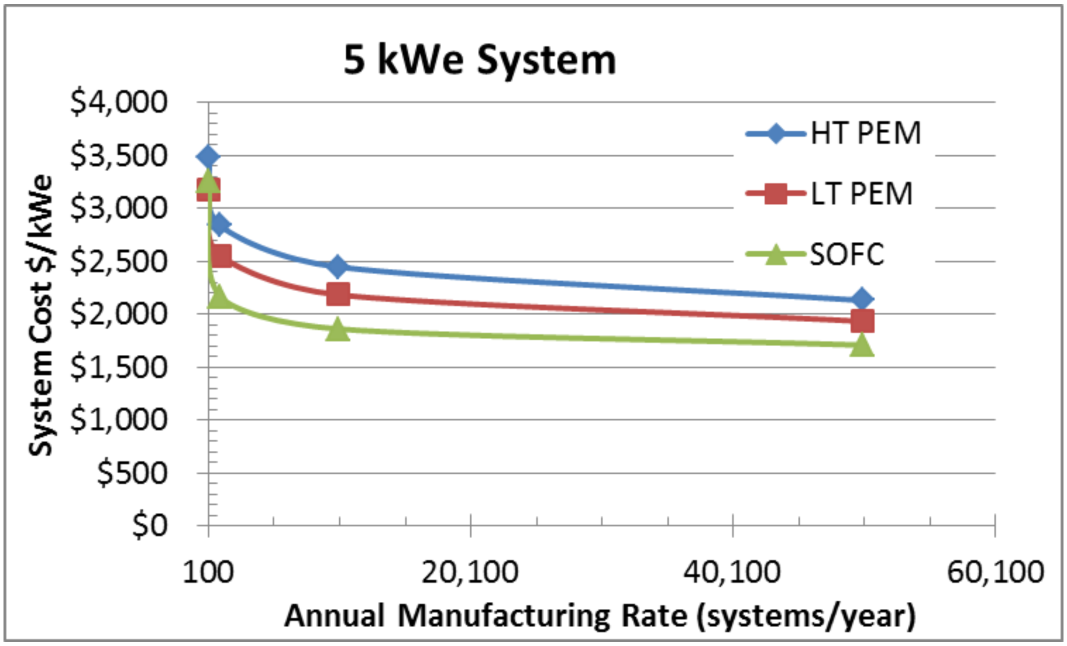

Figure 75: Cost Comparison between Technologies for 5 kWe Systems

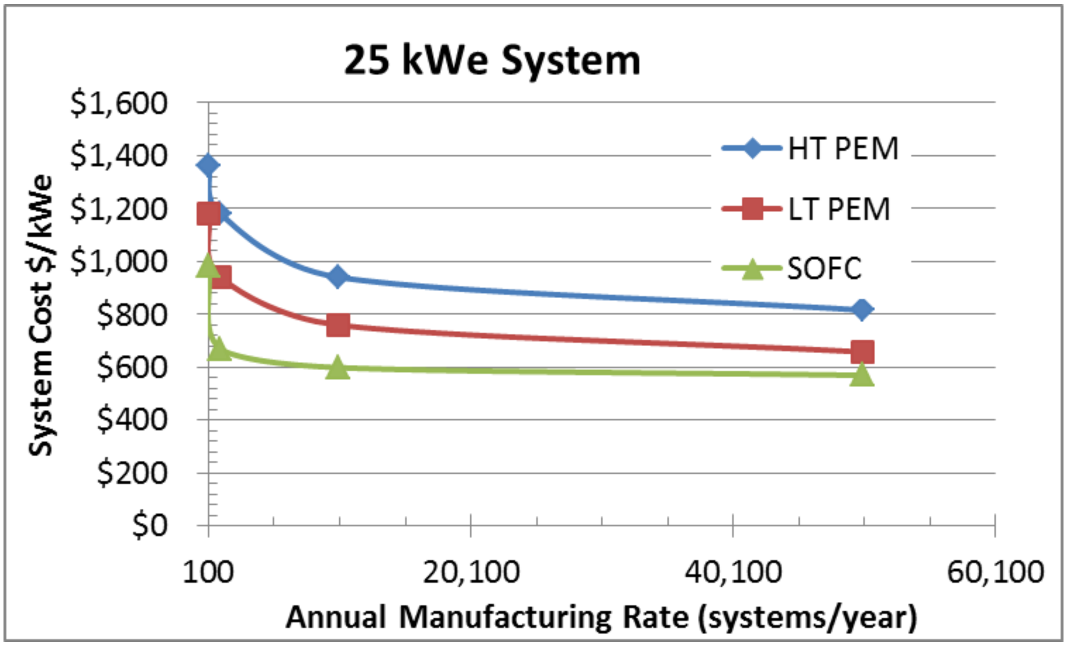

Figure 76: Cost Comparison between Technologies for 25 kWe Systems

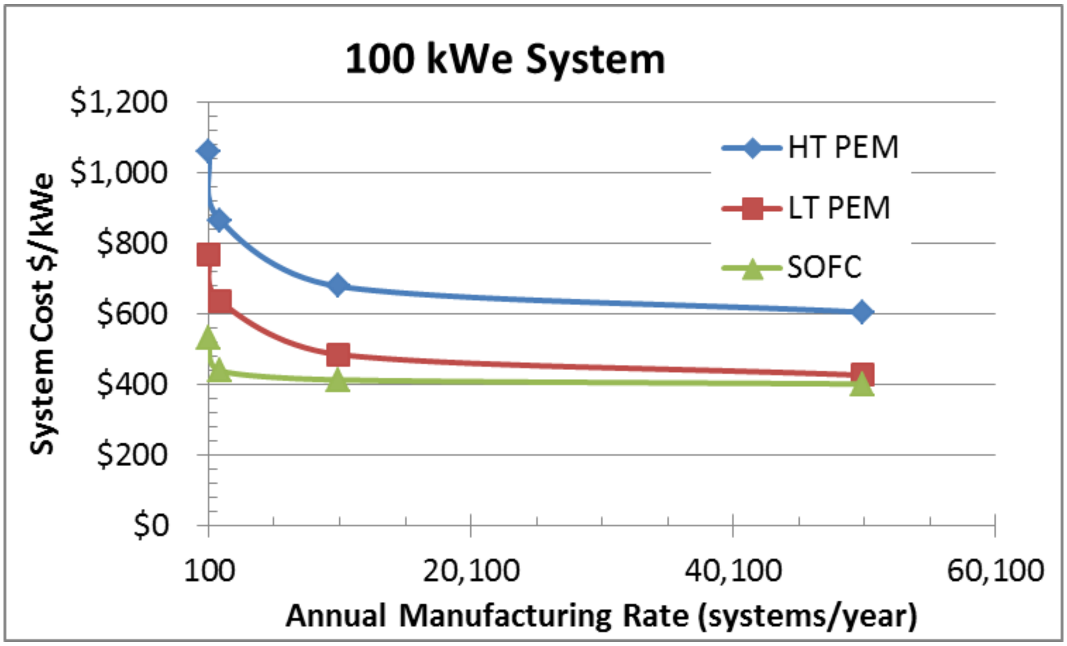

Figure 77: Cost Comparison between Technologies for 100 kWe Systems

7 Conclusions

The primary findings of this analysis of stationary CHP FCSs relate to the key cost drivers across the range of analysis, from the low power (1 kWe) FCSs to the large (100 kWe) FCSs and from low production (100 systems/year) to higher production rates (50,000 systems/year). Based on the analysis presented here, it was found that for a given cumulative global installed quantity, it is more cost-effective to produce fewer very large systems as compared to a large number of lower power systems. Thus, while both production quantity and system size drove cost down, cost was found to be more sensitive to system size than to production rate. Additional results quantify the relative cost contribution of various subsystems. The greatest contributors to the FCS capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing 1/2 to 3/4ths of the total system capital cost. Furthermore, model results indicate that the addition of CHP and grid-independent operation adds only about 10% to total system capital costs, compared with a base case design involving no CHP or grid-independent operation. Finally, model results indicate that SOFC system capital costs are expected to be the lowest for most scenarios investigated.

Modeling results for LT PEM, HT PEM, and SOFC systems underscore a few salient points:

- SOFC systems are projected to have the lowest system capital cost of the three technologies examined.
- As system size and system manufacturing rate increase, system cost decreases.
- In comparing the effect of system size and manufacturing rate on capital cost, increasing system size appears to have a greater impact on reducing costs per kilowatt than increasing manufacturing rate over the range of values plotted.
- For the same cumulative global installed capacity in a given year, FCSs with a higher electrical power output are several times more economical per kilowatt of electric power than systems with a lower power output.
- Across the range of system size levels, the greatest contributors to the capital cost are the fuel processing subsystem and the fuel cell subsystem, together representing half or more of the total system capital cost in all cases.
  The primary cost drivers for the FP BOP vary more with system size than with manufacturing rate.
- The primary cost drivers for the FP BOP may include NG compressors/blowers, water pumps, flammable gas alarm sensors, gas flow control solenoids, pressure regulators, and/or condensers, depending on fuel cell system size and type.

Modeling results for LT PEM CHP systems emphasize several key points:

- Modeling results for FCS capital costs are broadly consistent with manufacturer price values provided by Japan's Ene Farm program for similar system sizes and production rates if one considers that modeling cost results do not include: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. Further investigation is required for a direct comparison of expected system price.

- The combined cost of the FC and FP subsystems account for greater than 70% of total capital costs.
- For the 1 kWe system, the FP subsystem is relatively more costly than the FC subsystem at all production levels.
- For the 100 kWe system, the FC subsystem is more expensive than the FP subsystem at lower production levels, specifically at 1,000 sys/yr and below.
- For the 1 kWe system, the FP's costs are dominated by the BOP. This modeling result is consistent with the manufacturer test results of Japan's Ene Farm program, which found that a primary cost driver for CHP LT PEM systems was the FP sub-system balance of plant (BOP).
- At higher power levels, the FP BOP component costs decline significantly as a proportion of the total.
- For 1 kWe FCSs, the primary cost drivers for the FP BOP are the natural gas compressor, the flammable gas alarm sensors, and the gas flow control solenoids, in that order.
- For 100 kWe FCSs, the primary cost drivers for the FP BOP are the water pump and the condenser, in that order.
- For 1 kWe FCSs, BOP component costs constitute as much as 70% of FC subsystem costs.
- For 100 kWe FCSs, FC stack costs constitute as much as 80% of FC subsystem costs.
- At both the 1 kWe and 100 kWe size range, fuel cell subsystem assembly costs are estimated to be fairly negligible.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 1% and 3% and for adding grid-independent capability, it is between 10% and 12%.
- For a 100 kWe FCS at 50 k sys/yr, the marginal increase in capital cost from adding either CHP capability or grid-independent capability is not significant (numerical results not shown.)

Modeling results for HT PEM CHP systems emphasize additional important points:

- Modeling results for HT PEM FCS capital costs are broadly consistent with manufacturer values provided via a 2012 DOE deployment program of HTPEM systems. Modeling results indicate an unmarked-up manufacturing capital cost of roughly $3,500/kWe for 5kWe systems at manufacturing rates of 100 sys/yr. Manufacturer provided capital prices are roughly $13,000/kWe at a similar production rate.[90, 91] The difference between cost and price is significant as the reported modeling cost results do not include: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. Further investigation is needed to reconcile cost estimates with manufacturer price.

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[90] Colella, W.G. and Pilli, S.P., 2012, "Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings," *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11 and Fig. 5.

[91] Colella, W.G. and Pilli, S.P., 2012, "Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings," *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11 and Fig. 5.

- For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at all production levels.
- By contrast, for the 100 kWe system, the FC subsystem accounts for between 55% and 65% of capital costs.
- The lower power density of the HTPEM stack results in a large mass and volume of FC stack needed, compared with the LTPEM. At the same time, the HT and LT PEM system designs are very similar, and costs tend to scale with mass and/or volume. As a result, HT PEM stack costs are higher and contribute to a larger percentage of total system costs.
- At the 1 kWe size, BOP costs dominate FP subsystem costs. At the 100 kWe size, fuel processor costs dominate FP subsystem costs.
- For 1 kWe FCSs, the primary cost drivers for the FP BOP are the natural gas compressor, the flammable gas alarm sensors, and the gas flow control solenoids, in that order.
- For 100 kWe FCSs, the primary cost drivers for the FP BOP are the water pump and the condenser, in that order.
- At low power (1 kWe), the FP subsystem cost is dominated by the FP BOP components.
- At high power (100 kWe), the FC stack cost dominates the total system cost.
- At 1 kWe, FC BOP component costs constitute 60% or more of FC subsystem costs.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 3% and 4% and for adding grid-independent capability, it is between 7% and 11%.

Modeling results for SOFC CHP systems underscore some additional key points:

- Modeling results for SOFC capital costs are broadly consistent with manufacturer values provided by Ceramic Fuel Cells Limited (CFCL) of Australia. Modeling results indicate a unmarked-up manufacturing cost of roughly $11,830/kWe for 1kWe systems at manufacturing rates of about 100 sys/yr. Manufacturer provided capital prices are roughly $22,000/kWe at a similar production rate.[92, 93] Modeling cost results do not include:: profit and markup; one-time costs such as non-recurring research, design, and engineering costs; general and administrative (G&A) costs; warranties; advertising; and sales taxes. Further investigation is needed to reconcile cost estimates with manufacturer price.
- For the 1 kWe and 100 kWe system sizes, the FC and FP subsystems combined account for the majority of FCS capital costs, about 60% of total capital costs at a minimum.
- For the 1 kWe system, model results indicate that the FP subsystem is relatively more costly than the FC subsystem at production levels of 1,000 sys/yr and above. By contrast, for the 100 kWe system, the FC subsystem contributes about 65% to total cost.

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[92] Colella, W.G. and Pilli, S.P., 2012, “Energy System and Thermoeconomic Analysis of Combined Heat and Power (CHP) High Temperature Proton Exchange Membrane (HTPEM) Fuel Cell Systems (FCSs) for Light Commercial Buildings,” *ASME Journal of Fuel Cell Science and Technology*, (in print). PNNL-SA-86986. Fig. 11 and Fig. 5.

[93] Colella, W.G. and Pilli, S.P., 2012, “Independent Evaluation of Micro-Cogenerative Fuel Cell Systems For Commercial Buildings,” *Proceedings of the ASME 2012 10th Fuel Cell Science, Engineering and Technology Conference*, July 23-26, 2012, San Diego, CA, USA. ESFuelCell2012-91479. PNNL-SA-84709. Fig. 11 and Fig. 5.

- For the 1 kWe and 100 kWe systems, the fuel processing subsystem costs are dominated by the FP BOP.
- At low power (1kWe), at production rates above 1,000 sys/yr, the FP subsystem cost is dominated by the BOP components.
- At 100 kWe, FC stack costs constitute over 90% of FC subsystem costs.
- For a 1 kWe FCS at 50 k sys/yr, the marginal increase in capital cost for adding CHP capability is between 2% and 3% and for adding grid-independent capability, it is between 11% and 13% of the base cost.

8 Appendices of System Detailed Cost Results

8.1 Appendix A: Stack BOM

8.1.1 LT PEM Stack BOM

		Low Temperature PEM Systems							
Annual Production Rate	*systems/year*	*100*				*1,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.19*	*5.93*	*29.67*	*118.70*	*1.19*	*5.93*	*29.67*	*118.70*
Stacks per System	*stacks/system*	*1*	*1*	*4*	*4*	*1*	*1*	*4*	*4*
Cost per Stack									
Component Costs per Stack									
Bipolar Plates (Stamped)	**$/stack**	$162	$327	$289	$678	$55	$236	$258	$609
Bipolar Plate Coating Choice		Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone
MEAs		$607	$1,956	$2,018	$6,655	$407	$1,449	$1,554	$5,476
Membranes	**$/stack**	$114	$552	$684	$2,708	$114	$552	$684	$2,430
Catalyst Ink & Application (NSTF)	**$/stack**	$61	$278	$341	$1,361	$55	$272	$340	$1,360
GDLs	**$/stack**	$125	$539	$580	$1,997	$101	$431	$446	$1,459
M & E Hot Pressing	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
M & E Cutting & Slitting	**$/stack**	$6	$7	$2	$6	$1	$2	$2	$5
MEA Frame/Gaskets	**$/stack**	$301	$581	$411	$582	$136	$192	$82	$222
Coolant Gaskets Production Choice		Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding
Coolant Gaskets	**$/stack**	$11	$55	$61	$154	$11	$55	$56	$109
End Gaskets Production Choice		Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing
Coolant Gaskets	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
End Plates	**$/stack**	$31	$29	$26	$36	$21	$25	$19	$29
Current Collectors	**$/stack**	$5	$4	$3	$5	$3	$3	$3	$5
Compression Bands	**$/stack**	$14	$34	$36	$63	$14	$34	$35	$63
Stack Housing	**$/stack**	$70	$208	$244	$625	$9	$25	$41	$101
		$0	$0	$0	$0	$0	$0	$0	$0
Stack Assembly	**$/stack**	$12	$55	$56	$103	$12	$55	$56	$73
Stack Conditioning	**$/stack**	$122	$122	$122	$122	$117	$117	$64	$64
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$1,034	$2,791	$2,855	$8,441	$649	$2,000	$2,088	$6,529
Total Cost for all Stacks	$/stacks	$1,034	$2,791	$11,421	$33,764	$649	$2,000	$8,353	$26,116
Total Stacks Cost	**$/kW (Net)**	$1,034.22	$558.23	$456.86	$337.64	$648.75	$399.90	$334.10	$261.16
Total Stacks Cost	**$/kW (Gross)**	$871.32	$470.31	$384.90	$284.46	$546.56	$336.92	$281.48	$220.03

		Low Temperature PEM Systems							
Annual Production Rate	*systems/year*	*10,000*				*50,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.19*	*5.93*	*29.67*	*118.70*	*1.19*	*5.93*	*29.67*	*118.70*
Stacks per System	*stacks/system*	*1*	*1*	*4*	*4*	*1*	*1*	*4*	*4*
Cost per Stack									
Component Costs per Stack									
Bipolar Plates (Stamped)	**$/stack**	$50	$221	$163	$421	$46	$151	$151	$403
Bipolar Plate Coating Choice		Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone
MEAs		$278	$1,215	$1,117	$3,178	$251	$900	$780	$2,323
Membranes	**$/stack**	$114	$552	$388	$754	$114	$312	$166	$310
Catalyst Ink & Application (NSTF)	**$/stack**	$54	$272	$340	$1,319	$54	$272	$329	$1,315
GDLs	**$/stack**	$80	$324	$311	$888	$65	$248	$211	$512
M & E Hot Pressing	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
M & E Cutting & Slitting	**$/stack**	$0	$1	$1	$5	$0	$1	$1	$4
MEA Frame/Gaskets	**$/stack**	$29	$67	$75	$212	$18	$67	$72	$181
Coolant Gaskets Production Choice		Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding
Coolant Gaskets	**$/stack**	$10	$25	$14	$42	$5	$12	$14	$37
End Gaskets Production Choice		Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing
Coolant Gaskets	**$/stack**	$0	$0	$0	$0	$1	$1	$0	$0
End Plates	**$/stack**	$13	$10	$15	$25	$11	$10	$8	$15
Current Collectors	**$/stack**	$3	$2	$4	$5	$3	$2	$3	$4
Compression Bands	**$/stack**	$14	$34	$35	$62	$14	$33	$34	$60
Stack Housing	**$/stack**	$3	$6	$21	$48	$2	$5	$19	$44
		$0	$0	$0	$0	$0	$0	$0	$0
Stack Assembly	**$/stack**	$9	$30	$23	$38	$9	$19	$19	$33
Stack Conditioning	**$/stack**	$44	$44	$43	$43	$44	$44	$42	$42
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$423	$1,588	$1,435	$3,864	$384	$1,175	$1,070	$2,963
Total Cost for all Stacks	$/stacks	$423	$1,588	$5,739	$15,457	$384	$1,175	$4,280	$11,852
Total Stacks Cost	**$/kW (Net)**	$423.10	$317.54	$229.54	$154.57	$384.01	$235.08	$171.20	$118.52
Total Stacks Cost	**$/kW (Gross)**	$356.46	$267.52	$193.39	$130.22	$323.52	$198.05	$144.24	$99.85

8.1.2 HT PEM Stack BOM

		High Temperature PEM Systems							
Annual Production Rate	*systems/year*	*100*				*1,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.19*	*5.93*	*29.67*	*119.57*	*1.19*	*5.93*	*29.67*	*119.57*
Stacks per System	*stacks/system*	*1*	*1*	*1*	*2*	*1*	*1*	*1*	*2*
Cost per Stack									
Component Costs per Stack									
Bipolar Plates (Stamped)	**$/stack**	$179	$375	$803	$1,427	$64	$289	$660	$1,324
Bipolar Plate Coating		Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone
MEAs		$950	$3,580	$14,810	$28,376	$730	$2,973	$13,537	$22,775
Membranes	**$/stack**	$194	$939	$4,645	$9,264	$194	$939	$4,645	$6,395
Catalyst Ink & Application (NSTF)	**$/stack**	$233	$1,132	$5,630	$11,329	$226	$1,126	$5,623	$11,326
GDLs	**$/stack**	$201	$876	$3,730	$6,395	$164	$691	$2,816	$4,558
M & E Hot Pressing	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
M & E Cutting & Slitting	**$/stack**	$6	$7	$11	$14	$1	$2	$6	$12
MEA Frame/Gaskets	**$/stack**	$315	$626	$795	$1,374	$146	$215	$448	$485
Coolant Gaskets Production Choice		Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding
Coolant Gaskets	**$/stack**	$14	$66	$120	$241	$14	$66	$130	$188
End Gaskets Production Choice		Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printing	Screen Printin	Screen Printin
Coolant Gaskets	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
End Plates	**$/stack**	$39	$37	$112	$95	$25	$33	$92	$85
Current Collectors	**$/stack**	$6	$5	$17	$15	$4	$5	$17	$15
Compression Bands	**$/stack**	$16	$36	$41	$66	$16	$36	$41	$65
Stack Housing	**$/stack**	$81	$255	$505	$1,042	$10	$30	$60	$137
		$0	$0	$0	$0	$0	$0	$0	$0
Stack Assembly	**$/stack**	$12	$56	$54	$98	$12	$56	$54	$98
Stack Conditioning	**$/stack**	$122	$122	$122	$122	$117	$117	$117	$64
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$1,420	$4,533	$16,586	$31,482	$991	$3,604	$14,708	$24,751
Total Cost for all Stacks	$/stacks	$1,420	$4,533	$16,586	$62,964	$991	$3,604	$14,708	$49,502
Total Stacks Cost	**$/kW (Net)**	$1,419.88	$906.65	$663.43	$629.64	$991.30	$720.80	$588.34	$495.02
Total Stacks Cost	**$/kW (Gross)**	$1,196.23	$763.85	$558.93	$526.61	$835.16	$607.27	$495.67	$414.02

		High Temperature PEM Systems							
Annual Production Rate	*systems/year*	*10,000*				*50,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.19*	*5.93*	*29.67*	*119.57*	*1.19*	*5.93*	*29.67*	*119.57*
Stacks per System	*stacks/system*	*1*	*1*	*1*	*2*	*1*	*1*	*1*	*2*
Cost per Stack									
Component Costs per Stack									
Bipolar Plates (Stamped)	**$/stack**	$58	$256	$555	$1,010	$53	$183	$488	$955
Bipolar Plate Coating		Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone	Treadstone
MEAs		$580	$2,622	$9,758	$16,192	$533	$1,987	$7,821	$13,729
Membranes	**$/stack**	$194	$902	$2,014	$1,875	$183	$405	$817	$841
Catalyst Ink & Application (NSTF)	**$/stack**	$225	$1,126	$5,585	$11,173	$225	$1,118	$5,539	$11,149
GDLs	**$/stack**	$127	$509	$1,881	$2,616	$102	$376	$1,208	$1,320
M & E Hot Pressing	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
M & E Cutting & Slitting	**$/stack**	$0	$2	$6	$12	$0	$2	$6	$7
MEA Frame/Gaskets	**$/stack**	$33	$83	$273	$517	$22	$86	$251	$412
Coolant Gaskets Production Choice		Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding	Laser Welding
Coolant Gaskets	**$/stack**	$13	$25	$53	$82	$5	$22	$34	$64
End Gaskets Production Choice		Screen Printing	Screen Printing	Screen Printin	Screen Printin	Screen Printing	Screen Printing	Screen Printing	Screen Printing
Coolant Gaskets	**$/stack**	$0	$0	$0	$0	$1	$1	$0	$0
End Plates	**$/stack**	$19	$15	$95	$85	$16	$15	$57	$55
Current Collectors	**$/stack**	$4	$3	$19	$17	$4	$3	$13	$13
Compression Bands	**$/stack**	$15	$35	$40	$64	$15	$34	$39	$62
Stack Housing	**$/stack**	$3	$8	$15	$46	$2	$6	$11	$38
		$0	$0	$0	$0	$0	$0	$0	$0
Stack Assembly	**$/stack**	$9	$30	$30	$31	$9	$19	$19	$31
Stack Conditioning	**$/stack**	$44	$44	$43	$43	$44	$44	$43	$42
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$745	$3,037	$10,609	$17,572	$682	$2,314	$8,526	$14,991
Total Cost for all Stacks	$/stacks	$745	$3,037	$10,609	$35,144	$682	$2,314	$8,526	$29,982
Total Stacks Cost	**$/kW (Net)**	$744.83	$607.49	$424.35	$351.44	$681.86	$462.71	$341.05	$299.82
Total Stacks Cost	**$/kW (Gross)**	$627.51	$511.81	$357.51	$293.93	$574.46	$389.83	$287.33	$250.76

8.1.3 SOFC Stack BOM

		Solid Oxide Fuel Cell Systems							
Annual Production Rate	*systems/year*	*100*				*1,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.16*	*5.63*	*28.13*	*112.90*	*1.16*	*5.63*	*28.13*	*112.90*
Stacks per System	*stacks/system*	*1*	*1*	*1*	*2*	*1*	*1*	*1*	*2*
Cost per Stack									
Component Costs per Stack									
Cells		$2,417	$2,849	$6,899	$9,062	$366	$1,020	$4,138	$7,919
Tape Casting (Electrolye)	**$/stack**	$120	$137	$410	$274	$16	$34	$83	$129
Tape Casting (Substrate)	**$/stack**	$241	$285	$865	$640	$34	$77	$210	$349
Isostatic Pressing (Substrate)	**$/stack**	$42	$45	$57	$52	$5	$8	$20	$33
Laser Cutting (Holes)	**$/stack**	$230	$1,107	$3,406	$5,589	$153	$590	$2,747	$5,507
Stamping (Holes)	**$/stack**	$49	$50	$152	$79	$5	$6	$17	$12
Isostatic Pressing (Electrolyte)	**$/stack**	$42	$45	$57	$52	$5	$8	$20	$33
Laser Cutting (Sheets)	**$/stack**	$1	$4	$11	$23	$1	$4	$11	$16
High Temp Sintering (Sheets)	**$/stack**	$519	$702	$1,549	$2,860	$94	$320	$1,449	$2,835
Anode Deposition (Spraying)	**$/stack**	$407	$627	$1,956	$3,026	$92	$312	$1,419	$2,757
Annealing (Anode)	**$/stack**	$243	$269	$385	$418	$30	$57	$197	$418
Cathode Screen Printing	**$/stack**	$327	$399	$1,031	$1,138	$49	$121	$475	$860
Annealing (Cathode)	**$/stack**	$243	$269	$385	$418	$30	$57	$197	$418
Laser Cutting (Cells)	**$/stack**	$3	$17	$41	$81	$3	$17	$41	$57
Anode Current Collector		$24	$113	$133	$240	$19	$75	$113	$222
Stamping (Anode Current Collector)	**$/stack**	$1	$3	$5	$8	$1	$2	$4	$8
Wash Coating (Anode Col.)	**$/stack**	$23	$110	$127	$231	$18	$73	$109	$215
Cathode Current Collector		$352	$314	$634	$340	$32	$36	$77	$61
Stamping (Cathode Current Collector)	**$/stack**	$1	$3	$5	$8	$0	$2	$4	$7
MCO (Spray)	**$/stack**	$351	$311	$629	$332	$31	$33	$73	$54
Seals		$419	$725	$2,532	$4,388	$114	$491	$2,142	$4,241
Tape Casting (Seals)	**$/stack**	$118	$244	$961	$1,509	$41	$168	$711	$1,398
Stamping (Seals)	**$/stack**	$18	$18	$25	$14	$2	$2	$3	$2
High Temp Sintering (Seals)	**$/stack**	$283	$463	$1,546	$2,865	$70	$321	$1,428	$2,841
Laser Cutting (Seals)	**$/stack**	$9	$312	$619	$829	$61	$179	$331	$664
Interconnects		$360	$392	$789	$681	$44	$76	$250	$412
Stamping (Interconnects)	**$/stack**	$9	$40	$183	$365	$8	$39	$182	$364
MCO (Spray)	**$/stack**	$350	$352	$606	$316	$35	$37	$69	$48
Stack Housing	**$/stack**	$53	$446	$888	$992	$14	$53	$106	$162
Stack Assembly	**$/stack**	$10	$44	$42	$75	$10	$44	$42	$75
Stack Conditioning	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$3,635	$4,883	$11,917	$15,778	$598	$1,796	$6,868	$13,093
Total Cost for all Stacks	$/stacks	$3,635	$4,883	$11,917	$31,557	$598	$1,796	$6,868	$26,186
Total Stacks Cost	**$/kW (Net)**	$3,634.73	$976.68	$476.69	$315.57	$597.53	$359.15	$274.73	$261.86
Total Stacks Cost	**$/kW (Gross)**	$3,130.39	$867.96	$423.63	$279.50	$514.62	$319.17	$244.15	$231.93

		Solid Oxide Fuel Cell Systems							
Annual Production Rate	*systems/year*	*10,000*				*50,000*			
System Net Electric Power (Output)	*kWnet*	*1*	*5*	*25*	*100*	*1*	*5*	*25*	*100*
System Gross Electric Power (Output)	*kWgross*	*1.16*	*5.63*	*28.13*	*112.90*	*1.16*	*5.63*	*28.13*	*112.90*
Stacks per System	*stacks/system*	*1*	*1*	*1*	*2*	*1*	*1*	*1*	*2*
Cost per Stack									
Component Costs per Stack									
Cells		$193	$888	$3,893	$7,784	$182	$867	$3,874	$7,770
Tape Casting (Electrolye)	**$/stack**	$6	$28	$64	$129	$6	$27	$64	$129
Tape Casting (Substrate)	**$/stack**	$14	$66	$174	$349	$14	$65	$174	$348
Isostatic Pressing (Substrate)	**$/stack**	$1	$4	$9	$17	$1	$2	$8	$17
Laser Cutting (Holes)	**$/stack**	$112	$532	$2,730	$5,474	$111	$532	$2,725	$5,472
Stamping (Holes)	**$/stack**	$1	$2	$4	$5	$0	$1	$2	$4
Isostatic Pressing (Electrolyte)	**$/stack**	$1	$4	$9	$17	$1	$2	$8	$17
Laser Cutting (Sheets)	**$/stack**	$1	$3	$7	$12	$1	$2	$6	$11
High Temp Sintering (Sheets)	**$/stack**	$65	$301	$1,411	$2,830	$62	$298	$1,409	$2,829
Anode Deposition (Spraying)	**$/stack**	$61	$280	$1,371	$2,742	$58	$279	$1,366	$2,740
Annealing (Anode)	**$/stack**	$9	$47	$197	$397	$10	$44	$197	$395
Cathode Screen Printing	**$/stack**	$22	$93	$426	$848	$19	$93	$422	$846
Annealing (Cathode)	**$/stack**	$9	$47	$197	$397	$10	$44	$197	$395
Laser Cutting (Cells)	**$/stack**	$3	$12	$25	$41	$2	$9	$20	$39
Anode Current Collector		$15	$73	$110	$220	$15	$72	$109	$219
Stamping (Anode Current Collector)	**$/stack**	$0	$2	$4	$6	$0	$2	$3	$5
Wash Coating (Anode Col.)	**$/stack**	$15	$70	$107	$214	$15	$70	$107	$214
Cathode Current Collector		$4	$17	$34	$60	$3	$14	$29	$57
Stamping (Cathode Current Collector)	**$/stack**	$0	$2	$4	$6	$0	$2	$3	$5
MCO (Spray)	**$/stack**	$4	$15	$30	$54	$3	$12	$26	$52
Seals		$97	$464	$2,112	$4,237	$96	$462	$2,110	$4,235
Tape Casting (Seals)	**$/stack**	$34	$164	$697	$1,398	$34	$163	$697	$1,398
Stamping (Seals)	**$/stack**	$0	$1	$1	$1	$0	$0	$1	$1
High Temp Sintering (Seals)	**$/stack**	$63	$300	$1,414	$2,838	$62	$298	$1,413	$2,837
Laser Cutting (Seals)	**$/stack**	$32	$150	$323	$647	$31	$150	$322	$646
Interconnects		$12	$52	$202	$405	$11	$50	$202	$405
Stamping (Interconnects)	**$/stack**	$8	$39	$181	$364	$8	$39	$181	$364
MCO (Spray)	**$/stack**	$4	$12	$21	$42	$3	$10	$21	$42
Stack Housing	**$/stack**	$4	$14	$28	$78	$3	$10	$21	$71
Stack Assembly	**$/stack**	$7	$29	$29	$30	$7	$18	$18	$25
Stack Conditioning	**$/stack**	$0	$0	$0	$0	$0	$0	$0	$0
Stack Quality Control	**on/off**	On	On	On	On	On	On	On	On
Total Stack Cost	**$/stack**	$333	$1,536	$6,407	$12,814	$317	$1,493	$6,364	$12,782
Total Cost for all Stacks	$/stacks	$333	$1,536	$6,407	$25,628	$317	$1,493	$6,364	$25,564
Total Stacks Cost	**$/kW (Net)**	$332.56	$307.25	$256.30	$256.28	$317.27	$298.66	$254.54	$255.64
Total Stacks Cost	**$/kW (Gross)**	$286.42	$273.05	$227.77	$226.99	$273.25	$265.41	$226.21	$226.42

8.2 Appendix B: FC BOP BOM

8.2.1 LT PEM FC BOP BOM

	Low Temperature PEM Systems									
	1 kWe net Systems					5 kWe net Systems				
	Annual Production Rates					Annual Production Rates				
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$347	$314	$284	$264	1	$479	$433	$391	$365
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	*$24*	$22	$20	$19	1	$37	$33	$30	$28
Air Ducting (Including Cathode Ducting)	1	$69	$62	$56	$52	1	$95	$86	$78	$72
Anode Inlet Cooler	1	$129	$116	$105	$98	1	$177	$160	$145	$135
Membrane Air Humidifier	1	$107	$62	$60	$54	1	$156	$104	$96	$76
HTL Coolant Reservoir	1	$13	$13	$12	$9	1	$13	$13	$12	$9
HTL Coolant Pump	1	$51	$43	$36	$32	1	$70	$59	$50	$44
HTL Coolant DI Filter	1	$24	$22	$20	$19	1	$31	$28	$25	$23
HTL Thermostat & Valve	1	$24	$22	$20	$19	1	$31	$28	$25	$23
HTL Radiator	1	$50	$50	$50	$50	1	$50	$50	$50	$50
HTL Radiator Fan	1	$50	$46	$41	$38	1	$82	$74	$67	$62
HTL Coolant Piping	1	$18	$17	$15	$14	1	$22	$19	$18	$16
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$84	$75	$68	$64	1	$98	$89	$80	$75
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$15	$13	$11	$10	2	$34	$29	$24	$22
Voltage Sensors	1	$12	$10	$9	$8	1	$27	$23	$19	$17
Wiring	1	$84	$83	$78	$69	1	$88	$88	$82	$73
Fasteners for Wiring & Piping	1	$102	$95	$87	$80	1	$121	$113	$103	$94
Total FC BOP Cost, $/sys		$1,641	$1,463	$1,327	$1,194		$2,067	$1,842	$1,664	$1,493
Total FC BOP Cost, $/kWe		$1,640.83	$1,463.22	$1,327.05	$1,193.55		$413.30	$368.30	$332.70	$298.53

	Low Temperature PEM Systems									
	25 kWe net Systems					100 kWe net Systems				
		Annual Production Rates					Annual Production Rates			
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$661	$597	$540	$503	1	$872	$788	$713	$664
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	$49	$44	$40	$37	1	$110	$100	$90	$84
Air Ducting (Including Cathode Ducting)	1	$131	$118	$107	$100	1	$173	$156	$141	$132
Anode Inlet Cooler	1	$245	$221	$200	$186	1	$323	$292	$264	$246
Membrane Air Humidifier	1	$404	$336	$259	$156	1	$1,293	$1,112	$616	$285
HTL Coolant Reservoir	1	$13	$13	$12	$9	1	$13	$13	$12	$9
HTL Coolant Pump	1	$97	$81	$69	$61	1	$127	$107	$91	$80
HTL Coolant DI Filter	1	$61	$55	$50	$47	1	$122	$111	$100	$93
HTL Thermostat & Valve	1	$43	$39	$35	$33	1	$61	$55	$50	$47
HTL Radiator	1	$66	$66	$63	$57	1	$263	$262	$252	$228
HTL Radiator Fan	1	$133	$120	$108	$101	1	$201	$182	$164	$153
HTL Coolant Piping	1	$32	$29	$26	$24	1	$44	$39	$36	$33
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$115	$104	$94	$88	1	$132	$120	$108	$101
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$77	$65	$54	$48	2	$153	$129	$109	$97
Voltage Sensors	1	$61	$52	$44	$39	1	$123	$103	$87	$77
Wiring	1	$101	$101	$95	$84	1	$110	$109	$103	$91
Fasteners for Wiring & Piping	1	$152	$141	$129	$118	1	$183	$170	$155	$142
Total FC BOP Cost, $/sys		$2,937	$2,631	$2,322	$2,024		$4,880	$4,363	$3,542	$2,944
Total FC BOP Cost, $/kWe		$117.48	$105.24	$92.88	$80.94		$48.80	$43.63	$35.42	$29.44

8.2.2 HT PEM FC BOP BOM

	High Temperature PEM Systems									
	1 kWe System					5 kWe System				
	Annual Production Rates					Annual Production Rates				
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$347	$314	$284	$264	1	$479	$433	$391	$365
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	*$24*	$22	$20	$19	1	$37	$33	$30	$28
Air Ducting (Including Cathode Ducting)	1	$69	$62	$56	$52	1	$95	$86	$78	$72
Anode Inlet Cooler	1	$129	$116	$105	$98	1	$177	$160	$145	$135
HTL Coolant Reservoir	1	$15	$14	$12	$11	1	$15	$14	$12	$11
HTL Coolant Pump	1	$51	$43	$36	$32	1	$70	$59	$50	$44
HTL Coolant DI Filter	1	$24	$22	$20	$19	1	$31	$28	$25	$23
HTL Thermostat & Valve	1	$24	$22	$20	$19	1	$31	$28	$25	$23
HTL Radiator	1	$50	$50	$50	$50	1	$50	$50	$50	$50
HTL Radiator Fan	1	$54	$49	$44	$41	1	$88	$80	$72	$67
HTL Coolant Piping	1	$18	$17	$15	$14	1	$22	$19	$18	$16
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$84	$75	$68	$64	1	$98	$89	$80	$75
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$15	$13	$11	$10	2	$34	$29	$24	$22
Voltage Sensors	1	$12	$10	$9	$8	1	$27	$23	$19	$17
Wiring	1	$75	$74	$70	$62	1	$79	$78	$74	$65
Fasteners for Wiring & Piping	1	$98	$91	$84	$77	1	$117	$109	$100	$91
Total FC BOP Cost, $/sys		$1,527	$1,393	$1,258	$1,134		$1,905	$1,731	$1,561	$1,413
Total FC BOP Cost, $/kWe		$1,526.74	$1,392.98	$1,258.47	$1,133.89		$381.01	$346.21	$312.10	$282.56

	High Temperature PEM Systems									
	25 kWe System					100 kWe System				
	Annual Production Rates					Annual Production Rates				
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$661	$597	$540	$503	1	$872	$788	$713	$664
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	$49	$44	$40	$37	1	$110	$100	$90	$84
Air Ducting (Including Cathode Ducting)	1	$131	$118	$107	$100	1	$173	$156	$141	$132
Anode Inlet Cooler	1	$245	$221	$200	$186	1	$323	$292	$264	$246
HTL Coolant Reservoir	1	$15	$14	$12	$11	1	$15	$14	$12	$11
HTL Coolant Pump	1	$97	$81	$69	$61	1	$127	$107	$91	$80
HTL Coolant DI Filter	1	$61	$55	$50	$47	1	$122	$111	$100	$93
HTL Thermostat & Valve	1	$43	$39	$35	$33	1	$61	$55	$50	$47
HTL Radiator	1	$50	$50	$50	$50	1	$156	$155	$149	$135
HTL Radiator Fan	1	$143	$129	$117	$109	1	$217	$196	$177	$165
HTL Coolant Piping	1	$32	$29	$26	$24	1	$44	$39	$36	$33
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$115	$104	$94	$88	1	$132	$120	$108	$101
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$77	$65	$54	$48	2	$154	$130	$109	$97
Voltage Sensors	1	$61	$52	$44	$39	1	$123	$104	$87	$78
Wiring	1	$91	$90	$85	$75	1	$99	$98	$92	$82
Fasteners for Wiring & Piping	1	$147	$137	$125	$115	1	$179	$165	$151	$139
Total FC BOP Cost, $/sys		$2,515	$2,275	$2,045	$1,859		$3,482	$3,145	$2,823	$2,568
Total FC BOP Cost, $/kWe		$100.59	$90.99	$81.81	$74.36		$34.82	$31.45	$28.23	$25.68

8.2.3 SOFC FC BOP BOM

	Solid Oxide Fuel Cell Systems									
	1 kWe net Systems					5 kWe net Systems				
	Annual Production Rates					Annual Production Rates				
	1 kWe System	Annual Production Rates				5 kWe System	Annual Production Rates			
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$347	$314	$284	$264	1	$479	$433	$391	$365
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	*$24*	$22	$20	$19	1	$37	$33	$30	$28
Air Ducting (Including Cathode Ducting)	1	$69	$62	$56	$52	1	$95	$86	$78	$72
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$84	$75	$68	$64	1	$98	$89	$80	$75
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$15	$13	$11	$10	2	$33	$28	$24	$21
Voltage Sensors	1	$12	$10	$9	$8	1	$27	$23	$19	$17
Wiring	1	$71	$70	$66	$58	1	$72	$72	$68	$60
Fasteners for Wiring & Piping	1	$96	$90	$82	$75	1	$115	$106	$97	$89
Total FC BOP Cost, $/sys		$1,154	$1,054	$950	$845		$1,410	$1,283	$1,154	$1,033
Total FC BOP Cost, $/kWe		$1,154.25	$1,054.08	$949.76	$844.72		$282.06	$256.53	$230.76	$206.63

	Solid Oxide Fuel Cell Systems									
	25 kWe net Systems					100 kWe net Systems				
		Annual Production Rates					Annual Production Rates			
	25 kWe System	Annual Production Rates				100 kWe System	Annual Production Rates			
	Qty/System	100	1,000	10,000	50,000	Qty/System	100	1,000	10,000	50,000
Regenerative Air Blower	1	$661	$597	$540	$503	1	$872	$788	$713	$664
Air Mass Flow Sensor	1	$71	$64	$58	$54	1	$71	$64	$58	$54
Air Filter & Housing	1	$49	$44	$40	$37	1	$110	$100	$90	$84
Air Ducting (Including Cathode Ducting)	1	$131	$118	$107	$100	1	$173	$156	$141	$132
Pressure Transducer	1	$112	$95	$80	$71	1	$112	$95	$80	$71
Over-Pressure Cut-Off Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Purge Valve	1	$32	$27	$23	$20	1	$32	$27	$23	$20
Hydrogen Piping	1	$115	$104	$94	$88	1	$132	$120	$108	$101
System Controller	1	$172	$171	$159	$120	1	$172	$171	$159	$120
Current Sensors	2	$75	$63	$53	$47	2	$149	$126	$106	$94
Voltage Sensors	1	$60	$50	$42	$38	1	$120	$101	$85	$75
Wiring	1	$78	$78	$73	$65	1	$82	$81	$77	$68
Fasteners for Wiring & Piping	1	$142	$132	$120	$110	1	$172	$159	$145	$133
Total FC BOP Cost, $/sys		$1,806	$1,634	$1,466	$1,320		$2,381	$2,142	$1,914	$1,731
Total FC BOP Cost, $/kWe		$72.26	$65.38	$58.65	$52.81		$23.81	$21.42	$19.14	$17.31

8.3 Appendix C: FC Subsystem Summary

8.3.1 LT PEM FC Subsystem Summary

Fuel Cell Subsystem Cost Summary		Low Temperature PEM Systems							
Annual Production Rate		100				1,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	$/system	$3,066	$5,249	$14,750	$39,035	$2,286	$4,015	$11,158	$30,654
Fuel Cell Stacks	$/system	$1,034	$2,791	$11,421	$33,764	$649	$2,000	$8,353	$26,116
Balance of Plant	$/system	$1,641	$2,067	$2,937	$4,880	$1,463	$1,842	$2,631	$4,363
System Assembly & Testing	$/system	$391	$391	$391	$391	$174	$174	$174	$174
Total FC Subsystem Cost	$\$/\mathrm{kW}_{\mathrm{net}}$	$3,066.43	$1,049.81	$590.00	$390.35	$2,286.41	$803.09	$446.32	$306.54
Total Annual Cost	$/year	$306,643	$524,906	$1,474,991	$3,903,465	$2,286,413	$4,015,470	$11,157,935	$30,653,950
Cost/m^2 of Active Area	$\$/\mathrm{m}^2$	$8,775	$3,004	$1,688	$1,117	$6,543	$2,298	$1,277	$877
Cost/System	$/system	*$3,066*	*$5,249*	*$14,750*	*$39,035*	*$2,286*	*$4,015*	*$11,158*	*$30,654*
Cost/kW$_{\mathrm{gross}}$	$\$/\mathrm{kW}_{\mathrm{gross}}$	$2,583.44	$884.46	$497.07	$328.86	$1,926.28	$676.60	$376.02	$258.26

Fuel Cell Subsystem Cost Summary		Low Temperature PEM Systems							
Annual Production Rate		10,000				50,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	$/system	$1,870	$3,371	$8,181	$19,119	$1,691	$2,782	$6,417	$14,910
Fuel Cell Stacks	$/system	$423	$1,588	$5,739	$15,457	$384	$1,175	$4,280	$11,852
Balance of Plant	$/system	$1,327	$1,664	$2,322	$3,542	$1,194	$1,493	$2,024	$2,944
System Assembly & Testing	$/system	$120	$120	$120	$120	$114	$114	$114	$114
Total FC Subsystem Cost	$\$/\mathrm{kW}_{\mathrm{net}}$	$1,870.19	$674.24	$327.23	$191.19	$1,691.29	$556.35	$256.69	$149.10
Total Annual Cost	$/year	$18,701,860	$33,712,249	$81,807,747	$191,188,491	$84,564,713	$139,088,731	$320,867,688	$745,493,715
Cost/m^2 of Active Area	$\$/\mathrm{m}^2$	$5,352	$1,929	$936	$547	$4,840	$1,592	$735	$427
Cost/System	$/system	*$1,870*	*$3,371*	*$8,181*	*$19,119*	*$1,691*	*$2,782*	*$6,417*	*$14,910*
Cost/kW$_{\mathrm{gross}}$	$\$/\mathrm{kW}_{\mathrm{gross}}$	$1,575.61	$568.05	$275.69	$161.07	$1,424.90	$468.72	$216.26	$125.61

8.3.2 HT PEM FC Subsystem Summary

Fuel Cell Subsystem Cost Summary		High Temperature PEM Systems							
Annual Production Rate		100				1,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	$/system	$3,160	$6,651	$19,313	$66,659	$2,408	$5,359	$17,007	$52,671
Fuel Cell Stacks	$/system	$1,420	$4,533	$16,586	$62,964	$991	$3,604	$14,708	$49,502
Balance of Plant	$/system	$1,350	$1,728	$2,338	$3,305	$1,244	$1,582	$2,125	$2,995
System Assembly & Testing	$/system	$390	$390	$390	$390	$173	$173	$173	$173
Total FC Subsystem Cost	$\$/\mathrm{kW}_{\mathrm{net}}$	$3,159.51	$1,330.25	$772.53	$666.59	$2,408.10	$1,071.77	$680.28	$526.71
Total Annual Cost	$/year	$315,951	$665,123	$1,931,332	$6,665,935	$2,408,100	$5,358,866	$17,007,031	$52,670,906
Cost/m^2 of Active Area	$\$/\mathrm{m}^2$	$5,324	$2,241	$1,302	$1,115	$4,058	$1,806	$1,146	$881
Cost/System	$/system	*$3,160*	*$6,651*	*$19,313*	*$66,659*	*$2,408*	*$5,359*	*$17,007*	*$52,671*
Cost/kW$_{\mathrm{gross}}$	$\$/\mathrm{kW}_{\mathrm{gross}}$	$2,661.86	$1,120.72	$650.85	$557.51	$2,028.80	$902.96	$573.13	$440.52

Fuel Cell Subsystem Cost Summary		High Temperature PEM Systems							
Annual Production Rate		10,000				50,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	$/system	$1,996	$4,591	$12,647	$37,960	$1,817	$3,727	$10,386	$32,551
Fuel Cell Stacks	$/system	$745	$3,037	$10,609	$35,144	$682	$2,314	$8,526	$29,982
Balance of Plant	$/system	$1,132	$1,435	$1,919	$2,697	$1,022	$1,301	$1,747	$2,456
System Assembly & Testing	$/system	$119	$119	$119	$119	$113	$113	$113	$113
Total FC Subsystem Cost	$\$/\mathrm{kW}_{\mathrm{net}}$	$1,996.20	$918.18	$505.87	$379.60	$1,816.55	$745.43	$415.44	$325.51
Total Annual Cost	$/year	$19,961,958	$45,908,861	$126,468,546	$379,604,880	$90,827,722	$186,357,752	$519,302,366	$1,627,537,837
Cost/m^2 of Active Area	$\$/\mathrm{m}^2$	$3,364	$1,547	$852	$635	$3,061	$1,256	$700	$544
Cost/System	$/system	*$1,996*	*$4,591*	*$12,647*	*$37,960*	*$1,817*	*$3,727*	*$10,386*	*$32,551*
Cost/kW$_{\mathrm{gross}}$	$\$/\mathrm{kW}_{\mathrm{gross}}$	$1,681.78	$773.56	$426.19	$317.49	$1,530.43	$628.02	$350.01	$272.24

8.3.3 SOFC FC Subsystem Summary

Fuel Cell Subsystem Cost Summary		Solid Oxide Fuel Cell Systems							
Annual Production Rate		100				1,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	**$/system**	$5,178	$6,682	$14,113	$34,327	$1,825	$3,251	$8,676	$28,501
Fuel Cell Stacks	$/system	$3,635	$4,883	$11,917	$31,557	$598	$1,796	$6,868	$26,186
Balance of Plant	$/system	$1,154	$1,410	$1,806	$2,381	$1,054	$1,283	$1,634	$2,142
System Assembly & Testing	$/system	$389	$389	$389	$389	$173	$173	$173	$173
Total FC Subsystem Cost	**\$/kW$_{net}$**	$5,177.73	$1,336.49	$564.50	$343.27	$1,824.58	$650.27	$347.03	$285.01
Total Annual Cost	$/year	$517,773	$668,245	$1,411,253	$3,432,661	$1,824,579	$3,251,358	$8,675,640	$28,500,701
Cost/m^2 of Active Area	\$/m^2	$10,821	$2,882	$1,217	$738	$3,813	$1,402	$748	$613
Cost/System	$/system	*$5,178*	*$6,682*	*$14,113*	*$34,327*	*$1,825*	*$3,251*	*$8,676*	*$28,501*
Cost/kW$_{gross}$	\$/kW$_{gross}$	$4,459.29	$1,187.71	$501.66	$304.04	$1,571.41	$577.88	$308.39	$252.43

Fuel Cell Subsystem Cost Summary		Solid Oxide Fuel Cell Systems							
Annual Production Rate		10,000				50,000			
System Net Electric Power (Output)		1	5	25	100	1	5	25	100
Component Costs/System	**$/system**	$1,401	$2,809	$7,992	$27,661	$1,275	$2,639	$7,796	$27,407
Fuel Cell Stacks	$/system	$333	$1,536	$6,407	$25,628	$317	$1,493	$6,364	$25,564
Balance of Plant	$/system	$950	$1,154	$1,466	$1,914	$845	$1,033	$1,320	$1,731
System Assembly & Testing	$/system	$119	$119	$119	$119	$113	$113	$113	$113
Total FC Subsystem Cost	**\$/kW$_{net}$**	$1,401.19	$561.79	$319.70	$276.61	$1,274.62	$527.81	$311.86	$274.07
Total Annual Cost	$/year	$14,011,930	$28,089,391	$79,924,765	$276,610,465	$63,731,151	$131,953,726	$389,819,679	##############
Cost/m^2 of Active Area	\$/m^2	$2,928	$1,212	$689	$595	$2,664	$1,138	$673	$589
Cost/System	$/system	*$1,401*	*$2,809*	*$7,992*	*$27,661*	*$1,275*	*$2,639*	*$7,796*	*$27,407*
Cost/kW$_{gross}$	\$/kW$_{gross}$	$1,206.77	$499.25	$284.11	$245.00	$1,097.76	$469.06	$277.14	$242.75

8.4 Appendix D: Fuel Processing Reactor BOM

8.4.1 LT PEM Reactor BOM

		Low Temperature PEM Systems							
		1 kW System				5 kW System			
		100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders		$89	$88	$88	$87	$342	$341	$341	$340
Cylinder Annealing		$125	$24	$11	$8	$125	$47	$23	$14
Endplates		$9	$3	$2	$2	$9	$3	$3	$2
Catalyzed Monoliths									
Finned monolith substrate		$103	$66	$35	$32	$184	$126	$72	$67
Washcoating (includes catalyst)		$102	$86	$41	$41	$241	$226	$181	$181
Mixing Plates and PROX Air Tube									
Mixing Plates		$13	$7	$5	$3	$14	$8	$6	$4
PROX Air Supply Tube		$1	$0	$0	$0	$1	$1	$1	$1
Burner		$33	$28	$24	$21	$70	$59	$50	$44
Burner Gas Spacing Coil		$4	$4	$4	$4	$9	$9	$9	$9
Insulation		$30	$30	$30	$30	$91	$91	$91	$91
Assembly		$254	$37	$15	$12	$254	$37	$15	$12
Reactor Total	$/system	$763	$373	$255	$240	$1,343	$949	$793	$766
Reactor Total	$/kWe net	$763.35	$373.14	$255.39	$240.18	$268.55	$189.88	$158.51	$153.11

		Low Temperature PEM Systems							
		25 kW System				100 kW System			
		100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders		$1,668	$1,667	$1,666	$1,666	$6,669	$6,668	$6,662	$6,662
Cylinder Annealing		$376	$203	$98	$87	$921	$469	$351	$340
Endplates		$11	$5	$4	$4	$23	$17	$16	$14
Catalyzed Monoliths									
Finned monolith substrate		$494	$352	$246	$224	$1,721	$1,090	$906	$817
Washcoating (includes catalyst)		$940	$925	$879	$879	$3,766	$3,677	$3,518	$3,512
Mixing Plates and PROX Air Tube									
Mixing Plates		$19	$12	$10	$8	$54	$45	$34	$31
PROX Air Supply Tube		$3	$3	$3	$3	$10	$10	$10	$10
Burner		$142	$120	$101	$90				
Burner Gas Spacing Coil		$20	$20	$20	$20	$79	$79	$79	$79
Insulation		$368	$368	$368	$368	$1,470	$1,470	$1,470	$1,470
Assembly		$254	$37	$15	$12	$293	$76	$47	$40
Reactor Total	$/system	$4,294	$3,711	$3,410	$3,358	$15,519	$14,033	$13,457	$13,299
Reactor Total	$/kWe net	$171.78	$148.44	$136.38	$134.32	$155.19	$140.33	$134.57	$132.99

8.4.2 HT PEM Reactor BOM

		High Temperature PEM Systems							
		1 kWe System				5 kWe System			
		100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders		$89	$88	$88	$87	$342	$341	$341	$340
Cylinder Annealing		$125	$24	$11	$8	$125	$47	$23	$14
Endplates		$10	$4	$3	$3	$12	$5	$5	$4
Catalyzed Monoliths						$0	$0	$0	$0
Finned monolith substrate		$43	$25	$17	$12	$70	$48	$33	$25
Washcoating (includes catalyst)		$69	$50	$34	$34	$196	$177	$162	$162
Mixing Plates and PROX Air Tube						$0	$0	$0	$0
Mixing Plates		$9	$3	$2	$2	$9	$4	$3	$2
PROX Air Supply Tube		$0	$0	$0	$0	$0	$0	$0	$0
Burner		$33	$28	$24	$21	$70	$59	$50	$44
Burner Gas Spacing Coil		$4	$4	$4	$4	$9	$9	$9	$9
Insulation		$30	$25	$21	$19	$84	$71	$60	$53
Assembly		$252	$35	$13	$11	$252	$35	$13	$11
Reactor Total	$/system	$664	$286	$218	$201	$1,170	$797	$698	$665
Reactor Total	$/kWe net	$664.42	$286.31	$217.56	$201.45	$234.06	$159.37	$139.63	$133.03

		High Temperature PEM Systems							
		25 kWe System				100 kWe System			
		100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders		$1,668	$1,667	$1,666	$1,666	$6,670	$6,668	$6,662	$6,662
Cylinder Annealing		$376	$203	$98	$87	$921	$469	$351	$340
Endplates		$20	$13	$12	$12	$55	$49	$48	$46
Catalyzed Monoliths		$0	$0	$0	$0				
Finned monolith substrate		$176	$137	$93	$83	$600	$447	$331	$292
Washcoating (includes catalyst)		$835	$815	$800	$799	$3,337	$3,266	$3,199	$3,198
Mixing Plates and PROX Air Tube		$0	$0	$0	$0				
Mixing Plates		$11	$5	$4	$3	$25	$19	$14	$12
PROX Air Supply Tube		$0	$0	$0	$0	$0	$0	$0	$0
Burner		$142	$120	$101	$90	$512	$432	$364	$323
Burner Gas Spacing Coil		$20	$20	$20	$20	$79	$79	$79	$79
Insulation		$305	$258	$217	$193	$1,102	$930	$784	$696
Assembly		$252	$35	$13	$11	$284	$67	$46	$39
Reactor Total	$/system	$3,805	$3,272	$3,024	$2,963	$13,585	$12,425	$11,877	$11,687
Reactor Total	$/kWe net	$152.19	$130.88	$120.97	$118.53	$135.85	$124.25	$118.77	$116.87

8.4.3 SOFC Reactor BOM

Solid Oxide Fuel Cell Systems

	1 kWe System				5 kWe System			
	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders	$45	$44	$44	$43	$102	$101	$101	$100
Cylinder Annealing	$125	$24	$11	$8	$125	$47	$23	$14
Endplates	$10	$4	$3	$3	$12	$5	$5	$4
Catalyzed Monoliths								
Finned monolith substrate	$38	$21	$14	$9	$49	$31	$18	$12
Washcoating (includes catalyst)	$37	$18	$3	$3	$41	$22	$7	$6
Mixing Plates	$9	$3	$2	$2	$9	$4	$3	$2
Burner	$19	$16	$13	$12	$25	$21	$17	$15
Burner Gas Spacing Coil	$2	$2	$2	$2	$3	$3	$3	$3
Insulation	$18	$15	$13	$12	$34	$29	$24	$21
Assembly	$251	$35	$13	$11	$251	$35	$13	$11
Reactor Total	$554 /sys	$183 /sys	$118 /sys	$105 /sys	$649 /sys	$296 /sys	$213 /sys	$190 /sys
Reactor Total	$554.07 /kWe net	$182.65 /kWe net	$118.34 /kWe net	$104.86 /kWe net	$129.77 /kWe net	$59.11 /kWe net	$42.58 /kWe net	$37.91 /kWe net

Solid Oxide Fuel Cell Systems

	25 kWe System				100 kWe System			
	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cylinders	$357	$356	$356	$355	$1,032	$1,030	$1,030	$1,029
Cylinder Annealing	$374	$202	$97	$87	$374	$202	$97	$87
Endplates	$20	$13	$12	$12	$20	$13	$12	$12
Catalyzed Monoliths								
Finned monolith substrate	$83	$59	$28	$26	$93	$67	$35	$32
Washcoating (includes catalyst)	$58	$39	$24	$24	$188	$111	$89	$89
Mixing Plates	$11	$5	$4	$3	$11	$5	$4	$3
Burner	$36	$30	$26	$23				
Burner Gas Spacing Coil	$4	$4	$4	$4	$12	$12	$12	$12
Insulation	$97	$82	$69	$61	$207	$174	$147	$130
Assembly	$251	$35	$13	$11	$251	$35	$13	$11
Reactor Total	$1291 /sys	$826 /sys	$634 /sys	$606 /sys	$2279 /sys	$1728 /sys	$1506 /sys	$1464 /sys
Reactor Total	$51.65 /kWe net	$33.03 /kWe net	$25.36 /kWe net	$24.24 /kWe net	$22.79 /kWe net	$17.28 /kWe net	$15.06 /kWe net	$14.64 /kWe net

8.5 Appendix E: FP BOP BOM

8.5.1 LT PEM FP BOP BOM

		Stationary Low Temp PEM			
System Net Electric Power (Output)	**1 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$85	$80	$76	$73
Air Flow Control Solenoids	**1**	$150	$142	$133	$128
Condenser	**1**	$200	$173	$149	$134
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**1**	$162	$140	$121	$109
Demin Water Filter	**1**	$28	$24	$21	$19
Pressure Regulators	**0**	$171	$164	$157	$152
Desulfurizer	**1**	$55	$55	$55	$55
Gas Flow Control Solenoids	**2**	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**1**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**1**	$1,121	$967	$835	$753
Temperature Transmitter Sensor, Reactor Body	**1**	$77	$69	$61	$56
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$69	$60	$52	$47
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**3**	$37	$35	$34	$34
Total BOP Cost, $/system		$3,137	$2,763	$2,440	$2,237
Total BOP Cost, $/kWe net		$3,136.50	$2,763.36	$2,439.72	$2,237.11

		Stationary Low Temp PEM			
System Net Electric Power (Output)	**5 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$85	$80	$76	$73
Air Flow Control Solenoids	**1**	$150	$142	$133	$128
Condenser	**1**	$447	$386	$333	$300
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**2**	$155	$134	$115	$104
Demin Water Filter	**1**	$28	$24	$21	$19
Pressure Regulators	**0**	$171	$164	$157	$152
Desulfurizer	**1**	$55	$55	$55	$53
Gas Flow Control Solenoids	**2**	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**1**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**1**	$2,508	$2,163	$1,866	$1,683
Temperature Transmitter Sensor, Reactor Body	**1**	$77	$69	$61	$56
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$69	$60	$52	$47
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**3**	$37	$35	$34	$34
Total BOP Cost, $/system		$4,918	$4,300	$3,765	$3,431
Total BOP Cost, $/kWe net		$983.60	$860.03	$753.09	$686.15

		Stationary Low Temp PEM			
System Net Electric Power (Output)	**25 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$85	$80	$76	$73
Air Flow Control Solenoids	**1**	$150	$142	$133	$128
Condenser	**1**	$1,000	$863	$744	$671
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**1**	$710	$543	$479	$439
Demin Water Filter	**2**	$27	$23	$20	$18
Pressure Regulators	**1**	$201	$193	$184	$179
Desulfurizer	**1**	$55	$55	$53	$47
Gas Flow Control Solenoids	**2**	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**1**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**0**	$5,607	$4,837	$4,173	$3,763
Temperature Transmitter Sensor, Reactor Body	**1**	$77	$69	$61	$56
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$69	$60	$52	$47
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**3**	$37	$35	$34	$34
Total BOP Cost, $/system		$3,589	$3,103	$2,760	$2,540
Total BOP Cost, $/kWe net		$143.57	$124.14	$110.41	$101.59

		Stationary Low Temp PEM			
System Net Electric Power (Output)	**100 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**6**	$81	$77	$73	$71
Air Flow Control Solenoids	**6**	$143	$135	$127	$122
Condenser	**1**	$2,000	$1,725	$1,488	$1,342
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$83	$66	$53	$45
Water Pump, Reactor	**4**	$658	$504	$445	$408
Demin Water Filter	**8**	$24	$21	$18	$17
Pressure Regulators	**1**	$338	$323	$309	$300
Desulfurizer	**1**	$55	$55	$48	$22
Gas Flow Control Solenoids	**8**	$141	$121	$103	$90
Mass Flow Sensor, Reactor NG	**4**	$65	$60	$55	$52
Mass Flow Sensor, Burner NG	**4**	$65	$60	$55	$52
Natural Gas Blower/Compressor	**0**	$11,215	$9,674	$8,346	$7,527
Temperature Transmitter Sensor, Reactor Body	**4**	$70	$62	$55	$51
Temperature Transmitter Sensor, Reactor Inlet Streams	**8**	$65	$56	$49	$44
Temperature Transmitter Sensor, Reactor Outlet Streams	**8**	$15	$14	$12	$11
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**12**	$36	$35	$34	$33
Total BOP Cost, $/system		$10,155	$8,724	$7,776	$7,146
Total BOP Cost, $/kWe net		$101.55	$87.24	$77.76	$71.46

8.5.2 HT PEM FP BOP BOM

		Stationary HighTemp PEM			
System Net Electric Power (Output)	**1 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	1	$79	$68	$58	$52
Air Flow Control Solenoids	0	$0	$0	$0	$0
Condenser	1	$200	$173	$149	$134
Level Transmitter Sensors	1	$15	$13	$11	$10
Water Tank	1	$47	$38	$30	$26
Water Pump, Reactor	1	$162	$140	$121	$109
Demin Water Filter	1	$28	$24	$21	$19
Pressure Regulators	0	$171	$164	$157	$152
Desulfurizer	1	$55	$55	$55	$55
Activated Carbon	1	$18	$10	$5	$3
Gas Flow Control Solenoids	2	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	1	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	1	$69	$63	$58	$55
Natural Gas Blower/Compressor	1	$1,121	$967	$835	$753
Temperature Transmitter Sensor, Reactor Body	1	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	2	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	2	$16	$15	$13	$12
Flammable Gas Alarm Sensors	1	$480	$416	$360	$325
Check Valve, Anode Purge Line	3	$37	$35	$34	$34
Shut-off Valve	4	$9	$8	$7	$6
Pressure Release	2	$21	$18	$16	$14
Total BOP Cost, $/system		$3,044	$2,659	$2,329	$2,123
Total BOP Cost, $/kWe net		$3,043.77	$2,658.77	$2,328.52	$2,123.20

		Stationary HighTemp PEM			
System Net Electric Power (Output)	**5 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	1	$79	$68	$58	$52
Air Flow Control Solenoids	0	$0	$0	$0	$0
Condenser	1	$447	$386	$333	$300
Level Transmitter Sensors	1	$15	$13	$11	$10
Water Tank	1	$47	$38	$30	$26
Water Pump, Reactor	2	$155	$134	$115	$104
Demin Water Filter	1	$28	$24	$21	$19
Pressure Regulators	0	$171	$164	$157	$152
Desulfurizer	1	$55	$55	$55	$53
Activated Carbon	1	$12	$6	$3	$2
Gas Flow Control Solenoids	2	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	1	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	1	$69	$63	$58	$55
Natural Gas Blower/Compressor	1	$2,508	$2,163	$1,866	$1,683
Temperature Transmitter Sensor, Reactor Body	1	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	2	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	2	$16	$15	$13	$12
Flammable Gas Alarm Sensors	1	$480	$416	$360	$325
Check Valve, Anode Purge Line	3	$37	$35	$34	$34
Shut-off Valve	4	$9	$8	$7	$6
Pressure Release	2	$21	$18	$16	$14
Total BOP Cost, $/system		$4,819	$4,192	$3,652	$3,316
Total BOP Cost, $/kWe net		$963.73	$838.42	$730.48	$663.14

		Stationary HighTemp PEM			
System Net Electric Power (Output)	**25 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$79	$68	$58	$52
Air Flow Control Solenoids	**0**	$0	$0	$0	$0
Condenser	**1**	$1,000	$863	$744	$671
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**1**	$710	$543	$479	$439
Demin Water Filter	**2**	$27	$23	$20	$18
Pressure Regulators	**1**	$201	$193	$184	$179
Desulfurizer	**1**	$55	$55	$53	$47
Activated Carbon	**1**	$7	$4	$2	$1
Gas Flow Control Solenoids	**2**	$149	$133	$120	$110
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**1**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**0**	$5,607	$4,837	$4,173	$3,763
Temperature Transmitter Sensor, Reactor Body	**1**	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**3**	$37	$35	$34	$34
Shut-off Valve	**4**	$9	$8	$7	$6
Pressure Release	**2**	$21	$18	$16	$14
Total BOP Cost, $/system		$3,486	$2,993	$2,646	$2,424
Total BOP Cost, $/kWe net		$139.43	$119.73	$105.84	$96.95

		Stationary HighTemp PEM			
System Net Electric Power (Output)	**100 kW System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$79	$68	$58	$52
Air Flow Control Solenoids	**0**	$0	$0	$0	$0
Condenser	**1**	$2,000	$1,725	$1,488	$1,342
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$83	$66	$53	$45
Water Pump, Reactor	**4**	$658	$504	$445	$408
Demin Water Filter	**8**	$24	$21	$18	$17
Pressure Regulators	**1**	$338	$323	$309	$300
Desulfurizer	**1**	$55	$55	$48	$22
Activated Carbon	**1**	$5	$3	$1	$1
Gas Flow Control Solenoids	**8**	$141	$121	$103	$90
Mass Flow Sensor, Reactor NG	**4**	$65	$60	$55	$52
Mass Flow Sensor, Burner NG	**4**	$65	$60	$55	$52
Natural Gas Blower/Compressor	**0**	$11,215	$9,674	$8,346	$7,527
Temperature Transmitter Sensor, Reactor Body	**4**	$89	$79	$70	$65
Temperature Transmitter Sensor, Reactor Inlet Streams	**8**	$40	$34	$30	$27
Temperature Transmitter Sensor, Reactor Outlet Streams	**8**	$15	$14	$12	$11
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**12**	$36	$35	$34	$33
Shut-off Valve	**4**	$9	$8	$7	$6
Pressure Release	**2**	$21	$18	$16	$14
Total BOP Cost, $/system		$8,845	$7,484	$6,603	$6,016
Total BOP Cost, $/kWe net		$88.45	$74.84	$66.03	$60.16

8.5.3 SOFC FP BOP BOM

		Stationary SOFC			
System Net Electric Power (Output)	**1 kWe System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$79	$68	$58	$52
Air Flow Control Solenoids	**0**	$150	$0	$0	$0
Condenser	**1**	$199	$172	$148	$134
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**1**	$162	$140	$121	$109
Demin Water Filter	**1**	$28	$24	$21	$19
Pressure Regulators	**0**	$171	$164	$157	$152
Desulfurizer	**1**	$55	$55	$55	$55
Activated Carbon	**1**	$18	$10	$5	$3
Gas Flow Control Solenoids	**1**	$152	$140	$129	$122
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**0**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**1**	$1,118	$965	$832	$750
Temperature Transmitter Sensor, Reactor Body	**1**	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**2**	$37	$35	$35	$34
Shut-off Valve	**4**	$9	$8	$7	$6
Pressure Release	**2**	$21	$18	$16	$14
Total BOP Cost, $/system		$2,790	$2,431	$2,123	$1,933
Total BOP Cost, $/kWe net		$2,790.08	$2,430.62	$2,122.83	$1,933.24

		Stationary SOFC			
System Net Electric Power (Output)	**5 kWe System**	**Annual Production Rates**			
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	**1**	$79	$68	$58	$52
Air Flow Control Solenoids	**0**	$150	$0	$0	$0
Condenser	**1**	$446	$385	$332	$299
Level Transmitter Sensors	**1**	$15	$13	$11	$10
Water Tank	**1**	$47	$38	$30	$26
Water Pump, Reactor	**2**	$155	$134	$115	$104
Demin Water Filter	**1**	$28	$24	$21	$19
Pressure Regulators	**0**	$171	$164	$157	$152
Desulfurizer	**1**	$55	$55	$55	$54
Activated Carbon	**1**	$12	$6	$3	$2
Gas Flow Control Solenoids	**1**	$152	$140	$129	$122
Mass Flow Sensor, Reactor NG	**1**	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	**0**	$69	$63	$58	$55
Natural Gas Blower/Compressor	**1**	$2,500	$2,157	$1,861	$1,678
Temperature Transmitter Sensor, Reactor Body	**1**	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	**2**	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	**2**	$16	$15	$13	$12
Flammable Gas Alarm Sensors	**1**	$480	$416	$360	$325
Check Valve, Anode Purge Line	**2**	$37	$35	$35	$34
Shut-off Valve	**4**	$9	$8	$7	$6
Pressure Release	**2**	$21	$18	$16	$14
Total BOP Cost, $/system		$4,560	$3,960	$3,443	$3,123
Total BOP Cost, $/kWe net		$912.04	$791.97	$688.60	$624.69

			Stationary SOFC		
System Net Electric Power (Output)	**25 kWe System**		**Annual Production Rates**		
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	1	$79	$68	$58	$52
Air Flow Control Solenoids	0	$150	$0	$0	$0
Condenser	1	$997	$860	$742	$669
Level Transmitter Sensors	1	$15	$13	$11	$10
Water Tank	1	$47	$38	$30	$26
Water Pump, Reactor	1	$710	$543	$479	$439
Demin Water Filter	2	$27	$23	$20	$18
Pressure Regulators	1	$201	$193	$184	$179
Desulfurizer	1	$55	$55	$54	$48
Activated Carbon	1	$7	$4	$2	$1
Gas Flow Control Solenoids	1	$152	$140	$129	$122
Mass Flow Sensor, Reactor NG	1	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	0	$69	$63	$58	$55
Natural Gas Blower/Compressor	0	$5,591	$4,823	$4,161	$3,752
Temperature Transmitter Sensor, Reactor Body	1	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	2	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	2	$16	$15	$13	$12
Flammable Gas Alarm Sensors	1	$480	$416	$360	$325
Check Valve, Anode Purge Line	2	$37	$35	$35	$34
Shut-off Valve	4	$9	$8	$7	$6
Pressure Release	2	$21	$18	$16	$14
Total BOP Cost, $/system		$3,233	$2,766	$2,442	$2,236
Total BOP Cost, $/kWe net		$129.32	$110.63	$97.67	$89.44

			Stationary SOFC		
System Net Electric Power (Output)	**100 kWe System**		**Annual Production Rates**		
Component Names	**Qty/System**	**100 sys/yr**	**1,000 sys/yr**	**10,000 sys/yr**	**50,000 sys/yr**
Air Mass Flow Sensors	1	$79	$68	$58	$52
Air Flow Control Solenoids	0	$0	$0	$0	$0
Condenser	1	$1,994	$1,720	$1,484	$1,338
Level Transmitter Sensors	1	$15	$13	$11	$10
Water Tank	1	$83	$66	$53	$45
Water Pump, Reactor	4	$658	$504	$445	$408
Demin Water Filter	8	$24	$21	$18	$17
Pressure Regulators	1	$338	$323	$309	$300
Desulfurizer	1	$55	$54	$50	$28
Activated Carbon	1	$5	$3	$1	$1
Gas Flow Control Solenoids	1	$152	$140	$129	$122
Mass Flow Sensor, Reactor NG	1	$69	$63	$58	$55
Mass Flow Sensor, Burner NG	0	$69	$63	$58	$55
Natural Gas Blower/Compressor	0	$11,182	$9,646	$8,321	$7,505
Temperature Transmitter Sensor, Reactor Body	1	$96	$85	$76	$70
Temperature Transmitter Sensor, Reactor Inlet Streams	2	$43	$37	$32	$29
Temperature Transmitter Sensor, Reactor Outlet Streams	2	$16	$15	$13	$12
Flammable Gas Alarm Sensors	1	$480	$416	$360	$325
Check Valve, Anode Purge Line	2	$37	$35	$35	$34
Shut-off Valve	4	$9	$8	$7	$6
Pressure Release	2	$21	$18	$16	$14
Total BOP Cost, $/system		$6,466	$5,378	$4,733	$4,312
Total BOP Cost, $/kWe net		$64.66	$53.78	$47.33	$43.12

8.6 Appendix F: FP Subsystem Assembly

8.6.1 LT PEM FP Subsystem Assembly

FP Subsys. Assy Cost, $

	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$339.19	$346.58	$347.94	$535.97
1,000 sys/yr	$126.39	$133.19	$134.45	$307.59
10,000 sys/yr	$75.10	$81.46	$82.63	$249.70
50,000 sys/yr	$69.83	$75.90	$77.02	$236.67

FP Subsys. Assy Cost per kWnet

	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$339.19	$69.32	$13.92	$5.36
1,000 sys/yr	$126.39	$26.64	$5.38	$3.08
10,000 sys/yr	$75.10	$16.29	$3.31	$2.50
50,000 sys/yr	$69.83	$15.18	$3.08	$2.37

8.6.2 HT PEM FP Subsystem Assembly

FP Subsys. Assy Cost, $

	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$400.85	$405.00	$401.98	$508.21
1,000 sys/yr	$183.17	$186.98	$184.21	$282.03
10,000 sys/yr	$128.19	$131.76	$129.16	$225.80
50,000 sys/yr	$121.52	$125.96	$122.45	$212.83

FP Subsys. Assy Cost per kWnet

	1 kW/sys	5 kW/sys	25 kW/sys	100 kW/sys
100 sys/yr	$400.85	$81.00	$16.08	$5.08
1,000 sys/yr	$183.17	$37.40	$7.37	$2.82
10,000 sys/yr	$128.19	$26.35	$5.17	$2.26
50,000 sys/yr	$121.52	$25.19	$4.90	$2.13

8.6.3 SOFC FP Subsystem Assembly

FP Subsys. Assy Cost, $

	1 kWe/sys	5 kWe/sys	25 kWe/sys	100 kWe/sys
100 sys/yr	$379.26	$386.64	$383.63	$371.06
1,000 sys/yr	$164.23	$171.03	$168.26	$156.68
10,000 sys/yr	$110.70	$117.06	$114.47	$103.64
50,000 sys/yr	$104.84	$110.91	$108.43	$98.10

FP Subsys. Assy Cost per kWe net

	1 kWe/sys	5 kWe/sys	25 kWe/sys	100 kWe/sys
100 sys/yr	$379.26	$77.33	$15.35	$3.71
1,000 sys/yr	$164.23	$34.21	$6.73	$1.57
10,000 sys/yr	$110.70	$23.41	$4.58	$1.04
50,000 sys/yr	$104.84	$22.18	$4.34	$0.98

8.7 Appendix G: Power Electronics BOM

8.7.1 LT PEM Power Electronics BOM

Power Conditioning Subsystem

		Low Temperature PEM Systems							
Systems per year	System/year	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$24*	*$24*	*$43*	*$43*	*$20*	*$20*	*$36*	*$36*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$24**	*$24*	*$43*	*$43*	**$20**	*$20*	*$36*	*$36*
Reformer System Controller		*$218*	*$218*	*$218*	*$218*	*$188*	*$188*	*$188*	*$188*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$218**	*$218*	*$218*	*$218*	**$188**	*$188*	*$188*	*$188*
Power Management Box		*$211*	*$211*	*$211*	*$211*	*$182*	*$182*	*$182*	*$182*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$211**	*$211*	*$211*	*$211*	**$182**	*$182*	*$182*	*$182*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$267	$362	$362	**$0**	$249	$338	$338
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$97**	**$97**	**$97**	**$97**	**$78**	**$78**	**$78**	**$78**
AC/DC Inverter		*$150*	*$599*	*$704*	*$808*	*$130*	*$520*	*$611*	*$702*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$150**	$599	$704	$808	**$130**	$520	$611	$702
Diode		*$79*	*$79*	*$79*	*$158*	*$73*	*$73*	*$73*	*$145*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$79**	**$79**	**$79**	**$158**	**$73**	**$73**	**$73**	**$145**
Wiring		*$91*	*$158*	*$176*	*$192*	*$78*	*$137*	*$153*	*$166*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$91**	**$158**	**$176**	**$192**	**$78**	**$137**	**$153**	**$166**
Total Power Conditions System	$/system	$773	$1,289	$1,431	$1,631	$671	$1,120	$1,243	$1,420
Total Power Conditions System	$/kW	$773.00	$257.87	$57.25	$16.31	$671.36	$223.98	$49.70	$14.20

Power Conditioning Subsystem

		Low Temperature PEM Systems							
Systems per year	System/year	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$17*	*$17*	*$30*	*$30*	*$15*	*$15*	*$26*	*$26*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$17**	*$17*	*$30*	*$30*	**$15**	*$15*	*$26*	*$26*
Reformer System Controller		*$162*	*$162*	*$162*	*$162*	*$146*	*$146*	*$146*	*$146*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$162**	*$162*	*$162*	*$162*	**$146**	*$146*	*$146*	*$146*
Power Management Box		*$157*	*$157*	*$157*	*$157*	*$142*	*$142*	*$142*	*$142*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$157**	*$157*	*$157*	*$157*	**$142**	*$142*	*$142*	*$142*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$233	$315	$315	**$0**	$222	$300	$300
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$62**	**$62**	**$62**	**$62**	**$53**	**$53**	**$53**	**$53**
AC/DC Inverter		*$113*	*$452*	*$531*	*$610*	*$103*	*$410*	*$481*	*$553*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$113**	$452	$531	$610	**$103**	$410	$481	$553
Diode		*$67*	*$67*	*$67*	*$134*	*$63*	*$63*	*$63*	*$126*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$67**	**$67**	**$134**	**$63**	**$63**	**$63**	**$126**
Wiring		*$67*	*$118*	*$132*	*$144*	*$61*	*$107*	*$119*	*$130*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$118**	**$132**	**$144**	**$61**	**$107**	**$119**	**$130**
Total Power Conditions System	$/system	$583	$973	$1,079	$1,237	$529	$882	$978	$1,123
Total Power Conditions System	$/kW	$583.34	$194.59	$43.16	$12.37	$528.91	$176.40	$39.11	$11.23

8.7.2 HT PEM Power Electronics BOM

Power Conditioning Subsystem

High Temperature PEM Systems

Systems per year	System/year	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$24*	*$24*	*$43*	*$43*	*$20*	*$20*	*$36*	*$36*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$24**	*$24*	*$43*	*$43*	**$20**	*$20*	*$36*	*$36*
Reformer System Controller		*$218*	*$218*	*$218*	*$218*	*$188*	*$188*	*$188*	*$188*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$218**	*$218*	*$218*	*$218*	**$188**	*$188*	*$188*	*$188*
Power Management Box		*$211*	*$211*	*$211*	*$211*	*$182*	*$182*	*$182*	*$182*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$211**	*$211*	*$211*	*$211*	**$182**	*$182*	*$182*	*$182*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$267	$362	$362	**$0**	$249	$338	$338
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$97**	**$97**	**$97**	**$97**	**$78**	**$78**	**$78**	**$78**
AC/DC Inverter		*$150*	*$599*	*$704*	*$808*	*$130*	*$520*	*$611*	*$702*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$150**	$599	$704	$808	**$130**	$520	$611	$702
Diode		*$79*	*$79*	*$79*	*$158*	*$73*	*$73*	*$73*	*$145*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$79**	**$79**	**$79**	**$158**	**$73**	**$73**	**$73**	**$145**
Wiring		*$91*	*$158*	*$176*	*$192*	*$78*	*$137*	*$153*	*$166*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$91**	**$158**	**$176**	**$192**	**$78**	**$137**	**$153**	**$166**
Total Power Conditions System	$/system	$773	$1,289	$1,431	$1,631	$671	$1,120	$1,243	$1,420
Total Power Conditions System	$/kW	$773.00	$257.87	$57.25	$16.31	$671.36	$223.98	$49.70	$14.20

Power Conditioning Subsystem

High Temperature PEM Systems

Systems per year	System/year	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$17*	*$17*	*$30*	*$30*	*$15*	*$15*	*$26*	*$26*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$17**	*$17*	*$30*	*$30*	**$15**	*$15*	*$26*	*$26*
Reformer System Controller		*$162*	*$162*	*$162*	*$162*	*$146*	*$146*	*$146*	*$146*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$162**	*$162*	*$162*	*$162*	**$146**	*$146*	*$146*	*$146*
Power Management Box		*$157*	*$157*	*$157*	*$157*	*$142*	*$142*	*$142*	*$142*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$157**	*$157*	*$157*	*$157*	**$142**	*$142*	*$142*	*$142*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$233	$315	$315	**$0**	$222	$300	$300
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$62**	**$62**	**$62**	**$62**	**$53**	**$53**	**$53**	**$53**
AC/DC Inverter		*$113*	*$452*	*$531*	*$610*	*$103*	*$410*	*$481*	*$553*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$113**	$452	$531	$610	**$103**	$410	$481	$553
Diode		*$67*	*$67*	*$67*	*$134*	*$63*	*$63*	*$63*	*$126*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$67**	**$67**	**$134**	**$63**	**$63**	**$63**	**$126**
Wiring		*$67*	*$118*	*$132*	*$144*	*$61*	*$107*	*$119*	*$130*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$118**	**$132**	**$144**	**$61**	**$107**	**$119**	**$130**
Total Power Conditions System	$/system	$583	$973	$1,079	$1,237	$529	$882	$978	$1,123
Total Power Conditions System	$/kW	$583.34	$194.59	$43.16	$12.37	$528.91	$176.40	$39.11	$11.23

8.7.3 SOFC Power Electronics BOM

Power Conditioning Subsystem

		Solid Oxide Fuel Cell Systems							
Systems per year	System/year	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$24*	*$24*	*$43*	*$43*	*$20*	*$20*	*$36*	*$36*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$24**	*$24*	*$43*	*$43*	**$20**	*$20*	*$36*	*$36*
Reformer System Controller		*$218*	*$218*	*$218*	*$218*	*$188*	*$188*	*$188*	*$188*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$218**	*$218*	*$218*	*$218*	**$188**	*$188*	*$188*	*$188*
Power Management Box		*$211*	*$211*	*$211*	*$211*	*$182*	*$182*	*$182*	*$182*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$211**	*$211*	*$211*	*$211*	**$182**	*$182*	*$182*	*$182*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$267	$362	$362	**$0**	$249	$338	$338
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$97**	**$97**	**$97**	**$97**	**$78**	**$78**	**$78**	**$78**
AC/DC Inverter		*$150*	*$599*	*$704*	*$808*	*$130*	*$520*	*$611*	*$702*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$150**	$599	$704	$808	**$130**	$520	$611	$702
Diode		*$79*	*$79*	*$79*	*$158*	*$73*	*$73*	*$73*	*$145*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$79**	**$79**	**$79**	**$158**	**$73**	**$73**	**$73**	**$145**
Wiring		*$91*	*$158*	*$176*	*$192*	*$78*	*$137*	*$153*	*$166*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$91**	**$158**	**$176**	**$192**	**$78**	**$137**	**$153**	**$166**
Total Power Conditions System	$/system	$773	$1,289	$1,431	$1,631	$671	$1,120	$1,243	$1,420
Total Power Conditions System	$/kW	$773.00	$257.87	$57.25	$16.31	$671.36	$223.98	$49.70	$14.20

Power Conditioning Subsystem

		Solid Oxide Fuel Cell Systems							
Systems per year	System/year	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
Electrical Enclosure / Cabinets		*$17*	*$17*	*$30*	*$30*	*$15*	*$15*	*$26*	*$26*
Enclosures per System	**enclosures/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$17**	*$17*	*$30*	*$30*	**$15**	*$15*	*$26*	*$26*
Reformer System Controller		*$162*	*$162*	*$162*	*$162*	*$146*	*$146*	*$146*	*$146*
Controllers per System	**controllers/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/controller**	**$162**	*$162*	*$162*	*$162*	**$146**	*$146*	*$146*	*$146*
Power Management Box		*$157*	*$157*	*$157*	*$157*	*$142*	*$142*	*$142*	*$142*
Boxes per System	**boxes/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/box**	**$157**	*$157*	*$157*	*$157*	**$142**	*$142*	*$142*	*$142*
DC/DC Converter		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Inverters per System	**inverters/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$0**	$233	$315	$315	**$0**	$222	$300	$300
DC Regulator		*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Regulators per System	**regulators/system**	0	0	0	0	0	0	0	0
Cost	**$/system**	**$62**	**$62**	**$62**	**$62**	**$53**	**$53**	**$53**	**$53**
AC/DC Inverter		*$113*	*$452*	*$531*	*$610*	*$103*	*$410*	*$481*	*$553*
Inverters per System	**inverters/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$113**	$452	$531	$610	**$103**	$410	$481	$553
Diode		*$67*	*$67*	*$67*	*$134*	*$63*	*$63*	*$63*	*$126*
Diodes per System	**diodes/sys**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$67**	**$67**	**$134**	**$63**	**$63**	**$63**	**$126**
Wiring		*$67*	*$118*	*$132*	*$144*	*$61*	*$107*	*$119*	*$130*
Wiring per System	**wiring/system**	**1**	*1*	*1*	*1*	**1**	*1*	*1*	*1*
Cost	**$/system**	**$67**	**$118**	**$132**	**$144**	**$61**	**$107**	**$119**	**$130**
Total Power Conditions System	$/system	$583	$973	$1,079	$1,237	$529	$882	$978	$1,123
Total Power Conditions System	$/kW	$583.34	$194.59	$43.16	$12.37	$528.91	$176.40	$39.11	$11.23

8.8 Appendix H: Housing and Final System Assembly

8.8.1 LT PEM Housing and Final System Assembly

		Low Temperature PEM Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$828	$844	$1,448	$1,448	$711	$725	$1,245	$1,245
Final System Assy		$123	$123	$159	$202	$72	$72	$105	$146
Total "Housing & Final Sys Assy" Cost	$/system	$951	$966	$1,607	$1,650	$783	$797	$1,350	$1,390
Total "Housing & Final Sys Assy" Cost	$/kWe	$950.52	$193.28	$64.28	$16.50	$783.08	$159.35	$54.00	$13.90

		Low Temperature PEM Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$611	$623	$1,070	$1,070	$550	$560	$962	$962
Final System Assy		$64	$64	$95	$132	$60	$60	$90	$126
Total "Housing & Final Sys Assy" Cost	$/system	$675	$687	$1,164	$1,202	$610	$621	$1,052	$1,088
Total "Housing & Final Sys Assy" Cost	$/kWe	$675.23	$137.39	$46.58	$12.02	$609.95	$124.10	$42.09	$10.88

8.8.2 HT PEM Housing and Final System Assembly

		High Temperature PEM Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$857	$955	$1,437	$3,212	$737	$821	$1,235	$2,760
Final System Assy		$123	$123	$159	$202	$72	$72	$105	$146
Total "Housing & Final Sys Assy" Cost	$/system	$980	$1,078	$1,596	$3,414	$809	$893	$1,340	$2,906
Total "Housing & Final Sys Assy" Cost	$/kWe	$980.12	$215.63	$63.82	$34.14	$808.52	$178.56	$53.60	$29.06

		High Temperature PEM Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$633	$706	$1,061	$2,372	$570	$635	$955	$2,134
Final System Assy		$64	$64	$95	$132	$60	$60	$90	$126
Total "Housing & Final Sys Assy" Cost	$/system	$697	$770	$1,156	$2,504	$630	$695	$1,045	$2,260
Total "Housing & Final Sys Assy" Cost	$/kWe	$697.09	$153.90	$46.24	$25.04	$629.61	$138.95	$41.78	$22.60

8.8.3 SOFC Housing and Final System Assembly

		Solid Oxide Fuel Cell Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$844	$888	$1,123	$1,918	$725	$764	$965	$1,648
Final System Assy		$123	$123	$158	$202	$72	$72	$105	$146
Total "Housing & Final Sys Assy" Cost	$/system	$966	$1,011	$1,281	$2,120	$797	$835	$1,070	$1,794
Total "Housing & Final Sys Assy" Cost	$/kWe	$966.09	$202.20	$51.25	$21.20	$796.66	$167.05	$42.81	$17.94

		Solid Oxide Fuel Cell Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
Housing Cost		$623	$656	$829	$1,417	$560	$590	$746	$1,274
Final System Assy		$64	$64	$95	$132	$60	$60	$90	$126
Total "Housing & Final Sys Assy" Cost	$/system	$687	$720	$924	$1,549	$620	$650	$836	$1,400
Total "Housing & Final Sys Assy" Cost	$/kWe	$686.90	$144.02	$36.96	$15.49	$620.46	$130.06	$33.44	$14.00

8.9 Appendix I: CHP

8.9.1 LT PEM CHP

		Low Temperature PEM Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
CHP HX		$158	$354	$791	$1,581	$136	$305	$682	$1,364
Total CHP Cost	$/system	$158	$354	$791	$1,581	$136	$305	$682	$1,364
Total CHP Cost	$/kWe	$158.11	$70.71	$31.62	$15.81	$136.40	$61.00	$27.28	$13.64

		Low Temperature PEM Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
CHP HX		$118	$263	$588	$1,177	$106	$237	$531	$1,061
Total CHP Cost	$/system	$118	$263	$588	$1,177	$106	$237	$531	$1,061
Total CHP Cost	$/kWe	$117.66	$52.62	$23.53	$11.77	$106.12	$47.46	$21.22	$10.61

8.9.2 HT PEM CHP

		High Temperature PEM Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
CHP HX		$187	$418	$935	$1,871	$161	$361	$807	$1,614
Total CHP Cost	$/system	$187	$418	$935	$1,871	$161	$361	$807	$1,614
Total CHP Cost	$/kWe	$187.08	$83.67	$37.42	$18.71	$161.39	$72.17	$32.28	$16.14

		High Temperature PEM Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	kWe net	1	5	25	100	1	5	25	100
CHP HX		$139	$311	$696	$1,392	$126	$281	$628	$1,256
Total CHP Cost	$/system	$139	$311	$696	$1,392	$126	$281	$628	$1,256
Total CHP Cost	$/kWe	$139.22	$62.26	$27.84	$13.92	$125.56	$56.15	$25.11	$12.56

8.9.3 SOFC CHP

		Solid Oxide Fuel Cell Systems							
Systems per year	systems/yr	100	100	100	100	1,000	1,000	1,000	1,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
CHP HX		$115	$256	$573	$1,146	$99	$221	$494	$988
Total CHP Cost	$/system	$115	$256	$573	$1,146	$99	$221	$494	$988
Total CHP Cost	$/kWe	$114.56	$51.23	$22.91	$11.46	$98.83	$44.20	$19.77	$9.88

		Solid Oxide Fuel Cell Systems							
Systems per year	systems/yr	10,000	10,000	10,000	10,000	50,000	50,000	50,000	50,000
System kWe net	**kWe net**	1	5	25	100	1	5	25	100
CHP HX		$85	$191	$426	$853	$77	$172	$384	$769
Total CHP Cost	$/system	$85	$191	$426	$853	$77	$172	$384	$769
Total CHP Cost	$/kWe	$85.26	$38.13	$17.05	$8.53	$76.89	$34.39	$15.38	$7.69

8.10 Appendix J: Tabular Summary of Costs at the Subsystem Level

8.10.1 LT PEM Tabular Summary of Costs at the Subsystem Level

1 kW: Total System Cost ,$/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$918.71	$714.01	$601.66	$548.34
Housing & Final Assembly	$950.52	$783.08	$675.23	$609.95
Power/Electronics	$773.00	$671.36	$583.34	$528.91
Fuel Processor Subsystem	$4,239.05	$3,262.89	$2,770.22	$2,547.11
Fuel Cell Subsystem	$3,066.43	$2,286.41	$1,870.19	$1,691.29
CHP Subsystem	$158.11	$136.40	$117.66	$106.12
Total System	$10,105.82	$7,854.16	$6,618.30	$6,031.73

5 kW: Total System Cost ,$/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$289.31	$232.40	$198.67	$175.88
Housing & Final Assy	$193.28	$159.35	$137.39	$124.10
Power/Electronics	$257.87	$223.98	$194.59	$176.40
Fuel Processor Subsystem	$1,321.46	$1,076.55	$927.89	$854.44
Fuel Cell Subsystem	$1,049.81	$803.09	$674.24	$556.35
CHP Subsystem	$70.71	$61.00	$52.62	$47.46
Total System	$3,182.45	$2,556.37	$2,185.42	$1,934.64

25 kW: Total System Cost , $/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$107.24	$85.53	$69.06	$59.81
Housing & Final Assy	$64.28	$54.00	$46.58	$42.09
Power/Electronics	$57.25	$49.70	$43.16	$39.11
Fuel Processor Subsystem	$329.27	$277.96	$250.10	$238.99
Fuel Cell Subsystem	$590.00	$446.32	$327.23	$256.69
CHP Subsystem	$31.62	$27.28	$23.53	$21.22
Total System	$1,179.66	$940.78	$759.66	$657.91

100 kW: Total System Cost , $/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$70.11	$57.89	$44.22	$38.86
Housing & Final Assembly	$16.50	$13.90	$12.02	$10.88
Power/Electronics	$16.31	$14.20	$12.37	$11.23
Fuel Processor Subsystem	$262.10	$230.64	$214.83	$206.81
Fuel Cell Subsystem	$390.35	$306.54	$191.19	$149.10
CHP Subsystem	$15.81	$13.64	$11.77	$10.61
Total System	$771.17	$636.82	$486.39	$427.50

8.10.2 HT PEM Tabular Summary of Costs at the Subsystem Level

1 kW: Total System Cost ,$/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$920.88	$717.76	$609.01	$554.68
Housing & Final Assembly	$980.12	$808.52	$697.09	$629.61
Power/Electronics	$773.00	$671.36	$583.34	$528.91
Fuel Processor Subsystem	$4,109.04	$3,128.25	$2,674.28	$2,446.17
Fuel Cell Subsystem	$3,159.51	$2,408.10	$1,996.20	$1,816.55
CHP Subsytem	$187.08	$161.39	$139.22	$125.56
Total System	$10,129.63	$7,895.38	$6,699.14	$6,101.50

5 kW: Total System Cost ,$/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$316.62	$258.17	$222.54	$193.83
Housing & Final Assy	$215.63	$178.56	$153.90	$138.95
Power/Electronics	$257.87	$223.98	$194.59	$176.40
Fuel Processor Subsystem	$1,278.79	$1,035.18	$896.47	$821.36
Fuel Cell Subsystem	$1,330.25	$1,071.77	$918.18	$745.43
CHP Subsystem	$83.67	$72.17	$62.26	$56.15
Total System	$3,482.82	$2,839.83	$2,447.95	$2,132.13

25kW: Total System Cost ,$/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$123.87	$107.38	$85.51	$74.18
Housing & Final Assy	$63.82	$53.60	$46.24	$41.78
Power/Electronics	$57.25	$49.70	$43.16	$39.11
Fuel Processor Subsystem	$307.70	$257.98	$231.98	$220.38
Fuel Cell Subsystem	$772.53	$680.28	$505.87	$415.44
CHP Subsystem	$37.42	$32.28	$27.84	$25.11
Total System	$1,362.60	$1,181.23	$940.61	$816.01

100 kW: Total System Cost , $/kW

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$96.51	$78.80	$61.80	$55.11
Housing & Final Assembly	$34.14	$29.06	$25.04	$22.60
Power/Electronics	$16.31	$14.20	$12.37	$11.23
Fuel Processor Subsystem	$229.38	$201.92	$187.05	$179.17
Fuel Cell Subsystem	$666.59	$526.71	$379.60	$325.51
CHP Subsystem	$18.71	$16.14	$13.92	$12.56
Total System	$1,061.64	$866.82	$679.79	$606.16

8.10.3 SOFC Tabular Summary of Costs at the Subsystem Level

1 kWe: Total System Cost ,$/kWe

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$1,075.48	$616.89	$510.86	$464.38
Housing & Final Assy	$966.09	$796.66	$686.90	$620.46
Power/Electronics	$773.00	$671.36	$583.34	$528.91
Fuel Processing Subsystem	$3,723.41	$2,777.49	$2,351.86	$2,142.94
Fuel Cell Subsystem	$5,177.73	$1,824.58	$1,401.19	$1,274.62
CHP Subsystem	$114.56	$98.83	$85.26	$76.89
Total System	$11,830.27	$6,785.81	$5,619.42	$5,108.20

5 kWe: Total System Cost ,$/kWe

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$296.69	$197.08	$169.31	$155.35
Housing & Final Assy	$202.20	$167.05	$144.02	$130.06
Power/Electronics	$257.87	$223.98	$194.59	$176.40
Fuel Processing Subsystem	$1,119.14	$885.28	$754.58	$684.79
Fuel Cell Subsystem	$1,336.49	$650.27	$561.79	$527.81
CHP Subsystem	$51.23	$44.20	$38.13	$34.39
Total System	$3,263.63	$2,167.86	$1,862.42	$1,708.80

25 kWe: Total System Cost , $/kWe

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$89.22	$60.97	$54.45	$51.78
Housing & Final Assy	$51.25	$42.81	$36.96	$33.44
Power/Electronics	$57.25	$49.70	$43.16	$39.11
Fuel Processing Subsystem	$196.31	$150.39	$127.61	$118.01
Fuel Cell Subsystem	$564.50	$347.03	$319.70	$311.86
CHP Subsystem	$22.91	$19.77	$17.05	$15.38
Total System	$981.45	$670.66	$598.93	$569.58

100 kWe: Total System Cost , $/kWe

	100 sys/yr	1,000 sys/yr	10,000 sys/yr	50,000 sys/yr
Cost Margin	$48.34	$39.97	$37.64	$36.57
Housing & Final Assy	$21.20	$17.94	$15.49	$14.00
Power/Electronics	$16.31	$14.20	$12.37	$11.23
Fuel Processing Subsystem	$91.17	$72.62	$63.42	$58.74
Fuel Cell Subsystem	$343.27	$285.01	$276.61	$274.07
CHP Subsystem	$11.46	$9.88	$8.53	$7.69
Total System	$531.74	$439.62	$414.05	$402.31