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Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems

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Cost Study for Manufacturing of Solid Oxide Fuel Cell Power Systems

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Pacific Northwest National Laboratory

August, 2013

Executive Summary

Solid oxide fuel cell (SOFC) power systems can be designed to produce electricity from fossil fuels at extremely high net efficiencies, approaching 70%. However, in order to penetrate commercial markets to an extent that significantly impacts world fuel consumption, their cost will need to be competitive with alternative generating systems, such as gas turbines.

This report discusses a cost model developed at PNNL to estimate the manufacturing cost of SOFC power systems sized for ground-based distributed generation. The power system design was developed at PNNL in a study on the feasibility of using SOFC power systems on more electric aircraft to replace the main engine-mounted electrical generators [Whyatt and Chick, 2012]. We chose to study that design because the projected efficiency was high (70%) and the generating capacity was suitable for ground-based distributed generation (270 kW).

The electricity costs for a mass manufactured solid oxide fuel cell could be competitive with centralized power production plants with costs estimated to be in the \$0.07-0.08/kWh range based on a cost model using a standard approach to manufacturing solid oxide fuel cells. A process flow sheet was developed to understand the steps required to manufacture the units, as well as to estimate the materials, equipment, and labor required to make them. Equipment was sized to meet a production volume of 10,000 units per year. Appropriate material and equipment prices were collected.

A sputtering approach was also examined using the model to project the decreases in costs associated with the process. The process not only reduces material costs but increases the power density of the fuel cell by 50%. The increased power density reduces the number of repeat units required to make up the 270 kW fuel cell stack. Stack costs decreased by 33%. However, due to the BOP and the remainder of costs associated in power system manufacturing and installation, the cost of electricity was only reduced by \$0.002/kWh.

In addition, to the 10,000 units per year production scale model was adjusted to reflect the costs of production at 50, 250, 1000 and 4000 units of production per year. Material prices were adjusted to reflect purchase levels. Machinery and labor were adjusted to reflect the production scale.

Introduction

Solid oxide fuel cell (SOFC) power systems can be designed to produce electricity from fossil fuels at extremely high net efficiencies, approaching 70%. However, in order to penetrate commercial markets to an extent that significantly impacts world fuel consumption, their cost will need to be competitive with alternative generating systems, such as gas turbines.

This report discusses a cost model developed at PNNL to estimate the manufacturing cost of SOFC power systems sized for ground-based distributed generation. The power system design was developed at PNNL in a study on the feasibility of using SOFC power systems on more electric aircraft to replace the main engine-mounted electrical generators [Whyatt and Chick, 2012]. Figure 1 is a drawing of the proposed system, which is described in detail in Whyatt and Chick, 2012. That study showed that the SOFC systems would likely be too heavy for the fuel savings to justify the added weight. However, because the projected efficiency was high (70%) and the generating capacity was suitable for ground-based distributed generation (270 kW), we chose the design for the cost study.

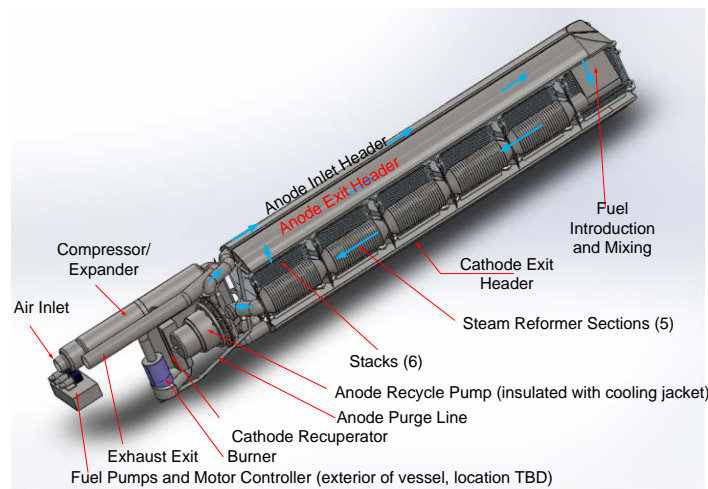


Figure 1. CAD drawing of 270kW SOFC power system described in Whyatt and Chick, 2012. The system is approximately 10 feet long and 2 feet in diameter.

The more electric aircraft power system design was based on a small-scale prototype system that was demonstrated at PNNL [Powell et al. 2012]. The demonstration system, fueled by methane, used adiabatic steam reforming and anode recycle to achieve high efficiency. While the demonstration system was operated at ambient pressure, experiments at PNNL have demonstrated that significant benefits would be obtained by operating the power system at elevated pressure [Chick et al. 2012]. The power density (W/cm^2 active cell area) increased by ~80% by increasing the pressure from one to eight atmospheres. The resulting decrease in the number of cells required will more than offset the cost of the pressure vessel. The power system is designed so that the energy necessary to compress the cathode air to eight atmospheres is obtained by combusting and expanding the anode purge stream [Whyatt and Chick, 2012].

In order to discern whether economies of large-scale power system production would lower the cost of electricity sufficiently to significantly penetrate commercial markets, we based the estimate on production of ten thousand power systems per year or 2.7 gigawatts installed per year.

In addition, the study was extended to evaluate the reduced costs associated with a potential innovation in the manufacturing process: sputtering. The approach discussed in more detail in a later section replaces many manufacturing steps and reduces the number of firings and in turn lowers manufacturing costs but also increases the cell power density by as much as 50%.

Thus, two separate manufacturing cost estimates were developed for the SOFC system: the standard production process and a manufacturing process for sputtering. A process flow sheet was developed for each of manufacturing processes and a corresponding major machinery layout was developed to understand the flow of products throughout the manufacturing facility. The primary focus of the costing effort was on the development of the stack, while less emphasis was placed on costing the balance of plant (BOP). The BOP is described in Whyatt and Chick, 2012.

SOFC Stack Design

Figure 2 is a drawing of SOFC components. These cells have $\sim 100 \text{ cm}^2$ active area. The cost study was based on cells having $\sim 400 \text{ cm}^2$ active area, but the materials set and fabrication methods are the similar. The larger cells are closer to the “sweet spot” identified in Thijssen 2007 (Figure 0-5), where economy of scale is balanced with cell failure rate due to processing flaws.

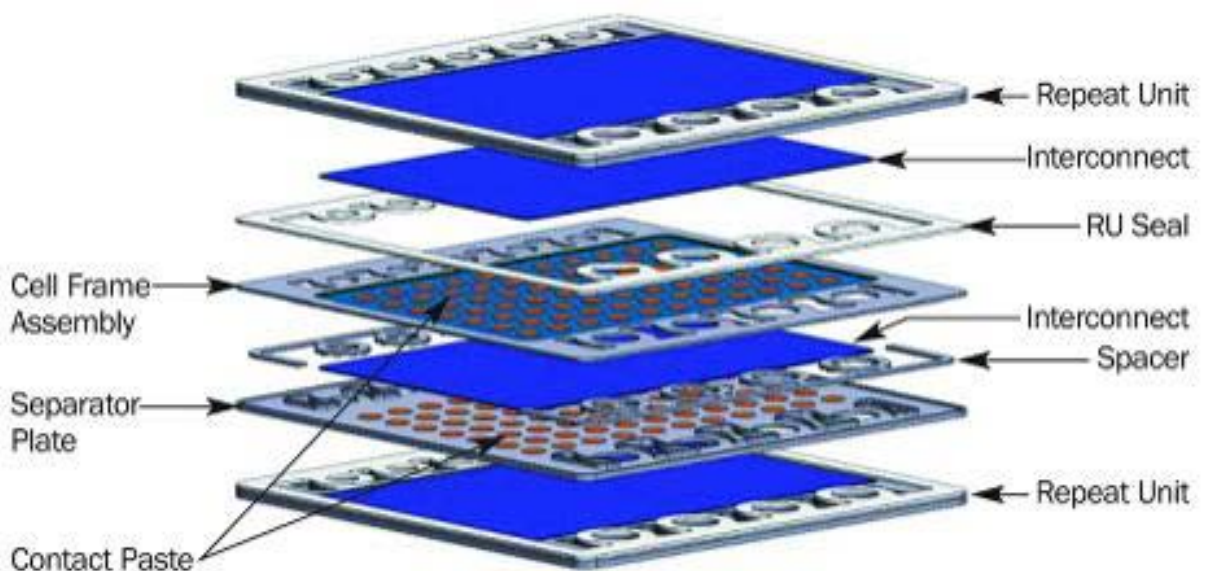


Figure 2. SOFC repeat unit components

The figure shows three repeat units, with an exploded view of the middle one.

Process Flow Diagrams for Stack Manufacturing (L)

The process flow diagram for the standard manufacturing approach is shown in Figure 3. The steps are color coded and the key in the upper-right corner relates the colors to specific sections in the following process descriptions. Figure 4 is the process flow diagram for the approach using sputtering.

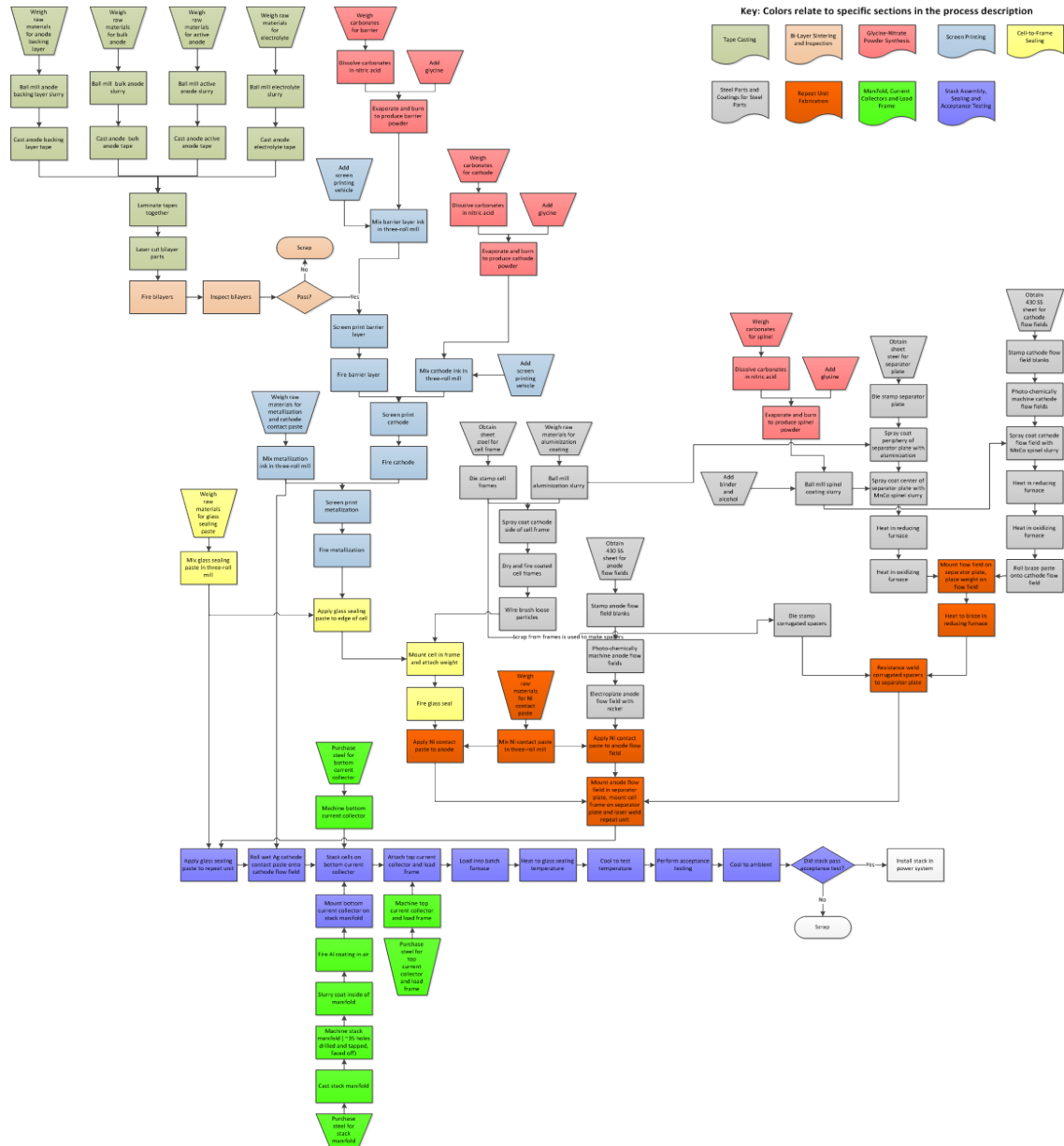


Figure 3. Process flow diagram for standard approach

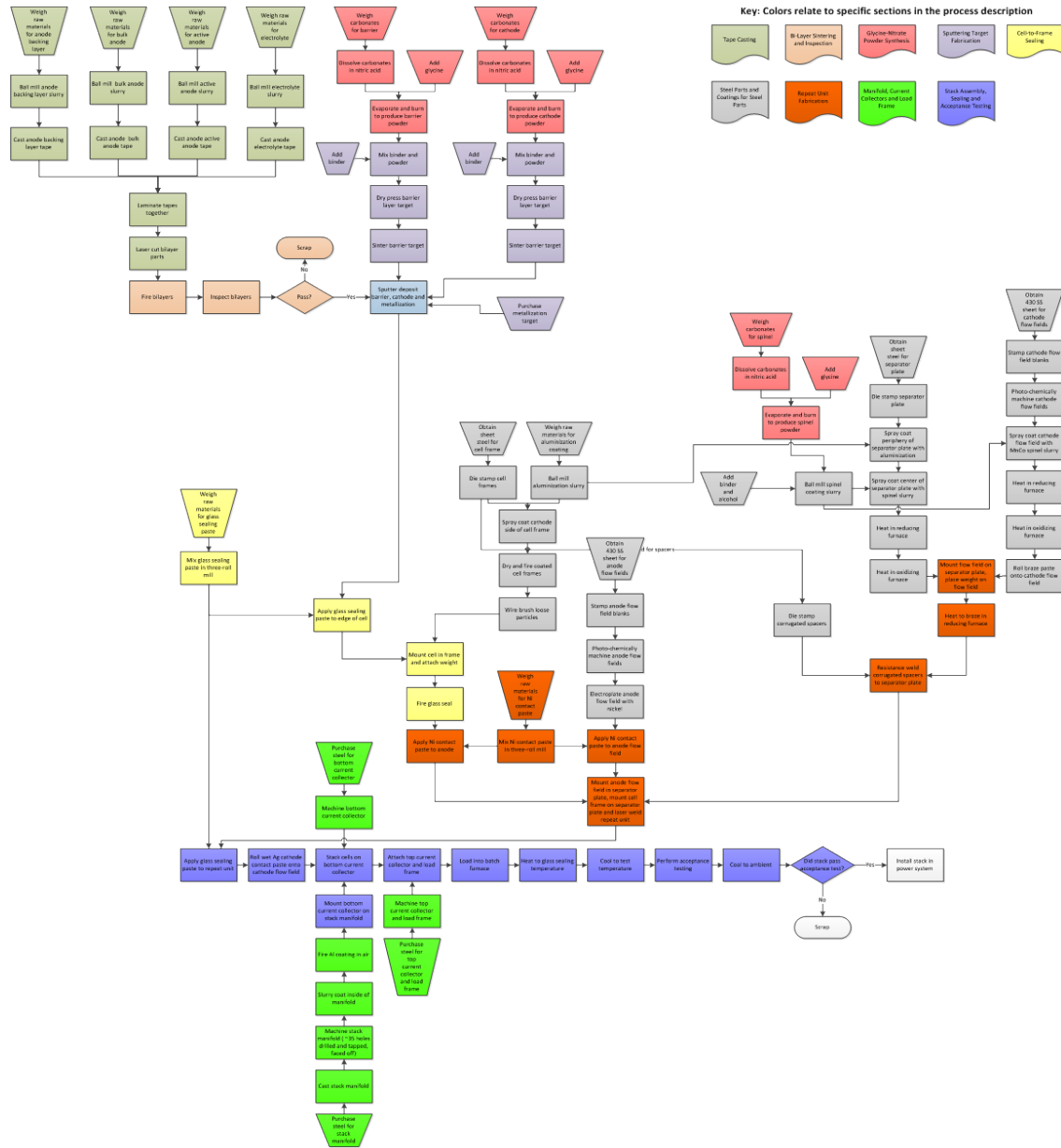


Figure 4. Process flow diagram for approach using sputtering

Standard Production Process

Based on the power density expected from the cells made by the standard process, about 36,000 cells must be made per day (three shifts, 310 days/year) in order to produce 10,000 power systems per year.

The chemical vendors shown in the following tables are those used for our laboratory scale development processing. For the cost model, prices from vendors that supply bulk quantities were used. For the results shown in the tables no materials wastage was assumed. However, in costing the materials needed, a 10% wastage was assumed.

The furnace heating schedules listed below were developed in the laboratory and are very conservative. For the cost study, furnaces were sized based on experience of the vendors and the heating rates were generally much more aggressive.

The cells are made by laminating and firing six cast tapes, followed by successively screen printing and firing three more layers. The component layers are, from the bottom:

1. anode backing layer cast tape
2. bulk anode, composed of three cast tapes
3. active anode cast tape
4. electrolyte cast tape
5. screen printed ceria backing layer
6. screen printed cathode
7. screen printed metallization layer

Tape Casting

Tape casting starts with preparation of a slurry containing the ceramic powder(s), pore formers, dispersant, binder, plasticizer and solvent(s). The batch is blended in a ball mill for 12 hours. Tables 1 through 4 list the materials and chemicals used and their proportions in units of grams per cell. Whereas the active area of each cell is 403 cm², the area of the entire cell is 460 cm², including a cathode-free boarder, which is about 9 mm wide to accommodate an electrically insulating gap and a glass-sealing surface.

Table 1. Components of anode backing layer tape casting slurry

Backing Layer Components	Grams per 460 cm² cell
Baker NiO (99.99%) Electronics Grade	5.593
Graphite (Asbury 4006)	1.246
Ethanol	1.027
Methyl Ethyl Ketone (Fischer)	4.212
Dispersant (Akzo Nobel PS-236)	0.065
Ethocellulose (Dow Ethocel 45)	0.917
Di-Butyl Phthalate (Aldrich)	0.563

Table 2. Components of bulk anode tape casting slurry

Bulk Anode Components	Grams per 460 cm² cell
SiC (Superior Graphite Grade 1200)	2.071
Ytria Stabilized Zirconia (Unitec 5Y)	72.449
NiO (Baker 99.99% Electronics Grade)	99.395
Carbon Black (Cancarb N990 Ultrapure)	12.553
Ethanol	9.707
Methyl Ethyl Ketone (Fischer)	39.817
Dispersant (Akzo Nobel PS-236)	2.238
Polyvinyl Buterol (Solutia Butvar B-79)	11.306
Benzyl Butyl Phthalate (Aldrich)	10.469

Table 3. Components of active anode tape casting slurry

Active Anode Components	Grams per 460 cm² cell
Yttria Stabilized Zirconia (Diiachi 8YSZ)	4.566
Baker NiO (99.99%) Electronics Grade	4.646
Ethanol	0.891
Methyl Ethyl Ketone (Fischer)	3.657
Dispersant (Akzo Nobel PS-236)	0.129
Ethocellulose (Dow Ethocel 45)	0.605
Di-Butyl Phthalate (Aldrich)	0.428

Table 4. Components of electrolyte tape casting slurry

Electrolyte Components	Grams per 460 cm² cell
Yttria Stabilized Zirconia (Diiachi 8YSZ)	8.256
Ethanol	0.986
Methyl Ethyl Ketone (Fischer)	4.043
Dispersant (Akzo Nobel PS-236)	0.111
Ethocellulose (Dow Ethocel 45)	0.661
Di-Butyl Phthalate (Aldrich)	0.504

After ball milling the tapes are cast. The bulk anode is composed of three tape layers. The g/cell numbers in Table 2 include materials masses for the three bulk anode tapes combined. The wet cast slurry passes through a drying hood in which the solvents evaporate, leaving the flexible tapes. The six tapes are stacked and then bonded together by running the stack through a hot roll laminator. The laminated tape is then laser cut to the proper dimensions to make the cell blanks. The tape casting slurries are all prepared by weighing the components into a ball mill and milling for 12 hours.

Ball Mills

Bulk anode requires 7505 kg of slurry per day, 3753 kg per ball mill load. Ball Mill: 5 ton capacity, 37 kW, with yttria-stabilized zirconia lining and milling media. The other tape cast components are active anode (431 kg/day), backing layer (393 kg/day) and electrolyte (420 kg/day). These each require 0.5 ton capacity, 7.5 kW, with yttria-stabilized zirconia lining and milling media. They will each require one load per day.

Tape Casting Machines

Information was based on discussions with a leading vendor of large tape casting machines. The vendor estimated we would need four 100 foot long machines for the bulk anode tapes (~\$1.2M each). These cast 52 inch wide tapes and run at 120 inches per minute. The required drying time was estimated at 10 minutes using under-bed heaters and forced air. For the thinner tapes (backing layer, active anode and electrolyte) the vendor recommended three 50 foot long machines (~\$670K each).

Laser Cutter

The laser cutter was estimated at \$22K by a vendor. Only one is required.

The laminator was not explicitly costed.

Bi-Layer Sintering and Inspection

The cell blanks are stacked on kiln furniture and fired in air to 1375°C using the furnace schedule shown in Table 5.

Table 5. Firing schedule for bi-layers

Segment	Rate/Time	Temperature
Ramp	0.5°/min	190°C
Hold	2 hr	190°C
Ramp	0.5°/min	450°C
Hold	1 hr	450°C
Ramp	3°/min	1375°C
Hold	1 hr	1375°C
Ramp	5°/min	Ambient

The fired bilayers are inspected for pinholes in the electrolyte. They are wiped with alcohol (isopropyl), which wicks through any pin holes and stains the underlying electrolyte. This process could be automated, with the defective parts optically detected.

Bi-Layer Sintering Furnaces

Estimates were obtained from a leading manufacturer of continuous “pusher”-type furnaces. Our laboratory-developed debinding and firing schedule (above) is excessively long for large-scale production. The vendor stated, “We have a tremendous amount of experience with debinding of various ceramic bodies and sintering. Very often the ratio of debinding to sintering is 2:1 or in cases of difficult binders is 3:1.” He assumed 3:1 to estimate the furnaces. He recommended 16 furnaces each 95 feet long. These cost \$750,000 each.

Robotics

Estimates for pick-and-place robots to load and unload the bi-layer sintering furnaces were obtained. Each was \$165K.

Equipment to inspect the bi-layers was not specifically costed.

Glycine-Nitrate Powder Synthesis

Three oxide ceramic materials will be synthesized in-house by glycine-nitrate combustion synthesis (GNP). These are the barrier layer, $\text{Ce}_{0.80}\text{Sm}_{0.18}\text{Fe}_{0.02}\text{O}_2$, the cathode, $\text{La}_{0.6}\text{Sr}_{0.4}\text{Co}_{0.2}\text{Fe}_{0.8}\text{O}_3$ and the spinel, $\text{Mn}_{1.5}\text{Co}_{1.5}\text{O}_4$. The raw materials are metal carbonates, which are dissolved in nitric acid. Glycine is added and the solution is heated to boil off water. Eventually the solution ignites and burns, producing ash, which is the desired material. As discussed below, the barrier and cathode materials would be made into ink and screen printed. The spinel would be made into a slurry and sprayed onto

metal parts. The synthesis would be carried out in a custom made machine (developed by PNNL) similar to a small rotary kiln.

Equipment for Combustion Synthesis

Our GNP reactor, built in 1992 produced 1.2 kg/hr (2.64 lb/hr), which is big enough to make the barrier layer powder, if operated three shifts per day. Instead, we assumed that a scaled up version would be built and we'd use it to make all three powders. Each powder would have a dedicated bag house. The machine would be connected to the appropriate bag house each shift. Total capital cost for the entire system was estimated to be \$650K.

Screen Printing

Screen printing inks are prepared by mixing in a three-roll mill. Compositions are shown in Tables 6-8.

Table 6. Components of barrier layer ink

Barrier Layer Material	Grams per 460 cm ² Cell
Sm-doped Ceria, Ce _{0.80} Sm _{0.18} Fe _{0.02} O ₂ (Synthesized in-house)	1.000
Vehicle (Ferro BD75-717)	1.000

Table 7. Components of cathode ink

Cathode Material	Grams per 460 cm ² Cell
LSCF6428, La _{0.6} Sr _{0.4} Co _{0.2} Fe _{0.8} O ₃ (Synthesized in-house)	5.018
Vehicle (Ferro BD75-717)	3.345

Table 8. Components of cathode metallization ink

Metallization	Grams per 460 cm ² Cell
Single component electrode paste, 52% solids, Ag (Ferro EL44-016)	3.237

The printing screen with the pattern to be printed is placed over the cell and the ink is squeegeed across the screen to fill the pattern. The screen printed parts are dried at 80°C for ½ hour before firing. The prints parts are then fired air using the furnace schedules listed in Tables 9-11.

Table 9. Firing schedule for barrier layer

Segment	Rate/Time	Temperature
Ramp	3°/min	1225°C
Hold	2 hr	1225°C
Ramp	5°/min	Ambient

Table 10. Firing schedule for cathode

Segment	Rate/Time	Temperature
Ramp	3°/min	1000°C

Hold	1 hr	1000°C
Ramp	5°/min	Ambient

Table 11. Firing schedule for metallization

Segment	Rate/Time	Temperature
Ramp	3°/min	1000°C
Hold	1 hr	1000°C
Ramp	5°/min	Ambient

Three-Roll Mills

Discussions with a vendor indicated the barrier ink and metallization would each require a 6" x 12" mill, \$21K. Cathode ink would require a 9" x 26" mill, \$51K.

Screen Printing Machines

An automated screen printer vendor specified devices to load the pusher furnaces, unload the furnaces, load cassettes with parts to be printed, perform the screen printing and then load the next pusher furnace. Each screen printing/firing step (barrier, cathode and metallization) would require six parallel lines. Each barrier coating line was estimated at \$245K plus furnace. Each cathode and metallization line was estimated at \$265K plus furnace.

Pusher Furnaces for Firing Prints

For the three printing steps, with six parallel lines each, the furnace vendor recommended a total of 24 pusher furnaces each 93 feet long. Each would cost \$750K.

Steel Parts

Each repeat unit contains two main steel parts, the cell frame and the separator plate. These are stamped from 0.012" thick ferritic stainless steel, either 430 or 441 alloy. The blanks are appx. 32.5 x 24.4 cm and weigh 180.5 grams. Gas manifold ports are stamped out of each piece. This results in scrapping about 5.2% of each. The frame also has a cell cavity stamped out. This results in scrapping an additional 55.2% of each frame. So, 361 grams of stainless steel must be purchased for each repeat unit and of that 32.8% is scrapped.

Smaller anode cavity spacers are also stamped from 430 or 441 alloy. We can assume they would be stamped from the scrap that is produced when the cell cavity is removed from the cell frame. These spacers do not require coatings. We assume these spacers, which encircle the anode inlet and outlet ports, are formed as two "trees", one for the inlet ports and one for the outlet ports.

These steel parts would be made in one die stamping press, estimated at \$320K, which can do 600 strokes per minute. Three sets of tooling would be made for the separator plate, cell frame and anode spacers. The same press would be used to make the stack

current collectors and load frame (see section on Manifold, Current Collectors and Load Frame).

Flow Fields

Flow fields are 430 or 441 steel parts that are photochemically etched using ferric chloride. They make multiple point contact to the adjacent structures, but provide flow channels for the anode and cathode gasses. Both flow fields are etched from 40 mil thick blanks 5.7 x 11.2 inches. Both sides of the cathode field must be coated with the MnCo spinel (see below). The anode flow field is electroplated with nickel.

Photochemical Machining Equipment

Quote was obtained from a manufacturer of etching equipment. He recommended making the pieces with two etching passes of 25 minutes and 15 minutes. The machines are composed of a series of dual primary etch modules (DPEM). A total of 8 machines would be required, composed of 80 DPEMs. Additionally, equipment is needed to rejuvenate the etchant with HCl and sodium chlorate, develop and later strip the photo-activated polymer resist and chemically clean the parts. Total capital cost was \$9.2M.

The electroplating equipment was not explicitly costed.

Coatings for Steel Parts

After stamping, both steel parts must be coated on the cathode side to prevent chrome from volatilizing and poisoning the cathode. The area of the separator plate that covers the cell, appx. 438 cm², must be coated with Mn_{1.5}Co_{1.5}O₄ spinel, which is electrically conductive. The cathode flow field must also be coated with the spinel. The periphery of both parts must be coated with alumina, Al₂O₃, which is electrically insulating, but prevents chrome volatility and adheres well to the sealing glass. The anode sides of these pieces require no coatings.

Al₂O₃ Coating: A slurry spray approach has been developed by the SECA Core program at PNNL. After the parts are sprayed and dried, 0.00345 grams of Al and binder have been added per cm² of coated surface. The Al coated area of the frame is 314 cm². The Al coated area of the separator plate is the same. The components of the Al coating slurry are listed in Table 12. These figures are based on coupon experiments and assume zero wastage.

Table 12. Components of Al coating slurry

Al Coating Slurry Component	Grams per repeat unit
Binder (ESL 450)	1.082
Al metal powder (Alpha Aesar 304 micron)	1.082
Isopropyl alcohol	2.164

After coating and drying, the pieces require heating to 1000°C in air for 1 hour to form the Al₂O₃ coating and bond to the substrate. After firing the coating is wire brushed to remove loose particles.

Mn_{1.5}Co_{1.5}O₄ Spinel Coating: This slurry spray process is less well-developed. However, we do have some key knowledge and can suggest two different approaches to large-scale production: First, it has been demonstrated that, if the particles in the applied slurry are the spinel oxide, Mn_{1.5}Co_{1.5}O₄, they will not sinter to form a high density coating in air. The slurry coated pieces must first be heat-treated in a reducing atmosphere (2% H₂) at 850°C for ½ hour. This causes the spinel to phase-separate into Co metal and MnO₂, which when heated in air at 1000°C for 1 hr will densify nicely.

A second approach, which has not been tried, would be to combine Co metal and MnO₂ powders in the slurry mix, spray coat and heat in air. However, it has been pointed out the Co metal powders with acceptable particle size for this process may be so much more expensive than the spinel powder that the H₂ heat treatment (first process) is justified. We chose the first approach for the cost study.

There is also some doubt as to the optimum thickness of the spinel coating. There is some evidence that the area-specific electrical resistance of the spinel improves with thickness. For this cost study, we assume 5 microns would be sufficient. Therefore, the coating would be 0.0027 grams per cm² over the 438 cm² area on each separator plate.

Ball Mill

Two 0.5 ton capacity ball mills are needed, one for the alumina and one for the spinel (~\$10K each).

Sprayers

Sprayers were not explicitly costed.

Furnaces

Quotes were obtained for the reducing furnace and the oxidizing furnace. The reducing furnace was \$465K and the oxidizing furnace was \$555K. One reducing furnace is needed for the spinel. Two oxidizing furnaces are needed, one for the alumina and one for the spinel.

Cassette Fabrication and Glass Sealing

There are two glass sealing operations, one to seal each cell into its frame, which can be done piece-by-piece and one to seal all of the repeat units together to form the stack. It is assumed that the glass seal material would be applied as a paste by a robotic dispenser. The estimated amounts of materials for the glass seals per repeat unit are listed in Table 13. The target seal dimensions are 5 mm width and 0.3 mm thick.

Table 13. Components of glass seal paste

	% in wet paste	grams per repeat unit
Benzyl n-butyl phthalate (Alfa Aesar, Stock# B24769)	5.28%	1.151
n-Butyl alcohol, 99.9% (Fisher Scientific, item# A399-1)	18.95%	4.134
Polyvinyl Butyral, BUTVAR B-79 (Solutia Inc., Reference# 462)	6.09%	1.329
Phospholan™ PS-236 surfactant (AkzoNobel)	0.68%	0.147
Glass Powder (VIOX #1716)	69.00%	15.049

Three-Roll Mill

A 9" x 26" three-roll mill (\$51K), as used to make the cathode ink, is appropriate to make the glass sealing paste.

Cell-to-Frame Sealing

A bead of glass sealing paste is applied to the edge of the cell by a low-cost two-axis robot. The pasted pieces are then dried in air at 80°C for one hour. Next the cell is placed onto the frame and a weighted plate is placed onto the cell. The pieces would then enter a belt furnace and be heated in air according to the schedule shown in Table 14. Pick-and-place robots would be used to load and unload the belt furnace.

Table 14. Heating schedule for sealing cells into frames

Segment	Rate/Time	Temperature
Ramp	3°/min	600°C
Ramp	5°/min	875°C
Hold	1 hr	875°C
Ramp	15°C/min	50°C

Drying Belt Furnace

The low-temperature belt furnace was not explicitly costed.

Furnace

The oxidizing furnace discussed in the metals coating section (\$555K) is suitable for this glass sealing step.

Robotics

The estimate for pick-and-place robots to load and unload the furnaces was \$165K each. The two-axis glass applicator robots were not explicitly costed.

Repeat Unit Fabrication

The cathode flow field is brazed to the cathode side of the separator plate. First metallization paste is robotically dispensed onto the separator plate. This is the same composition shown in Table 8. Assume the amount needed for this step is about 20% of that needed to metalize the cathode, or about 0.65 grams per repeat unit. Next the flow field is placed onto the separator plate. A weighted plate is placed onto the flow field and the assembly is run through a belt furnace. The heating schedule is listed in Table 15.

Table 15. Heating schedule for brazing cathode flow field to separator plate

Segment	Rate/Time	Temperature
Ramp	20°/min	1000°C
Ramp	20°/min	50°C

Next the inlet and outlet spacer trees are laser tack welded to the anode side of the separator plates. The anode flow field is laser tack welded to the separator plate. Ni contact paste is applied robotically to the cell anode. While the paste is still wet, the cell-in-frame is placed onto the separator plate assembly and the two are laser welded together. The components of the Ni contact paste are the same as listed in Table 8, with Ni substituted for Ag.

Furnace

The reducing furnace discussed in the metals coating section (\$465K) is suitable for this glass sealing step.

Robotics

Four pick-and-place robots (\$165K each) would be required to load and unload the furnace and to place the anode spacers and anode flow fields.

Manifold, Current Collectors and Load Frame

Figure 5 is a CAD drawing of a completed stack. Masses of the balance-of-stack components are listed in Table 16. We assume all parts are 430 or 441 SS. The load frame and current collectors are stamped sheet steel. The manifold is cast followed by some machining. The inside of the cathode side of the manifold must be coated with aluminum slurry and oxidized in air to form an alumina coating. It was assumed that these few parts can be fired in one of the oxidizing pusher furnaces used to make repeat units.

The die press costed out in the section on steel repeat unit parts would be used to make the current collectors and load frame.

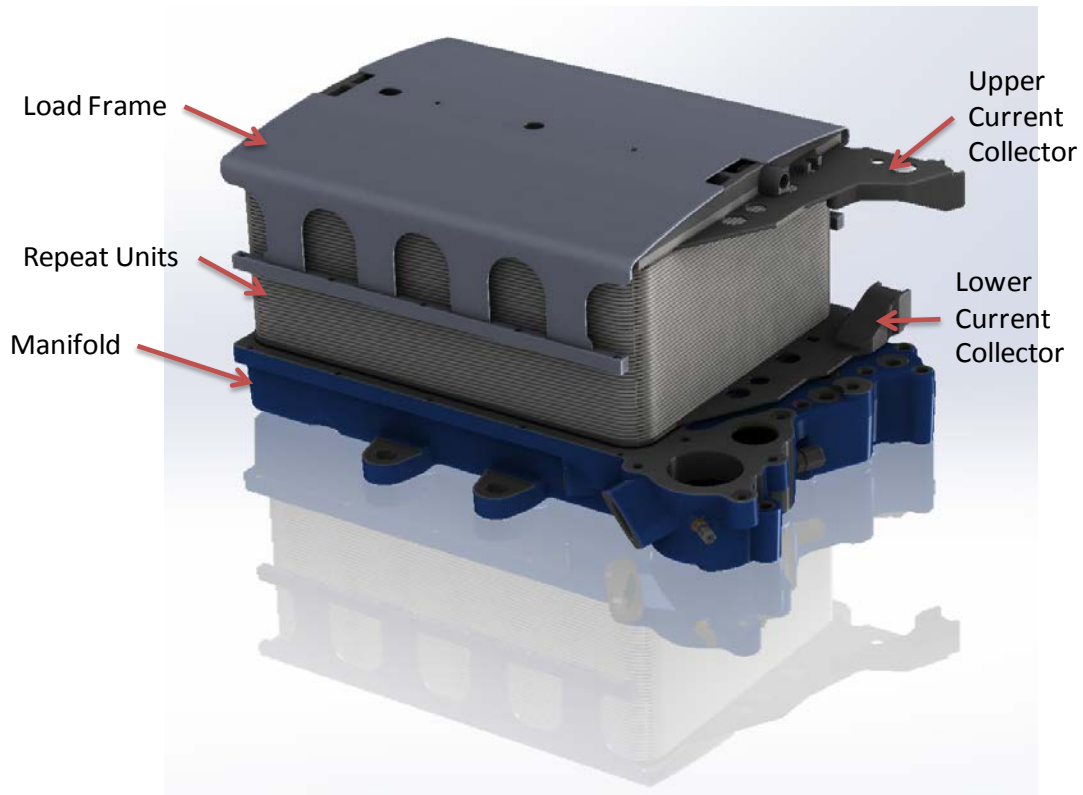


Figure 5. Stack assembly.

Table 16. Manifold, Current Collectors and Load frame

Component	Material	Mass (kg)
Manifold	430 or 441 SS	19.30
Load Frame	430 or 441 SS	6.20
Lower Current Collector	430 or 441 SS	1.96
Upper Current Collector	430 or 441 SS	2.22

Casting Costs

Cost of the cast manifold was estimated using the SEER for Manufacturing Software (Galorath. 2010.)

Stack Assembly, Sealing and Acceptance Testing

The repeat units are stacked up on a cast steel manifold in a frame, the components of which are described in the next section. A current collector plate is attached to the top. The top of the load frame is attached and the assembly is loaded into a furnace. A load of 82 lbs is applied to the top of the stack. The stack is then heated according to the schedule shown in Table 17 with air flowing through both the anode and cathode cavities. During this process, the binder burns out of the glass paste, the glass softens and flows and the repeat units are compressed together and sealed.

Table 17. Heating schedule for sealing a stack

Segment	Rate/Time	Temperature
Ramp	3°/min	600°C
Hold	1 hr	600°C
Ramp	5°/min	875°C
Hold	4 hr	875°C

Next the furnace temperature is lowered to 750°C at 5°C/min and reducing gas (~2% H₂ in N₂) is flowed through the anode cavities for 2 hrs to reduce the NiO to Ni metal.

The stack is now ready for electrochemical acceptance testing. The anode is supplied with a mixture of 50% H₂ and 50% N₂ and an I-V curve and a fuel utilization curve are taken. These tests require no more than one hour to complete.

The furnace is then cooled to ambient at 5°C/min. The furnace is opened, the load frame is bolted down and the stack is removed and is ready for installation into the power system. The entire heating, reducing, testing and cooling procedure is estimated at 14.9 hours. The remaining 9 hours of each day would be devoted to loading and unloading the furnaces.

Batch furnaces for Stack Assembly, Sealing and Acceptance Testing

It was assumed that six stacks can be assembled in each batch furnace. Each furnace would be loaded and unloaded by a pick-and-place robot. Thirty two such furnaces, each with a robot would be required. Each robot was \$165K, as above. The vendor quoted the basic furnace at \$175K each. Adding a load frame, gas manifolding, mass flow meters and electrical load bank and test equipment for each furnace was estimated to add another \$100K. Each of the thirty two build stations would be \$440K.

Production Process Utilizing Sputtering

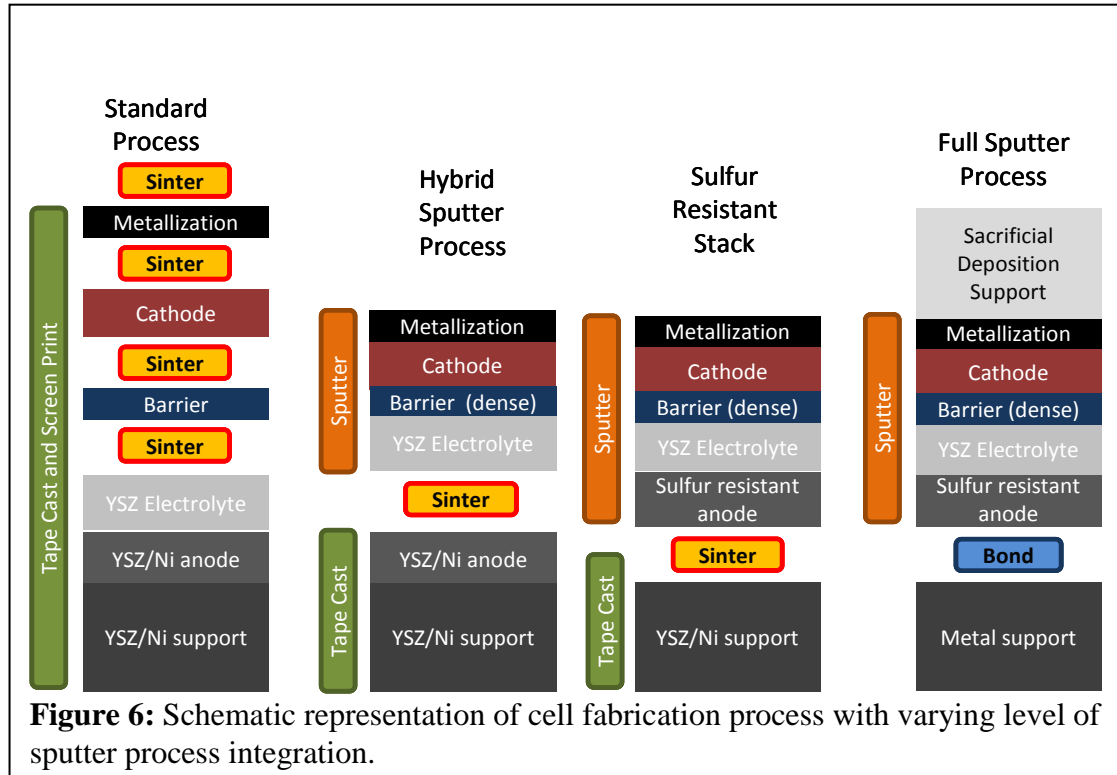
As discussed above, after the bi-layers are sintered, the standard process requires sequential screen printing, firing and cooling of three more layers. In all, these steps require 18 high temperature pusher furnaces. The process discussed in this section would use sputtering to apply these layers. The electrolyte would also be applied by sputtering. Comparing the process flow diagrams, Figures 3 and 4, the Screen Printing steps are eliminated in Figure 4. These steps are replaced by production of sputtering targets and by the sputtering step.

Although much equipment was eliminated in going to the sputtering process, by far the majority of the projected cost savings was due to a projected 50% increase in cell power density due to elimination of undesired porosity in the barrier layer and to thinning the electrolyte down to 1 micron.

New process flow and performance improvements

In the new process flow, the goal would be to deposit a subset of the ceramic layers using sputtering to reduce the number of firing steps, reduce the overall material consumption by enabling thinner layers, and improving the power density to reduce the total amount of cell area in a system of given power.

Figure 6 shows the multiple implementation options that are possible, though for this cost study, the focus was on the first stage (hybrid sputter process), where the stack is partially deposited using traditional tape casting and partially sputtered.



A key factor in this sputtering process was that the individual layer thicknesses would be reduced and an increase in power density would be achieved. The electrolyte in current cells is $\sim 8 \mu\text{m}$ simply because it is very difficult to prepare thinner layers by tape casting. Based on measured cell performance and the known ionic resistivity of YSZ and $\text{Sm}_{0.2}\text{Ce}_{0.8}\text{O}_2$ barrier layer, we calculate that decreasing the thickness of the electrolyte from $8 \mu\text{m}$ to $1 \mu\text{m}$ and the barrier layer from $5 \mu\text{m}$ to $1 \mu\text{m}$ would increase the power density by 7% at 650°C and 9% at 800°C . This effect of decreasing the ionic resistance is mostly due to thinning the electrolyte. A much bigger improvement comes from eliminating the unintentional porosity in the barrier layer, which would increase performance by 40%. The combined effects of thinning the electrolyte-barrier layer and producing a fully dense barrier layer can reasonably be expected to increase power density by about 50%.

Based on these improvements in power density, it was estimated that the amount of cells needed per system would be reduced from 1009 to 673, which lead to 6.7M cells required

per year. The sputtering process is not as efficient in area as, for example, ink-jet printing. Each substrate must be mounted in a carrier, or platen, that holds multiple substrates as they move through the system. For the standard cell size of 296.4mm x 155.2mm, an optimal packing of 8 across and 2 down gives a total platen size of approximately 1.28m by 0.6m. This corresponds very well to the current standard for thin film solar panels of 1.2x0.6m and ensures that similar equipment can be used. Using 6.7M total substrates/year, 16 substrates/platen, and 0.768m²/platen and factoring in 90% yield; the approximate capacity demand is 357k m²/year, which is quite low for a typical sputtering line, so the added complexity of the process should align well.

Process Equipment

The major piece of process equipment needed would be the sputtering deposition itself. Because sputtering systems are typically highly customized for substrate size, process and throughput; getting a precise system cost was difficult without a final process. However, solar processing systems provide a reasonable baseline as they have similar throughputs, multiple layers and (in the case of the TCO layer) complex oxides.

Figure 7 shows a typical multi-chamber sputtering system designed for solar thin film deposition (in this case, a transparent conductive oxide, or TCO, layer.) This system

platform can be configured with a range of modules for different materials, rates, and layers. For a system designed for TCO deposition, prices range from \$6.5M to \$11M for throughputs from 400k to 1.6M square meters per year. Because the multi-layer SOFC process is more complex and has

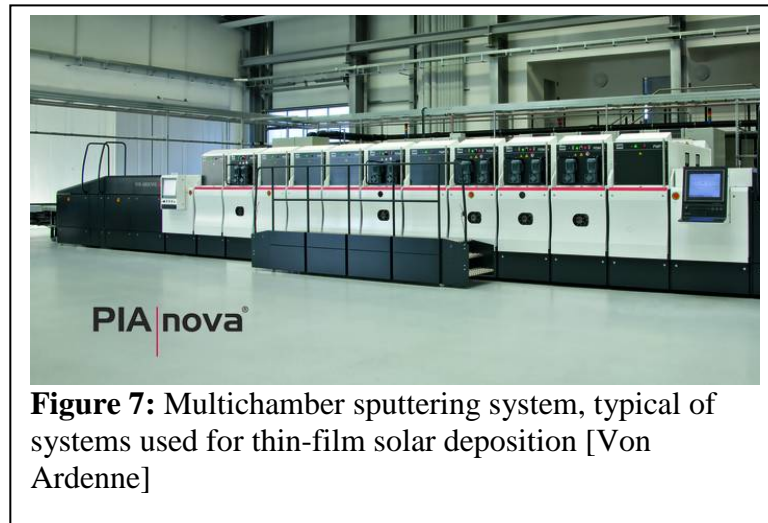


Figure 7: Multichamber sputtering system, typical of systems used for thin-film solar deposition [Von Ardenne]

a specifically designed system would have more deposition modules and a lower throughput than a standard TCO system.

Based on a four layer oxide process, compared to a single ITO layer, the throughput would be cut by 4. In addition, the layers are thicker for the SOFC process, 1-4 μ m each, compared to \sim 1 μ m for typical ITO layers. Combining these reductions gives an overall reduction in throughput of approximately a factor of 8 to 10. Therefore, to achieve the targeted 357,000 m²/year, two systems capable of 1.2-1.6M m²/year of ITO provides a useful reference. Systems in this class have an unadjusted initial capital cost around \$8-9M. After discussions with people familiar with system design, we estimate that a full system optimized for SOFC stack deposition would cost approximately 50-100% more, or \$12-18M in order to achieve a throughput of 357 k m²/year. Higher throughputs

could be achieved with sub-linear price increases, but for manufacturing optimization, multiple tools are desirable to better manage both planned and un-planned downtime.

Using these approximations and the fact that a fully sputtered structure has not yet been demonstrated, we conservatively based the capital cost on two \$15M systems. Additional costs of \$330k/system (\$660k total) are added to provide for robotic loading and unloading of the platens. This was based on a cost estimate from a robotics vendor of \$165k for a pick and place robot, with one robot at each end of the deposition system.

For sputtering, targets of the required materials are needed for deposition (Figure 8). The specifics of making these targets are discussed below. The total number of targets can be estimated as follows. The cost model addressed each layer independently, but the overall calculation was the same. For each material, several parameters are specified, including : film thickness, deposition utilization (percentage of material that reaches the platen), target utilization (percentage of target material that can be consumed before the target must be replaced) and target reclaim (percentage of used target material that can be reused). These values can vary depending on the type of material, the ease of recycling, and the target design.

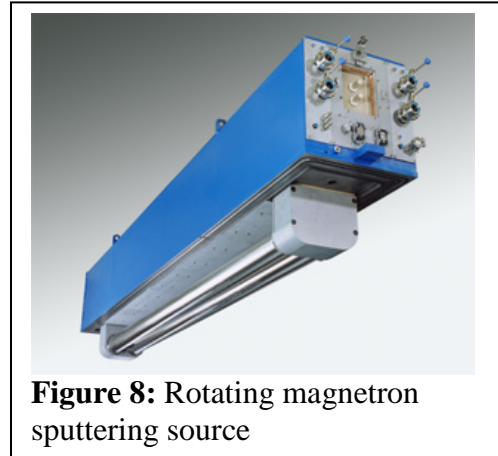


Figure 8: Rotating magnetron sputtering source

Using the barrier layer as an example, the target thickness is $1\mu\text{m}$ and the deposition utilization was assumed as 70%, which is conservative for a 1.3m wide substrate. The assumed target consumption was 50%, which should be achievable with either a planar or rotary magnetron system and does not account for additional O_2 that can be added during the process to counter the uneven sputtering yield of Ce and O. The reclamation rate was estimated to be 75% (of the remaining 50% left on the target). The layer thickness, combined with the film porosity (in this case 0% as a fully dense barrier is desired) and density ($7.13\text{g}/\text{cm}^3$) gives a usage density of $10.2\text{g}/\text{m}^2$. By combining these, a total of $7.2\text{g}/\text{m}^2$ is used in coating the platen with the 16 substrates and using the 70% deposition utilization, 10.2g of target would be consumed for every m^2 produced.

Typical targets are the same width as the platen (1.28m) and are around 10cm wide and 2cm thick. Combining this with the material density ($7.13\text{g}/\text{cm}^3$ for CeO) the total mass per target can be calculated, in this case 9.14kg. Then, by combining with the amount of target that can be effectively used (50%), the total used material per target can be obtained (4.57kg). Using the total g/m^2 to coat a platen and the total number of platens along with the recycling capacity, it was possible to determine both the total amount of material needed each year (4595kg/year) and the number of targets needed each year (805). Because target fabrication has both variable (material content) and fixed (target holder) costs, it is important to provide both the total amount of material needed and the number of discrete targets that must be made.

Sputtering Target Fabrication

The silver targets for the metallization layer would be purchased. The ceramic targets for the electrolyte, barrier and cathode would be made on-site by isostatic pressing (60,000 psi) and sintering of ceramic powders. Powder for the electrolyte, 8 mole% yttria stabilized zirconia would be purchased. Powder for the cathode and barrier would be made by combustion synthesis, as discussed above for the standard process. After sintering the targets would need to be surface ground so that the faces are parallel. Each target would be made in two pieces, each 64cm x 10cm x 2cm.

Cold Isostatic Press

Quote was \$249K.

Ceramic Surface Grinder

Quote was \$120K.

Batch Furnaces

Quote for two 24" x 24" x 36" furnaces was \$200K each.

Equipment for combustion synthesis discussed in standard process.

Description of Cost Study

The project developed two separate cost projections for two different SOFC power system manufacturing processes: the standard production process and the sputtering process. The primary emphasis of the cost estimating focused on the manufacturing process for the SOFC stack for both approaches and less detail was taken in development of the balance of plant components because of the emphasis in reducing the costs of the stack. The same balance of plant was used for both the standard production process and the sputtering process. In addition to the costs for manufacturing, an estimate of the levelized cost for power for each system was developed.

The primary components for developing stack costs are materials, capital (building and equipment), electricity due to the high power requirements of furnaces, operations and maintenance (O&M), and labor.

The approach taken required the development of a flow sheet for each of the manufacturing processes for the stack. From the process flow sheet, quantities of materials required in each manufacturing process were determined along with the major equipment required to perform that step. Annual quantities of materials were estimated to determine price discounts. The process flow sheet was also used to develop a plant layout. The annual production quantities were also used to size the equipment.

Materials

Most materials were priced from the Alibaba website. Materials were priced based on delivery to the center of the United States. The prices from Alibaba were also evaluated against prices from a US distributor to determine whether the Alibaba prices were competitive or significantly underpriced. Similar prices were received. Prices used in this study are shown in Table 18. Material costs contributed 55% of the total stack manufacturing costs. A 10 percent scrap rate was assumed for most material purchases and was included in the costs of materials for each process step. The steel scrap rate was an exception. The stamping of the cell frame and separator parts for each repeat unit results in an approximate 33% loss. The anode and cathode flow field blanks lose approximately 53% of the original material.

Capital

Major capital costs for each manufacturing step were estimated based on quotes from the manufacturers. The building was assumed to provide a 30 year life while equipment was based on a 7 year life. Cost to install equipment was assumed to be 65% of the FOB price. The cost of the major equipment was multiplied by 4.55 to obtain an estimate of the total capital cost of the manufacturing facility, including the cost of the building and auxiliary equipment (Peters and Timmerhaus 1991). A 6% sales tax was added to the cost of capital.

Annualized capital costs were separated into building and equipment and estimated separately using a 10% after-tax rate of return. The cost recovery factors are outlined in Table 19. The cost factors for equipment and buildings are based on the following formulas. A cost recovery factor was developed separately for equipment and buildings. The first equation provides a factor to annualize capital to a before tax rate of return and the second equation adds a factor to the first to account for taxes adjusted for tax depreciation to reach an after-tax rate of return.

$$CRF = (i * (1 + i)^n) / (((i * 1)^n) - 1) \quad (\text{eq. 1})$$

Where

CRF is the capital recovery factor,
i is the discount rate, and
n is the life of the asset.

$$FCRF = CRF * (1 - t * NPV) / (1 - t) \quad (\text{eq. 2})$$

Where

FCRF is the fixed charge recovery factor after taxes
t is the effective tax rate, and
NPV is the net present value of depreciation over life of the asset.

Table 18. Material prices used in this study

Material	Delivered Cost		
	\$/kg Low	\$/kg Average	\$/kg High
Ag Paste	908.28	1,356.00	3,000.28
Carbon Black (Cancarb N990 Ultrapure)	4.16	4.16	4.16
Graphite (Asbury 4006)	3.64	3.84	4.04
SiC (Superior Graphite Grade 1200)	16.05	16.05	16.05
Yttria Stabilized Zirconia (Unitec 5Y)	10.28	20.28	30.28
NiO Electronics Grade	28.28	30.78	33.28
Yttria Stabilized Zirconia (Diiachi 8YSZ)	20.28	35.28	50.28
Glass Powder (VIOX #1716)	24.20	36.53	53.91
Al metal powder	13.38	16.88	20.38
Al metal powder another price	14.01	28.20	42.38
Phospholan™ PS-236 surfactant	6.29	6.47	6.65
Polyvinyl Butyral, BUTVAR B-79	17.60	19.75	21.89
Benzyl n-butyl phthalate	4.01	5.01	6.01
Ethocellulose (Dow Ethocel 45)	25.20	25.20	25.20
Di-Butyl Phthalate (Aldrich) - Lab supplier	9.38	9.55	9.73
Vehicle (Ferro BD75-717)	15.33	15.80	16.28
Binder (ESL 450) - Electro Science Laboratories	8.00	9.00	10.00
Ethanol	1.02	1.02	1.02
Methyl Ethyl Ketone (Fischer) - Lab supplier	0.78	1.38	1.98
Isopropyl alcohol	3.82	3.82	3.82
n-Butyl alcohol, 99.9%	7.05	7.54	8.02
Stainless Alloy 430 or 441	2.25	2.46	2.67
Ce ₂ (CO ₃) ₃ *5H ₂ O	50.28	52.78	55.28
CoCO ₃	17.28	18.78	20.28
FeCO ₃ *H ₂ O	1.38	1.58	1.78
La ₂ (CO ₃) ₃ *8H ₂ O	60.28	70.28	80.28
MnCO ₃	1.54	2.58	2.85
Sm ₂ (CO ₃) ₃	22.28	90.7	91.99
SrCO ₃	1.26	2.27	3.28
Glycine	0.48	1.48	2.48
Nitric Acid (70%)	1.97	2.33	2.70
Nickel	16.56	22.42	28.28
Ferric Chloride	1.03	1.10	1.18
Soduim Chlorate	0.775	0.875	0.975
Muriatic Acid	0.455	0.5125	0.57

Multiplying the appropriate FCRF by the investment cost of equipment and buildings provides the annualized cost of capital per piece of equipment and buildings. Dividing the annualized costs of capital and equipment by the number of power systems produced per year provides the cost per power system.

Table 19. Cost factors to annualize capital costs

Equipment Factor	
Equipment Capital Recovery Factor	0.205
Present Value of Depreciation	0.803
Fixed Charge Recovery Factor	0.231
Buildings Factor	
Building Capital Recovery Factor	0.1061
Present Value of Depreciation	0.4924
Fixed Charge Recovery Factor	0.1404

Electricity

For equipment with significant electricity requirements, the cost of electricity was estimated separately. Furnaces were the main pieces of equipment with significant electricity requirements. The facility had more than 70 furnaces used to sinter materials at different processing steps. The furnaces varied in power draw from as low as 50 kW to as high as 400 kW. Electricity costs for each piece of equipment with known energy requirements was estimated using expected operating hours and the industrial rate of electricity from the EIA (\$0.0644/kWh).

O&M and Labor

Operations and maintenance costs include labor costs. O&M excluding labor was assumed to be 3% of total installed capital costs. Labor was estimated based upon the number of people required to operate each piece of equipment. A burdened labor rate of \$55/hour was used for all process labor. The plant was operated on a 3 shift basis. The plant operating factors are in Table 20.

Table 20. Plant Operations Factors

Plant Operations Assumptions	
Capacity Factor	85%
Days of operation	310
Shifts per day	3
Hours of Operation/shift	8
Hours per year	7,440

Stack loss

In addition, a 1% stack loss factor was assumed. The assumption added to the costs of production as 1 out of 100 stacks was assumed to not operate or meet quality assurance requirements.

Balance of Plant

The balance plant components were each priced based upon quotes from manufacturers with the exception of the steam methane reformer and the heat exchanger. The steam methane reformer price was based upon an analogy of a catalytic converter of size required to meet the fuel consumption requirements of the 270 kW power system. The

combustor/expander/compressor (essentially a jet engine) was estimated based on a quote from the manufacturer. The anode blower provides an indication of the cost decreases associated with mass manufacturing of the SOFC power system. The manufacturer doesn't currently make the blower in large volumes. They would need to build a larger plant to do so. According to the manufacturer's estimates, the costs would decrease from \$45,200 for 1 unit to slightly more than \$2,000 each for purchases of 10,000 per year. Similarly, the heat exchanger would drop from nearly \$40,000 to less than \$10,000 per unit with increased manufacturing volume.

We also assumed 1 person per shift, assisted by a robot, was required to operate each power system assembly station. Also, 1 person per shift was assumed to provide quality assurance on the system.

Overhead

In addition to direct expenses, we added other indirect expenses associated with the manufacturing plant. These expenses included general and administrative (G&A), property tax and markup. The assumptions associated with these costs and other general assumptions are shown in Table 21.

Table 21. Economic assumptions

Economic Assumptions	
Building Lifetime	30 years
Building Depreciation Life	20
Equipment Lifetime	7 years
Output per year	10,000
SOFC Life	15 Years
SOFC Install Costs	42%
BoP_Scaling_Factor	0.385
After-Tax Rate of Return	10%
Federal Tax Rate	35%
State Tax Rate	6%
Manufacturing Sales Tax Rate	6%
Retail Sales Tax Rate	6%
Effective Tax Rate	38.9%
Property Tax Rate	0.75%
Insurance Rate	1%
Weighted Labor Rate	55
G&A	0.1
Labor Overhead	0.2
Number of Workers	129.9
Markup	0.3
Workers per machine	1.5
Inflation rate	0.015
Discount Rate	0.03

Installed Costs

Adding the total indirect costs to the direct costs provides an estimate of the manufacturer's retail price at 10,000 units on a per unit basis. However, in order to estimate the levelized cost of electricity for the power system, the installed cost was required. We estimated that the cost of installation would be 42% of the FOB cost, based on Thijssen 2009. We didn't add a building cost to our estimate as we assumed the power system would be installed in the back section of a commercial building similar to a furnace with venting.

Levelized cost of electricity

The levelized cost of electricity was developed from the capital and operating costs associated with the SOFC power system. Capital costs were annualized. Fuel and O&M costs along with property taxes and insurance were added to approximate total costs.

The installed capital was annualized using equation 2 above. We assumed the same after-tax rate of return as for the manufacturing facility and a 15 year life for the power system. O&M costs were estimated at 3% of total installed costs. Property taxes and insurance were each estimated at 1% of total installed costs. The addition of property taxes assumes that assessors would revalue the facility when they know that improvements have been made to the property. The additional insurance assumes the owner would provide extra insurance to cover catastrophic events.

Fuel costs were based on steam reformation of de-sulfurized pipeline natural gas. NG costs were estimated from Cascade Natural Gas commercial delivered rates at \$8.69/MBTU. Based on the higher heating value, the electrical conversion efficiency was determined to be 64.8%, which resulted in 5,266 BTU's of natural gas required to make 1 kWh of electricity using the SOFC power system.

To obtain the levelized cost of electricity, the annualized cost of installed capital, plus all of the operating costs were totalled and divided by the annual output of the SOFC power system (see eq. 3 and eq. 4).

$$C = (K + OM + F + P + I)/kWh \quad (\text{eq. 3})$$

Where C is the cost/kWh,
 kWh is the annual electricity production in kilowatts,
 K is the annualized capital cost,
 OM is the operations and maintenance cost,
 F is the annual fuel cost,
 P is the added cost of property tax, and
 I is the added cost of insurance.

$$kWh = kW * 8760 * CF \quad (\text{eq. 4})$$

Where kW is power capacity of power system,
 8760 is the number of hours per year, and
 CF is the capacity factor or percent of the hours the power system operates.

Results

The standard processing approach to manufacturing the SOFC yielded an installed cost of production for the power system of a little more than \$174,178. The largest cost component, excluding installation, was the balance of plant at 60,459, followed by the stack cost at nearly \$25,000 per power system (see table 22).

The bulk-anode tape-casting step cost more than \$6,167 driven mainly by the cost of materials, NiO and YSZ. The manifold and stack assembly step, the second most expensive process included a large number of furnaces and a large number of robots, as well as a significant amount of labor to ensure a well built and functioning power system. As previously mentioned, the casting of the manifold was estimated using the SEER for manufacturing cost estimating software.

Once the four tape cast components are combined together into the “bi-layer”, the resulting laminated components are laser cut and fired. The bi-layer firing requires 16 furnaces and 16 robots. The equipment, electricity and labor associated with the robots and furnaces costs approximately \$2,000 (see Table A1 in Appendix A). The remaining cost for the 4 tape casting steps cost a total of \$8,200

Following the sintering of the bi-layer, three screen printing and firing steps take place to add the barrier layer, the cathode, and the metallization layers. These three steps require 24 furnaces. The combined cost of the three steps is approximately \$5,200.

Chemical etching of the anode and cathode flow fields is relatively expensive. The cathode flow field requires etching from steel followed by electroplating with silver. The silver price, currently \$1,100/kg, has been as high as \$2,400/kg within the last two years. The flow field blanks cost approximately \$1,500 prior to etching. Material loss during etching was estimated at 53 percent. The waste treatment costs were estimated at \$0.75/gallon based on an estimate from a chemical etching machine vendor.

At \$39,000, the power inverter was the single largest component of the balance of plant. The heat exchanger was second at almost \$9,900. The expander/compressor was estimated at ~\$3,300 based on internet pricing. The anode blower/pump is not manufactured at 10,000 units per year but the company estimated their costs for this project at \$2060/per system, significantly below their one unit cost of \$45,000.

Table 22. Standard production method costs.

	Materials Costs			Annualized Capital and O&M				Low	Average	High
	Low	Avg	High	Capital	Electricity	O&M	Labor			
Bulk Anode	4,413	5,570	6,727	400	42	111	45	5,010	6,167	7,324
Active Anode	278	370	463	59	6	16	25	383	476	568
Backing Layer	219	238	257	59	6	16	25	325	344	363
Electrolyte	217	359	500	1,284	14	87	282	1,885	2,026	2,168
Barrier Layer	110	139	147	823	19	107	233	1,293	1,321	1,329
Cathode	424	493	562	771	12	93	213	1,513	1,582	1,651
Cathode Flow Field	1,650	2,133	3,702	763	1	349	90	2,852	3,336	4,905
Metalization Layer	838	1,245	2,737	769	12	92	225	1,936	2,343	3,835
Anode Flow Field	891	973	1,055	763	1	349	41	2,045	2,127	2,209
Glass Seal	473	688	988	67	21	19	25	605	820	1,120
Steel Parts	911	996	1,081	26	1	7	45	990	1,075	1,160
Spinel Coating	141	160	177	125	55	35	49	405	424	441
Alumina Coating	35	41	46	48	20	13	16	132	137	143
Stack Assembly and QC	184	197	210	1,370	39	374	475	2,442	2,455	2,468
Stack loss factor	108	136	187	73	2	17	18	218	246	297
Total	10,892	13,738	18,839	7,401	251	1,684	1,806	22,034	24,879	29,981
		11%								
Balance of Plant										
Expander/compressor								2,966	3,295	3,625
Heat Exchanger								8,878	9,864	10,851
Steam Methane Reformer								450	500	550
Pressure vessel								130	145	159
Insulation								1,620	1,800	1,980
Anode Blower/Pump								1,854	2,060	2,266
Desulfurization								2,270	2,522	2,774
Inverter								35,147	39,052	42,957
Labor								994	1,105	1,215
Equipment								113	126	138
Total Balance of Plant								54,422	60,469	66,516
Total Direct Costs								76,455	85,348	96,496
G&A								7,646	8,535	9,650
Property Tax								202	202	202
Insurance								270	270	270
Markup								25,372	28,306	31,985
Total								33,489	37,313	42,107
Total Costs Per System								109,944	122,661	138,603
Installation Costs per System								46,177	51,517	58,213
Total Installed Cost Per System								156,121	174,178	196,816
Total Installed Cost Per kW								602	672	759

A 30% markup was added to cover minor pieces of equipment that were not explicitly costed. For example, sprayers, laminators, and laser cutters were not included directly in the estimate as their costs were considered insignificant. As a significant number of costs were budgetary in nature, some element of markup is needed. At this level of design, a 30 percent contingency is not unreasonable.

The levelized cost of electricity based on the estimated installed costs of the power system indicates that the SOFC system could be a competitive form of distributed electrical generation if the manufacturing costs estimated in this study could be realized. The average cost of electricity was projected to be \$0.0668/kWh. Fuel cost was the primary driver of LCOE, amounting to nearly 71% of total costs (see table 23).

Because the fuel cost dominates the levelized cost of electricity, the high net efficiency (65% HHV) of the SOFC power system gives it a substantial cost advantage over other generating technologies. By comparison a microturbine of similar generating capacity (200 kW, Capstone Turbine Corporation) is 30% efficient based on HHV. The cost of

natural gas alone for this turbine is \$0.10/kWh. For a diesel generator (225 kW Cummins), the cost of fuel alone is \$0.30/kWh.

Table 23. Levelized cost of electricity (LCOE) Constant \$2010 with standard process

Levelized Cost of Electricity	Low	Average	High
Levelized Capital Costs	27,633	30,829	34,836
Property Tax	1,171	1,306	1,476.12
Insurance	1,561	1,742	1,968
Fixed O&M	4,684	5,225	5,904
Variable O&M	97,403	97,403	97,403
Total Annual Costs of electricity	132,451	136,505	141,587
kilowatthours produced	2,043,533	2,043,533	2,043,533
Levelized Cost Electricity	0.0648	0.0668	0.0693

Table 23a. LCOE nominal 2010\$ with standard process

Levelized Cost of Electricity	Low	Average	High
Levelized Capital Costs	27,633	30,829	34,836
Property Tax	1,170.91	1,306.34	1,476.12
Insurance	1,561	1,742	1,968
Fixed O&M	5,566	6,210	7,017
Variable O&M	115,761	115,761	115,761
Total Annual Costs of electricity	151,692	155,848	161,058
kilowatthours produced	2,043,533	2,043,533	2,043,533
Levelized Cost Electricity	0.0742	0.0763	0.0788

Standard process compared with sputtering process

As previously mentioned, a portion of this study was to estimate the difference in costs associated with the standard versus the sputtering process. Figure 9 compares the stack-only costs per kW for the standard versus the sputtering process. The sputtering process was estimated to decrease the stack cost from \$91.29/kW down to \$61.53, a decrease of 33%.

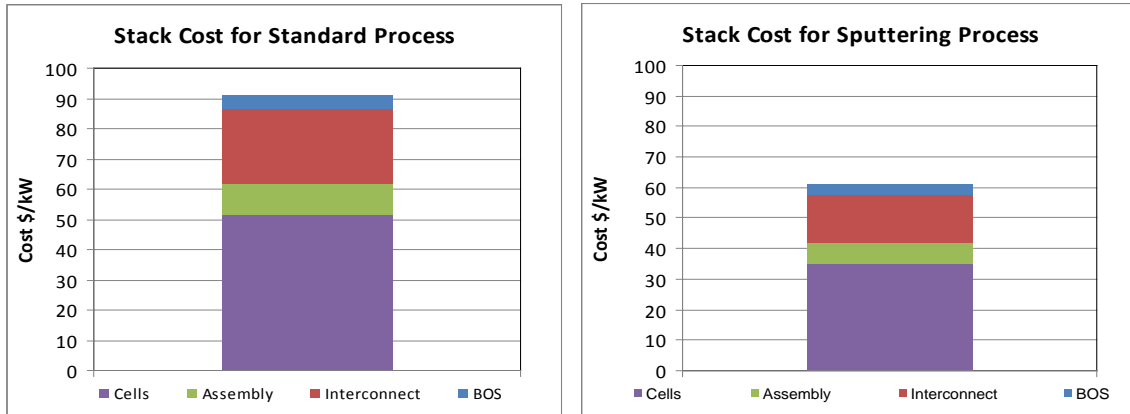


Figure 9. Stack cost per kW for standard process (left) and sputtering process (right).

Aspects of the two processes are compared in Table 24 (for a completed breakdown of costs see Table 25). The main reason that the sputtering lowers the cost per kW was due to the 50% increased cell power density, which not only decreases the number of cells required per power system, but also decreases the number of furnaces, robots and stack assembly/test stations.

Table 24. Comparison of standard process with the sputtering process

	Standard Process	Sputtering Process
Estimated cell power density	0.69 W/cm ²	1.03 W/cm ²
No. cells made per day	32,500	21,700
No. pusher furnaces	36	14
No. pick-and-place robots	72	51
No. stack assembly stations	40	27
Stack materials cost per power system	\$ 13,738	\$ 8,831
Stack capital cost per power system	\$ 7,401	\$ 5,295
Total direct stack cost per power system	\$ 24,879	\$ 16,700
Total direct costs per power system	\$85,348	\$76,917
Levelized cost of electricity	\$0.0668/kW-hr	\$0.0630/kW-hr

It is interesting to compare costs per installed kW to those estimates by Thijssen (2006). Figure 10 shows Thijssen’s numbers compared to ours for the standard process. Thijssen assumed the cell power density would be lower than ours, 0.4 versus 0.69 W/cm². The costs in the plot on the right have therefore been adjusted by a factor of 0.69/0.4 to put them on the same basis. After adjusting for the difference in power density the results are remarkably similar to Thijssen’s.

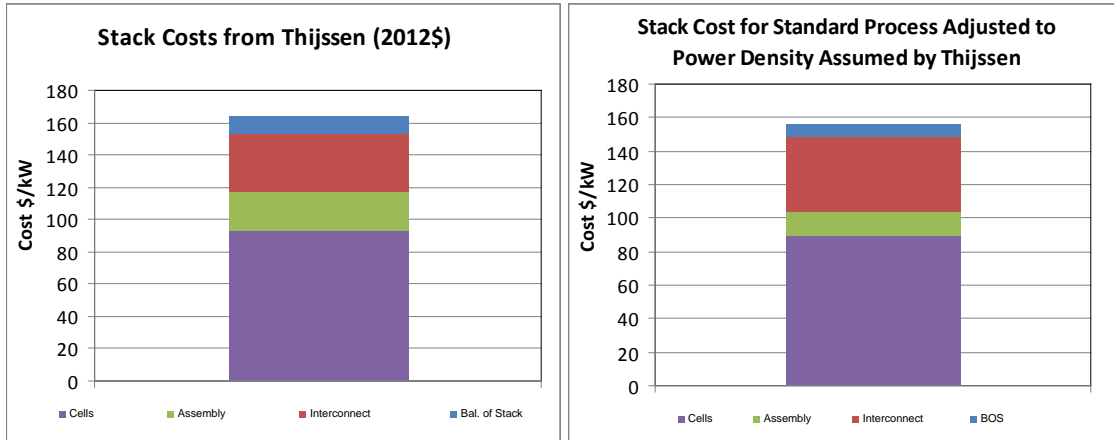


Figure 10. Comparison of stack cost from standard process with those of Thijssen

Table 25. Summary of costs for SOFC power system using sputtering

Component	Materials Costs			Annualized Capital and O&M				Totals		
	Low	Avg	High	Capital	Electricity	O&M	Labor	Low	Average	High
Bulk Anode	2,917	3,680	4,444	201	22	56	45	3,240.79	4,004.46	4,768.14
Active Anode	185	246	307	57	6	16	25	287.12	348.10	409.07
Backing Layer	147	159	172	57	6	16	25	249.06	261.54	274.02
Electrolyte	24	26	27	2,807	120	626	82	3,658.47	3,659.75	3,661.03
Barrier Layer	51	54	57	-	-	-	-	51.15	53.85	56.54
Cathode	41	43	46	-	-	-	-	41.26	43.43	45.60
Cathode flow Field	982	1,071	1,160	297	1	173	90	1,542.79	1,631.95	1,721.12
Metalization Layer	1,037	1,092	1,146	-	-	-	-	1,037.26	1,091.85	1,146.44
Anode Flow Field	536	586	635	289	1	95	82	1,003.30	1,052.72	1,102.15
Glass Seal	313	455	653	104	21	29	33	498.88	640.66	838.67
Steel Parts	541	592	642	28	1	8	45	622.36	672.85	723.34
Spinel Coating	501	512	522	131	55	36	33	756.75	768.12	778.48
Alumina Coating	28	31	35	50	20	14	16	126.92	130.53	134.13
Stack Assembly anc	184	197	210	1,222	35	333	389	2,161.84	2,175.13	2,188.41
Stack loss factor	75	87	101	52	3	14	9	152.78	165.35	178.47
Total	7,562	8,831	10,156	5,295	288	1,414	872	15,431	16,700	18,026
Balance of Plant										
JetCat USA P120-SX Engine								\$2,966	\$3,295	\$3,625
Heat Exchanger								\$8,878	\$9,864	\$10,851
Steam Methane Reformer								\$450	\$500	\$550
Pressure vessel								\$130	\$145	\$159
Insulation								\$1,620	\$1,800	\$1,980
Anode Blower/pump								\$1,850	\$2,056	\$2,262
Desulfurization								\$2,270	2,522.00	\$2,774
Inverter								\$35,147	39,052.00	\$42,957
Labor								\$773	859.32	\$945
Equipment								\$111	123.53	\$136
Total Balance of Plant								\$54,195	\$60,217	\$66,239
Total Direct Costs								69,626	76,917	84,264
G&A								6,962.61	7,691.73	8,426.44
Property Tax								145	145	145
Insurance								193	193	193
Markup								23,078	25,484	27,908
Total								30,378	33,513	36,672
Total Costs Per System								100,004	110,430	120,937
Installation Costs								42,002	46,381	50,793
Total Installed Costs per system								142,006	156,811	171,730
Total Installed Cost Per kW								526	581	636

Effect of Production Volume on Cost of NGSOFC

Currently only a few NGSOFC power systems are being manufactured each year. We developed cost estimates at 50, 250, 1000, and 4000 units per year after we initially estimated costs for a mature market at 10,000 units per year. Materials prices were adjusted to reflect change in the markup for smaller versus larger quantities. Those prices are shown in Table 26.

Table 26. Material prices used for each level of manufacturing

Material	Average 50	Average 250	Average 1000	Average 4000	Average 10000
Ag Paste	1,439.70	1,423.04	1,408.85	1,394.79	1,356.00
Carbon Black	8.32	6.51	5.27	4.27	4.16
Graphite	7.68	6.02	4.87	3.95	3.84
SiC	32.11	25.14	20.36	16.49	16.05
Yttria Stabilized Zirconia 5YSZ	49.11	38.45	31.14	25.23	20.28
NiO Electronics Grade	47.73	42.37	38.24	34.51	30.78
Yttria Stabilized Zirconia 8YSZ	61.87	54.92	49.56	44.73	35.28
Glass Powder	80.44	62.64	50.74	41.10	36.53
Al metal powder	58.47	40.09	28.97	20.93	16.88
Al metal powder another price	97.66	66.96	48.38	34.95	28.20
Phospholan™ PS-236 surfactant	12.94	10.13	8.21	6.65	6.47
Polyvinyl Butyral, BUTVAR B-79	39.49	30.92	25.05	20.29	19.75
Benzyl n-butyl phthalate	17.36	11.91	8.60	6.21	5.01
Ethocelluose (Dow Ethocel 45)	50.39	39.45	31.96	25.89	25.20
Di-Butyl Phthalate	33.08	22.68	16.39	11.84	9.55
Vehicle (Ferro BD75-717)	31.60	24.74	20.04	16.23	15.80
Binder (ESL 450)	18.00	14.09	11.42	9.25	9.00
Ethanol	2.04	1.60	1.30	1.05	1.02
Methyl Ethyl Ketone	2.75	2.15	1.74	1.41	1.38
Isopropyl alcohol	7.64	5.98	4.84	3.92	3.82
n-Butyl alcohol, 99.9%	15.07	11.80	9.56	7.74	7.54
Stainless Alloy 430 or 441, 0.012" thick sheet	4.92	3.85	3.12	2.53	2.46
Ce ₂ (CO ₃) ₃ *5H ₂ O	105.55	82.64	66.94	54.22	52.78
CoCO ₃	37.55	29.40	23.81	19.29	18.78
FeCO ₃ *H ₂ O	3.17	2.48	2.01	1.63	1.58
La ₂ (CO ₃) ₃ *8H ₂ O	70.28	70.28	70.28	70.28	70.28
MnCO ₃	5.16	4.04	3.27	2.65	2.58
Sm ₂ (CO ₃) ₃	181.5	142.10	115.1	93.2	90.7
SrCO ₃	4.53	3.55	2.87	2.33	2.27
Glycine	2.95	2.31	1.87	1.52	1.48
Nitric Acid (70%)	7.36	5.76	4.67	3.78	2.33
Nickel	48.19	37.73	30.56	24.75	22.42
Ferric Chloride	2.20	1.72	1.40	1.13	1.10
Soduim Chlorate	1.75	1.37	1.110	0.899	0.875
Muriatic Acid	1.03	0.80	0.65	0.53	0.51

Stack costs

Stack costs increased by more than 8-fold between 10,000 and 50 units per year. The main cause was that the capital costs per unit climbed as fewer units were made. For each

reduced production volume, the stack production process was re-designed. The major equipment items are shown in Table 27 for each production volume. For example, the most expensive items are the bi-layer and screen print layer sintering furnaces. At 10,000 units per year a total of 40 continuous belt or “pusher” sintering furnaces were required, each over 90 feet long and loaded and unloaded by robotics. At 50 units per year the sintering was done in four batch furnaces, loaded and unloaded by hand labor. At 1000, 4000 and 10,000 units per year, the factory was assumed to operate three 8 hour shifts per day; at 250 units/yr, two 8hr shifts and at 50 units/yr, one shift. For 10,000 units/yr, 43 laborers were required per shift; for 4000 units/yr, 27 laborers per shift and for 1000 units/yr, 20 laborers per shift. The lower production volumes used more labor and less robotics. For 250 units/yr, 18 laborers were assumed per shift; for 50 units/yr, 10 laborers/shift. These counts did not include supervisors, engineers, management, administrator or building maintenance personnel.

Table 27. FOB cost of major equipment for each production volume.

Units Produced per Year	10000		4000		1000		250		50	
	Equipment	Cost	Equipment	Cost	Equipment	Cost	Equipment	Cost	Equipment	Cost
Tape Casting Machines	Four 100 ft.x52" Three 50 ft.x52"	\$6,900,000	Two 100 ft.x52" Three 50 ft.x26"	\$3,750,000	One 100 ft.x52" Three 50 ft.x26"	\$2,550,000	Two 50 ft.x12"	\$800,000	One 50 ft.x26"	\$450,000
Bi-Layer Sintering Furnaces	Sixteen each 95'	\$12,000,000	Six each 100'	\$4,800,000	Two each 75'	\$1,350,000	One at 57'	\$500,000	One Batch Furnace	\$250,000
Screen Print Layer Sintering Furnaces	24 each 93'	\$18,000,000	Nine each 93'	\$6,750,000	Three each 70'	\$1,950,000	Three each 26'	\$1,500,000	Three Batch Furnaces	\$750,000
Chemical Etching, Dual Primary Etch Modules	80 DPEMs	\$9,200,000	32 DPEMs	\$4,750,000	8 DPEMs	\$1,550,000	2 DPEMs	\$900,000	One DPEM	\$675,000
Robots	72	\$11,880,000	30	\$4,950,000	13	\$2,145,000	Labor	-	Labor	-
Batch Furnaces for Stack Assembly	32	\$8,800,000	13	\$3,575,000	4	\$1,400,000	1	\$350,000	1	\$350,000
Other Equipment		\$22,795,110		\$12,899,934		\$6,508,894		\$5,916,003		\$3,550,412
Total		\$89,575,110		\$41,474,934		\$17,453,894		\$9,966,003		\$6,025,412

Tables 28 through 31 list total stack costs for each reduced production volume. These should be compared to Table 22, which shows total stack cost for a volume of 10,000 units per year (average) of \$24,879 versus \$202,271 for a volume of 50 units per year, more than a factor of eight higher.

Table 28. Stack costs for 4000 units of production

Component	Materials Costs			Annualized Capital and O&M						
	Low	Avg	High	Capital	Electricity	O&M	Labor	Low	Average	High
Bulk Anode	5,802	6,414	7,027	503	55	140	113	6,612	7,224	7,837
Active Anode	376	440	504	96	14	27	61	574	638	702
Backing Layer	254	264	275	96	14	27	61	452	463	473
Electrolyte	345	448	552	1,310	36	132	348	2,171	2,274	2,377
Barrier Layer	113	153	171	885	48	159	353	1,559	1,599	1,617
Cathode	428	549	670	751	31	121	302	1,633	1,754	1,875
Cathode flow Field	1,763	2,193	3,679	986	2	411	225	3,387	3,817	5,303
Metalization Layer	928	1,280	2,687	750	30	122	332	2,162	2,514	3,921
Anode Flow Field	924	1,005	1,087	986	2	411	102	2,425	2,507	2,588
Glass Seal	626	769	911	169	52	45	61	953	1,095	1,237
Steel Parts	936	1,023	1,111	65	1	18	113	1,133	1,220	1,308
Spinel Coating	145	191	236	313	139	87	123	806	852	897
Alumina Coating	40	46	53	119	49	33	41	281	288	294
Stack Assembly and	188	201	215	1,453	53	397	552	2,644	2,657	2,671
Stack loss factor	129	150	192	85	5	21	28	268	289	331
Total	12,995	15,128	19,368	8,567	531	2,150	2,816	27,059	29,191	33,431

Table 29. Stack costs for 1000 units of production

Component	Materials Costs			Annualized Capital and O&M				Low	Average	High
	Low	Avg	High	Capital	Electricity	O&M	Labor			
Bulk Anode	6,701	7,443	8,185	1,009	118	279	450	8,557	9,299	10,042
Active Anode	421	492	563	384	57	106	246	1,213	1,285	1,356
Backing Layer	288	300	312	384	57	106	246	1,081	1,093	1,105
Electrolyte	387	502	617	1,808	143	345	1,350	4,033	4,148	4,263
Barrier Layer	140	189	212	1,276	192	355	798	2,762	2,811	2,833
Cathode	464	603	741	1,000	122	277	593	2,456	2,595	2,734
Cathode flow Field	1,971	2,424	3,942	1,297	10	498	491	4,267	4,720	6,239
Metalization Layer	941	1,296	2,717	776	120	217	716	2,770	3,126	4,547
Anode Flow Field	1,132	1,233	1,334	1,297	10	498	614	3,552	3,652	3,753
Glass Seal	806	950	1,094	650	206	178	246	2,086	2,230	2,374
Steel Parts	1,156	1,263	1,371	260	6	72	450	1,943	2,051	2,159
Spinel Coating	179	236	291	1,252	555	347	491	2,823	2,881	2,936
Alumina Coating	52	61	70	475	195	132	164	1,018	1,026	1,035
Stack Assembly and	222	239	256	2,410	125	662	1,637	5,056	5,073	5,089
Stack loss factor	149	172	217	143	19	41	85	436	460	505
Total	15,007	17,403	21,923	14,421	1,934	4,115	8,576	44,053	46,450	50,969

Table 30. Stack costs for 250 units of production

Component	Materials Costs			Annualized Capital and O&M				Low	Average	High
	Low	Avg	High	Capital	Electricity	O&M	Labor			
Bulk Anode	7,763	8,665	9,567	1,371	314	1,118	1,200	11,767	12,669	13,571
Active Anode	472	551	631	1,349	151	380	1,200	3,552	3,632	3,711
Backing Layer	328	342	355	26	10	13	109	486	500	514
Electrolyte	435	563	691	4,564	240	808	3,055	9,103	9,230	9,358
Barrier Layer	173	233	261	3,102	129	403	2,128	5,934	5,995	6,023
Cathode	508	669	830	1,928	326	534	1,582	4,879	5,040	5,200
Cathode flow Field	2,226	2,705	4,261	3,039	27	986	1,309	7,587	8,066	9,622
Metalization Layer	954	1,313	2,749	1,928	320	540	1,910	5,652	6,012	7,447
Anode Flow Field	1,390	1,514	1,638	3,039	27	986	1,637	7,078	7,202	7,326
Glass Seal	1,028	1,175	1,321	2,576	550	714	655	5,523	5,669	5,816
Steel Parts	1,427	1,560	1,693	1,040	15	288	1,200	3,970	4,104	4,237
Spinel Coating	220	291	359	5,009	1,479	1,388	1,309	9,405	9,476	9,545
Alumina Coating	68	80	92	1,900	521	527	436	3,452	3,464	3,476
Stack Assembly and	264	285	306	1,739	257	474	2,182	4,917	4,938	4,958
Stack loss factor	173	199	248	326	44	92	199	833	860	908
Total	17,429	20,146	25,002	32,937	4,408	9,251	20,114	84,139	86,856	91,711

Table 31. Stack costs for 50 units of production

Component	Materials Costs			Annualized Capital and O&M				Low	Average	High
	Low	Avg	High	Capital	Electricity	O&M	Labor			
Bulk Anode	9,247	10,381	11,514	7,682	786	5,590	2,728	26,032	27,166	28,300
Active Anode	540	631	721	132	24	67	-	764	854	944
Backing Layer	383	399	415	132	24	67	-	606	622	638
Electrolyte	500	645	790	5,128	599	2,482	2,728	11,438	11,582	11,727
Barrier Layer	220	298	334	11,789	322	2,015	5,456	19,802	19,880	19,915
Cathode	573	765	958	4,861	816	2,378	-	8,628	8,821	9,013
Cathode flow Field	2,595	3,112	4,718	11,475	66	3,348	3,274	20,758	21,276	22,881
Metalization Layer	971	1,335	2,787	4,861	801	2,409	-	9,042	9,406	10,858
Anode Flow Field	1,764	1,922	2,080	11,475	66	3,348	2,728	19,381	19,539	19,697
Glass Seal	1,293	1,510	1,728	8,251	1,375	3,569	2,728	17,216	17,434	17,651
Steel Parts	1,822	1,992	2,162	5,202	37	1,442	2,728	11,231	11,401	11,571
Spinel Coating	281	372	459	14,131	3,697	6,940	4,092	29,141	29,232	29,319
Alumina Coating	94	111	128	4,871	1,302	2,633	-	8,900	8,917	8,934
Stack Assembly and	326	353	379	8,591	643	2,371	2,182	14,113	14,140	14,166
Stack loss factor	206	238	292	986	106	387	286	1,971	2,003	2,056
Total	20,815	24,064	29,466	99,568	10,664	39,045	28,930	199,022	202,271	207,672

The Balance of Plant

A comparison of the balance of plant costs are shown in Table 32. Balance of plant costs were scaled using equation 5.

$$C = C_0 \left(\frac{V_0}{V} \right)^n \quad (\text{eq. 5})$$

Where C is the cost at the production volume, V , C_0 is the cost at the production volume, V_0 and n is the scaling factor. We used $n=0.385$, which was derived from a blower vendor’s cost estimate for a range of production volumes from 1 to 10000 blowers per year. Costs for the pressure vessel and the insulation were not scaled.

Table 32. Balance of Plant Cost at 50-10,000 units of production

Item	Units of Production				
	10,000	4,000	1,000	250	50
	(Total \$)				
Expander/Compressor	3,295	4,689	7,996	13,635	25,337
Heat Exchanger	9,864	14,037	23,937	40,819	75,852
Steam Methane Reformer	500	712	1,213	2,069	3,845
Pressure Vessel	145	145	145	145	145
Insulation	1,800	1,800	1,800	1,800	1,800
Anode Blower/Pump	2,060	2,931	4,999	8,524	15,840
Desulfurization	2,522	2,953	3,667	4,768	5,168
Inverter	39,052	43,233	50,425	58,813	70,317
Labor	1,105	3,069	15,959	34,918	54,560
Equipment	126	224	359	1,436	7,180
Total Balance of Plant	\$ 60,469	73,793	110,500	166,928	260,044

Figure 11 below depicts the installed capital cost curve (\$/ kW) at different levels of production. The costs per kW ranged from a high of \$3,667/kW at 50 units to a low of \$672/kW at 10,000 units of annual production.

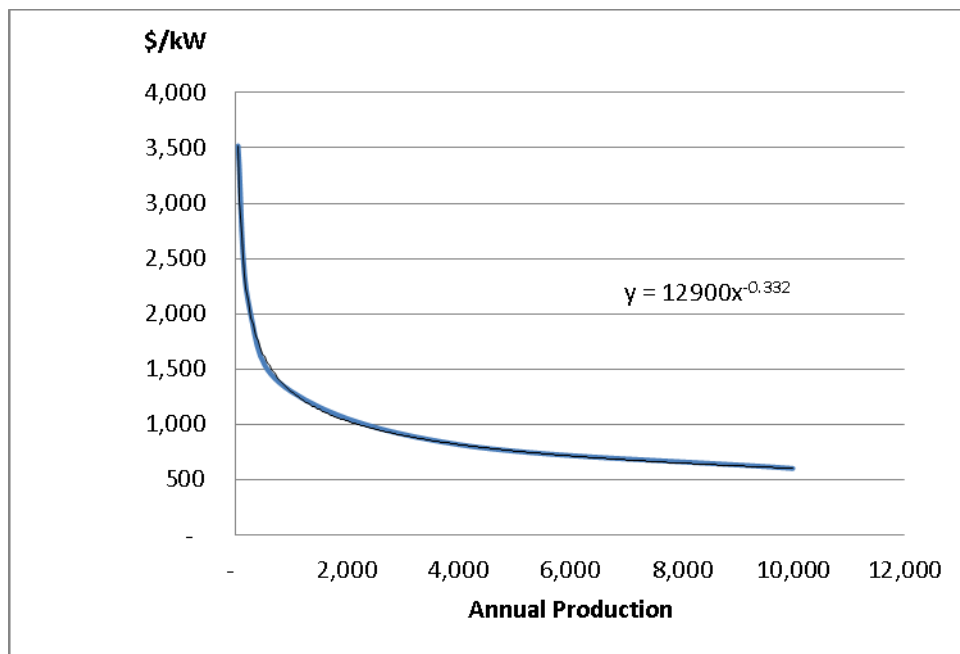


Figure 11. Costs/kW for different levels of annual production

Stack replacement costs.

Stack energy output declines over time so that the stack needs to be replaced in order to maintain adequate electricity production. The cost estimating for the mature technology with the high production volume of 10,000 units per year assumed that the stack lifetime had been improved to 15 years. However, current estimates of stack life are about 2

years (Thijssen 2011). Figure 12 below indicates the stack replacement costs as functions of the number of years to replacement and annual production level. Stack replacement costs were estimated as the direct costs of manufacturing the stack plus G&A, markup and installation. Installation costs were assumed to be 10% of direct and indirect costs of stack manufacturing. The costs were evaluated on an annualized basis for the stream of costs associated with replacement using the same fixed charge rate used to levelize capital costs.

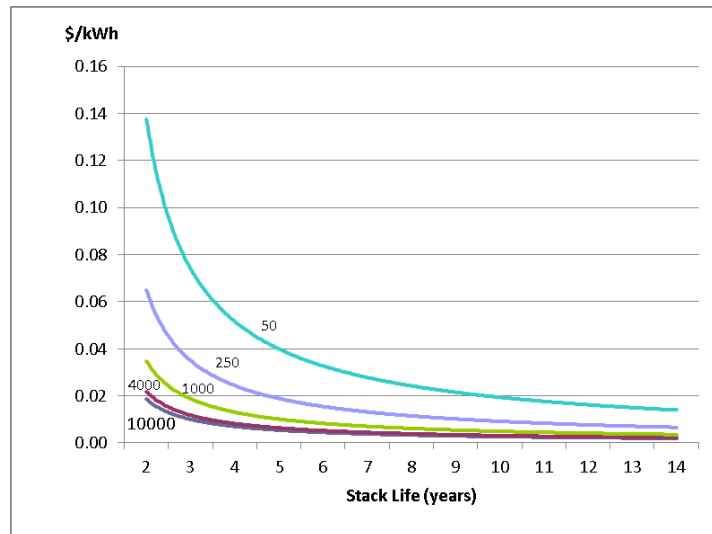


Figure 12. Stack replacement costs as a function of time
Between replacements and annual production quantity

Stack replacements were assumed to be at least two years apart at a minimum and assumed not to occur at the end of year 14. The stack replacement costs decline between production levels because of economies of scale in manufacturing the stack. Clearly when annual production is small and stack life is short, the stack replacement costs make NGSOFC infeasible even for distributed generation because even with the potential benefits of distributed generation, the net cost of power is greater than the national average retail price of electricity for commercial and residential level customers, 9.9-10¢/kWh and 11-12 ¢/kWh, respectively [EIA 2013] (see Figure 13). The LCOE at 250 units per year and stack life of 6-8 years is in the range where the net costs of the NGSOFC including the benefits of distributed generation might make the system economically feasible (see Chick et al 2013.).

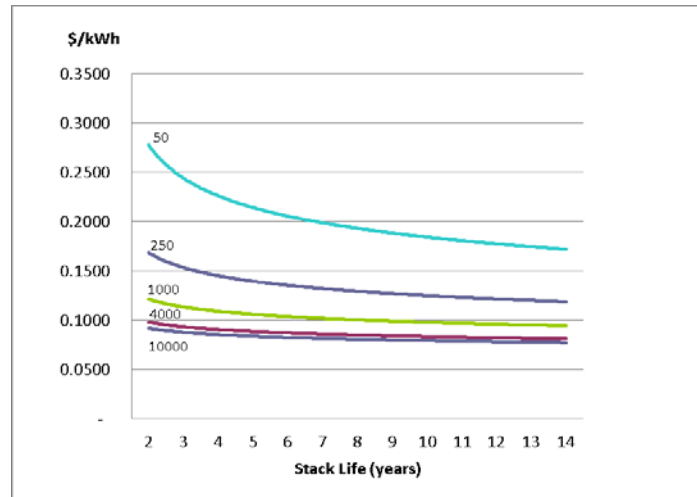


Figure 13. Impact of stack replacement costs on LCOE

Conclusions

The electricity costs for a mass manufactured 270kW solid oxide fuel cell power system could be competitive with centralized power production plants with costs estimated to be in the \$0.06-0.08/kWh range based on a cost model using a standard approach to manufacturing solid oxide fuel cells. The model was set up based on production of 10,000 units per year so that economies of scale could be evaluated for a mature technology with improved stack lifetime of 15 years. A standard manufacturing approach involving tape casting, screen printing and sintering was assumed as the baseline. A process flow sheet was developed to understand the steps required to manufacture the units and to estimate the materials, equipment and labor required to make them. Equipment was then sized to meet the production requirements. In addition material and equipment prices were collected from vendors.

A sputtering approach was also examined using the model to project the expected decreases in costs. The sputtering not only reduced material costs but would be expected to increase the power density of the fuel cell by 50%. The increased power density would reduce the number of repeat units required to make up the 270 kW fuel cell stack. Stack costs decreased by 33%. However, because LCOE was dominated by fuel cost and the system produced by sputtering would have the same high efficiency of the system produced by the standard process, the cost of electricity was only reduced by \$0.002/kWh.

The costs were also estimated for 50, 250, 1000 and 4000 units of annual production. The installed capital costs ranged from \$672/kW to \$3,667/kW. Increasing capital costs per unit and the balance of plant costs drove most of the increase in installed costs. The impact of stack replacement costs were evaluated and it was found that a stack life of 6-8 years and a production volume of 250 power systems per year were required to make the NGSOFC feasible if the potential benefits of distributed generation were included.

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Appendix A. Process Flow Sheets and Cost

Table A1. Process flow cost sheet for standard manufacturing process (cont'd)

SCREEN PRINTED COMPONENTS																
Barrier Layer	Ce2(CO3)3*5H2O	1.42	50.275	52.775	55.275	71.24	74.79	78.33								
Barrier Layer	Sm2(CO3)3	0.31	22.28	90.74	91.99	6.89	28.08	28.46								
Barrier Layer	Glycine	0.79	0.475	1.475	2.475	0.38	1.17	1.97	1	Combustion Synth						
Barrier Layer	Nitric Acid (70%)	7.37	1.969	2.332	2.695	14.52	17.20	19.87	54.15	4.79	15.01	20.46	0.5			
5									267.87		74.23	122.76	3			
									1.72	0.04	0.48	8.18	0.2			
5	Barrier Layer	Ferro Vehicle	1.12	15.325	15.8	16.275	<u>17.18</u>	<u>17.71</u>	<u>18.25</u>	499.36	14.37	17.30	81.84	2.0		
							110.22	138.95	146.88	823.09	19.20	107.00	233.24	5.70	1,321.49	
Cathode	CoCO3	0.60	17.275	18.775	20.275	10.37	11.27	12.17								
Cathode	FeCO3*H2O	2.70	1.375	1.583	1.78	3.72	4.28	4.81								
Cathode	La2(CO3)3*8H2O	4.56	60.275	70.275	80.275	274.76	320.34	365.93	1	Roll Mill	4.20	0.26	1.16	8.18	0.2	
Cathode	SrCO3	1.49	1.255	2.265	3.275	1.87	3.38	4.88	12	Screen Printer	267.87		74.23	122.76	3	
Cathode	Glycine	5.55	0.475	1.475	2.475	2.64	8.19	13.74	8	Sintering Furnace	499.36	11.98	17.30	81.84	2.0	
Cathode	Nitric Acid (70%)	37.00	1.969	2.332	2.695	72.86	86.29	99.72								
6																
6	Cathode	Ferro Vehicle	3.75	15.325	15.8	16.275	<u>57.47</u>	<u>59.25</u>	<u>61.03</u>							
							423.68	493.00	562.29	771.42	12.24	92.69	212.78	5.20	1,582.14	
Cathode Flow Field	Blanks	348.40	2.251	2.461	2.671	784.24	857.40	930.57	4	Etching Equipment	761.02	0.96	210.88	81.84	2	
	NaClO3	18.55	0.78	0.88	0.98	12.94	14.61	16.28		Waste Water Processing			137.34			
	Muriatic Acid	36.44	0.46	0.51	0.57	14.92	16.81	18.70								
Cathode contact paste	Ag Powder	0.907244534	908.275	1356	3000.275	824.03	1,230.22	2,721.98								
Cathode contact paste	Ferro vehicle	0.907244534	15.325	15.8	16.275	<u>13.90</u>	<u>14.33</u>	<u>14.77</u>	1	Roll Mill	<u>1.72</u>	<u>0.04</u>	<u>0.48</u>	<u>8.18</u>	<u>0.2</u>	
						1,650.03	2,133.38	3,702.29			762.74	0.99	348.69	90.02	2.20	3,335.83
7.2 Metallization Layer Ag Powder		0.907244534	908.275	1356	3,000.28	824.03	1,230.22	2,721.98	1	3-Roll Mill	1.72	0.04	0.48	20.46	0.5	
7.2 Metallization Layer Ferro vehicle		0.907244534	15.325	15.8	16.28	<u>13.90</u>	<u>14.33</u>	<u>14.77</u>	12	Screen Printer	267.87		74.23	122.76	3.0	
						837.93	1,244.56	2,736.75	8	Sintering Furnace	499.36	11.98	17.30	81.84	2.0	
											768.94	12.01	92.00	225.06	5.50	2,342.57
Anode Flow Field	Blanks	348.40	2.251	2.461	2.671	784.24	857.40	930.57	1	Etching Equipment	761.02	0.96	210.88	20.46	0.5	
	NaClO3	18.55	0.78	0.88	0.98	12.9	14.6	16.3		Waste Water Processing			137.34			
	Muriatic Acid	36.44	0.46	0.51	0.57	14.9	16.8	18.7								
7.5 Anode Contact Pa NiO Electronics Grade		1.81	28.28	30.78	33.28	51.29	55.82	60.36	1	Roll Mill	1.72	0.04	0.48	20.46	0.5	
7.5 Anode Contact Pa Vehicle (Ferro BD75-717)		1.81	15.325	15.8	16.275	<u>27.80</u>	<u>28.66</u>	<u>29.52</u>								
						891.19	973.31	1,055.42			762.74	0.99	348.69	40.92	1.00	2,126.65

Table A1. Process flow cost sheet for standard manufacturing process (cont'd)

DISPENSED GLASS SEAL																			
8	Glass Seal	Phospholan™ PS-236 surfactant (AkzoNobel)	0.17	6.29	6.47	6.47	1.04	1.07	1.10	1	Roll Mill	4.20	0.26	1.16	8.18	0.2			
8	Glass Seal	Polyvinyl Butyral, BUTVAR B-79 (Solutia Inc., Referen	1.49	17.60	19.75	21.89	26.22	29.41	32.61	1	Glass Applicator								
8	Glass Seal	Benzyl n-butyl phthalate (Alfa Aesar, Stock# B24769)	1.29	4.01	5.01	6.01	5.18	6.47	7.76	1	Belt Furnace 900C	46.30	17.97	12.83	8.18	0.2			
8	Glass Seal	n-Butyl alcohol, 99.9% (Fisher Scientific, item# A399-1	4.63	7.051	7.535	8.019	32.68	34.92	37.16	0	noteRobotics	-	-	-	-	0.0			
8	Glass Seal	Glass Powder (VIOX #1716)	16.87	24.2	36.53	53.91	408.30	616.33	909.57	1	Low Temperature Fi	16.95	2.40	4.70	8.18	0.2			
8							473.41	688.20	988.20			67.45	20.63	18.69	24.55	0.60			819.52
STAMPED STEEL PARTS																			
9	Steel Parts	Stainless Alloy 430 or 441, 0.012" thick sheet	404.72	2.251	2.461	2.671	911.03	996.02	1,081.01	1	Laser Welder	1.83	0.00	0.51	8.18	0.2			
9							911.03	996.02	1,081.01	1	Die Stamping Equip	24.18	0.55	6.70	36.83	0.9			
											26.01	0.55	7.21	45.01	1.10				1,074.80
SLURRY SPRAYED COATINGS																			
	Spinel Coating	CoCO3	2.27	17.275	18.775	20.275	39.19	42.60	46.00										
	Spinel Coating	MnCO3	2.19	1.54	2.58	2.85	3.37	5.66	6.26										
	Spinel Coating	Glycine	2.97	0.475	1.475	2.475	1.41	4.38	7.35	1	Ball Mill	1.21	0.36	0.33	8.18	0.20			
	Spinel Coating	Nitric Acid (70%)	19.64	1.969	2.332	2.695	38.67	45.80	52.93	1	Sprayer								
11										2	NotReducing Furnace	77.71	35.94	21.53	32.74	0.40			
	Spinel Coating	Binder (ESL 450)	2.99	8.00	9.00	10.00	23.89	26.87	29.86	1	Oxidizing Furnace	46.30	19.17	12.83	8.18	0.20			
	Spinel Coating	Isopropyl alcohol	8.96	3.82	3.82	3.82	34.21	34.21	34.21										
11							140.75	159.53	176.62			125.22	55.46	34.70	49.10	0.80			424.01
10	Alumina Coating	Binder (ESL 450)	1.21	8.00	9.00	10.00	9.70	10.92	12.13										
10	Alumina Coating	Al metal powder (Alpha Aesar 304 micron)	1.21	13.38	16.88	20.38	16.23	20.48	24.72	1	Ball Mill	1.21	0.36	0.33	8.18	0.20			
10	Alumina Coating	Isopropyl alcohol	2.43	3.82	3.82	3.82	9.27	9.27	9.27	1	Oxidizing Furnace	46.30	19.17	12.83	8.18	0.20			
10							35.20	40.66	46.12		47.50	19.52	13.16	16.37	0.40				137.22
Stack Assembly and QC																			
	Cast Parts		58.74	191.35	204.92	218.50	172.21	184.43	196.65	1	Mar Casting Equipment	19.13			20.46	0.50			224.03
										1	Machine Drill Taps				8.18	0.20			8.18
										1	Fire Manifold	16.95	8.62	4.70	8.18	0.20			38.45
	Bottom Collector Plate		2.55	2.251	2.461	2.671	5.74	6.27	6.81	1	Stamping Equipmer	2.69	0.06	0.74	4.09	0.10			13.85
	Top Collector Plate		2.55	2.251	2.461	2.671	5.74	6.27	6.81										
										42	NotRobotics	590.30		163.57	171.86	4.20			925.73
										32	Batch Furnaces	740.77	30.66	205.27	261.89	6.40			1,238.59
							183.69	196.97	210.26		1,369.83	39.35	374.28	474.67	11.60			2,455.11	

Table A2. Process flow cost sheet for sputtering manufacturing process

TAPE CAST COMPONENTS		\$/kg							Number of Machines		Annual Capital Cost	Electricity Cost	O&M	Labor	Total Manufacturing		
		kg per syste	low price	avg price	high price	Low Cost	Avg Cost	High Cost									
1	Bulk Anode	SIC (Superior Graphite Grade 1200)	1.53	16.05	16.05	16.05	24.60	24.60	24.60								
1	Bulk Anode	Ytria Stabilized Zirconia (Unitec SY)	53.61	10.28	20.28	30.28	550.87	1,086.99	1,623.12								
1	Bulk Anode	NiO (Baker 99.99% Electronics Grade)	73.55	28.28	30.78	33.28	2,079.70	2,263.58	2,447.46								
1	Bulk Anode	Carbon Black (Cancarb N990 Ultrapur)	9.29	4.16	4.16	4.16	38.62	38.62	38.62								
1	Bulk Anode	Ethanol	7.18	1.02	1.02	1.02	7.34	7.34	7.34								
1	Bulk Anode	Methyl Ethyl Ketone (Fischer)	29.46	0.78	1.38	1.98	22.84	40.51	58.19								
1	Bulk Anode	Dispersant (Akzo Nobel PS-236)	1.66	6.29	6.47	6.47	10.42	10.71	11.00								
1	Bulk Anode	Polyvinyl Buterol (Solutia Buter 8-79)	8.37	17.60	19.75	21.89	147.25	165.20	183.15	1	Ball Mill	2.98	1.77	0.82	4	0.1	
1	Bulk Anode	Benzyl Butyl Phthalate (Aldrich)	7.75	4.54	5.54	6.54	35.13	42.88	50.63	2	Tape Cast	198.42	20.03	54.98	41	1	
1							2,916.78	3,680.45	4,444.12			201.40	21.80	55.81	45	1.1	
1																4,004.46	
2	Active Anode	Baker NiO (99.99%) Electronics Grade	3.44	28.28	30.78	33.28	97.21	105.81	114.40								
2	Active Anode	Ethanol	0.66	1.02	1.02	1.02	0.67	0.67	0.67								
2	Active Anode	Methyl Ethyl Ketone (Fischer)	2.71	0.78	1.38	1.98	2.10	3.72	5.34								
2	Active Anode	Dispersant (Akzo Nobel PS-236)	0.10	6.29	6.47	6.65	0.60	0.62	0.63								
2	Active Anode	Ytria Stabilized Zirconia (Diachi 8YSZ)	3.38	20.28	35.28	50.28	68.50	119.18	169.86								
2	Active Anode	Ethocelluose (Dow Ethocel 45)	0.45	25.20	25.20	25.20	11.28	11.28	11.28	1	Ball Mill	1.21	0.36	0.33	4	0.1	
2	Active Anode	Di-Butyl Phthalate (Aldrich)	0.32	13.43	13.61	13.78	4.26	4.31	4.37	1	Tape Cast	55.39	5.30	15.35	20	0.5	
2							184.63	245.60	306.57			56.60	5.66	15.68	25	0.6	
2																348.10	
3	Backing Layer	NiO Electronics Grade	4.14	28.28	30.78	33.28	117.02	127.36	137.71								
3	Backing Layer	Ethanol	0.76	1.02	1.02	1.02	0.78	0.78	0.78	1	Laminator					20	0.5
3	Backing Layer	Methyl Ethyl Ketone (Fischer)	3.12	0.78	1.38	1.98	2.42	4.29	6.16	1	100 W, CO2 Laser	1.83		0.51	8	0.2	
3	Backing Layer	Dispersant (Akzo Nobel PS-236)	0.05	6.29	6.47	6.65	0.30	0.31	0.32	9	Bi-layer Furnace	561.78	77.62	161.97	92	2.25	
3	Backing Layer	Ethocelluose (Dow Ethocel 45)	0.68	25.20	25.20	25.20	17.10	17.10	17.10	18	Robotics	290.19		80.4114675	74	1.8	
3	Backing Layer	Di-Butyl Phthalate (Aldrich)	0.42	13.43	13.61	13.78	5.59	5.67	5.74	1	Ball Mill	1.21	0.36	0.33	4	0.1	
3	Backing Layer	Graphite (Asbury 4006)	0.92	3.64	3.84	4.04	3.36	3.54	3.73	1	Tape Cast	55.39	5.30	15.35	20	0.5	
3							146.56	159.04	171.52			56.60	5.66	15.68	25	0.6	
3																261.54	
4	Electrolyte	Ethanol	-	1.02	1.02	1.02	-	-	-								
4	Electrolyte	Methyl Ethyl Ketone (Fischer)	-	0.78	1.38	1.98	-	-	-	1.00	Combustion Synth	56.22	4.79	15.58	10	0.25	
4	Electrolyte	Dispersant (Akzo Nobel PS-236)	-	6.29	6.47	6.65	-	-	-	1	Isostatic Press	23.11	0.96	1.33	10	0.25	
4	Electrolyte	Ytria Stabilized Zirconia (Diachi 8YSZ)	-	20.28	35.28	50.28	-	-	-	1	Ceramic Surface Grinder	12.40	0.96	3.44	10	0.25	
4	Electrolyte	Ethocelluose (Dow Ethocel 45)	-	25.20	25.20	25.20	-	-	-	1	Batch Furnace	46.30	17.25	6.41	10	0.25	
4	Electrolyte	Di-Butyl Phthalate (Aldrich)	-	13.43	13.61	13.78	-	-	-	2	Sputtering Equipment	2,668.96	95.83	598.76	41	1	
4																	
4		From Target worksheet					24.34	25.63	26.91			2,806.98	119.78	625.51	81.84	2.00	
4																3,659.75	

Top 4 equipment items are to fabricate sputtering targets. One combustion synthesis machine will make powders for the barrier layer, cath

Table A2. Process flow cost sheet for sputtering manufacturing process (cont'd)

DISPENSED GLASS SEAL																
8	Glass Seal	Phospholan™ PS-236 surfactant (AkzoNobel)	0.11	6.29	6.47	6.47	0.69	0.71	0.72	1	Roll Mill	4.20	0.26	1.16	8	0.2
8	Glass Seal	Polyvinyl Butyral, BUTVAR B-79 (Solutia Inc., Reference# 462)	0.98	17.60	19.75	21.89	17.30	19.41	21.52	1	Glass Applicator					
8	Glass Seal	Benzyl n-butyl phthalate (Alfa Aesar, Stock# B24769)	0.85	4.54	5.54	6.54	3.86	4.72	5.57	1	Belt Furnace 900C	48.36	17.97	13.40	8	0.2
8	Glass Seal	n-Butyl alcohol, 99.9% (Fisher Scientific, item# A399-1)	3.06	7.051	7.535	8.019	21.57	23.05	24.53	2	Robotics	32.24		8.93	8	0.2
8	Glass Seal	Glass Powder (VIOX #1716)	11.14	24.2	36.53	53.91	269.50	406.82	600.37	1	Low Temperature Furnace	19.02	2.40	5.27	8	0.2
8							312.93	454.70	652.71			103.82	20.63	28.77	32.74	0.80
																640.66
STAMPED STEEL PARTS																
9	Steel Parts	Stainless Alloy 430 or 441, 0.012" thick sheet	240.43	2.251	2.461	2.671	541.20	591.69	642.18	1	1 Laser Welder	1.83	0.00	0.51	8	0.2
9							541.20	591.69	642.18	1	1 Die Stamping Equipment	26.04	0.55	7.22	37	0.9
												27.87	0.55	7.72	45.01	1.10
																672.85
SLURRY SPRAYED COATINGS																
	Spinel Coating	CoCO3	1.35	17.275	18.775	20.275	23.28	25.31	27.33		Combustion synthesis equipment and labor included in electrolyte					
	Spinel Coating	MnCO3	1.30	1.54	2.58	2.85	2.00	3.36	3.72							
	Spinel Coating	Glycine	1.76	0.475	1.475	2.475	0.84	2.60	4.37	1	Ball Mill	1.21	0.36	0.33	8	0.2
11	Spinel Coating	Nitric Acid (70%)	12.24	1.969	2.332	2.695	24.10	28.54	32.99	1	Sprayer					
										2	Note: one (Reducing Furnace	81.85	35.94	22.68	16	0.4
	Spinel Coating	Binder (ESL 450)	1.77	8.00	9.00	10.00	14.19	15.96	17.74	1	Oxidizing Furnace	48.36	19.17	13.40	8	0.2
	Spinel Coating	Isopropyl alcohol	114.24	3.82	3.82	3.82	436.30	436.30	436.30							
11							500.72	512.08	522.44			131.42	55.46	36.42	32.74	0.80
																768.12
	10 Alumina Coating	Binder (ESL 450)	0.80	8.00	9.00	10.00	6.41	7.21	8.01							
	10 Alumina Coating	Al metal powder (Alpha Aesar 304 micron)	0.80	18.99	22.49	25.99	15.20	18.00	20.81	1	Ball Mill	1.21	0.36	0.33	8	0.2
	10 Alumina Coating	Isopropyl alcohol	1.60	3.82	3.82	3.82	6.12	6.12	6.12	1	Oxidizing Furnace	48.36	19.17	13.40	8	0.2
10							27.72	31.33	34.93			49.57	19.52	13.74	16.37	0.40
10																130.53
Stack Assembly and QC																
	Cast Parts		58.74	191.35	204.92	218.50	172.21	184.43	196.65	2	Manufacturing Casting Equipment	19.13			20	0.5
										1	Machine Drill Taps				8	0.2
										1	Fire Manifold	19.02	8.62	5.27	8	0.2
	Bottom Collector Plate		2.55	2.251	2.461	2.671	5.74	6.27	6.81	1	Stamping Equipment	2.89	0.06	0.80	4	0.1
	Top Collector Plate		2.55	2.251	2.461	2.671	5.74	6.27	6.81							
										31	Note: two (Robotics	499.77		138.49	127	3.1
										27	Batch Furnaces	680.83	25.87	188.66	221	5.4
							183.69	196.97	210.26			1,221.64	34.56	333.22	388.74	9.50
										130						2,175.13
Material Grand Total Per Systems																
							213.53					5,242.18	285.58	1,400.02	863.41	21.10
																16,534.92