The Impact of Scale-Up and Production Volume on SOFC Manufacturing Cost

DOE/NETL-XXXX/XXXX (optional)

April 2, 2007

Disclaimer

The Impact of Scale-Up and Production Volume on SOFC Manufacturing Cost

---

DOE/NETL-XXXX/XXXX

April 2, 2007

NETL Contact: Heather Quedendfeld

Name
Title
Organizational Element

Prepared by:

Jan H. J. S. Thijssen
J. Thijssen, LLC

National Energy Technology Laboratory
www.netl.doe.gov

This page intentionally left blank

Chapter 0 Executive Summary

Background & Objective

Understanding the relative importance of production volume and cell scale-up on the manufactured cost of SOFC is important to allow rational management of the DOE's SOFC program. Therefore, the US DOE recognized the need for a study to quantify the impact of cell scale-up, specifically to:

- Quantify the impact of both cell size and production volume on production cost of state-of-the-art SOFC;
- Assess the trade-off between increased cell size and production volume with respect to the impact on cost;
- Consider impacts of all relevant phenomena (E.g. range of viable applications of cells of each size and its impact on manufacturing yield).

Scale-Up and Production Volume Considerations

To assess the effect of stack scale-up we considered two types of products: a 5 kW mobile system and a 3.1 MW hybrid stationary system with a 2 MW class SOFC stack. Stack scale-up was conceptualized via scale-up of individual cells, with active surface areas ranging from ~100 cm2 to 2000 cm2 per cell, as well as modular scale-up. While for 5 kW systems the smaller cells suffice (and may even be preferable as more cells can produce a higher stack voltage), either the small or the large cells can be scaled-up modularly to the target 2 MW by aggregating individual cells into stack modules and stack modules into stacks which interface with the system as a single unit.

SOFC stack scale-up for larger systems could provide a cost-reduction over modular scale-up via reduced material cost (inactive area becomes smaller as a percentage of total area), reduced fabrication cost (by reducing the component count of the system), and reduced balance of plant cost (reduced cost of manifolding and inter-stack connections).

We also analyzed the impact of changes in production volume from 5 to 500 MW/yr (per production facility). In addition to the impact on individual product lines we considered mixed market scenarios in which both 5 kW and 2 MW stack products are produced.

Stack Technologies Analyzed

For the analysis we considered four stack technologies relevant to the SECA program and distinguished by their cell geometry: planar rectangular and circular cells, and tubular cathode supported and anode-supported cells. We started with the state-of-the-art of each of the stack technologies as publicly described, but we assumed some limited improvements will be made.

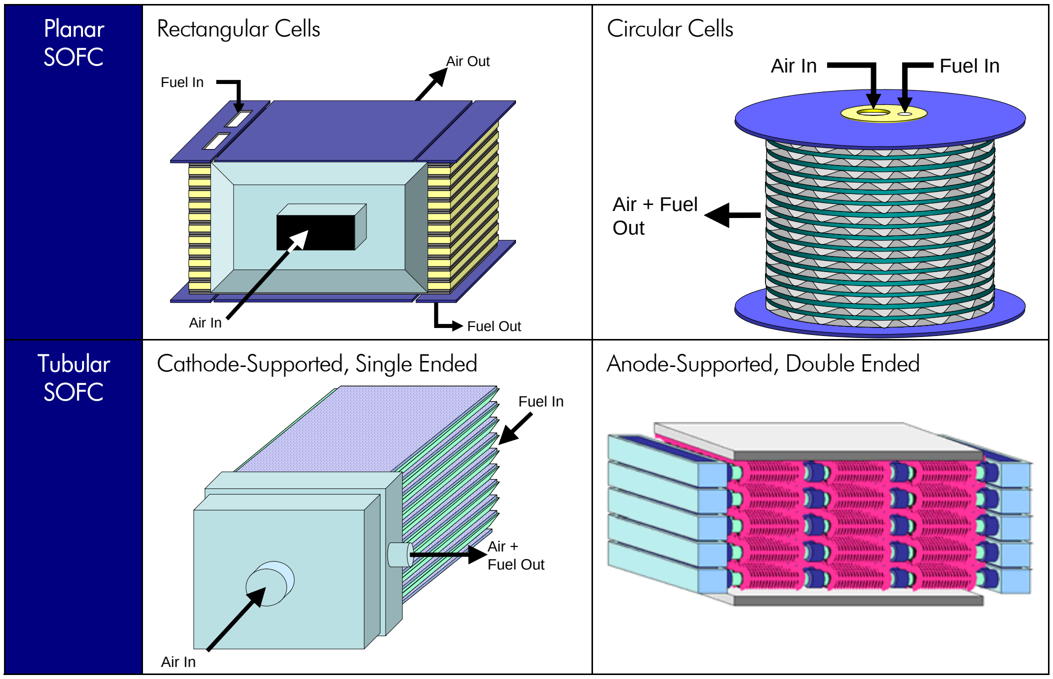


Figure 0-1 Overview of Stack Technologies Considered

For each of the cell types, a modular stack scale-up approach was developed to satisfy the requirements for the 5 kW and 2 MW products (the latter using either small or large cells). An example of such an approach is shown in Figure 0-2 along with an overview of the cell, stack module, and stack characteristics.

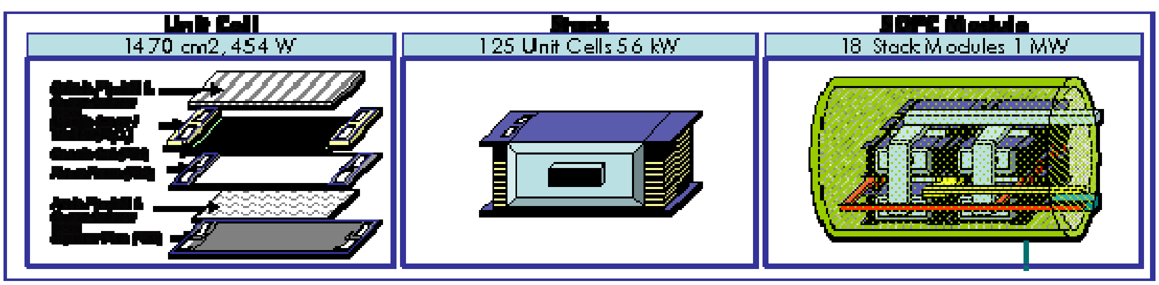


Figure 0-2 Example of Modular Stack Scale-Up

Production Methods

The production methods assumed for the cost assessment are based on the recipes used to produce state-of-the-art developmental cells, but scaled-up to the appropriate production volume using production-type machinery. To assure a high degree of fidelity in the manufactured cost estimates a bottom-up detailed model of the production processes is used, which quantifies the capital cost, labor cost, and variable cost associated with each of the manufacturing steps. The model has the flexibility to allow rigorous assessment of the impact of cell size, stack size, and production volume. For each stack type a detailed production process was conceptualized and laid out.

Results

The analysis results indicate that production volume is the dominant factor determining early SOFC manufactured cost (with a 4x – 8x impact on stack cost), while cell and stack scale-up can provide additional economy of scale cost reduction but with much more limited impact (10-20% cost reduction potential).

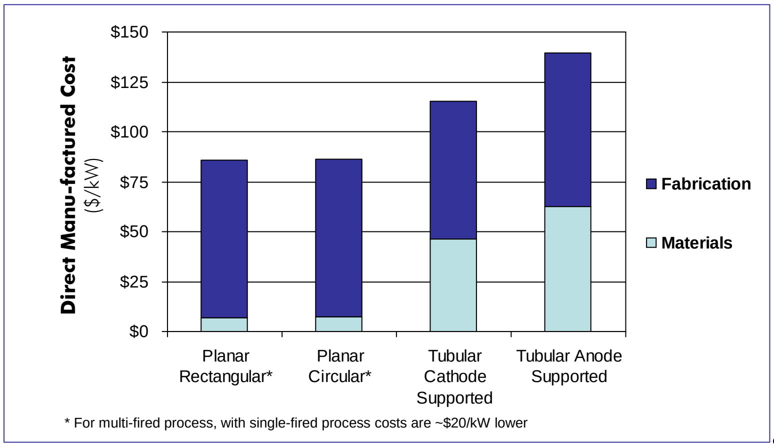
Baseline 5 kW Stack Costs

Contrary to some earlier studies' results, the analysis indicates that manufacturing cost dominates the cost of planar anode-supported ceramic cells, with tubular cells costing more due to higher materials costs and a lower per-unit area power density (see Figure 0-3a)[1]. This difference with previous studies is due to lower (more realistic) assumptions for ceramic material cost and usage (Due to thinner cells), and a higher (also more realistic) cost for material handling and quality control equipment and labor (QC) in the manufacturing process.

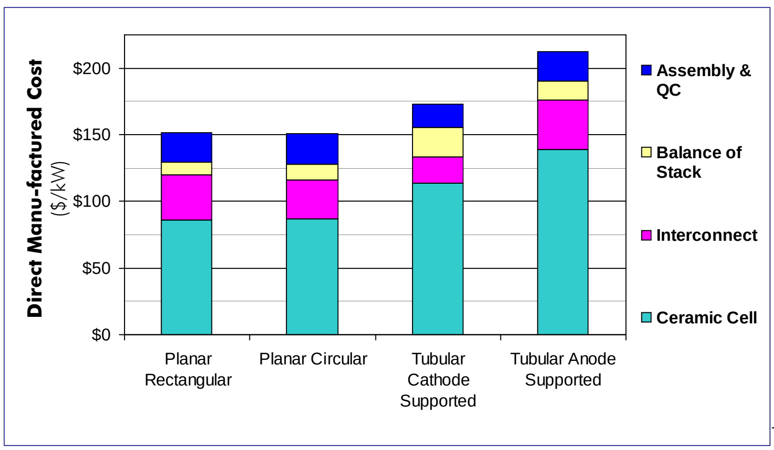
When we include the interconnects, other repeat elements, and the non-repeat stack hardware (i.e. the end-plates, tie-bolts, busbar, etc.), the cost difference between the SOFC architectures considered is qualitatively similar to that for the ceramic cells (see Figure 0-3b).

The cost of the repeat units and the cost of the insulation are the most important factors in determining the overall cost of the 5 kW SOFC stacks studied; in planar anode-supported technologies have a potential cost advantage over tubular technologies because of their lower cell cost and because their compact construction minimizes stack packaging cost. Figure 0-4a shows that complete 5 kW stack units (i.e. including stack manifolds, busbar, packaging, etc.) based on planar anode-supported cells cost substantially less (about 2x) to manufacture than those based on tubular cells. For these 5 kW stacks the differences between stacks based on rectangular and circular planar cells are not statistically significant and neither are the differences between stacks based on anode – and cathode-supported tubular cells.

[1] Cost of tubular anode-supported cells includes the cost of the cathode-side silver current collector



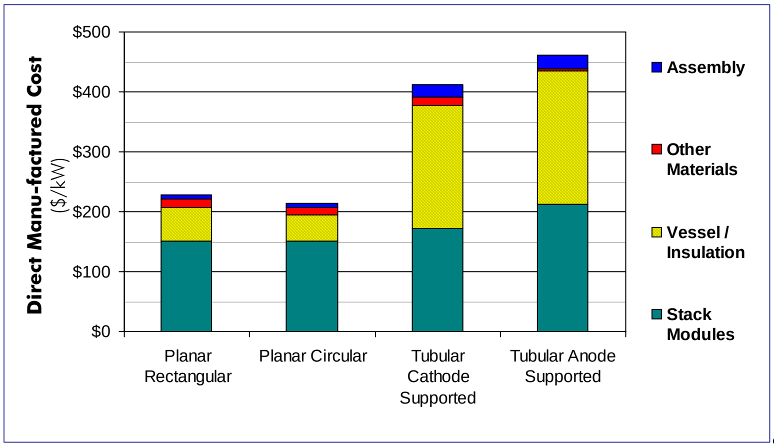
a



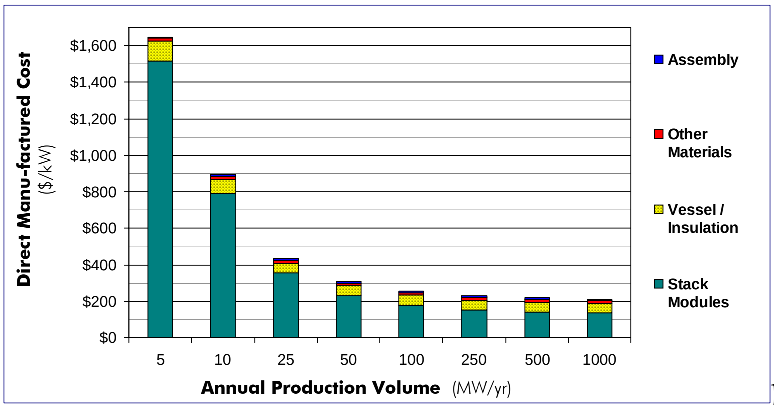
b

Figure 0-3 Baseline Estimated Direct Manufactured Cost of Ceramic Cells for Small Cells (a) and Build-Up of Stack Module Direct Manufactured Cost Estimates for 5 kW Units(b).

Production volume is the only factor that has a greater impact on SOFC stack cost than cell type or power density, leading to stack cost reduction of 4-8x as production volume increases from 5 – 500 MW/yr (per plant). Higher utilization of production equipment and of labor are the primary reasons for the cost reduction. The results for stacks based on planar rectangular cells (Figure 0-4 b) are typical; similar trends are found with the other stack types.



a



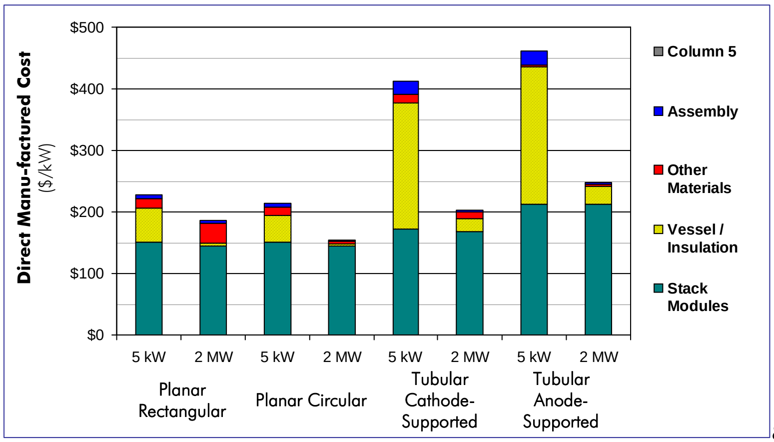
b

Figure 0-4 Build-Up of Stack Direct Manufactured Cost Estimates, 5 kW Stacks (a), and Effect of Production Volume on Estimated Direct Manufactured Cost ($/kW) for Stacks with Planar Rectangular Cells (b).

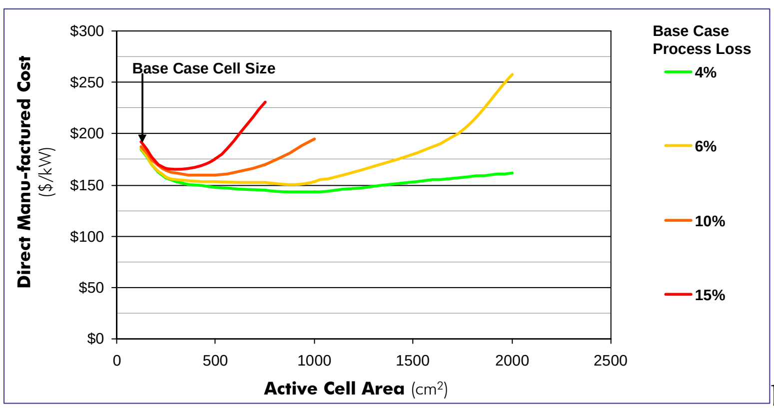
Large (2MW) Stacks

Modular scale-up of the small stack modules to ~2MW stacks results in a significant reduction of the stack packaging cost(vessel & insulation), strongly reducing the differences in cost between the stack types based on planar and tubular cells (see Figure 0-5a). While the tubular anode-supported technology studied appears to be statistically more expensive, the cost of the planar and tubular cathode-supported stack technologies show significant overlap in the sensitivity analysis.

Scale-up of the cells can provide additional cost reduction, but the extent of this benefit strongly depends on the manufacturing yield that can be achieved (Figure 0-5b). As the cell size increases the manufacturing losses are expected to increase roughly proportionally, leading to a cost-increase which eventually off-sets the benefits in material cost, manufacturing cost, and manifolding cost that arise from larger cells. Despite this uncertainty, it appears that scale-up of the planar cells to about 750 – 1000 cm^2 would provide up to 20% additional cost reduction. Clearly this further stresses the importance of improving the manufacturing yield in SOFC production. Tubular technologies may not benefit as much from cell scale-up; for cathode-supported technology there is limited scope because the cells are already quite large, and for tubular anode-supported technology the benefits of scale-up are more limited due to the prominence of the cost of the silver current collector, the cost of which is cannot be appreciably reduced via cell scale-up.



a



b

Figure 0-5 Effect of Scale-Up from 5 kW to 2 MW Based on Small Cells (a), and Effect of Ceramics Processing Losses and Cell Scale-Up on 2 MW Planar Rectangular Stack Direct Manufactured Cost ($/kW) (b).

Combined Impact of Production Volume and Cell Scale

Comparing the effects of volume and cell scale in mixed-product markets (i.e. where both large and small stacks are needed) clearly shows that achieving high production volume should have priority over cell scale-up early on, at least when it comes to cost reduction. As shown in Figure 0-6, for low-volume markets splitting the production into small and large cell stacks leads to an almost 50% higher aggregate cost of meeting market demands (i.e. total direct manufacturing cost to supply entire market demand). At higher production volumes the cost difference becomes smaller and eventually, at production volumes greater than those considered here, there is a clear benefit to making both cell sizes to fit the individual market requirements best. The results for the other stack types are similar to those shown for stacks based on planar rectangular cells in Figure 0-6. Once SOFC are applied to utility-scale coal-based applications, these very large production volumes may be reached rapidly as single-plants would likely require 100s of MW of SOFC capacity.

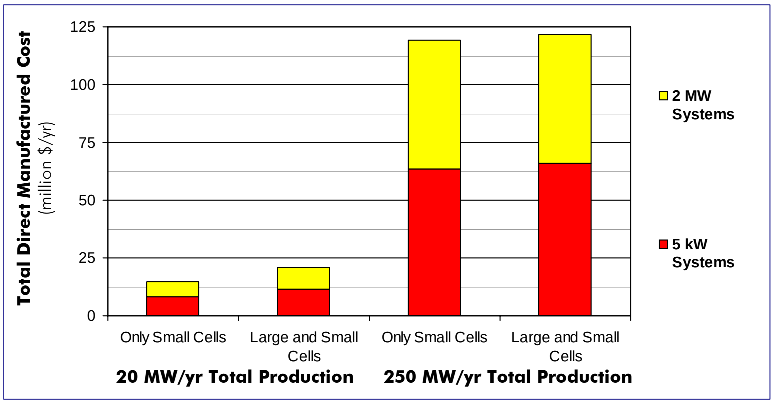


Figure 0-6 Impact of Making Large Cells on Total Production Cost in Mixed Product Market Scenarios, Planar Rectangular Cells

System Cost Implications

In a system context the impacts of scale-up and production volume are similar. The analysis shows that the SECA targets can be met at high volume, even without cell scale-up. Both 5 kW mobile and 3.1 MW stationary systems can achieve the $500/kW SECA target with planar anode-supported cells. But with tubular cells the targets can be met for the larger stationary system only.

Conclusions

Production volume impacts the cost of producing SOFC strongly while scale-up of the SOFC cells could have a modest effect on direct manufactured cost:

- Increasing production volume from 10 MW to 500 MW per year the direct manufactured cost of each of the cell technologies will decrease 4 – 8 times.
- Scale-up of cells from ~100 – 150 cm^2 to as much as ~1000 cm^2 could reduce cost by around 10 – 20%.
- Especially at low production volumes, it does not pay to develop large cell sizes because the added production volume achieved for the entire market by producing one size easily outweighs the benefits of scale-up for large-capacity applications

Chapter 1 Background and Objectives

Background

Understanding the relative importance of production volume and cell scale-up on the manufactured cost of SOFC is important for well-informed management of the DOE's SOFC program.

Over the past decades, the US DOE has supported the development of solid oxide fuel cell (SOFC) technology, most recently in the current US Department of Energy (DOE) Solid State Energy Conversion Alliance (SECA) and FutureGen programs. These programs have supported a wide range of cell types and materials and have been scaled up to cell sizes ranging from a few Watts (W) to more than one hundred W per cell. Now two quite different perspectives on further development aimed at developing competitive SOFC products, especially for power generation applications, have emerged:

- Some think scale-up of cells to larger sizes (E.g. several hundred W to several kW) is critical for practical products and to achieve the necessary cost-reduction;
- Others believe that scale-up of cells is not so critical, it is more important to rapidly achieve high manufacturing volumes of smaller cells that can be used in a wide range of applications (sometimes referred to as mass-customization).

Both perspectives are supported by some arguments as illustrated in Table 1-1.

Table 1-1 Advantages and Disadvantages of Cell-Scale-Up for SOFC

	Larger Cells	Smaller Cells
Technical complexity of developing cells	-	+
Impact production yield	-	+
Complexity of system integration	+	-
Economy of scale (each cell)	+	-
Economy of scale (production)	-	+
Adaptability for wide range of applications	-	+

To decide which argument is right, a quantitative trade-off analysis is necessary. Though a few studies and publications have addressed SOFC manufacturing cost, none have quantified the impacts of scale-up or production volume, much less the trade-off between them. In addition, the trade-off between these factors will likely be different at different stages of market penetration; i.e. at different overall production levels.

Today, these tradeoffs are no longer academic as the perspective on their impact should influence the emphasis in research and funding. Moreover, to make astute decisions in this area, a qualitative understanding of these phenomena is insufficient: a quantitative understanding is required.

Objectives

Therefore, the US DOE has recognized the need for a study to quantify the impact of cell scale-up, specifically to:

- Quantify the impact of both cell size and production volume on production cost of state-of-the-art SOFC;
- Assess the trade-off between increased cell size and production volume with respect to the impact on cost;
- Consider impacts of all relevant phenomena (E.g. range of viable applications of cells of the each size and the impact on manufacturing yield).

Scale-Up Considerations

To assess the effect of stack scale-up we considered two products: a 5 kW mobile system and a 3.1 MW hybrid stationary system with a 2 MW class SOFC stack. Stack scale-up was achieved by scale-up of individual cells (representative of larger stationary systems), with active surface areas ranging from ~100 cm^2 cells to 1000-2000 cm^2, as well as modular scale-up. While for 5 kW systems the smaller cells suffice, either the small or the large cells can be scaled-up modularly to the target 2 MW by aggregating individual cells into stack modules and stack modules into stacks with a single connection for each input and output.

One of the objectives of this study is to elucidate the effect of stack scale-up approach on the manufacturing cost of SOFC systems. Since few developers have discussed stack scale-up in technical detail (let alone its potential cost implications) we attempt to define the range of impact different scale-up approaches can have on cost. For our study we consider scale-up from 5 kW to 2 MW electrical system output. Further scale-up to multi-hundred MW modules for utility-scale plant would follow a modular scale-up approach.

In principle, any fuel cell stack can be scaled-up by increasing:

- *Individual cell capacity*. This provides obvious economy of scale benefits, but it also presents the greatest technical challenges. The current cell size for planar systems typically ranges from 50 to 200 cm2 in active area ((Zizelman 2003; Steinberger-Wilckens, Vinke et al. 2004; Borglum 2005; Christiansen, Kristensen et al. 2005; Minh and Rehg 2005) GE recently produced a 12.75 inch or about 900 cm^2 cell, which has reportedly undergone preliminary testing in a stack so far (Minh and Rehg 2005; Schultz 2006)), whereas tubular SOFC cells and MCFC cells have been successfully scaled and produced using mass-manufacturing techniques to more than 1500 cm².

- *Number of Cells Per Stack Module*. In most SOFC technologies the stacks are built in modules that comprise a number of individual cells that are electrically connected (in parallel and / or series) and manifolded together. These modules can be further combined to form larger stacks which again are electrically connected and manifolded together to interface with the system as a single unit. Experience with current technologies is limited to about 8 to 80 cells per module (Steinberger-Wilckens, Vinke et al. 2004; Borglum 2005; Christiansen, Kristensen et al. 2005). The methods for integration into modules are typically proprietary in nature. It is not conceivable at current time that single modules could be developed to suit all required system capacities.
- *Increase the number of stack modules in a Single Stack Enclosure*. Modules are combined into single modules with single connections for fuel, air, and electric power to facilitate stack scaling and integration into the system (Thijssen 2004).
- *Use Multiple Stacks.* This is often referred to as modular scale-up.

Because we are interested in the range of potential impacts, we focus on the extreme cases: scale-up of cells and modules to the maximum extent practical and modular combination of 5 kW units. An overview of the scale-up scenarios considered is provided in Figure 1-1.

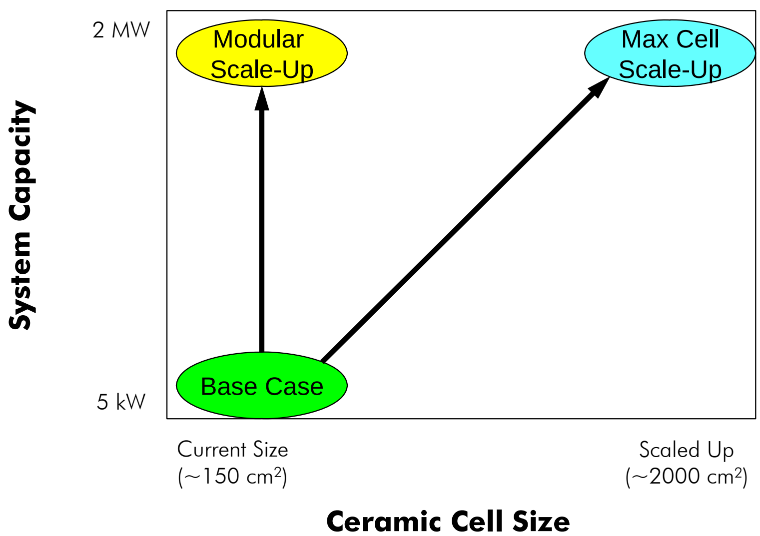


Figure 1-1 Overview of Scale-Up Scenarios Considered

The base cases for the individual types of stack architectures studied use ceramic cells with dimensions similar to those found in current planar prototypes. However, the stack architecture may vary slightly to account for expected future developments (e.g. planar cells may have partially external manifolding instead of the fully internally manifolded cassette-type designs).

For both modular scale-up and the designs with the scaled-up cell sizes a number of characteristics were maintained (compared with the base case representative of the current state-of-the-art):

- Ceramic layer thicknesses, except where adjustment is required for electrical conductivity or mechanical reasons. In principle, there is no reason to alter the thicknesses. Although it is a knee-jerk reaction of many to simply make a larger part thicker to make it stronger, this is not necessarily appropriate in this case. A better understanding of the yield losses during manufacturing and failure mechanisms during operation will be needed to develop a rational approach to determine the appropriate thickness for larger cells;
- Power density and fuel utilization. We assume that cells achieve performance that is a slight stretch from current day performance (at a stack level, namely 400 mW/cm^2 at 0.7V and 85% utilization of the fuel for planar cells and 300 mW/cm^2 under the same conditions for tubular cells)[2]. To justify this assumption for the scaled-up cells, we will adjust the thicknesses of the ceramic electrodes to maintain a constant area specific resistance (ASR) where necessary (e.g. in some tubular cell designs). The uncertainty in the power density assumption (which has a substantial impact on the cost of course) is a key part of the uncertainty analysis;
- Stack pressure drops. In order to maintain constant stack pressure drops we adjust both the manifold dimensions and the dimensions of passages within the fuel cell (e.g. cell pitch in planar cells and tube diameter or dimension in tubular systems) to compensate for longer flowpaths and for larger flows;
- Operating temperature window;
- Basic stack architecture.

At this point, it is worthwhile considering in some more detail the potential benefits and disadvantages of scaling up cell and stack size compared with an entirely modular scale-up approach. For a more detailed description of the assumptions on scale-up of cells, stack modules, and stacks the reader is referred to Chapter 2.

Potential Benefits of SOFC Stack Scale-Up

SOFC stack scale-up for larger systems could provide a cost-reduction over modular scale-up via reduced material cost (inactive area becomes smaller as a percentage of total area), reduced fabrication cost (by reducing the component count of the system), and reduced balance of plant cost (reduced cost of manifolding and inter-stack connections.).

The primary reason for the scale-up of power generation equipment (and indeed any type of industrial equipment) is to minimize capacity cost ($ per-kW) and ultimately electric power cost ($/kWh). Such economy-of-scale benefits are derived from a number scale-up phenomena:

---

[2] On a relative basis, this is a bit more of a stretch for tubular systems which typically achieve about 200 mW/cm^2, than for planar systems, which can achieve nearly 300 mW/cm^2

- Reduced Material Costs. Simple geometric scaling relationships show that the amount of material needed per kW output capacity is typically reduced when power generating equipment is scaled-up. Use of materials for rotating equipment (e.g. turbines) typically scales with a ~0.84 exponent of the scale (i.e. the cost of a piece of equipment with 2x the capacity only cost $2^{0.84}$=1.79 times as much), while in vessel-type equipment the scaling exponent is about 0.66.

  SOFC capacity scales linearly with the amount of active area, and this is roughly proportional to the amount of material used. A small benefit is gained scaling initially due to a reduction in the amount of active area per unit capacity, and due to the reduction of the cost of balance of stack equipment. The impact of scale-up on SOFC materials cost is quantitatively taken into account in this report.

- Reduced Balance of Plant Cost. By scaling up the SOFC stacks, the capacity of balance of plant components can be increased as well. Some components scale extremely favorably (e.g. controls cost is often almost constant over a wide range of system capacity) but even other components have more favorable scaling characteristics than the core power generation equipment itself. While it is possible to combine multiple smaller-capacity stacks with a single larger piece of balance of plant equipment this rapidly complicates the manifolding and physical integration.

  Because the SOFC stack itself tends not to provide a very strong economy of scale, economy of scale benefits of the balance of plant are even more important than for other power generation equipment. Most of the balance of plant has favorable scaling characteristics, except perhaps the power electronics. In addition, this effect will likely allow larger systems to be better optimized for efficiency. The benefits clearly apply in case either cell size or the number of cells per stack are increased. As long as high-temperature connection and high-current electrical connections between modules are integrated without significant additional hardware or controls, the benefits will also apply to scale-up by increasing the number of modules. The impact on balance of plant cost will be analyzed by analogy to other studies, such as a recent TIAX study.

- Reduced Manufacturing Cost. Because for larger systems fewer parts need to be made and assembled than for multiple smaller systems of equivalent capacity, manufacturing costs can be reduced. Considerable savings may be achieved in the area of QC, the cost of which depends more on the number of items checked than their size.

- Reduced Maintenance Cost. For many maintenance and inspection tasks the time consumed is not strongly related to the scale of the equipment. For example, checking a pressure drop takes about the same amount of time, independent of the flow associated with the pressure drop. This benefit is likely to be modest compared with the impact on capital cost. We will not analyze the maintenance cost impact in this report.

Though high reliability and availability are claimed as benefits of modular SOFC systems in many publications, the actual benefits will strongly depend on the approach to modularization and of course, to the reliability of individual modules.

In addition to the cost benefit, there is a technical benefit to scale-up that is harder to quantify or translate into economic benefit directly at this stage of technology development: use of larger stacks avoids unwieldy manifolding and cluttered stack arrangements. Building a 5 MW SOFC system out of 5 kW, individually manifolded, stacks results in a tangle of piping and electrical connectors, even if it is economically attractive.

Potential Challenges with SOFC Stack Scale-Up

SOFC stack scale-up also faces technical challenges (fabrication equipment limitations, thermo-mechanical stresses, contact uniformity) and economic limitations (e.g. effect of increased production losses due to scale-up)

The scale-up of SOFC, as that of other power generation technologies, is limited by technical, cost, and market factors. The limitations set by market demand are outside of the scope of this study. In the following we will analyze the technical and cost considerations that are relevant to scale-up of SOFC. This chapter treats the subjects generally, while in the next chapter specific implications for selected technologies are reviewed.

Technical limitations are the primary reason why SOFC stacks are not currently scaled-up to larger capacities. The technical limitations responsible for this are directly related to the core SOFC stack technologies.

Manufacturing Scaled-Up Ceramic Cells

The first challenge in scaling up SOFC stack cells, and the one currently perhaps most limiting scale-up, is to manufacture large cells with sufficient dimensional control. Practically, large cells often exhibit warping, pinholes, and other defects that can lead to thermo-mechanical failures. The difficulties in producing high-quality, high-performance, and reliable large cells arise from various factors, including:

- Availability of Manufacturing Equipment. High-volume manufacturing equipment for most SOFC stack architectures is readily commercially available (albeit expensive for some of the types of equipment). As shown in Table 1-2 for most of the architectures, the capabilities of commercially available manufacturing equipment are not a limiting factor in cell scale-up. However, for systems that require tape-casting of wide cells, this may be an issue. This equipment is used for a variety of applications (most of which are not making SOFC) and these various markets impose a certain degree of competitiveness on equipment prices. The table indicates that tape casters may provide the most restrictive component in the set.

Table 1-2 Typical Cell Size Capability for Key SOFC Manufacturing Steps

Unit Operation	Maximum Width (at least)	Maximum Length (at least; cm)
Tape Caster	50 cm	> 10 m
Plasma Spray	> 1 m	> 1 m
Screen Printing	> 1 m	> 1 m
CVD	> 1 m	>1 m
Extruder	50 cm	> 2 m
Sintering	110 cm	110 cm

- Deformation due to shrinkage of the green tape due to binder burn-out and differential expansion. In anode-supported cells the green anode tape typically shrinks by about 20% upon binder removal. Any other layers of materials in the package heated up must be able to accommodate this. Then, upon cool-down, the anode is again the portion of the cell that shrinks the most (Due to differential thermal expansion). Together, this can lead to such serious warping of the ceramics package, especially in planar cells, that the cells become unusable. If the same layer thicknesses are maintained this phenomenon will likely not get worse in larger cells, but if the layer thicknesses must be increased the effect may be exacerbated. In tubular cells the same phenomena play, but because of the symmetry the structure is more stable and deformation is rare. However, the same phenomena can result in internal stresses in tubular cells as well. These problems are strongly dependent on the precise materials used, binders, concentrations, temperatures and heating rates, and the cell architecture.
  Because of the variability, it is now impossible to quantify the limitation these problems will ultimately impose on SOFC cell size. Developers are optimizing processing conditions and developing work-arounds (E.g. sectioned electrodes) to avoid issues. Consequently, one can reasonably expect that solutions will be found to eventually allow large-scale cells to be made flat (or flattened during production), but that the development may be time-consuming.

- Formation of pin-holes in the electrolyte due to deformation. Deformation in the electrolyte during processing can lead to non-uniformity of the electrolyte which may lead to rejection or failure. This phenomenon will happen in small cells too, but as the cell size is increased, one would expect the chances of having a defect per cell to increase roughly with the size of the cell.
- Internal stresses in the cells due to differential expansion during operation and production. Stresses internal to the ceramic cell are not expected to rise as cells are scaled-up for most stack architectures. In most modern designs, the electrolyte and cathode layers are thin enough and the bond between the electrochemical layers strong enough to take up the shear stresses and accommodate. Modeling work (Thijssen and Sriramulu 2002) has confirmed this.

Constructing a Stack with Large Ceramic Cells

In constructing a stack from large ceramic cells one has to address the differential thermal expansion between the ceramic components of the cell and any metals components. As Figure 1-2 shows, even in a 10 cm cell the differential thermal expansion between the different cell components is considerable[3]. The ceramic cell typically expands at almost the same rate as the supporting ceramic. Even with anode-supported cells, in which the differential thermal expansion compared with stainless steel is smallest, modeling studies (Thijssen and Sriramulu 2002; Sriramulu 2003) have shown that the shear stresses are likely often too large even in a 10 cm cell to avoid slip between the interconnect and the cell. If one side of the cell is constrained, the components on the other side will experience a displacement with respect to one another of around 0.05% when operating at 800 °C (Figure 1-2). This seems little but it is large compared with the thickness of the seals, which may be on the same order as the displacement, or smaller when compressed. When the cell is scaled-up the displacement grows while the thickness of the components does not, making it more and more difficult for the seals to accommodate the displacement. Of course if the cell could be completely constrained, the stress will not change as a result of scale-up. However, this would likely require excessive compression of the stack and likely result in failures because of the mechanical load.

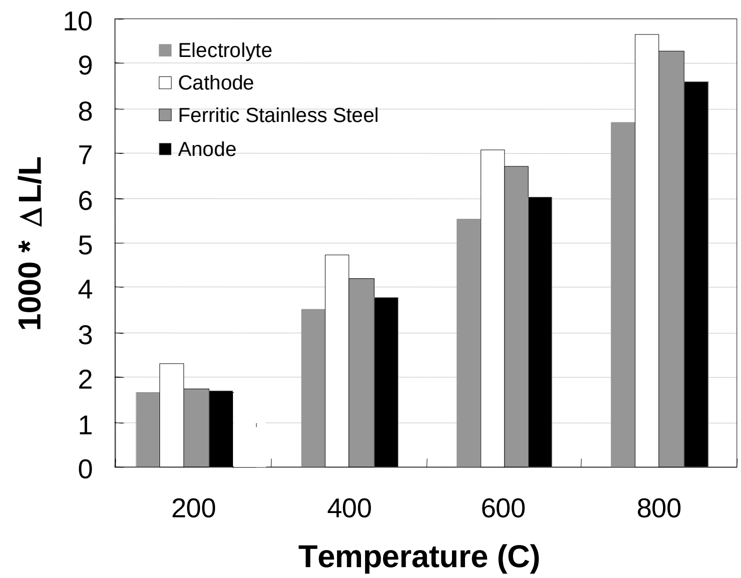


Figure 1-2 Differential Thermal Expansion of Key SOFC Materials

Another undesirable effect of this differential expansion is that the contact area of the metal will "rub" against the ceramic during thermal cycling, potentially causing repeated abrasion of the protective oxide layer on the metal.

[3] In reality, the ceramic components are fixed together stress-free at sintering temperature and then differentially contract as they cool down to either the operating temperature or ambient temperature.

It is difficult to quantify the limitation that this type of problem may place on the maximum scale to which SOFC can be built, because at this time this problem appears to even plague the smaller cells being tested.

Constructing a Stack with a Larger Number of Cells

When the number of cells in a stack is increased, two principal issues must be dealt with in planar bipolar stack configurations:

- The manifold size must be enlarged to assure continued uniform distribution of reactants over all the cells. This enlargement of the manifolds may force a reconsideration of the use of internal manifolds.
- The force required to assure adequate compression for contact (in stacks where force is required to provide good contact) increases more or less linearly with the number of cells. If the number of cells is increased too much, the required pressure will exceed the pressure the stack components are able to withstand. Either the metal interconnects will undergo plastic deformation or the ceramic cells will fail. Fortunately, when cells become larger in area, they become more flexible and thus this issue is alleviated somewhat.
- Mechanical stability of the stack may be compromised. Even small deviations in thickness of the layers may cause the stack to slide or buckle. CFCL has reported problems with this in their widely-reported ill-fated attempt at a 25 kW planar stack with metal interconnects.
- The chances of the entire stack failing due to the failure of one cell increase.

It is difficult to quantify the maximum number of bipolar cells stacked. TMI has reportedly built and operated a stack with more than 100 of their small-diameter cells, and Versa Power has built a stack-tower with 80 cells (though there are three intermediate "end"plates, making it look more like 4 x 20 cells). We assume that eventually 100 cells can be stacked.

For tubular technologies, no such limitations occur, since the cells are mechanically independent of one another.

Production Volume Considerations

In order to gain a better understanding of the impact of production volume on SOFC cost we considered production volumes ranging from 5 to 500 MW/yr (per plant). In addition to the impact on individual product lines we considered mixed market scenarios in which both 5 kW and 2 MW stack products are sold.

In addition to the impact of scale-up of cells and stack technology, we wanted to understand the impact of production volume on cost. Many past studies on SOFC cost have focused entirely on high volume production (250 – 2500 MW/yr, (Carlson 1999; Thijssen 2001; Koslowske 2003; Sriramulu 2003)). However, we now recognize that for SOFC to develop into a viable technology, lower production volumes characteristic of early market development will have to be considered.

Production volume can have an impact on SOFC cost in several ways:

- Higher production volume allows for higher efficiency of utilization of production equipment.
- Higher production volume may allow a lower-cost production technique to be used, which may be prohibitive at low volume due to high capital cost (e.g. automated assembly).
- Higher production volume may allow some reduction in the prices of raw materials and purchased components.

To characterize these production volume impacts we considered four market scenarios for a producer, as shown in Table 1-3.

Please note that the production volumes are for one producer. Assuming that multiple producers will be active, this implies a much greater market for SOFC overall.

Table 1-3 Overview of Market Scenarios Considered

Scenario	Annual Production (MW/yr)		
	5 kW Units	2 MW Units	Total
LV1	20	0	20
LV2	10	10	20
LV3	0	20	20
HV1	250	0	250
HV2	125	125	250
HV3	0	250	250

Chapter 2 Stack Technologies Analyzed

For the analysis we considered four stack technologies relevant to the SECA program and distinguished by their cell geometry: planar rectangular and circular cells, tubular cathode supported and anode-supported cells. We started with the state-of-the-art of each of the stack technologies as publicly described, but we made improvements that can be reasonably expected.

Background and Selection Criteria

A wide range of SOFC stack and cell technologies is under development, differing from each other in terms of:

- Cell materials used
- Thickness and morphology of cell materials
- Shape of cells
- Means and architecture of interconnects
- Means and architecture of gas flow manifolds
- Manufacturing methods used for each layer in the cell structure

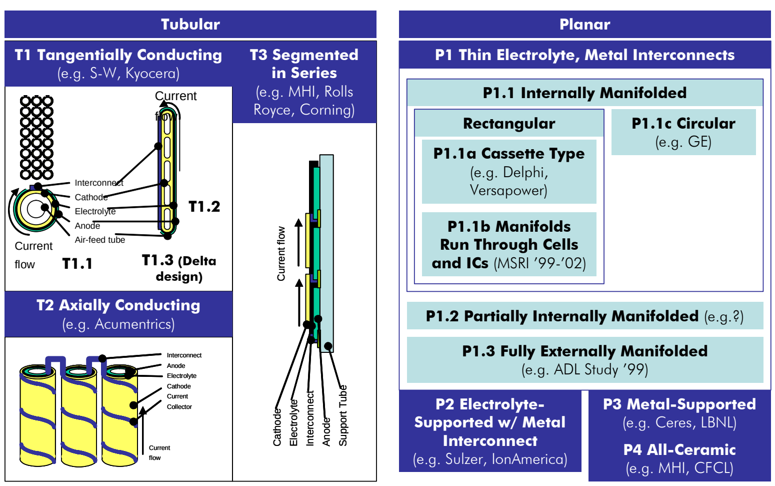


Figure 2-1 Overview of Most Common SOFC Architectures

These differences can strongly impact the cost of materials as well as the cost of manufacturing (Thijssen 2004). We wanted to ensure this study's relevance to most of the SOFC architectures under development in the SECA program. As can be seen in Figure 2-1 there is a large number of cell/stack architectures to consider, not to mention the range of material combinations and manufacturing methods.

Because we wanted this study to be as transparent as possible, we decided to base our analysis on generic cell/stack designs, rather than actual current designs:

- Limited information is publicly available about state-of-the-art stack designs, requiring us to make additional assumptions for most designs;
- Actual current cell/stack designs are still early-stage prototypes, more indicative of each technology's current development status than of its likely characteristics in future commercial systems;
- None of the developers, perhaps with exception of Siemens-Westinghouse, has published any information about their approaches for cell and stack scale-up, much less carried out relevant experiments. In most cases this is primarily because scale-up approaches have not yet been developed;
- It is our experience that using generic descriptions avoids confidentiality issues and provides a better platform for technical and scientific debate about R&D priorities than a study based on specific cell/stack designs would.

Stack Designs Studied

To meet the requirements set forth in the previous paragraph, we chose to develop four generic design, shown in Figure 2-2.

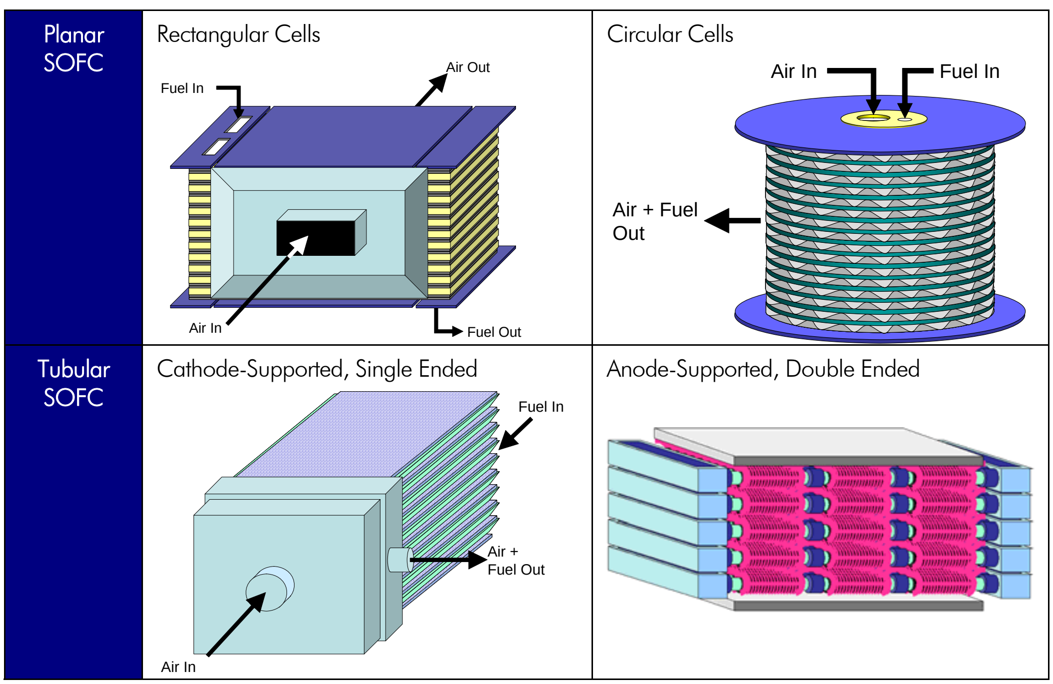


Figure 2-2 Overview of Stack Designs Studied

The remainder of this chapter provides descriptions of these stack designs for baseline (5 kW stack), modularly scaled-up (2 MW with same size cells as 5 kW), and scaled-up (2 MW with larger cells) cases (see Figure 1-1 for explanation), as well as their relationship to current prototype test designs.

Planar SOFC Designs

The majority of SOFC developers are currently focused on planar (mostly anode-supported) cells and they form a major thrust for and within the SECA program. All of the planar SOFC studied here are anode-supported, and we assume the cross-section of all planar SOFC to be identical, whether the cell shape is rectangular or circular, and whether the cells are small or large[4]. The dimensions and materials assumed are shown in Figure 2-3. The dimensions do not precisely reflect the structure used by any specific developer, but are well-representative of the leading developers' cell structures (Botti 2003; Mogensen and Hendriksen 2003; Steinberger-Wilckens, de Haart et al. 2003; Stevenson, Baskaran et al. 2003; Zizelman 2003; Christiansen, Kristensen et al. 2004; Minh 2004; Steinberger-Wilckens, Vinke et al. 2004; Borglum 2005; Borglum 2005; Borglum, Tang et al. 2005; Christiansen, Kristensen et al. 2005; Minh and Rehg 2005). In the sensitivity analysis, we vary the thickness of the layers, including the thicknesses reported by developers for current prototypes.

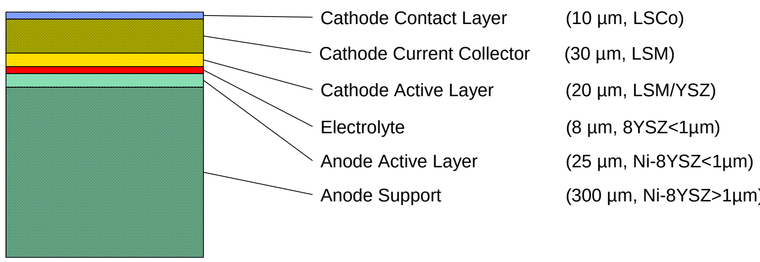


Figure 2-3 Assumed Structure of Ceramic Multilayer Structure for Planar SOFC.

The materials used in the planar cells, as well as those used in the tubular cells, are standardized to the ones shown in Figure 2-3 for the purpose of the analysis. The following considerations were made with respect to the materials' specifications:

- Most developers of planar anode-supported SOFC agree that a cathode contact layer is required to achieve acceptably low contact resistance between the cathode and the ferritic steel interconnects. We assume here that the layer is made of LSCo, although we recognize that a variety of materials is being used and considered.
- The cathode active layer is a finely structured composite of 8YSZ and LSM to provide sufficient ionic conductivity and sufficient triple boundary length (as compared with pure LSM). The active layer is assumed to be 40% LSM with a

[4] An earlier study confirmed that there is no fundamental structural reason to make larger cells thicker (Sriramulu, 2002)

balance of 8YSZ and a particle size less than 1 μm. Clearly a variety of alternative cathode materials is being considered, primarily to improve cathode performance at lower temperatures while minimizing degradation;

- The electrolyte is assumed to be 8 μm thick 8YSZ. To achieve the desired density, fine (<1μm) particles are used;
- The anode is assumed to be a Ni-8YSZ cermet (40% Ni by mass). The anode support is a relatively coarse material, while the anode active layer uses finer (<1μm particles).

We consider two principal types of planar cells: rectangular cells with semi-internal manifolds[5], and circular cells with semi-internal manifolds.

Rectangular Cells

The base case rectangular cell design was conceptualized based on the work of companies such as Delphi and Versapower in the US and Haldor Topsøe Fuel Cells and FZ Jülich abroad. The cell architecture and stack build-up approach for planar rectangular SOFC are shown in Figure 2-4.

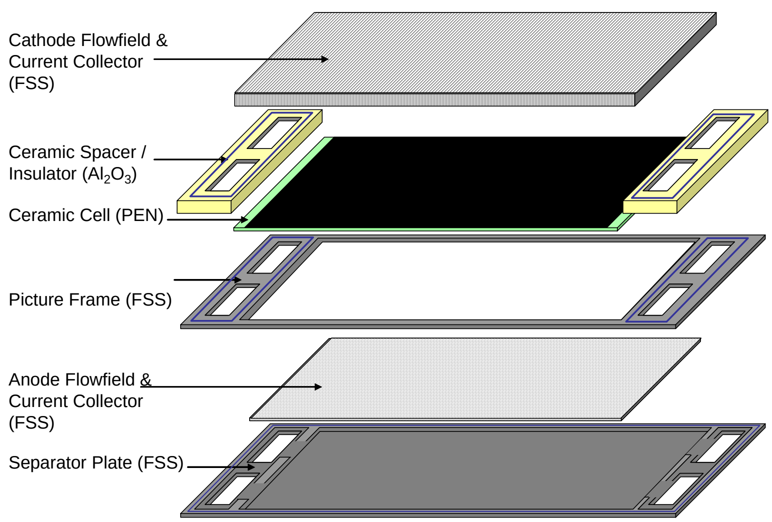


Figure 2-4 Unit Cell Architectures Assumed for Planar Rectangular SOFC

Some key characteristics of the cell technology considered include:

- The baseline cell is square, with a dimension of 12 x 12 cm (and an active area of 125 cm^2). This is roughly consistent with the state of the art in cell production. Current prototype stacks have been produced with cell sizes ranging from 100 to 400 cm^2. As a baseline we considered cells with a power density of 500 mW/cm^2 at 0.7V per cell and 80% utilization (roughly consistent with the peak stack-level

[5] With semi-internal manifolds considered here the fuel is internally manifolded while the air is externally manifolded.

performance reported to date). A 5 kW stack would then require about 80 cells, thus producing 56 V (just about right for a 48V DC battery charging system);

- For the scaled-up cells we consider rectangular cells with a dimension of 30 x 60 cm (1,800 cm^2). This is well beyond the current experience (cell area is over ten times larger). The aspect ratio of the cell is decreased to minimize the increase in the air-side pressure-drop (see below).
- Fuel manifolds are internal to the stack, but do not pierce the ceramic cell. This is similar to current practice (Botti 2003; Steinberger-Wilckens, Vinke et al. 2004; Borglum 2005; Christiansen, Kristensen et al. 2005; Minh and Rehg 2005). The fuel manifolds are scaled to maintain constant fuel velocity as the cell size and number of cells are increased. The total cross-sectional area of the manifolds is kept to 1.25 times the total cross-sectional area of the cells.
- Air manifolds are external. This is not common on SOFC currently, but it provides considerable benefits for larger stacks. The combination with internal fuel manifolds alleviates to some extent the challenge of sealing external manifolds.
- The flowfields for the cathode and anode are assumed to be a sponge or mesh with 75% open area.
- The area available for the gaskets and seals is maintained at 1 cm width uniformly.

Based on these considerations we developed conceptual scale-up approaches for all stack sizes considered (Figure 2-5).

To avoid drastic increases in pressure drop, both the thickness of the flowfields and the size of the manifolds must be modified as the cells are scaled up. Assuming constant power density, the amount of fuel and air required per unit stack area are also constant. As the dimensions of the cell increase, the pressure drop will tend to increase. The pressure drop in the flowfields depends on the flowfield thickness (s), and the length of the flowfield in the flow direction (L):

$$D_p \propto \frac{A^3}{\rho \nu} \bullet \frac{L^4}{s^3} \qquad \text{Equation 2-1}$$

The first portion is constant under our assumptions of constant operating conditions for the cells (ρ = density, A = amount of fresh fuel or air per unit cell area, ν = kinematic viscosity) and the proportionality relationship holds for flat plates, tubes, and rectangular channels as long as the flow is laminar (which it invariably is). Thus to keep the pressure drop constant we must keep the height of the flowfield proportional to the length in the flow direction to the 4/3 power:

$$s = \propto \left(\rho L^4\right)^{1/3} \qquad \text{Equation 2-2}$$

This has a significant impact on the cell pitch and, by implication, on the amount of material used in the cells. In MCFC designs at least the material use increase has been minimized by more careful design of the cathode flowfield (e.g. the use of louvred cathode flowfields).

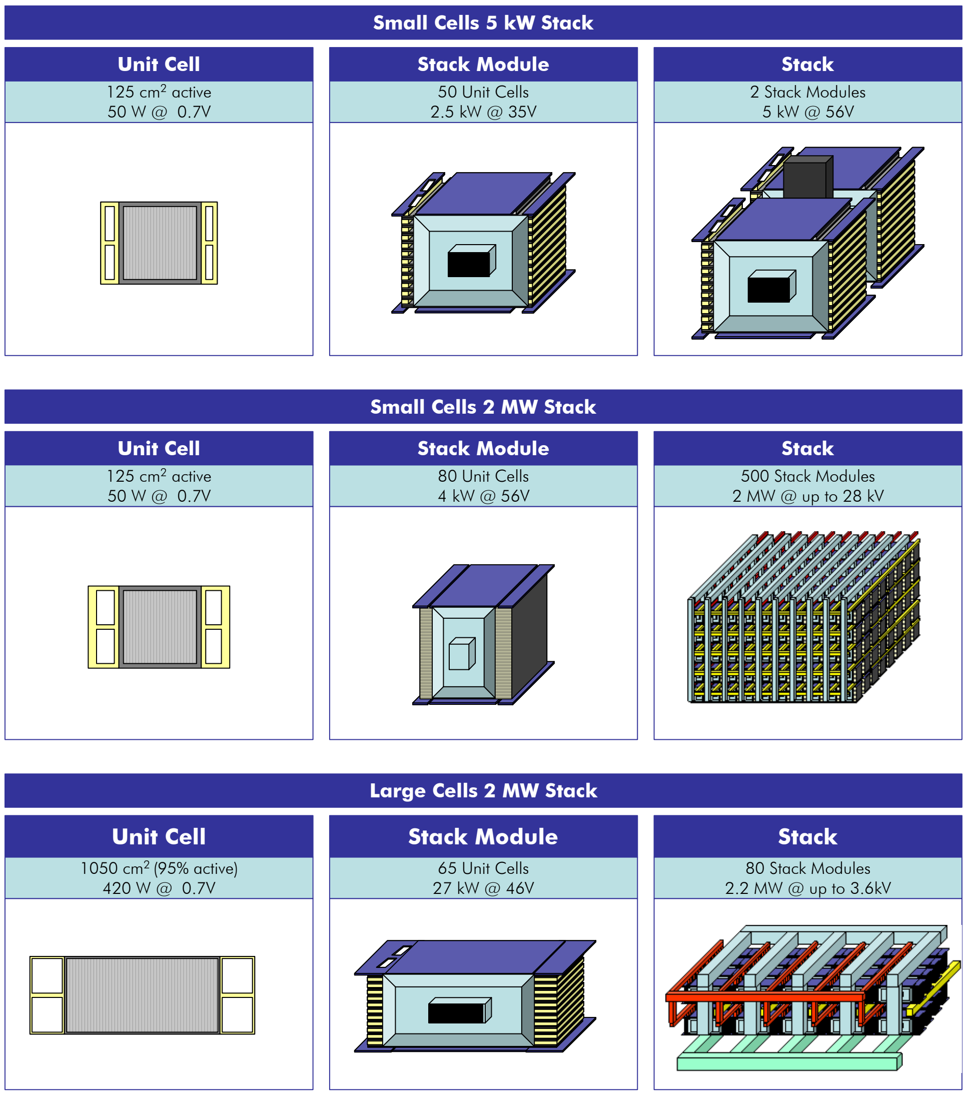


Figure 2-5 Scale-up Approach for Planar Rectangular SOFC

Circular Cells

The base case for the planar circular SOFC designs is based on publications by companies developing circular planar SOFC such as GE and Mitsubishi Materials. The basic unit cell structure assumed for our planar circular SOFC is shown in Figure 2-6.

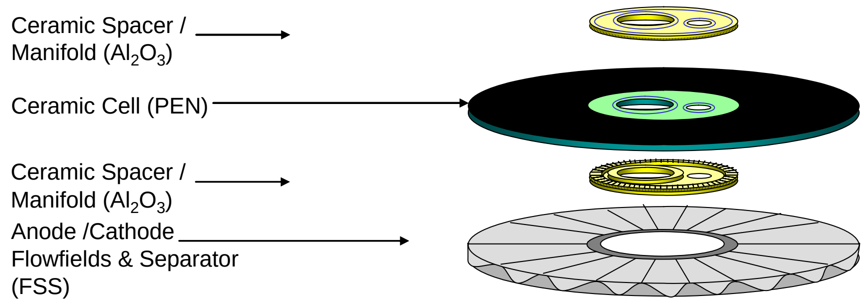


Figure 2-6 Unit Cell Structure Assumed for Planar Circular SOFC

In addition to the general considerations for planar SOFC and some of the considerations made for planar rectangular SOFC (notably the pressure drop considerations), the following are noteworthy:

- The baseline cells have a diameter of 14 cm with an active area of 122 cm^2. Scaled-up cells are assumed to be 23 cm in diameter with an active area of 850 cm^2.
- All cells are centrally fed air and fuel, creating a parallel flow pattern. This is similar to the approach taken by GE in some of its designs, as well as MMC, TMI, and FuCellCo, but different from Sulzer Hexis' approach and from some other GE approaches. This requires holes in the center of the cells but it simplifies the manifolding considerably.
- Reaction products from the cells are allowed to react at the edge of the stack. Again, while this approach is common to some of the developers' designs (Bossel 2003), in other designs the anode and cathode exhaust are manifolded separately (Minh and Rehg 2005).
- A central ceramic spacer / manifolding body is used to distribute reactants. This area represents some of the trickiest aspects of the circular planar SOFC design, as evidenced by the wide variety of solutions. This particular approach was chosen as it may well represent one of the lowest-cost options, with the fewest parts. Note that the dimensions of the manifolding must be adjusted to maintain a manageable pressure drop and that this adjustment affects the dimensions of all cell components.
- A stamped (radially corrugated) separator plate forms the flow passages for both anode and cathode. The profile can be controlled so that the flow area for cathode and anode can be individually controlled to the optimum level..

The approach to scale-up from a small-cell 5 kW stack system to a 2 MW system based on either small or large cells is shown in Figure 2-7. As in the planar SOFC the cell pitch must be adjusted to ensure that the pressure drop in the cells remains manageable.

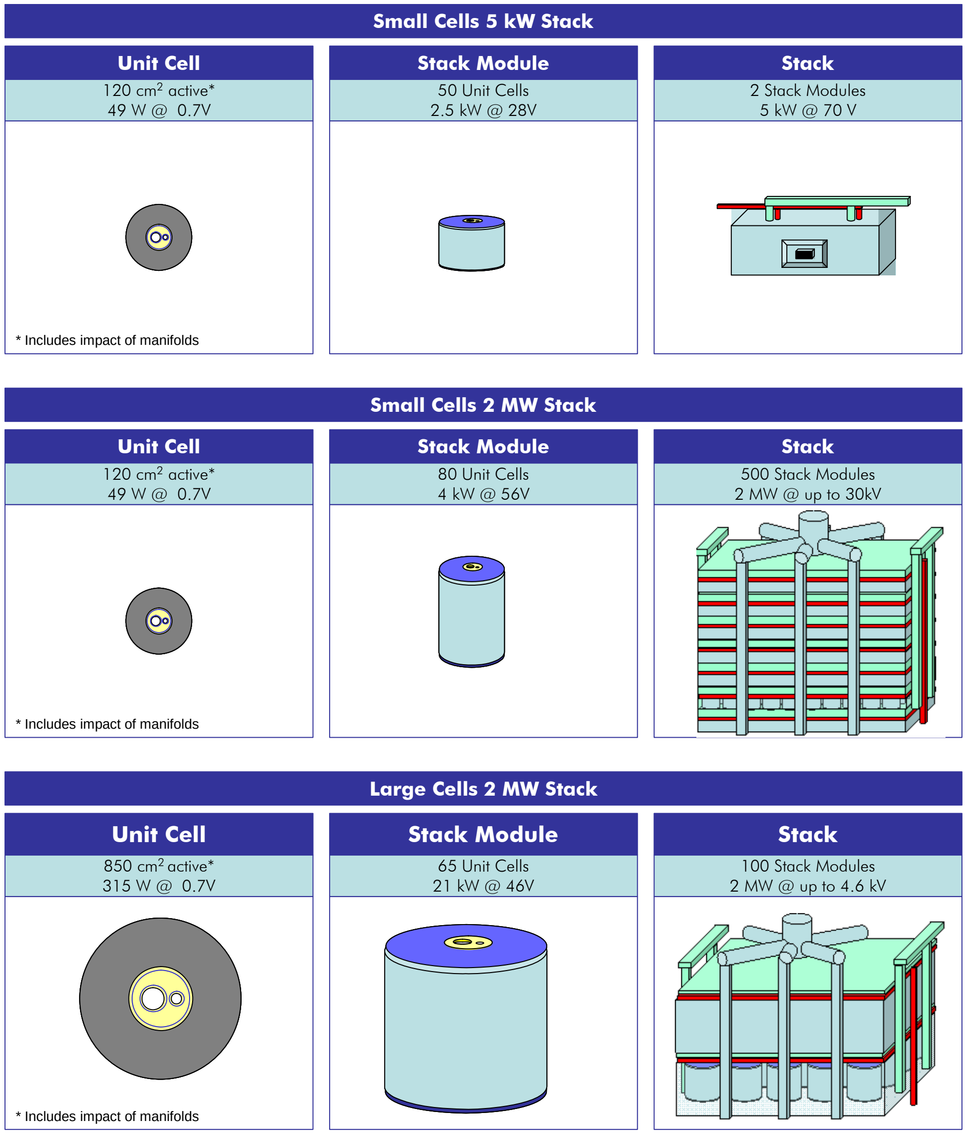


Figure 2-7 Scale-up Approach for Planar Circular SOFC.

Tubular SOFC

Where possible, we followed the same approach for tubular SOFC as we did for planar SOFC. The main differences in approach stem from the fundamental differences between the planar and tubular geometries. While the planar cells considered here are arranged in bi-polar stacks (current flow is mostly perpendicular to the electrolyte surface) the tubular cells cannot be arranged in bi-polar fashion. Current must be conducted either tangentially (e.g. in our tubular cathode-supported cells) or axially (tubular anode-supported cells) to current pick-up points where a connection to another cell can be made.

Cathode-Supported SOFC

For a long time cathode-supported tubular SOFC were more or less synonymous with Siemens-Westinghouse's original tubular SOFC (Singhal, Ruka et al. 1986; Singhal 2000). However, since the start of the SECA program Siemens-Westinghouse has produced several significant innovations in its technology which, while retaining the main defining characteristics of the technology (namely extruded cathode-supported tubes connected side-to-side), have resulted in cell geometries significantly different from the original tubular shape ((Vora 2004; Vora 2005)). Most cost studies to date have focused on the original tubular design. For our study we decided to develop a "generic" design based on the state of the art.

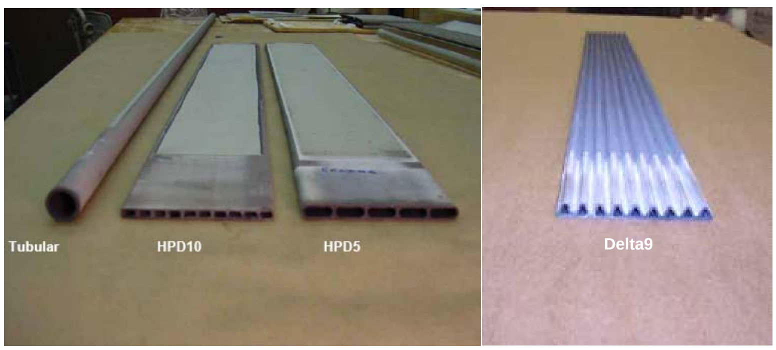


Figure 2-8 Overview of Development of Siemens-Westinghouse Tubular Technology

We consider Siemens-Westinghouse's latest design, named Delta9, as the state-of-the art in cathode-supported SOFC and we used it as the basis for our generic design.

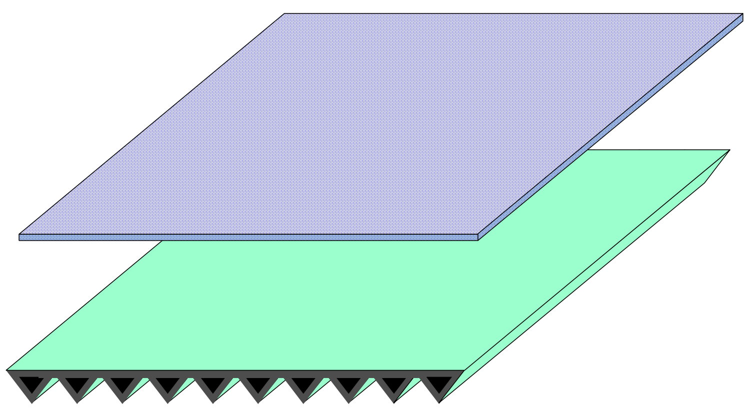


Figure 2-9 Schematic of Tubular SOFC Design Used

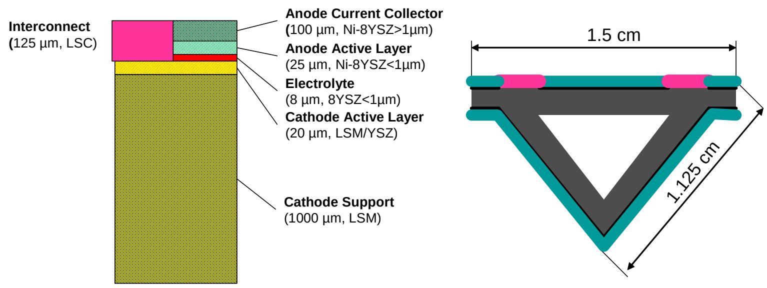


Figure 2-10 Structure of Tubular Cathode-Supported Cells

The design assumptions include the following:

- Each cell has 10 channels (vs 9 in S-W delta-9 design). With total dimensions of 1x13x70 cm^3 each cell has an active area of approximately 1700 cm^2: significantly larger than each of the planar cells. For perspective, we considered both scale-up cells (With 30% greater width) and scaled-down cells (with active areas down to 125 cm^2). Also noteworthy: each of the channels has roughly the same active area as a base-case planar cell.
- Layer thicknesses are kept consistent with the assumptions for the other cell types but the current collector and support thicknesses for the anode and cathode are calculated based on ASR considerations for the power density assumed (see Figure 2-10). In tubular cathode-supported SOFC current must be conducted tangentially around the tube (or in a triangular pattern for the delta-shaped cells) giving rise to significant in-sheet resistance. The in-sheet resistance can be reduced by increasing the thickness of the current collector / support. We assume therefore that the thickness of the cathode support tube and anode current collector are in fact determined by this resistance consideration, allowing for the other losses to be the same as those implied (Vora 2005) for the planar systems (i.e. additional resistance is responsible for all of the reduction in area-specific power density).
- Power density is assumed to be 300 mW/cm^2 at 0.7V and 85% utilization. This assumes similar improvement over measured values as that assumed for planar cells.
- Entire anode surface is accessible for fuel.
- The tubes are single-ended, with short air feed tubes (about 1/4th length).
- Air feed is fed from the manifold through a tube sheet.
- The anode and cathode exhaust are allowed to mix at the cell exit.
- Ferritic stainless steel foam is used as the contact pads between ceramic interconnect and next cell's anode.
- Ceramic stack plenum.

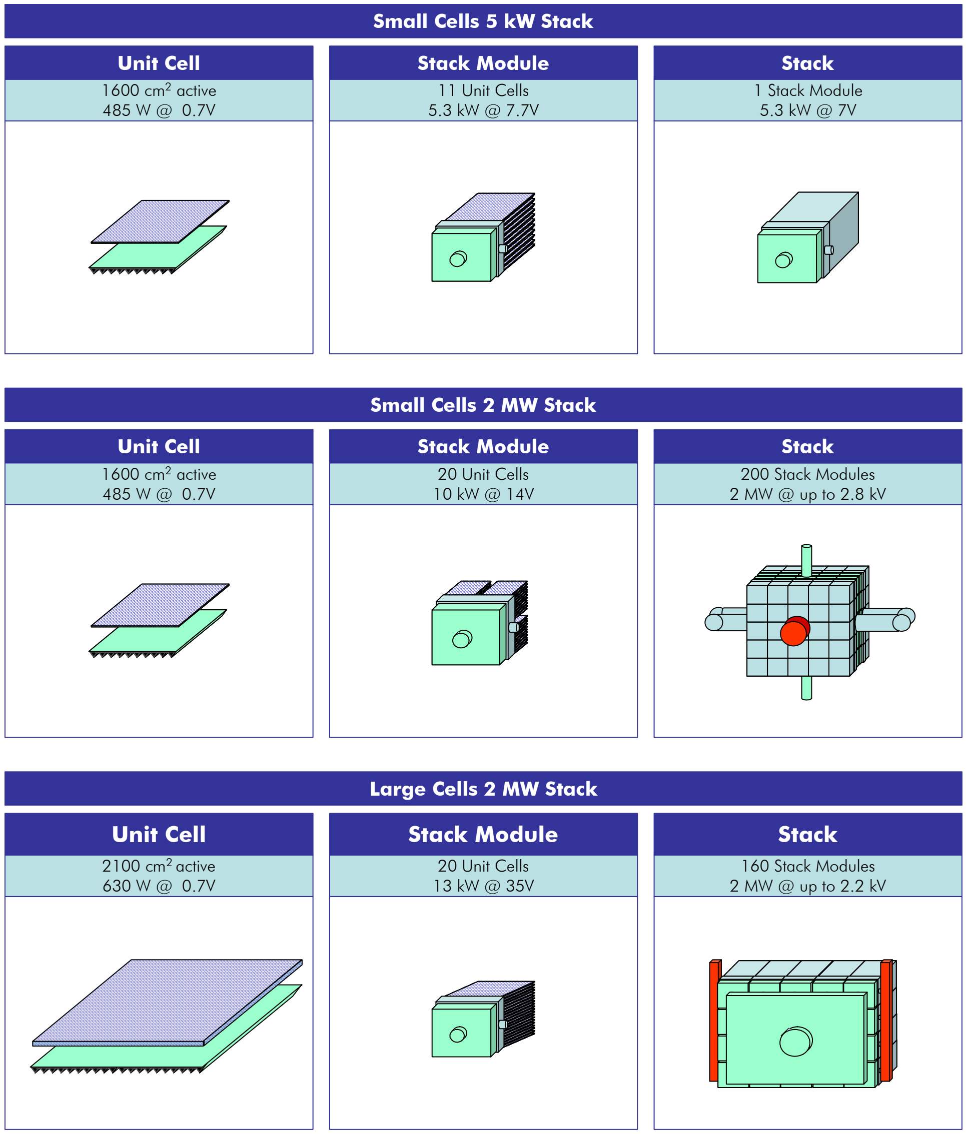


Figure 2-11 Overview of Scale-Up Approach for Tubular Cathode-Supported Stacks.

Scale-up of individual tubular SOFC cells merits different considerations than that for planar SOFC:

- Increasing the number of channels is limited primarily by manufacturing considerations, but also does not significantly reduce overhead costs from connections and manifolding.
- Increasing the length of the tubes would in principle require an increase in the diameter of the cells in order to avoid increased pressure drop. Alternatively the length could be approximately doubled if the cells can be open-ended (instead of single-ended) though this would require sealing the assembly on one side). For

the analysis we assume that the velocities in the tubes are maintained constant, thus requiring that the tube height scales with the square root of the length.

- Increasing the diameter of the tubes will increase the in-sheet conduction length and hence require a thicker electrodes. We assume that this thickness has no other influence on cell polarization than via the resistance (i.e. mass-transfer effects are ignored). For the analysis we assume that the in-sheet resistance is maintained constant, thus requiring the cathode thickness to scale with the square of the cross-sectional delta dimensions.

The scale-up assumptions for the tubular cathode-supported SOFC are illustrated in Figure 2-11. As can be easily seen, the number of cells per module and the number of modules per stack is considerably smaller than for the planar cells, resulting in a less complex manifolding design.

Tubular Anode-Supported

Although for anode-supported tubular cells a wide variety of cell geometries is possible, we focused on so-called micro-tubular anode-supported cells because of the relevance to the SECA program. For our analysis we assumed simple cylindrical tubes. Because the cell geometry requires in-sheet conduction over substantial distances (on the order of ten cm) minimizing in-sheet resistance in both electrodes is critical to cell performance. To that end our assumed cell design has multiple current take-offs and a silver current collector on the cathode. The design is loosely based on a published Acumentrics' stack design (Besette 2004; Besette 2005), including the following characteristics and assumptions (see also Figure 2-12):

- Cylindrical anode-supported tubes with a baseline diameter of 15 mm and a base length of 30 cm;
- The Ni-YSZ cermet anode of the cells are brazed to metal fittings on either end which in turn can be secured in the manifolds that supply the fuel;
- Air is supplied to the stack via the wind-box;
- All cells in one row are electrically in parallel, electrical interconnections are made through the current-take-offs and voltage build-up occurs between rows of cells;
- Anode has a uniform composition (i.e. no separate active layer) and is 1000 μm thick. The composition and material is assumed to be identical to that of the support layers for the planar anode-supported cell types described above.
- To minimize cathode-side in-sheet resistance we assumed that a silver wire harness is wound around the tube. The harness consist of axial strands and tangential strands. The thickness and number of these strands were chosen so as to result in an acceptable cell resistance.
- To minimize (Especially anode-side) in-sheet resistance we assumed that the tubes have 4 current take-off locations for the standard tubes.

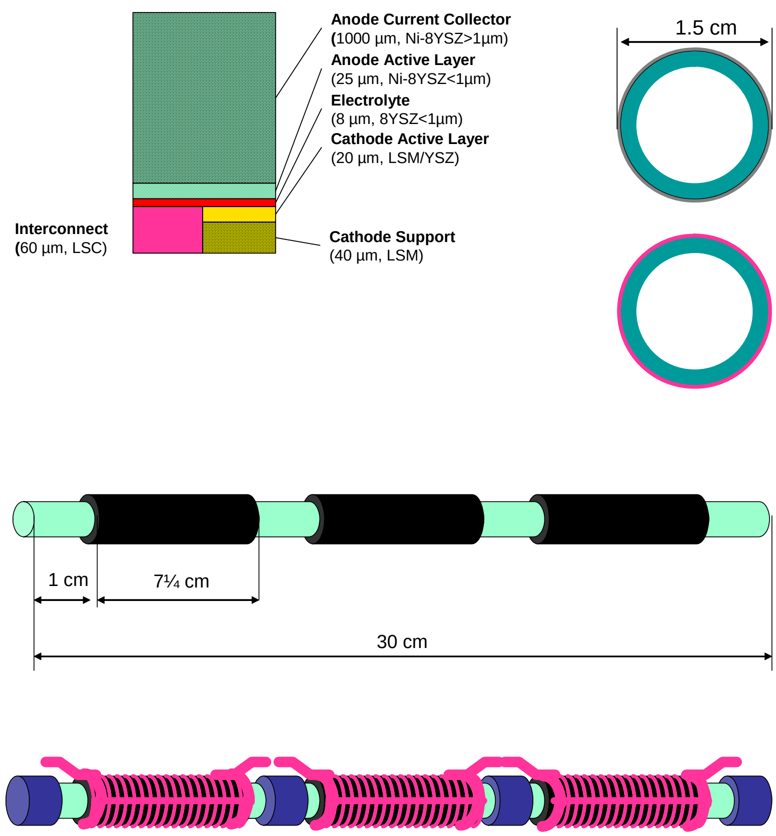


Figure 2-12 Structure and Characteristics of Tubular Anode-Supported Cells

With these dimensions the cells have a similar active area as the small planar cells. Scale-up of the cells and the stack is straightforward:

- Cells are combined in bundles through the manifold sections
- Bundles are combined to stack modules
- Stack modules are combined to stacks of the desired capacity

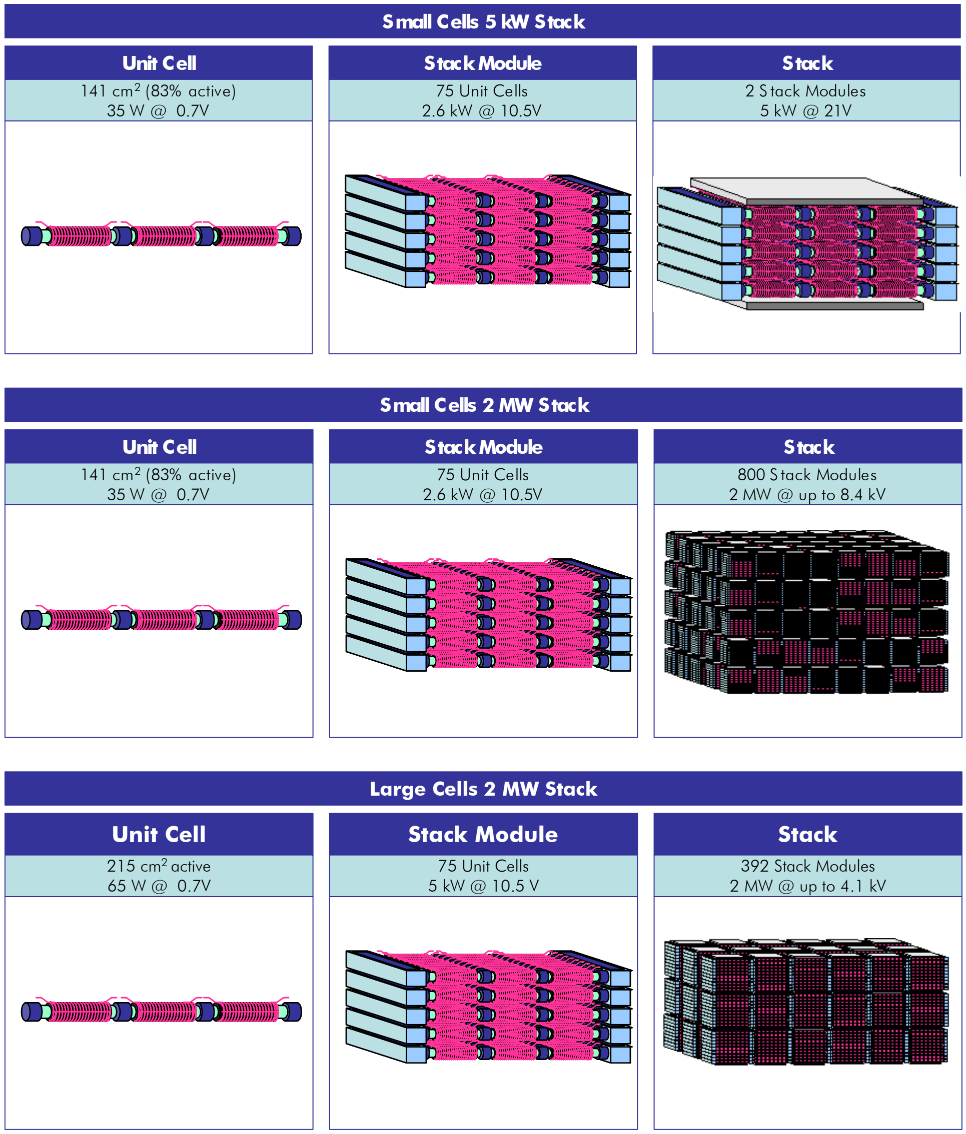


Figure 2-13 Overview of Scale-Up Approach for Tubular Anode-Supported Cells

Chapter 3 Manufacturing Processes

The manufactured cost estimates are made using a bottom-up detailed model of the production processes, which identify the capital cost, labor cost, and variable cost associated with each of the manufacturing steps. The model has the flexibility to allow assessment of the impact of cell size, stack size, and production volume.

Despite the large number of process technologies under development for the manufacture of the ceramic components for SOFC, fundamentally, the process consists of a number of common types of steps (Figure 3-1)

Common SOFC Ceramic Processing Steps		
Raw Materials Preparation	**Forming**	**Conditioning**
Powder production Powder preparation Size reduction / milling	Extrusion Tape casting Dip coating Flame / plasma spray EVD CVD Sputtering Calendaring	Drying Bisqueing Sintering

Figure 3-1 Common SOFC Ceramic Processing Steps

The manufacturing processes assumed for the stack technologies investigated here are chosen to be representative of the processes used by developers (Botti 2003; George and Casanova 2003; Mogensen and Hendriksen 2003; Singhal and Kendall 2003; Zizelman 2003; Besette 2004; Christiansen, Kristensen et al. 2004; Minh 2004; Besette 2005; Vora 2005). The remainder of this chapter first provides descriptions of processes assumed for the various technologies, followed by descriptions of main process steps considered.

Overview of Processes Used

Planar Cells

We considered a typical production method for the planar cell components, which is followed by a number of planar SOFC developers:

- Ceramic multi-layer cell produced by tape casting, flame spraying, and screen printing techniques
- Metallic interconnect components produced using typical sheetmetal fabrication techniques such as rolling, punching, stamping, brazing, and welding
- Production of ceramic spacers via extrusion and pressing, followed by sintering

Variations on these methods have been developed of which the approach assumed here appears to provide a reasonable representation. Therefore we decided to assume similar manufacturing processes for both rectangular and circular planar SOFC.

Ceramic Component Manufacture

The overall approach to producing the ceramic multi-layer for planar SOFC is almost universal. Despite a small minority of developers that is focusing on unique manufacturing techniques for planar SOFC (E.g. sputtering, vacuum plasma deposition, CVD), the overall flow and most of the processing steps are common to all developers' approaches (Figure 3-2):

- Virtually all developers start by tape-casting the anode support layer, then punching out the overall cell shape and bisque firing the cells;
- The anode active layer, cathode active layer and cathode current collector are typically screen-printed, and then sintered at~1100 °C;

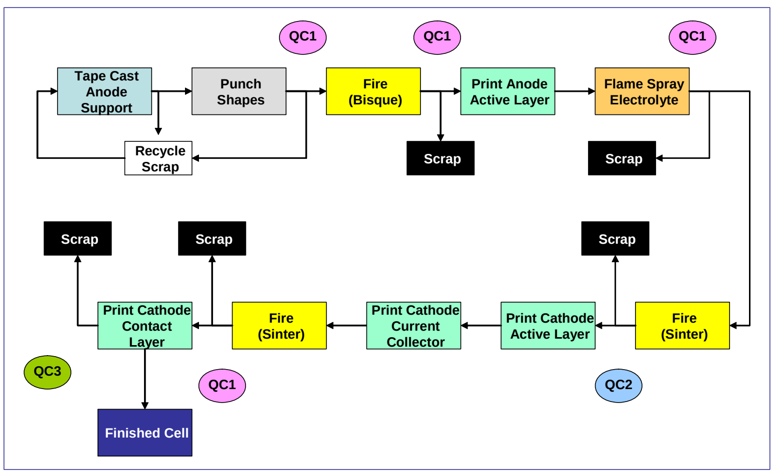


Figure 3-2 Typical Processing Steps in Planar SOFC Ceramic Multi-Layer Cell Production

Currently tape casters are commercially available with casting widths up to 18". With careful patterning the utilization of the tape can be optimized. For rectangular cells of the sizes we chose for the baseline patterning on a 18" tape is straightforward. However, for circular cells there are a few options to consider. Figure 3-3 shows some of the options.

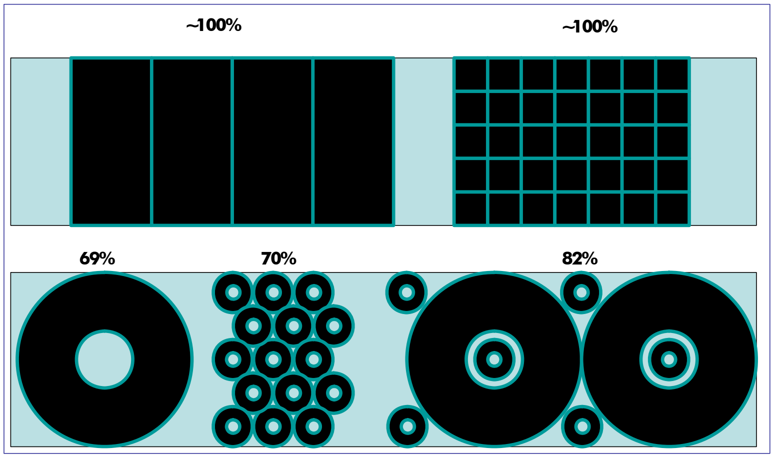


Figure 3-3 Patterning Options for Rectangular and Circular Planar Cells

Key choices made in the assumptions for the ceramic multi-layer component manufacturing process involved the deposition methods for the electrolyte and the number of firing steps:

- A variety of alternative methods are used for deposition of the electrolyte. The deposition method for the electrolyte is technically critical: failure will lead to failure of the electrolyte (e.g. due to pin-holes or uneven ionic resistance) and hence failure of the cell. Some developers use a combination of tape casting and calendaring (Singhal and Kendall 2003), others have proposed atmospheric plasma deposition, or screen printing (Virkar, Chen et al. 2000; Ghosh, Tang et al. 2001; Zizelman, Shaffer et al. 2003). Because flame slurry spraying appears to be both effective and have reasonable cost we used it in our analysis.
- We assumed a multi-fired approach in our base case analysis because it appears to have shown most consistent results in producing high-performance, durable cells. Given the challenges in achieving the targeted cell performance and durability this conservative approach seems warranted. However, at the same time it would seem plausible that over time developers will be able to perfect single-fired production methods, not only more than halve the cost of firing but might ultimately also reduce yield losses and QC cost (see discussion below).

For the production of the ceramic spacers, which may be made of YSZ or a suitable technical ceramic (with appropriate thermal expansion coefficient), we have assumed a two-step pressing / punching approach, followed by a single firing step.

Interconnect Fabrication

We assume that the metallic interconnects are produced from roll stock using stamping, punching, welding, and brazing techniques. One of the principal reasons for the move to planar anode-supported SOFC with ferritic steel interconnects is the possibility of using low-cost manufacturing methods. These techniques are common industrial practice, allowing for the efficient use of available toll-manufacturing facilities where appropriate and allowing for a high degree of automation in dedicated high-volume production facilities. Even though the scrap rate tends to be higher than with near-net-shape methods (such as powder metallurgy, casting, etc) the cost is usually still lower. The approach is outlined in Figure 3-4.

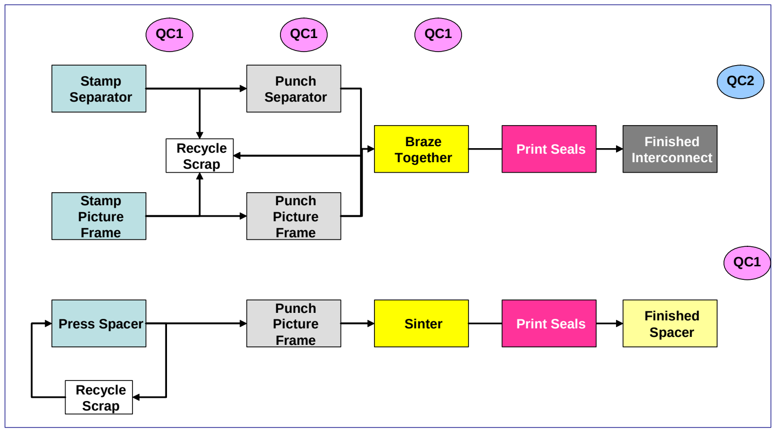


Figure 3-4 Overview of Fabrication Process for Interconnect Components

The fabrication steps involved in fabrication of the ceramic spacers is shown in Figure 3-4 as well. The flow-fields for the rectangular cells are purchased wire meshes cut to size before stack assembly.

The seals are printed on the interconnects and spacers as the last step in the process.

Assembly and QC

During the assembly process the stacks are built up from one of the end-plates, assembling each layer. The flowfield mesh, interconnects, and anodes are brazed together. After the end-plates are attached the stack compression hardware is installed, preserving the geometric integrity of the stack and allowing the stack to be handled. For the high-volume production this process is anticipated to be fully automated, while for the low-volume process a hand-assembly is envisioned.

During the QC process for the stack, it is heated up and tested for leaks, and for electrical performance. During the initial heat-up the seals are set.

Tubular Cathode-Supported Cells

Since the dominant developer of tubular cathode-supported SOFC is Siemens-Westinghouse, which has developed its manufacturing process over several decades, we chose to adopt a manufacturing technique similar to that used by Siemens-Westinghouse.

Ceramic Cells

The ceramic cells are made according to the process shown in Figure 3-5:

- Tubes are extruded and capped during the extrusion process;
- The electrolyte electrode, and interconnect layers are deposited via the lower-cost plasma-spray method, rather than the more expensive CVD or EVD processes used previously by Siemens-Westinghouse.
- The geometry and the deposition techniques require multiple masking steps. Insofar as the mask from a previous step is not burned-off it must be removed again prior to the previous step;
- The tubes are sintered once. Because the cathode is used as the support, and because it is most prone to sintering, there is no advantage to sintering twice as in the anode-supported cells. The disadvantage of this approach would presumably be reflected in the cell performance and process yield but insufficient parametric data is available to quantify the impact.

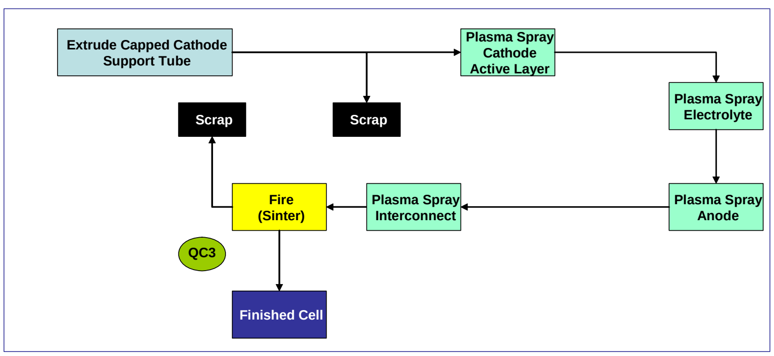


Figure 3-5 Overview of Tubular Cathode-Supported SOFC Fabrication Process

Interconnect Manufacture

The wire mesh ferritic stainless interconnect is cut to shape prior to stack assembly.

Stack Assembly and QC

The tubes and interconnects are assembled with the stack manifolds and inserted into the stack enclosure. Upon completion the stack is tested for leaks, and electrical performance. Hand-assembly is foreseen for the low production volumes but it will be automated for high-volume production.

Tubular Anode-Supported Cells

Tubular anode-supported cells are assume to be produced via a process that is similar to that used by Acumentrics.

Ceramic Cells

The tubular anode-supported cells are made via the following process (See Figure 3-6):

- Extrude or iso-press anode support tube;
- Bisque fire tube;
- Dip-coat electrolyte
- Plasma spray interconnect
- Fire to density electrolyte and interconnect
- Plasma spray cathode and fire cathode

Interconnects

The tube joints for the tubular anode-supported cells are produced via a near net shape injection method. The interconnect clips are made from rolled sheet metal stock via conventional sheet metal working techniques.

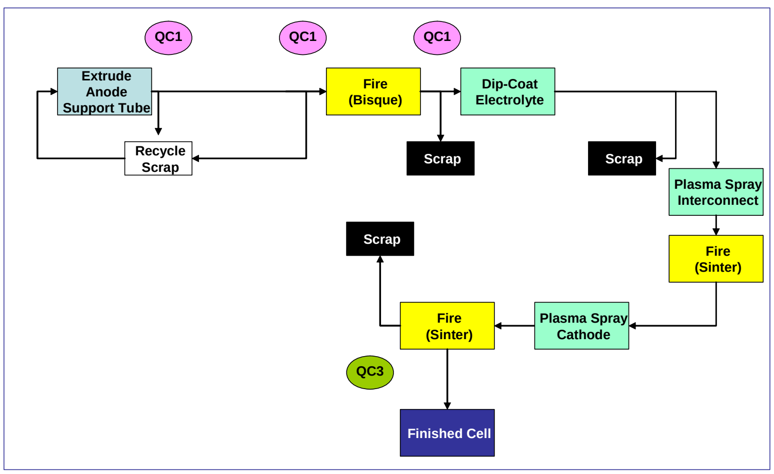


Figure 3-6 Overview of Production Process Assumed for Tubular Anode-Supported Cells

Production Step Yields

The product yield achieved in individual production steps and cumulatively has an important impact on the overall materials cost of SOFC, especially for the production of the ceramic multi-layer cells. In the production process, scrap is produced due to two distinct factors:

- The geometry of the product together with the manufacturing methods chosen result in scrap. For example, to produce a picture frame out of sheet one typically cuts out the center, which then may become scrap. This type of scrap rate can be minimized through optimized product design, the use of near-net-shape production methods, production planning, and sometimes through co-production of multiple products. In SOFC, this type of scrap affects mostly the manufacture of interconnects as the ceramic components are produced via net-shape methods

- Imperfections in the production process result in parts and components that do not meet quality standards or specifications, and have to be rejected. This type of scrap can be minimized by improvements in the production steps, given certain product geometry and specifications. This type of scrap primarily affects the ceramic components.

The impact of the first type of scrap can be relatively easily quantified given a certain geometry and given standard stock material sizes. But quantitatively estimating the second type of scrap for SOFC fabrication processes, especially for the multi-layer cells is difficult at the current time because:

- Few developers have published any information at all about production yields (Borglum, Fan et al. 2003; Borglum 2005).
- The cell technology is still evolving, especially with respect to the durability of cells. Hence, product specifications and component tolerances cannot be precisely defined yet.
- Few developers have done any systematic optimization of their production processes.

Thus we have little hard experimental information upon which to base our assumptions. Based on discussions with developers it appears that the overall yield from their current cell production hovers between 50% and slightly over 90%; a wide range.

However, the impact on cell scale on process losses place important limitations on meaningful yield assumptions. To a first approximation, the production losses in ceramics manufacture increase linearly with the volume of each individual ceramic product. Given the levels of scale-up we are considering the yield on the small cells must be well over 90% (lest the yield on the large cells would approach 0%). Therefore our baseline assumption for the smaller cells is that the yield is 94% on the support layer.

We start with the assumption that these yields can be achieved for each of the baseline cell types. However, clearly the base case tubular cathode-supported cells have a much greater weight (about 50 x greater) than the base case planar cells. It would seem likely that the yield on these larger cells is lower than that of the smaller cells but we assume it is the same (rather than the same per unit weight).

Description of Process Steps

Powder Production & Preparation

In our analysis all technologies start with supplied powders. Thus the powder preparation (material synthesis, purification, size reduction, classification, etc.) is not analyzed specifically in this study. The costs for these operations are included in the material costs assumed. For each type of deposition or forming method the powder needs to be further prepared (e.g. adding binder, making slurry). These further steps are considered as part of the individual forming steps.

Tape Casting

All of the planar cells technologies studied use tape casting as the initial forming step for the anode support layer. The anode powder is mixed with a binder into a slurry or paste and then cast onto a table, using a doctor blade to control the thickness of the tape. The tape thickness is greater than the desired thickness of the anode support layer to account for shrinkage. Tape casting is the standard industrial technology to form layers for multilayer capacitors and battery components. Given the thickness of the tape (~350 μm) typical casting speeds are 0.3- 1.5 cm/s. The maximum practical width used in industry today is around 0.6 m (widths of up to 1.5 m are used for some thinner products) with a casting table of ~25 m. Combined, this makes for a maximum production rate of green tape of 18 – 90 cm^2/s.

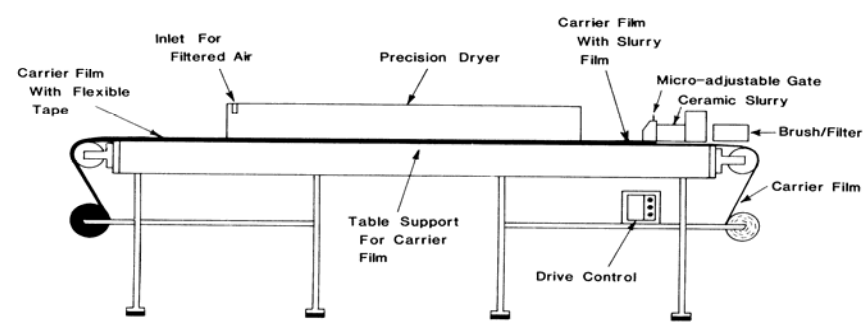


Fig. 26.6 Schematic of continuous tape casting machine.

Figure 3-7 Schematic of Typical Tape Caster

Fully automated tape casting machines capable of casting a 10-inch wide tape as thin as 3 micron are developed by Dreitek Inc. and cost approximately $150,000. For larger cells and higher-volume production, HED Industries sells machines capable of casts up to 52" wide in the thickness range desired, costing about $350,000 (?).

Even for the low production volume cases the tape casting is expected to be done with a continuous machine. For low production volumes machines with narrower width may be used, which may slightly reduce the capital cost. However, the casting speed hardly affects the cost of tape casting machines (since this is more a function of the rheology of the cast, temperatures, etc.).

A tape caster of sufficient width can be used to produce a mix of cell sizes, which can be stamped out of the green tape as desired.

Slurry preparation is critical in tape casting. The ceramic powders are mixed with (mostly organic) binders to achieve the desired density and viscosity that will ultimately produce the specified morphology and thickness of the anode layer.

Extrusion

In extrusion the ceramic powder is mixed with a binder into a paste which is then auger-forced through a mandril, thus forming the desired green shape. Optionally, the tube thus produced can be capped on the leading end, forming a single-ended tube. Although extrusion machines can in principle be used for a range of cell geometries, in practice the required changes in mandril and the handling equipment for the tubes (after they have been extruded) may be more difficult to change rapidly than the equipment for planar cells.

The cell length can be varied more easily and is determined by cutting the cell at the desired length.

Drying

After tape casting or extrusion the green form must be bisque fired to allow effective handling of the forms in subsequent steps prior to sintering. For the high-volume production cases this will likely be done in line with the tape casting and cutting to minimize handling requirements. However,

Punching / Cutting Green Tape

For the anode-supported cells, desired cell shapes are cut out of the green tape after tape casting and drying. The cells are cut somewhat larger than the desired ultimate dimension to account for the shrinkage associated with the sintering process. This process provides considerable flexibility and allows rapid changes in the produced geometry, even allowing for a mix of geometries to be produced on a single line.

However, depending on the dimensions of the tape caster and the cell geometry this may lead to losses in cell production.. Certainly with circular cell geometries it is impossible to use 100% of the rectangular tape. These losses can be recycled to the powder preparation for the tape casting process fairly efficiently but the tape caster and punching/cutting facilities must be accordingly oversized. Even for rectangular cells it is likely that some losses will occur. We expect losses in this step to range from

~5% to 50% of the tape, depending on the cell geometry. We assume that the tape caster is appropriately sized for the desired tape geometry.

Screen Printing

This is a batch process unlike tape casting and warm rolling. The materials to be printed are automatically loaded and adjusted. The drawback of screen-printing is the precise calibration of the material and squeegee to ensure a uniform thickness of print. Typically one unit is printed on at a time. Screen printers can be substantially equipped with optical sensors and computer control to ensure uniformity. To speed up the screen printing process a larger print area can be used for the application of print onto multiple surfaces. The problem with printing on multiple surfaces is aligning a fixture and its multiple units into the screen printing equipment as precisely as loading and aligning a single unit; the fixture will require more setup time. Screen-printing is a rapid process and requires minimal drying time for the ink. Adjusting the sintering properties of the screen-printing ink offers more flexibility in matching shrinkage rates during sintering. Screen-printing of SOFCs may eventually be converted into a continuous process, but presently there is no ongoing investigation into the development of a continuous process. Fully automated screen-printing machines capable of printing a 1 – 3 m^2 area with a cycle time of 10 - 40 seconds have been developed by companies such as Micro-tek and Pacific Trinetics Corporation cost approximately $145,000. ';

Flame / Plasma Spraying

In the flame / plasma-spray process the ceramic powder is heated up at a high rate with a hydrogen –oxygen flame or in an electrically-generated plasma and then accelerated onto the target cell. For SOFC purposes considered here we assume that it is operated atmospherically. Plasma spray allows for excellent control over the density and thickness of the film deposited and allows for the deposition of slightly thicker films than screen printing. It also is more easily applied to non-planar geometries than screen printing.

Plasma spraying, as screen printing, is currently typically a batch or semi-batch process. Fully automated plasma spray machines capable of processing targets of up to …inches with cycle times of .. sec per pass are available and cost around …

Dip Coating

Dip coating is a widely-used industrial process in which a shape is dipped into a bath with a ceramic powder paint. The thickness of the coating is primarily determined by the surface characteristics of the body to be coated, the properties of the paint, and the number of coatings.

The equipment for dip-coating is inexpensive, but cycle-times are relatively long due to the required dry time in between passes and the need for multiple passes to achieve thicker coatings.

Bisque Firing

During the bisque firing step, the binders in the green shape are (partially) burned off to produce a dimensionally stable (but brittle) shape. Bisque firing is typically accomplished at between 300 – 500 °C in a continuous oven (pusher, walking beam, moving belt).

Sinter Firing

During the sinter firing the ceramic powders in the bisqued shape are partially melted to produce the desired properties in the final product, including morphology, strength, density, and electrical properties. A number of requirements (depending on the materials used and the geometry processed) must be met and counterbalanced against the desire to minimize sinter time and temperature, including:

- A sufficiently high temperature must be held for a sufficiently long time to allow the ceramic particles to partially fuse;
- Heat-up and cool-down must not be too rapid to avoid damage to the product due to differential shrinkage and expansion and due to un-even heating
- A uniform temperature must be maintained to achieve uniform products and for geometric control.

Co firing layers can pose several special problems of which many can be solved. The first problem deals with shrinkage rates during sintering. Shrinkage rates can be matched by adjusting the binders, plasticizers and particle sizes. Co-Firing the anode, electrolyte and cathode at the same time poses a serious challenge. While the anode and electrolyte can easily be fired at the same temperature, the cathode layer typically benefits from a firing at a lower temperature. This difference in the sintering temperatures requires two different sintering cycles. The porous non-reactive sand layer separating the assemblies during sintering allows for shape stability and out gassing.

For high-temperature sintering the most widely used furnaces are batch furnaces. High Temperature furnaces capable of maintaining fully loaded temperature of 1450 C with internal dimensions of 44″ long x 44″ wide x 40″ high, are electric and have a capacity to fire approximately 13,000 assemblies (2/3 full load capacity with multiple stacks of 200 assemblies high). The high temperature furnaces developed by Micropyretics Heaters International Inc. and cost approximately $135,000. The low temperature furnaces have the same internal dimensions and capacities of the high temperature furnaces. The low temperature furnace chamber is under a positive pressure inert environment of either nitrogen or argon. These furnaces are developed by a number of companies, and we have had assistance from Micropyretics Heaters International Inc. The typical furnace cost is approximately $100,000.

Continuous furnaces may also be available but given the long sintering times required their benefit is not clear.

Metal Fabrication Techniques

For the manufacture of the interconnects a number of standard metal fabrication techniques is used. These techniques are so ubiquitous and widely used that we think it unnecessary to provide a detailed description here. For descriptions the reader is referred to an up-to-date textbook.

QC

Quality control (QC) will be critical in the production and assembly of SOFC, given the complexity of the product. However, based on currently available techniques and knowledge there is limited opportunity for inspections during the ceramics production process. Inspection steps will include:

- Visual inspection for density variations, pin-holes and other irregularities prior to sintering;
- Check dimensional tolerances after sintering;
- Full check for gas leaks and electrochemical performance after repeat units or stacks are completed.

The full electrochemical checks are also costly, providing another reason to minimize their use.

Finally, as is common in the manufacture of many types of internal combustion engines (including for automobiles), the complete system will require an operational check before shipping.

Chapter 4 Results

The analysis results indicate that production volume is the dominant factor determining early SOFC manufactured cost (with a 4x – 8x impact on stack cost), while cell and stack scale-up can provide additional economy of scale cost reduction but with much more limited impact (10-20% cost reduction potential).

This chapter provides an overview and discussion of the results of the analysis carried out. Detailed assumptions and results can be found in Appendices B and C.

Baseline Results

Based on the assumptions made, planar anode-supported SOFC may have somewhat lower cost than tubular ones because they have lower materials cost, higher power density, and because their more compact construction leads to lower cost for stack packaging.

The baseline results discussed assume a production volume of 250 MW / yr.

Stack Cost

Components

Contrary to some earlier studies' results, the analysis indicates that manufacturing cost dominates the cost of SOFC ceramic cells, with tubular cells costing more due to higher materials costs and a lower per-unit area power density.

The primary stack components for all SOFC stack types are the ceramic cells. As Figure 4-1 shows the cost of planar SOFC ceramic cells are lower than those for tubular SOFC. Also shown in Figure 4-1 is that the differences between the cell types mostly arise from the differences in material use.

Focusing on the planar cells, we note that the cell cost is dominated by the fabrication cost, where in reports from past studies the cost was dominated by materials cost (Carlson 1999; Thijssen and Sriramulu 2002; Koslowske 2003). For this there are several reasons:

- Our assumption for the thickness of the anode (which dominates the cell materials cost because of its thickness) is much thinner than in previous studies (325 μm now vs 1000 μm then);
- The DOE's estimates for material prices are different. Especially the YSZ prices are much lower ($10 or $25/kg now vs $100 - $125/kg then);

- Our new analysis contains more detailed (we think more realistic) estimates of the material handling and QC costs which raise the fabrication costs.

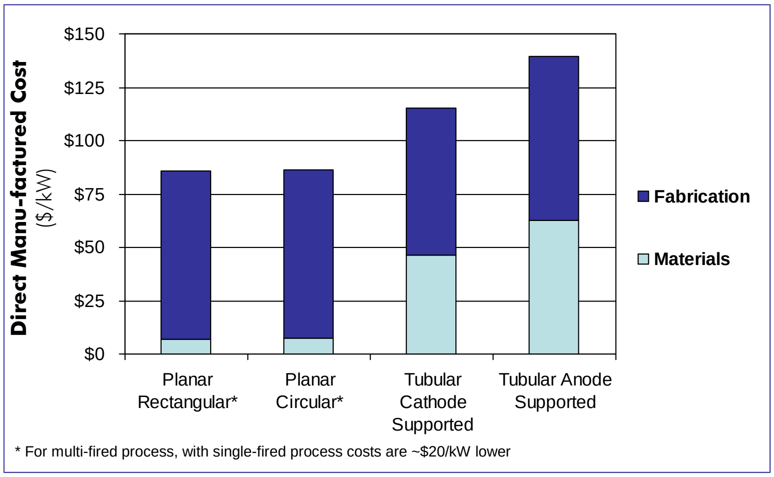


Figure 4-1 Baseline Estimated Direct Manufactured Cost of Ceramic Cells for Small Cells

As can be seen from Figure 4-1, the fabrication costs of needed for the cell types are similar. The tubular technologies have somewhat lower per unit weight or area fabrication cost because the smaller number of firing steps (in the case of the tubular cathode-supported technology) or because the smaller number of deposition steps assumed in case of the tubular anode-supported technology, but this is partially off-set by the lower power density. If a single-fired process were used for the planar cells their cost would likely be about $20/kW lower.

Most of the difference between the costs of various cell types thus stems from differences in material cost (see also Figure 4-2):

- Material cost for planar technologies is low because we assumed a thin (325 μm) support and because the DOE price assumptions for Ni and YSZ for the support layer are modest to low (composite price ~$8-9/kg)[6];
- The cost for the tubular cells (in $/kW) is higher because of their lower power density (300 vs 400 mW/cm^2);
- Material cost for tubular cathode-supported technology is high because a relatively thick LSM support is needed to provide conductivity (1000 μm) and because the LSM price ($12/kg) is about 1.5x that of the anode material[7];

[6] The price of nickel metal has risen dramatically over the past few years. 2006 price levels were 2-3x that assumed by DOE based on 2002 market prices. If a $20/kg price for nickel were assumed (instead of $8/kg), it would increase the cost of planar anode-supported SOFC by about 3-4 $/kW. The cost of tubular anode-supported cells would increase by 15-20$/kW

[7] A more thorough assessment of this price may be in order. If the price for the LSM were $9/kg instead of $12/kg, the cost of tubular cathode-supported would be reduced by $10/kW

- The tubular anode-supported technology has a lower cost for the ceramic materials in the cells than the tubular cathode-supported cells but the silver cathode current collector more than off-sets that benefits (accounting for about 25-50% of the total cell materials cost).

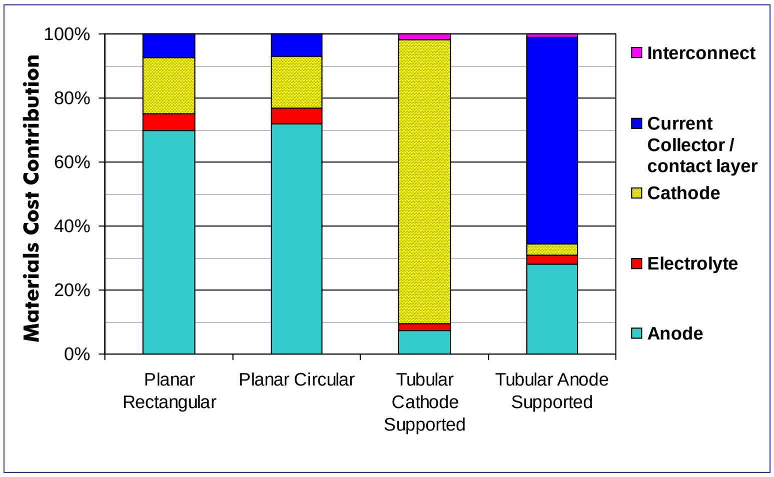


Figure 4-2 Distribution of Ceramic Cells Materials Cost, Small Cells

The recent rise in metal prices (notably nickel) reduces or eliminates the difference in cell cost between planar anode-supported and tubular cathode-supported cells but it further increases the cost disadvantage of tubular anode-supported cells.

Stack Modules

When we include the interconnects and the non-repeat stack hardware (i.e. the end-plates, tie-bolts, busbar, etc.), the picture is qualitatively the same as for the ceramic cells (see Figure 4-3):

- The cost of the ceramic cells represents approximately two thirds of the total direct manufactured cost of the stack modules; the rest is the cost of the interconnect, balance of stack components (i.e. the non-repeat elements of the stack module);
- For planar cells and tubular anode-supported cells, the interconnect represents approximately twenty percent of the stack module cost. For tubular cathode-supported cells the cost of the interconnect is only about ten percent of the total because of the simplicity of the interconnect. If nickel prices remain high finding alternative materials (e.g. Crofer) will be more critical;
- Assembly of the stack module and its quality control represent about ten to fifteen percent of the total direct manufactured cost of the module. This is mostly due to the QC cost, which must be carried out on each stack module and which takes about 12 hrs to complete (includes heat-up, reduction of the stack and full battery of functionality tests)

- The balance-of-stack components represent only a small portion of the planar stack modules: it only represents the air and fuel manifold connection (the part that is directly adjacent to the stack), end-plates, tiebolts and busbars. For the tubular systems the air (for the cathode-supported cells) and fuel (for anode-supported cells) manifolds are more complex and hefty, partly because they also have to physically support the cells.

The impact of the recent rise in metal prices is reducing the difference in cost between stack modules based on planar anode-supported cells vs that of tubular cathode-supported cells while enlarging the advantage either of these cell-types have over tubular anode-supported cells.

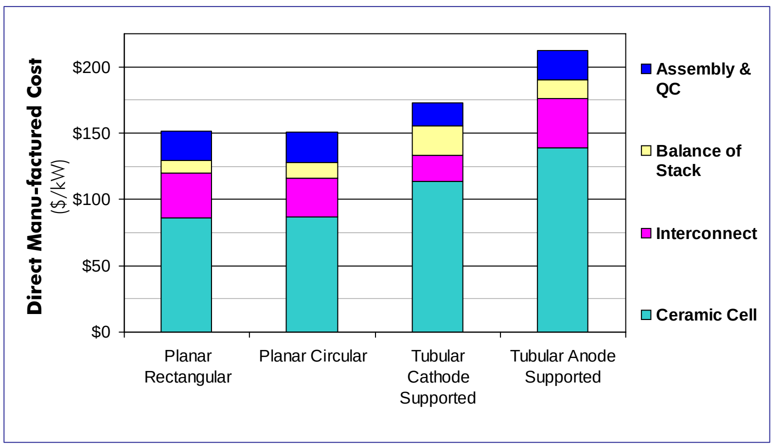


Figure 4-3 Build-Up of Stack Module Direct Manufactured Cost Estimates for 5 kW Units

Stacks

The cost of the repeat units and the cost of the insulation are the most important factors in determining the overall cost of the 5 kW SOFC stacks studied; in planar anode-supported technologies have a potential cost advantage over tubular technologies because of their lower cell cost and because their compact construction minimizes stack packaging cost

The stacks are then built by combining the stack modules to reach the desired output capacity (here 5 kW). Besides the stack modules the stacks also include the manifolding necessary to tie the modules together to single connections for air, fuel, and exhaust, and the vessel and insulation that contain the stack modules. To understand the differences between the packaging requirements for the four stack types it helps to look at the total system volume for the four systems (see Figure 4-4). The inherently lower packing density of the tubular cells leads to a 4-5 times larger stack volume for those types of stacks.

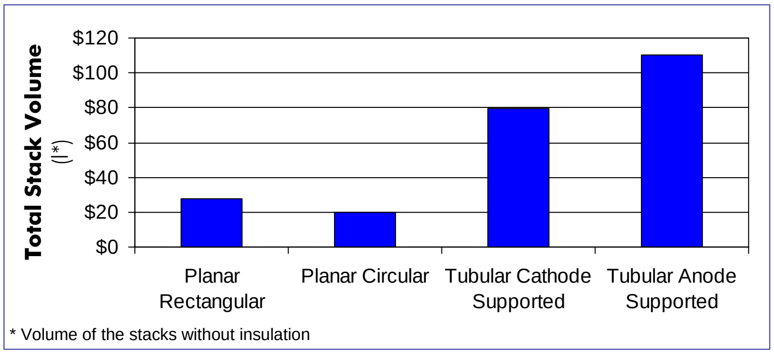


Figure 4-4 Stack Volume Projections

As Figure 4-5 shows, the cost of the insulation exacerbates the cost differences between the planar and the tubular sacks. The vessel and the insulation represent the bulk of the additional cost in the stack, as can be seen from Figure 4-5. The effect of the system volume is further exacerbated by the need to use an alumina liner in the insulation to avoid silica contamination of the stack (the silica volatilizes, especially in an environment where some water vapor is present and once in the stack interacts with the electrolyte to reduce the electrolyte's conductivity). In the planar systems the insulation is either not in communication with the stack innards (planar rectangular technology) or downstream of the stack (planar circular technology).

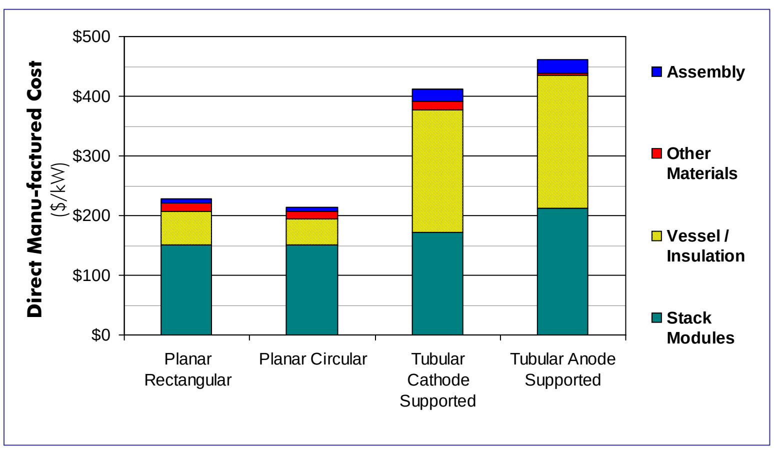


Figure 4-5 Build-Up of Stack Direct Manufactured Cost Estimates, 5 kW Stacks

System Cost

To understand how these cost profiles impact system-level direct-manufactured cost, we combined our stack cost estimates with the balance-of-plant estimates for a 5 kW gasoline-fueled POX/SOFC APU system (Thijssen 2001). As the results show (Figure 4-6) the cost estimates for the planar systems are in the same range as those for the original study, though the build-up is somewhat different.

The tubular technologies carry a higher cost for these 5 kW systems, due to the higher cost of the stack and the insulation. Because in the tubular cathode-supported system (part of) the recuperator is integrated into the stack (air preheat in the plenum and in the feeder tube) the higher cost of stack and insulation are partially off-set by lower cost of the recuperators and the rotating equipment. However, for the tubular anode-supported system such benefits appear not to be readily available, hence the cost difference is much larger.

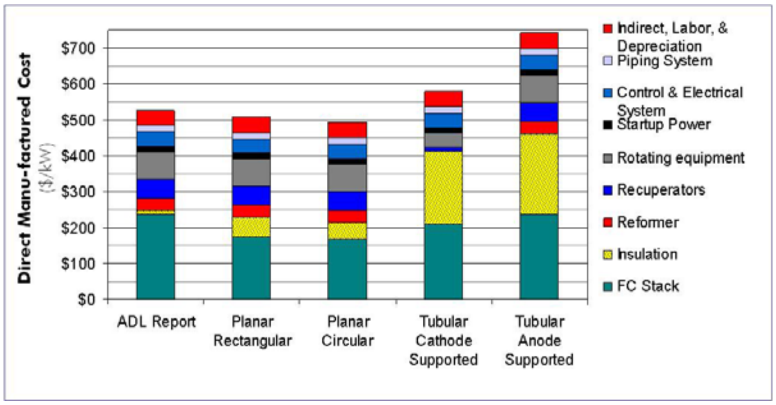


Figure 4-6 System Cost Estimates, 5 kW POX SOFC System

Effect of Production Volume

Production volume has a major impact on SOFC stack cost, allowing stack cost to be reduced 4x – 8x as production volume increases from 5 – 500 MW/yr (per plant). Higher utilization of production equipment and of labor are the primary reasons for the cost reduction.

Economy of scale effects can significantly reduce SOFC stack direct manufactured cost, with most of the benefit occurring at production volumes below 50 MW/yr. A similar effect is seen with the other stack technologies (see Appendix C). This economy of scale results mainly from the reduced cost of the stack modules, mostly of the ceramic cells. The key elements contributing to the economy of scale effect are:

- Higher utilization of production equipment capacity in the ceramics production line reduces the capital cost distribution. Limited scalability of the equipment can reduce the capacity factors from about 80% for or more for all process units at 250 MW/yr down to as low as 10-20% for some of the process equipment when the production is 5 MW/yr. Consequently the capital cost has to be amortized over a smaller production, raising unit cost. Partially this is because the number of shifts may be reduced from 3 to 2 in order to contain labor cost. However, even in that event the sintering ovens and QC testing will continue 24 hrs per day.

- As with the production equipment, the productivity of the workers also drops as it still takes the same number of workers to man a machine. Below 10 MW/yr the number of shifts may be reduced from 3 to 2..
- Materials cost is not strongly dependent on the production volume except it the lot sizes bought drop below 1000 kg. As mentioned in Chapter 3 we assumed a premium for small quantities. Though this strongly impacts the material cost for the electrolyte and some of the active layers, it has only a modest impact on the stack cost overall.

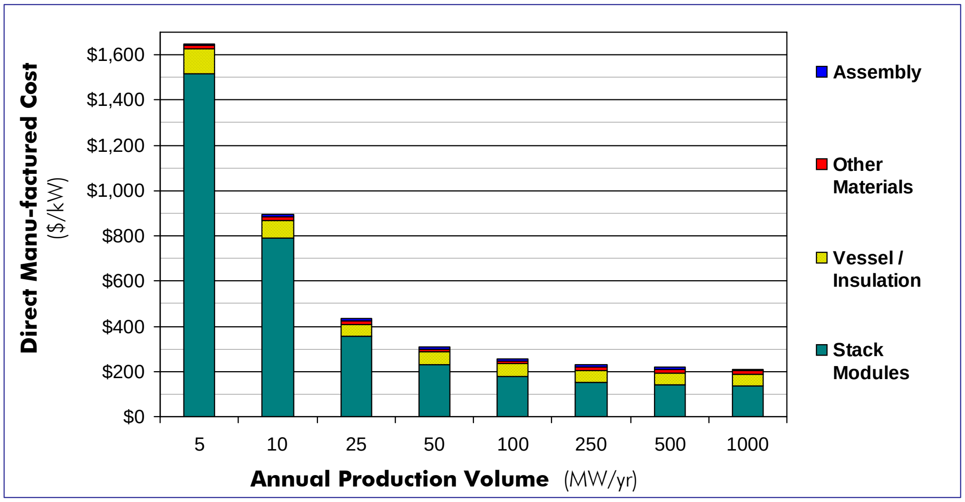


Figure 4-7 Effect of Production Volume on Estimated Direct Manufactured Cost ($/kW) for Stacks with Planar Rectangular Cells

Through analysis of a number of different scenarios and sensitivity analysis, we found that, given what we know today:

- For production volumes smaller than 25-50 MW per year stack cost is so high that it would make it difficult to meet the SECA targets within a system.
- Between about 50 and 250 MW per year significant economies of scale can be achieved.
- Beyond 250 MW/yr significant scale-up of production equipment would be required to allow further economies of scale to be realized. This would have to include faster or wider tape casters, bigger ovens, etc.

Overall, this suggests that it is critical for companies commercializing SOFC to rapidly grow to a production capacity of 25 – 50 MW per year.

Effect of Cell Size

2 MW System with Small Cells

Modular scale-up of the small stack modules to ~2MW stacks results in a significant reduction of the stack packaging cost (vessel & insulation), strongly reducing the differences in cost between the stack types based on planar and tubular cells. While the tubular anode-supported technology studied appears to be statistically more expensive, the cost of the planar and tubular cathode-supported stack technologies show significant overlap in the sensitivity analysis.

The scale-up of of stacks to 2 MW with stack modules based on small cells reduces the unit cost ($/kW) of stack packaging significantly, which especially benefits the tubular stack technologies.

As discussed in Chapter 2, the small cell modules, with capacities in the 2-10 kW range, can be combined to form 2 MW stacks with single connections for each of the flows and a single pair of electrical connections. As shown in Figure 4-8, the cost difference between tubular and planar technologies, which was substantial for the 5 kW stacks, is much reduced for the 2 MW systems. Noteworthy observations include:

- The cost ($/kW) of the stack module does not change much due to the scale-up, even though the number of cells in the modules was doubled in some of the configurations.
- The cost per kW of the stack packaging (vessel + insulation) is reduced by about 90%. This is in line with the scaling laws for vessels: based on a 400x increase in volume the cost of the box (which scales with the surface area) will tend to go up with the 0.65 power, resulting in a 88% decrease in cost per unit volume. It must be noted that while this approach is the lowest-cost approach, availability considerations may dictate that the stack modules are thermally isolated (and indeed electrically and with respect to flow). However, given the very limited data on stack durability and availability we deemed there to be insufficient data for a proper trade-off between the value of increased availability and the extra cost of additional packaging cost.
- The piping required to connect all for streams for all 500 planar rectangular stack modules (see Chapter 2) is complex and rather costly compared with the cost for the smaller systems. The tubesheet-type approaches used for the tubular technologies and for the planar circular technology provide a substantially more cost-effective solution.

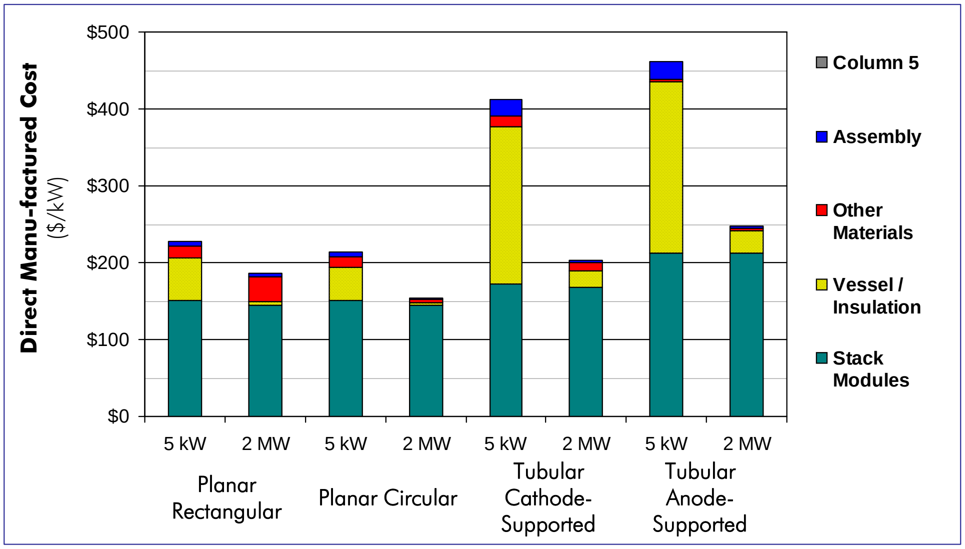


Figure 4-8 Effect of Scale-Up from 5 kW to 2 MW Based on Small Cells

When these stack costs are then included into the system analysis for the 3.1 MW (2.6 MW fuel cell, balance turbine) the costs for the various technologies are also much closer than for the smaller systems (Figure 4-9). Given the uncertainties

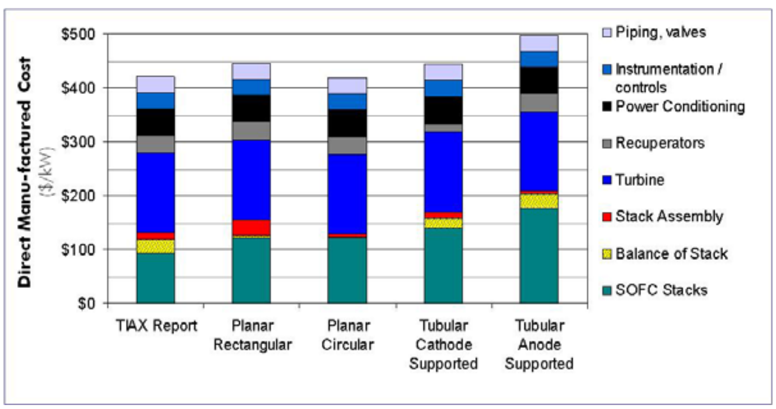


Figure 4-9 System Cost Estimates ($/kW) for 3.1 MW Stationary Hybrid SOFC Systems Based on Small Cell Stacks

Scale-Up of Stacks with Planar Cells

Scale-up of the cells can provide additional cost reduction, but the extent of this benefit strongly depends on the manufacturing yield that can be achieved. Despite the uncertainty in manufacturing yield, it appears that eventually scale-up of the planar cells to about 750 – 1000 cm2 would provide up to 20% additional cost reduction. Tubular technologies may not benefit as much from cell scale-up; for cathode-supported technology there is limited scope because the cells are already quite large, and for tubular anode-supported technology the benefits of scale-up are offset more rapidly by the increased cost of the silver current collector.

- The cost benefit of scaling up the cells for the 2 MW stacks is limited to about 15% cost reduction, as the gains made by reduction in the cost of the non-repeat elements is first partially and then more than off-set by the effect of increased production losses for the ceramic cells.

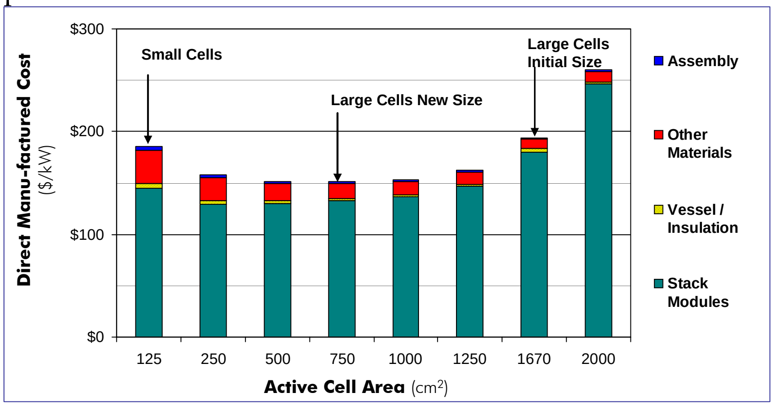


Figure 4-10 Effect of Cell Area on the Estimated Direct Manufactured Cost of 2 MW Stacks Based on Planar Rectangular Cells

When cells of planar SOFC are scaled up, several counteracting factors result in an optimum cell size (From a stack cost perspective, see Figure 4-10):

- The inactive area on the ceramic cell (taken up by seals primarily) becomes relatively smaller, so that the part of the ceramic cell that is active increases from 84% in a 125 cm^2 cell to 96% in a 2000 cm^2 cell;
- Counteracting this in the overall ceramic cell cost is the effect of production losses. The percent loss in a ceramic piece is assumed (for lack of better information) to be proportional to the total volume of the piece. As a consequence the initial assumed loss of 6% for the 125 cm^2 cells grows to 45% for a 1000 cm^2 cell. In fact for larger sizes larger than 500 cm^2 the increased losses outstrip the active area advantage, and for sizes greater than 1000 cm^2. Of course this effect is strongly dependent on the assumed losses (Figure 4-11). As mentioned in Chapter 3, the production losses assumed in the baseline (6%) are about the maximum for which meaningful cell scale-up can be considered. In actual practice losses are currently typically higher but as Figure 4-11 shows even with losses of 10% cell scale-up of planar cells is limited to about 1000 cm^2. On the other hand, even if the losses are reduced to 4% the minimum direct manufactured cost still occurs for cells of around 1000 cm^2. If, as is quite possible, the cells have to be made thicker as they are scaled-up, the optimum cell size will shift to even smaller sizes.
- The cost of the manifolding and other hardware connecting the stacks with one another decreases monotonically as the stack module size is increased.

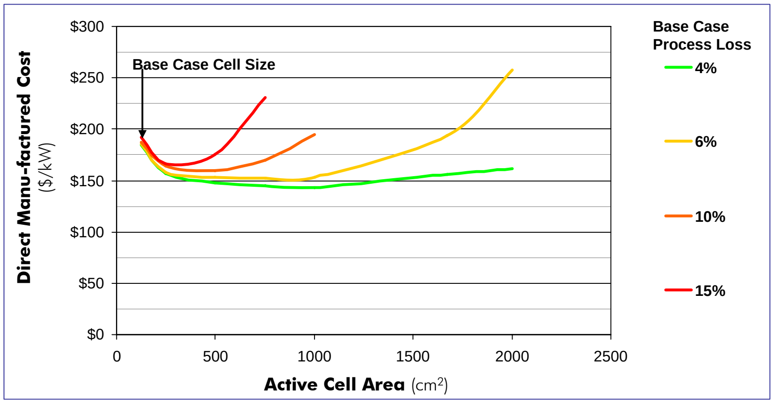


Figure 4-11 Effect of Ceramics Processing Losses and Cell Scale-Up on 2 MW Planar Rectangular Stack Direct Manufactured Cost ($/kW)

Based on the analysis depicted in Figure 4-11 we changed the cell size for the large cell stacks from the base case of 1670 cm^2 to 1000 cm^2 (see Appendix C for overview).

The results with the circular cells are similar to those with the planar cells, except that:

- The patterning options for the cell cutting change as the cell size changes. As a consequence the optimum size will depend more strongly on the precise width of tape casting machine available, and on whether the scrap from the anode punching step can be recycled.
- The cost of the manifolding is less substantial, and consequently there is less advantage in manifold scale-up due to cell scale-up.

We changed the size of the large circular cells for the remainder of the analysis from 1875 cm^2 to 1450 cm^2 to reflect these findings.

Scale-Up of Stacks with Tubular Cells

For the tubular anode-supported cells the effect of scale-up and ceramics processing losses is qualitatively similar to that for the planar cells, but the optimum cell scale is substantially smaller (about 200 cm^2 per cell, see Figure 4-12). This difference is due mainly to two factors:

- As the cell size increases in length, the diameter may have to increase and as a result the combined thickness of the silver contact as well;
- Because of the nature of the manifolding arrangement, not as much cost reduction results from cell size increase in manifolding as with planar cells;

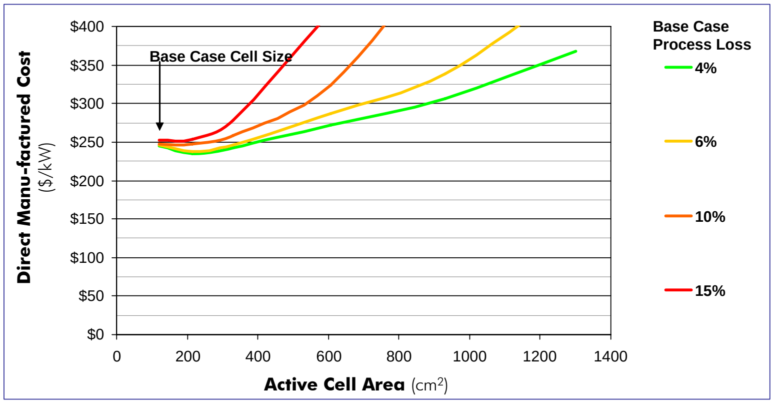


Figure 4-12 Effect of Ceramics Processing Losses and Cell Scale-Up on 2 MW Tubular Cathode-Supported Stack Direct Manufactured Cost ($/kW)

In summary, it appears that for large stack systems the tubular anode-supported cells could benefit somewhat from scale-up to around 200 cm² (i.e. 6 take-offs rather than 4), provided that the ceramics processing losses can be kept low. For the remainder of the analysis, we changed the cell size of the large tubular anode-supported cells to 330 cm² (from 1000 cm², see Appendix C for overview).

The stacks based on tubular cathode-supported cells the situation are already large in the base case, so only limited further scale-up is desirable (or possible within the constraints of currently available production equipment). However, by looking also at scale-down, the analysis demonstrates clearly the rationale for making the tubular cathode-supported cells as large as they currently are from the perspective of large-scale systems. However, depending on the actual process yield the optimum cell size appears to lie between about 1000 and 2000 cm² (Figure 4-13).

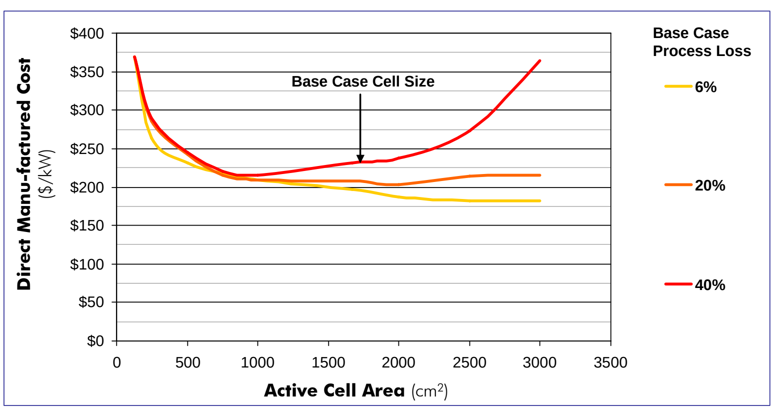


Figure 4-13 Effect of Ceramics Processing Losses and Cell Scale-Up on 2 MW Tubular Cathode-Supported Stack Direct Manufactured Cost ($/kW)

It is important to stress that the processing yield from the ceramics processing step can have a deciding impact on the scale-up. Considering that we assumed that the ceramics yield for the tubular cathode-supported technology is the same as for the other cells in the base case (see Chapter 3) even though the tubular cathode-supported cells are much larger we also show some cases in Figure 4-13 with higher yield losses. Even with those cases the yield loss per unit cell weight is lower than those assumed for the other technologies.

For these reasons we decided to change the cell area for the large size tubular cathode-supported cells to 13 deltas, or a total active cell area of 2100 cm^2 (see Appendix C for overview).

Impact of Large Cells on System Cost Estimates

At a system level, the potential savings from cell scale-up are carried through, but the overall impact becomes rather small in light of the current level of uncertainty in the system cost estimates as a whole (Figure 4-14).

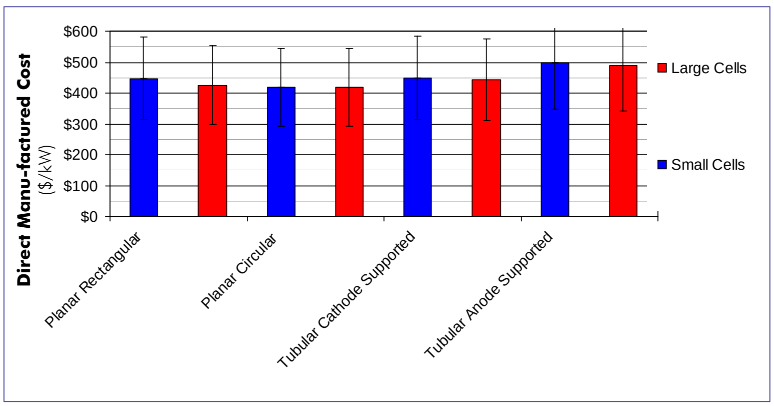


Figure 4-14 Impact of Cell Size on System Cost Estimates for 3.1 MW Hybrid System

Uncertainty in the Results

Sensitivity Analysis

To understand the statistical significance of these results we carried out a limited uncertainty analysis, using a Monte-Carlo approach. Uncertainty ranges were ascribed to each of the most important factors in the analysis (See Appendix B for details). Simple sensitivity charts show that the main uncertainty in determining the cost of the stacks is the power density (see Figure 4-15, also see Appendix C for charts on other technologies). This agrees well with previous studies (Carlson 1999; Koslowske 2003). Similarly, the capital cost (capital charge rate, and especially the of the sintering ovens) are a key factor in determining the stack cost.

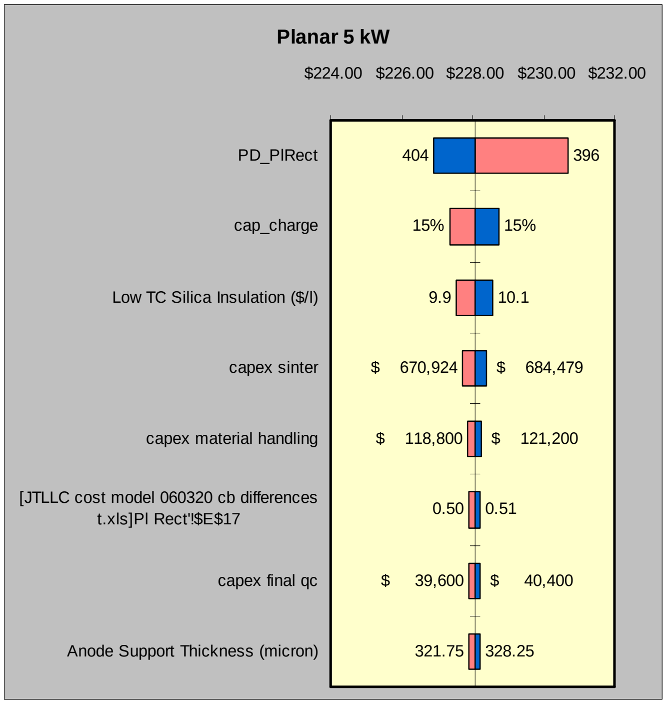


Figure 4-15 Sensitivity Chart of Cost of Planar 5 kW Stacks

Other factors of importance are the thickness of the support material (the anode in planar and tubular anode-supported cells and the cathode in tubular cathode-supported cells) the cost of the interconnect in the planar cells and the cost of the silver current collector for the tubular anode-supported cells.

One key cost component that had not been flagged as a major factor in other studies however is the insulation. The cost of the high temperature insulation (especially if high-purity alumina insulation is required) constitutes a key cost. Fortunately DOE has several programs that are aimed at developing lower-cost insulation materials.

Especially for the planar cells the manufacturing become important in the scaled-up cells.

Probability Results

Using the Monte-Carlo analysis we then assessed the statistical validity of the differences discerned and discussed above. The results of that analysis (see Appendix C for charts) shows that:

- The level of uncertainty in direct manufacturing cost estimates for SOFC stacks is +/- 25%.
- At small system capacity the cost differences between tubular and planar cells is statistically significant, but the differences between planar rectangular and planar

circular cells and between tubular cathode-supported and tubular anode-supported cells are not statistically significant.

- For large systems planar cells have a 60% probability of being lower in cost than and tubular cathode-supported cells but a 100% probability of being lower in cost than tubular anode-supported cells.

Combined Effects of Production Volume and Cell Size

Analysis of the combined effects of both production volume and cell size in the context of the market scenarios (see Chapter 1) shows clearly that achieving high production volume must be the priority in reducing SOFC production cost. Based on the analyses of the impact of cell size and production volume on SOFC cost we analyzed their combined effect on the total cost of serving the markets outlined in Chapter 1. The results for the cases where either only small or only large systems are required are trivial: the total market cost simply follows the per-stack results for the analogous cases.

The results for the mixed markets are most interesting. As shown in Figure 4-16 in especially the low-volume market making both small and large cell stacks is more expensive than making exclusively the small cells. When both types of cells are made only half the production volume is made, and this lower production volume more than off-sets the advantage of making the larger cells. For the high production volume the difference is smaller, and eventually making both cell sizes is less costly.

Figure 4-16 Impact of Making Large Cells on Total Production Cost in Mixed Product Market Scenarios, Planar Rectangular Cells

A caveat must be made by this analysis, however. In commercial practice in the co-production of two cell sizes certain economies of scale may well be achieved. Some of the equipment can be used for both cell sizes and thus help with achieving economies of scale (Even though allowances must then be made for tools changes etc.). In the case of the circular cells this was already taken into consideration in the treatment of the patterning of the anode punch from the tape, but other opportunities undoubtedly exist. However, these fall outside of the scope of this study.

Chapter 5 Conclusions

Production volume impacts the cost of producing SOFC strongly (by a factor 4x t o8x) while a modest economy of scale benefit (10 – 20%) could be gained from scale-up of the SOFC cells once production volumes are high already. The study analyzed both these effects using a detailed bottom-up cost model which takes into account the major factors affecting cell, stack, and system cost. Despite the early stage of development, some clear conclusions can be drawn:

- The model results indicate that as production volumes increase (from 5 MW per year to 500 MW per year from a single plant) there is opportunity for reduction of the direct manufactured cost of each of the cell technologies by a factor of 4-8.
- Scale-up of planar cells from the currently typical ~100 – 150 cm^2 per cell to ~1000 cm^2 per cell would substantially simplify the manifolding of the stacks and could potentially lead to a cost reduction of around 10 – 20%. For tubular cathode-supported cells manifolding is more straightforward and there is not quite so much scale-up potential, primarily because these cells are already fairly large.
- Because of the clear difference in magnitude of these effects it would likely be more cost-effective to first mass-produce one size of cells and stacks and adapt them to each application and later scale cell and stack technology to each specific application, rather than produce cells / stacks specifically sized for each of the applications from the start.
- While for large-scale systems (2 MW was studied here) the differences in cost potential between the various stack technologies are modest, at small sizes (5 kW) planar technologies clearly have the potential for lower cost than tubular technologies.

Appendix A Abbreviations & References

Abbreviations

AC	Alternating Current
CVD	Chemical vapor deposition
DC	Direct Current
DOE	(US) Department of Energy
EVD	Electrostatic vapor deposition
kW	Kilowatt
LSCo	Lanthanum Strontium Cobaltite
LSM	Lanthanum Strontium Manganate
mW	Milliwatt
MW	Megawatt
Ni	Nickel
QC	Quality Control
SECA	Solid State Energy Conversion Alliance
SOFC	Solid oxide Fuel Cell
(x)YSZ	Yttria Stabilized Zirconia (x denotes percentage Yttria)

References

Besette, N. (2004). Status of the Acumentrics SOFC Program. SECA 2004 Annual Meeting and Core Program Review, Boston, US DOE NETL.

Besette, N. (2005). Status of the Acumentrics Solid Oxide Fuel Cell Program. 2005 Fuel Cell Seminar, Palm Springs, CA, US DOE NETL.

Borglum, B. (2005). Cell Technology, Cost Reduction and Quality Management. 2nd Real-SOFC Workshop, Simmerath-Einruhr, Germany, EU.

Borglum, B. (2005). Stack Development Strategy, Performance and System Operation. 2nd Real-SOFC Workshop, Simmerath-Einruhr, Germany, EU.

Borglum, B., J.-J. Fan, et al. (2003). Following the Critical Path to Commercialization: an Update on Global Thermoelectric's SOFC Technology and Product Development. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Borglum, B., E. Tang, et al. (2005). Development of Natural Gas Fueled Solid Oxide Fuel Cells at Versa Power Systems. 2005 Fuel Cell Seminar, Palm Springs, CA, US Department of Energy.

Bossel, U. (2003). Portable SOFC Generator with Innovative SPIROCELLs. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Botti, J. J. (2003). The Revolution through Evolution: Delphi Solid Oxide Fuel Cell for APU and Hydrogen Reformation. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Carlson, E. (1999). Assessment of Planar Solid Oxide Fuel Cell Technology. Cambridge, MA, USA, US Department of Energy.

Christiansen, N., S. Kristensen, et al. (2005). Status and Recent Progress in SOFC Development at Haldor Topsøe A/S and /Risø. 2005 Fuel Cell Seminar, Palm Springs, CA, USA, US Department of Energy.

Christiansen, N., S. Kristensen, et al. (2004). Status and Recent Advances in SOFC Development at Haldor Topsøe/Risø. Sixth European Solid Oxide Fuel Cell Forum, Luzern, Switzerland, European Fuel Cell Forum.

George, R. and A. Casanova (2003). Developments in Siemens Westinghouse SOFC Program. 2003 Fuel Cell Seminar, Miami Beach, FL, USA, Department of Energy.

Ghosh, D., E. Tang, et al. (2001). Solid Oxide Fuel Cells VII, The Electrochemical Society.

Koslowske, M. (2003). A Process Based Cost Model for Multi-Layer Ceramic Manufacturing of Solid Oxide Fuel Cells. Materials Science. Worcester, MA, USA, Worcester Polytechnic Institute**:** 42.

Minh, N. (2004). Solid Oxide Fuel Cell Technology - Development Status. 2004 Fuel Cell Seminar, San Antonio, TX, USA, US Department of Energy.

Minh, N. and T. Rehg (2005). Solid Oxide Fuel Cell Based Power System Development. 2005 Fuel Cell Seminar, Plam Springs, CA, USA, US Department of Energy.

Mogensen, M. and P. V. Hendriksen (2003). Experimental Requirements in Determination of SOFC Electrode Kinetics. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Schultz, T. (2006).

Singhal, S. C. (2000). "Science and Technology of Solid Oxide Fuel Cells." MRS Bulletin **25**(3): 16 - 21.

Singhal, S. C. and K. Kendall, Eds. (2003). High Temperature Solid Oxide Fuel Cells: Fundamentals, Design and Applications. Oxford, UK, Elsevier Ltd.

Singhal, S. C., R. J. Ruka, et al. (1986). Anode Development for Solid Oxide Fuel Cells. Pittsburgh, PA, United States Department of Energy.

Sriramulu, S. (2003). Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System. Cambridge, MA, USA, US Department of Energy.

Steinberger-Wilckens, R., L. G. J. de Haart, et al. (2003). Recent Results of Stack Development at Forschungszentrum Jülich. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Steinberger-Wilckens, R., I. C. Vinke, et al. (2004). Progress in SOFC Stack Development at Forschungszentrum Jülich. Sixth European Solid Oxide Fuel Cell Forum, Luzern, der Schweiz, European Fuel Cell Forum.

Stevenson, J. W., S. Baskaran, et al. (2003). Solid Oxide Fuel Cell Development at PNNL. Eight International Symposium on Solid Oxide Fuel Cells (SOFC VIII), Paris, France, The Electrochemical Society, Inc.

Thijssen, J. (2001). Conceptual Design of POX / SOFC 5 kW Net System. Cambridge, MA, Arthur D. Little for U.S. Department of Energy, National Energy Technology Laboratory.

Thijssen, J. and S. Sriramulu (2002). Structural Limitations in the Scale-Up of Anode-Supported SOFCs. Cambridge, MA, USA, Arthur D. Little for US DOE.

Thijssen, J. H. J. S. (2004). Scale-Up Potential of SOFC Technologies -
An Assessment of Technical and Economic Factors. Redmond, WA, USA, EPRI.

Thijssen, J. H. J. S. and S. Sriramulu (2002). Assessment of Solid Oxide Fuel Cell Technology:
Comparison of Alternative Design Approaches. Cambridge, MA, EPRI.

Virkar, A. V., J. Chen, et al. (2000). Solid State Ionics **131**: 189 - 198.

Vora, S. D. (2004). SECA Program at Siemens Westinghouse. SECA 2004 Annual Meeting and Core Program Review, Boston, US DOE NETL.

Vora, S. D. (2005). Development of High Power Density Seal-less SOFCs. 2005 Fuel Cell Seminar, Palm Springs, CA, USA, US DOE NETL.

Zizelman, J. (2003). Development Update on Delphi's Solid Oxide Fuel Cell System: From Gasoline to Electric Power. 4th SECA Annual Meeting, Seattle, WA, USA, Department of Energy.

Zizelman, J., S. Shaffer, et al. (2003). Delphi's Generation 2 APU System: from Gasoline to Electric Power. 2003 Fuel Cell Seminar, Miami Beach, FL, USA, Department of Energy.

Appendix B Detailed Assumptions

Material Prices

Most material prices for the analysis were taken from the DOE guidelines for the SECA teams. The ranges for the prices for the uncertainty analysis were based on actual market fluctuations.

Material	Price Units	Baseline	Low	High
Lanthanum Strontium Manganite (LSM)	$/kg	12	9	15
Yttria Stabilized Zirconia (YSZ) (>1um)		10	8	12
Yttria Stabilized Zirconia (YSZ) (<1um)		25	20	30
Lanthanum Strontium Ferrite (LSF)		10	8	12
Lanthanum Strontium Cobaltite (LSC)		36	30	42
Lanthanum Strontium Cobalt$_{0.2}$ Ferrite$_{0.8}$ (LSCF)		25	20	30
Ni metal		8	7.5	18
Cr metal		16	12	20
Co metal		26	20	32
Stainless Steel		2.5	2	5
High-purity alumina insulation	$/l	50	30	65
Alumina (for manifolds)	$/kg	50	30	65
Fiberglass insulation	$/l	1	.8	1.5

The figures above are for quantities > 1000 kg per year (large bulk). For smaller quantities, a premium was assumed. For quantities from 100 – 1000 kg/yr a 50% premium was assumed and for quantities <100 kg/yr a 100% premium was assumed.

General Cost Model Assumptions

Quantity	Unit	Base	Low	High
Production Volume	MW/yr	250	5	2500
Capital Charge Rate	% of initial capital	15%	12%	18%
Maintenance		4%	3%	6%
# shifts	#/day	3	2	3
Fabrication Mark-Up (For manifolds etc.)		200%	100%	300%
Assembly Factor (For general assembly)	% of assembly materials	10%		
Stack module QC test time	Hours per stack module	12	4	24

Process Step	Capital Cost ($1000)	Labor (workers / shift)	Capacity
Tape Caster	300 – 390 - 480	0.2	**1000 m^2/hr**
Continuous Sintering Oven HT	680	0.2	**4 layers x ~0.5 m^2/hr**
Extruder	625	0.4	**18 m/hr**
Contiuous Bisqueing / Sintering Oven	325	0.2	**4 layers x ~1 m^2/hr**
Screen printers	140	0.4	**360 m^2/hr**
Atmospheric plasma spray	450		**50 cm^2/s**
QC station (unit cell / stack test)	2000	4	**50,000 stacks/yr**
Robot loader	80 - 200	0.1	**5 million cells/ yr**

For the uncertainty analysis the variables describing the manufacturing process steps were assigned a Gaussian distribution with a standard deviation of 10% of the expected value.

Appendix C Additional Results

Additional Results

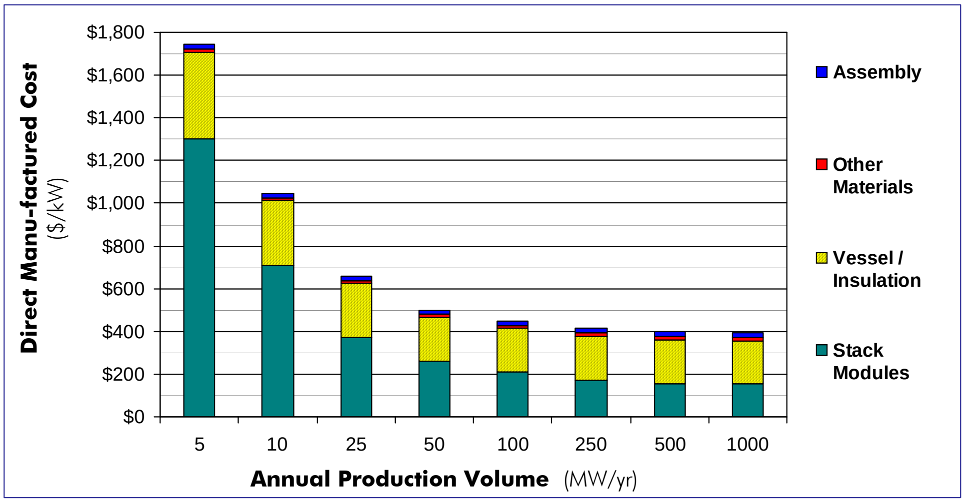


Figure C-1 Impact of Production Volume on the Estimated Direct Manufactured Cost for Stacks with Tubular Cathode-Supported Cells for 5 kW Systems

Overview of Final Cell, Stack Module, and Stack Characteristics

Stack Size	Property	Units	Planar Rectangular	Planar Circular	Tubular Cathode-Supported	Tubular Anode-Supported
5 kW						
	Cell area	Cm^2	125	120	1610	120
	Cell Power	W	50	49.0	485	35.5
	Cells in Module	#	50.0	50	11	75
	Module Power	W	2510	2500	5330	2650
	Modules in Stack	#	2	2	1	2
	Stack Power	kW	5.02	5.00	5.33	5.30
2 MW, Small Cells						
	Cell area	Cm^2	125	120	1610	120
	Cell Power	W	50.0	49.0	485	35.5
	Cells in Module	#	80	80	20	75
	Module Power	W	4010	3930	9700	2650
	Modules in Stack	#	500	540	200	800
	Stack Power	kW	2010	2100	1940	2120
2 MW, Large Cells						
	Cell area	Cm^2	1050	850	2100	215
	Cell Power	W	420	315	630	65.0
	Cells in Module	#	65	65	20	75
	Module Power	W	27400	20500	12600	4850
	Modules in Stack	#	80	100	160	392
	Stack Power	kW	2190	2050	2020	1900

Figures are rounded to next “five” at 3 significant digits

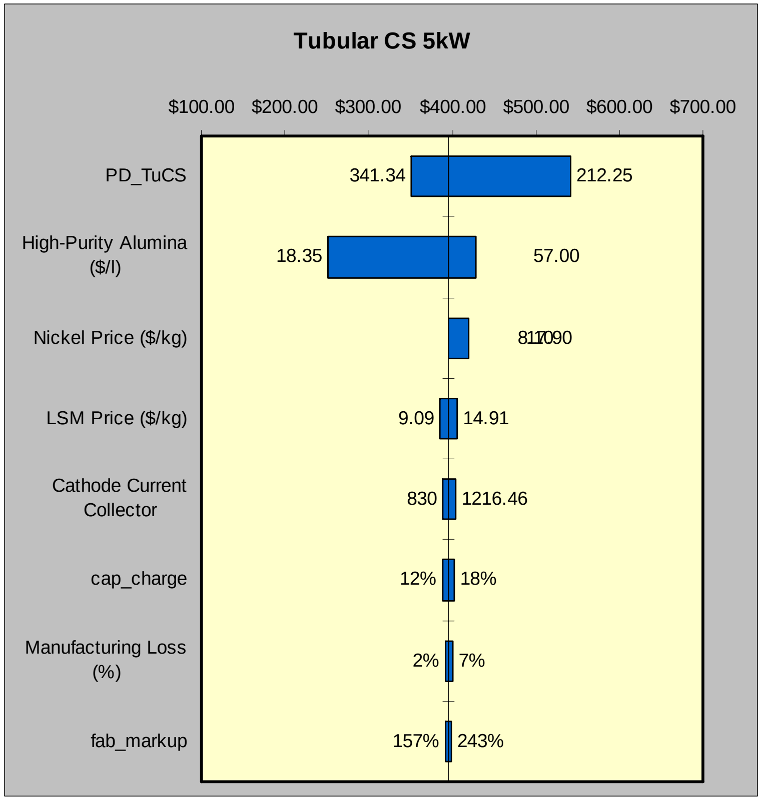
Tabulated Results for the Base Cases

			5 kW Stacks					2 MW Stacks, Small Cells			
			Planar Rectangular	Planar Circular	Tubular CS	Tubular AS		Planar Rectangular	Planar Circular	Tubular CS	Tubular AS
Stack											
Stack Module											
	Ceramic Cell										
	Material Cost Total Used (|		$ 7	$ 7	$ 45	$ 62		$ 7	$ 7	$ 45	$ 62
	Cell Manufacturing cost		$ 79	$ 79	$ 51	$ 77		$ 79	$ 79	$ 51	$ 77
	Total Ceramic Cell Cost		*$ 86*	*$ 86*	*$ 97*	*$ 139*		*$ 86*	*$ 86*	*$ 97*	*$ 139*
	Interconnect										
	Interconnect Material Cost		$ 15	$ 10	$ 19	$ 15		$ 14	$ 10	$ 19	$ 15
	Interconnect Fabrication C	215.31	$ 19	$ 19	$ 1	$ 22		$ 19	$ 19	$ 1	$ 22
	Total Interconnect Cost	4	*$ 34*	*$ 29*	*$ 20*	*$ 37*		*$ 33*	*$ 29*	*$ 20*	*$ 37*
	Balance of Stack										
	End-Plates / manifold		*$ 3*	*$ 4*	*$ 5*	*$ 7*		*$ 2*	*$ 3*	*$ 5*	*$ 7*
	Tie-bolts / feeder tubes + t		*$ 1*	*$ 3*	*$ 11*	*$ 2*		*$ 2*	*$ 2*	*$ 8*	*$ 2*
	Busbar		*$ 5*	*$ 5*	*$ 5*	*$ 5*		*$ 5*	*$ 5*	*$ 5*	*$ 5*
	Total Balance of Stack		*$ 9*	*$ 12*	*$ 22*	*$ 14*		*$ 9*	*$ 10*	*$ 18*	*$ 14*
	Assembly & QC		*$ 22*	*$ 23*	*$ 18*	*$ 22*		*$ 17*	*$ 20*	*$ 15*	*$ 22*
	Total Stack Module Cost		*$ 151*	*$ 151*	*$ 155*	*$ 212*		*$ 145*	*$ 145*	*$ 150*	*$ 212*
vessel / insulation			$ 55	$ 44	$ 204	$ 224		$ 5	$ 2	$ 21	$ 30
Other materials			$ 15	$ 13	$ 15	$ 3		$ 32	$ 5	$ 11	$ 3
Assembly			$ 7	$ 6	$ 22	$ 23		$ 4	$ 1	$ 3	$ 3
Total Stack Cost			$ 228	$ 213	$ 396	$ 462		$ 186	$ 153	$ 186	$ 248
					$ 168	$ 234				$ 0	$ 63
System											
FC Stack			$ 173	$ 170	$ 192	$ 238	S(	$ 122	$ 122	$ 126	$ 178
Insulation			$ 55	$ 44	$ 204	$ 224	Ba	$ 4	$ 2	$ 18	$ 25
Reformer			$ 34	$ 34	$ 34	$ 34	St	$ 30	$ 5	$ 12	$ 5
Recuperators			$ 52	$ 52	$ 52	$ 52	Tu	$ 148	$ 148	$ 148	$ 148
Rotating equipment			$ 76	$ 76	$ 76	$ 76	Re	$ 32	$ 32	$ 32	$ 32
Startup Power			$ 16	$ 16	$ 16	$ 16	Pc	$ 50	$ 50	$ 50	$ 50
Control & Electrical System			$ 41	$ 41	$ 41	$ 41	In:	$ 30	$ 30	$ 30	$ 30
Piping System			$ 17	$ 17	$ 17	$ 17	Pi	$ 30	$ 30	$ 30	$ 30
Indirect, Labor, & Depreciation			$ 43	$ 43	$ 43	$ 43		$ -	$ -	$ -	$ -
total			$ 507	$ 493	$ 675	$ 741		$ 446	$ 419	$ 446	$ 499

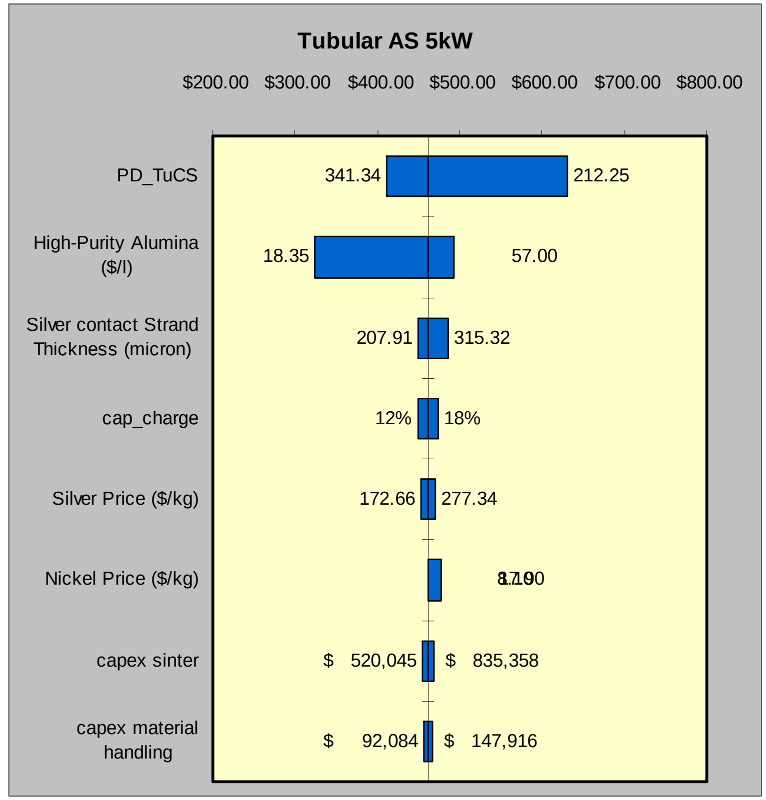
Additional Sensitivity Analysis Results

Assumptions for the uncertainty analysis are listed in Appendix B, assuming 250 MW/yr production volumes

Direct Manufactured Cost

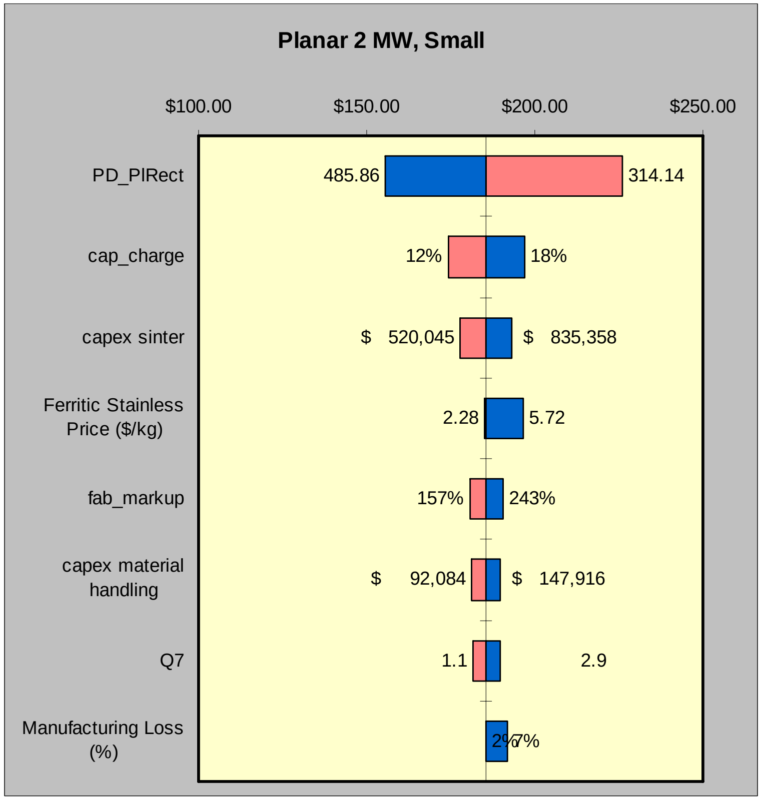


Tubular Cathode Supported Cells, 5 kW Stacks

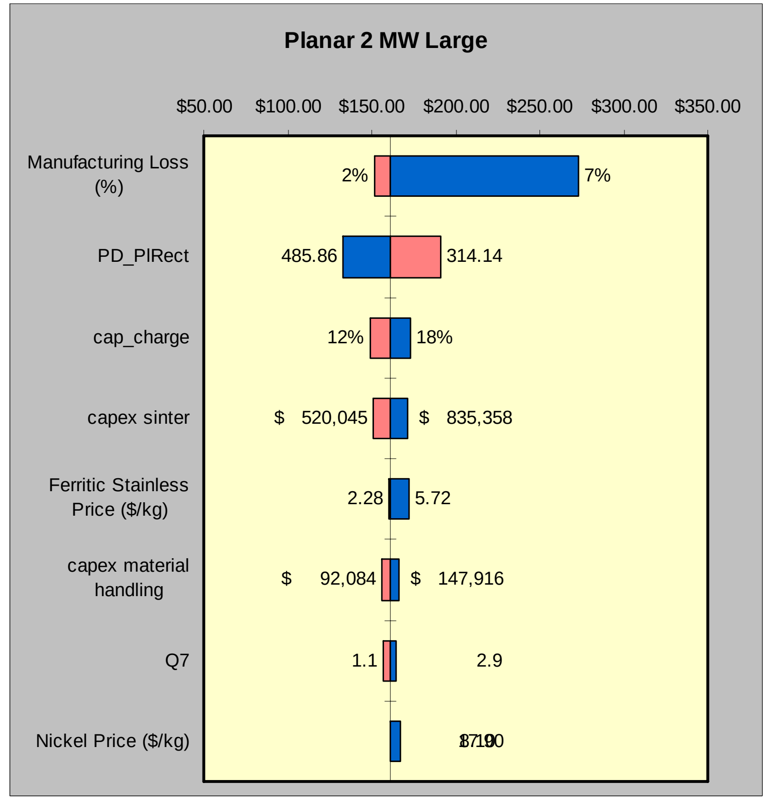


Tubular Anode-Supported Cells, 5 kW Stacks

Direct Manufactured Stack Cost

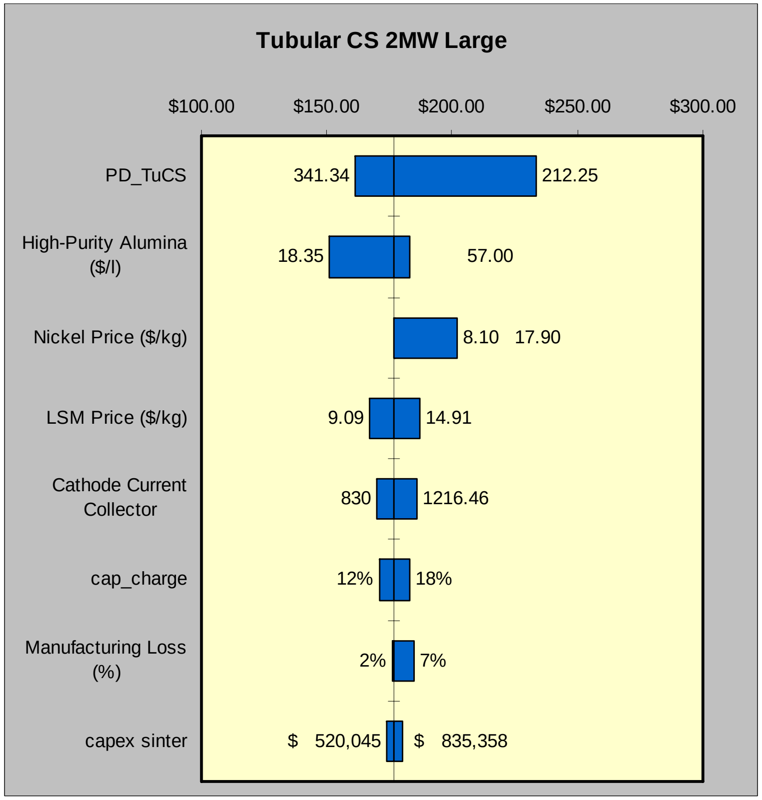


Planar Rectangular Small Cells, 2 MW Stacks

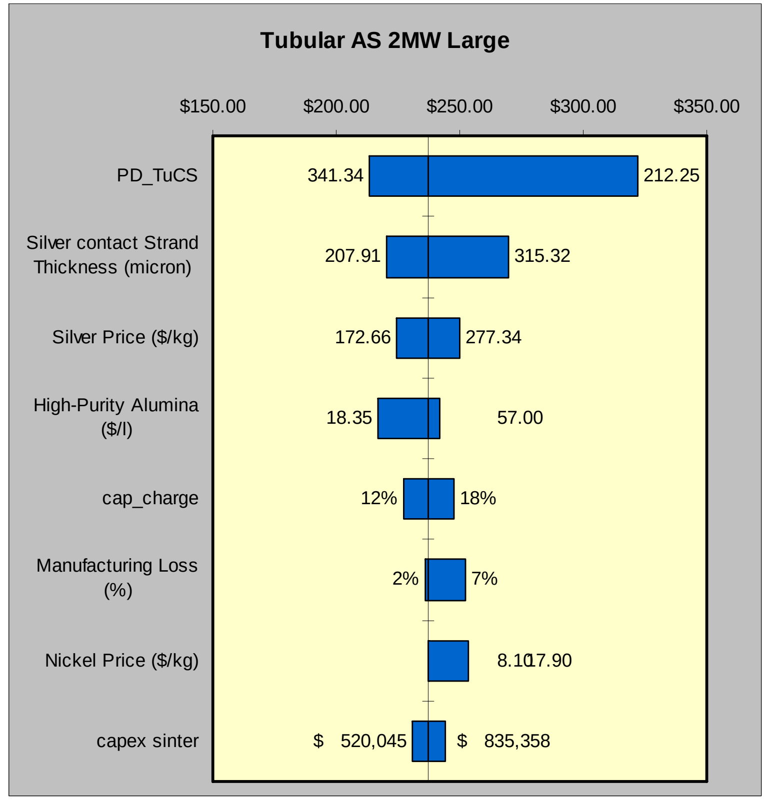


Planar Rectangular Large Cells, 2 MW Stacks

Direct Manufactured Stack Cost



Tubular Cathode-Supported Large Cells, 2 MW Stacks

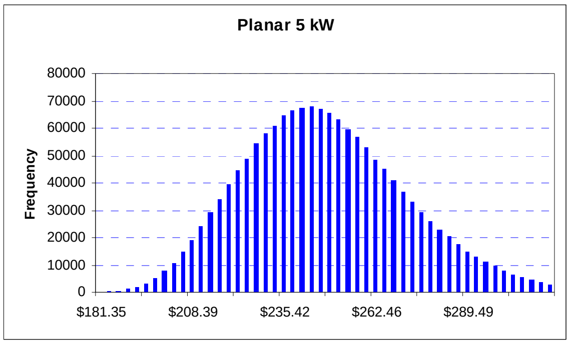


Tubular Anode-Supported Large Cells, 2 MW Stacks

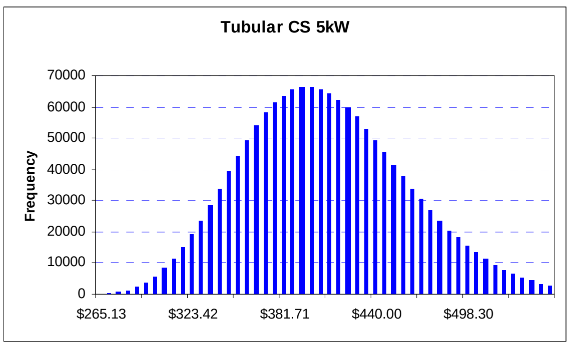
Uncertainty Analysis Results

Assumptions for the uncertainty analysis are listed in Appendix B, assuming 250 MW/yr production volumes

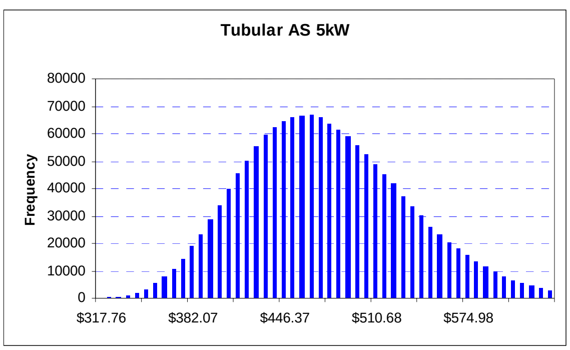
5 kW System Results



Planar Rectangular Cells



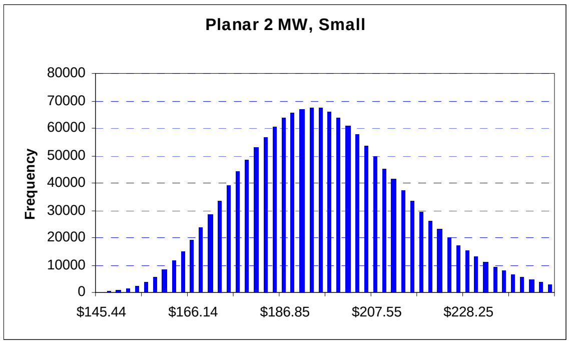
Tubular Cathode-Supported Cells

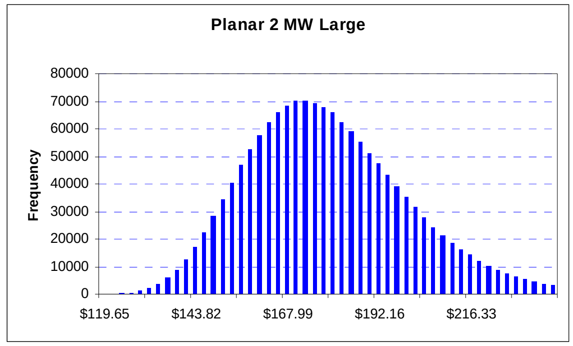


Tubular Anode-Supported Cells

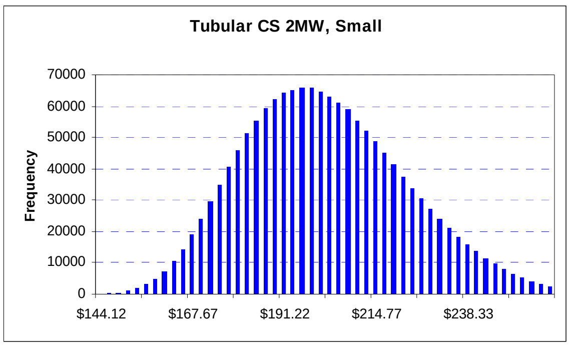
In small stacks planar rectangular cells have a cost advantage over tubular cathode-supported cells with 90% probability, and over tubular anode-supported cells with 100% probability.

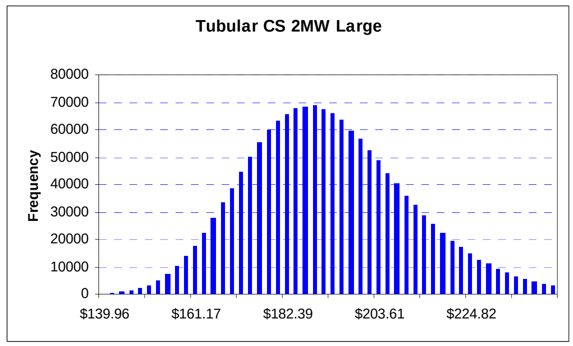
Planar Rectangular Cells



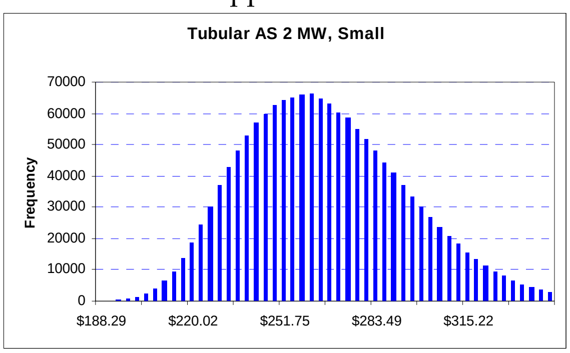


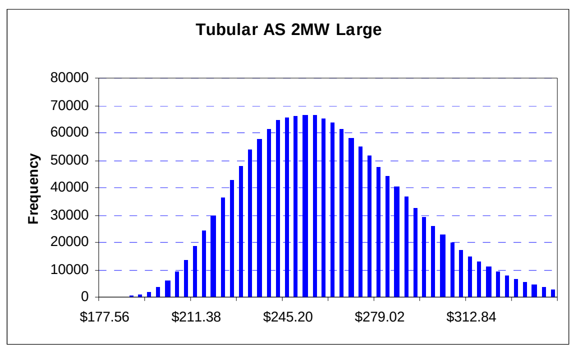
Tubular Cathode-Supported Cells





Tubular Anode-Supported Cells





- Planar rectangular 2 MW stacks have lower direct manufactured cost than tubular cathode-supported stacks with 60% probability, and lower cost than tubular anode-supported stacks with 90% probability.
- Large tubular cathode-supported cells provide a cost-advantage over small tubular anode-supported cells with 100% probability
- Large tubular anode-supported cells provide a cost-advantage over small tubular anode-supported cells with 80% probability
-