# Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation

## SOFC Scaleup for Hybrid and Fuel Cell Systems
## Final Topical Report

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## DISCLAIMER

## ABSTRACT

This report summarizes the work performed by Hybrid Power Generation Systems, LLC (HPGS) during the April to October 2004 reporting period in Task 2.3 (SOFC Scaleup for Hybrid and Fuel Cell Systems) under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL), entitled “Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation”. This study analyzes the performance and economics of power generation systems for central power generation application based on Solid Oxide Fuel Cell (SOFC) technology and fueled by natural gas. The main objective of this task is to develop credible scale up strategies for large solid oxide fuel cell-gas turbine systems. System concepts that integrate a SOFC with a gas turbine were developed and analyzed for plant sizes in excess of 20 MW. A 25 MW plant configuration was selected with projected system efficiency of over 65% and a factory cost of under $400/kW. The plant design is modular and can be scaled to both higher and lower plant power ratings. Technology gaps and required engineering development efforts were identified and evaluated.

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## EXECUTIVE SUMMARY

The Solid Oxide Fuel Cell (SOFC) technology is regarded as one of the most promising future power generation technologies and perceived to have a range of advantages over competing technologies. The study presented in this report explores the possibility of the SOFC technology to challenge the technologies that dominate the central power generation market, the combined gas turbine-steam turbine cycle and the traditional coal powered steam plant. A minimum plant size of 20 MW was chosen for this study. The plant uses natural gas as fuel and delivers AC power at the grid voltage. The objective of the SOFC scale up task is to develop credible scale up strategies for large SOFC-gas turbine (GT) hybrid systems, and particularly, to understand the effects of system and stack architecture on plant scale up and performance.

The study identified the product requirements for a 20 MW central generation power plant based on the standards of competing GE products. The system is also required to meet or exceed the Solid State Energy Conversion Alliance (SECA) factory cost goal of $400/kW and to target system efficiencies in the 55-75% (LHV) range.

The large system size requirement provides an opportunity to integrate SOFC stacks with a gas turbine to achieve high system efficiency. In a hybrid with an SOFC, the gas turbine extracts useful work and generates power from the SOFC by-product heat, which leads to system efficiencies unmatched by either SOFC or gas turbines alone. A large number of system and stack concepts were generated in the program to address issues associated with the integration of SOFC stacks with a gas turbine. Four concepts were selected for conceptual analyses.

The four concepts were analyzed for system efficiency, factory cost, and reliability. The analysis results were compared to the product specification, and Concept 1 was selected because it was projected to have the best chance of meeting the product requirements. Concept 2 was chosen for a risk mitigation strategy.

The down selected concept was further analyzed. A 25 MW plant design was completed, and its performance, factory cost and projected reliability were estimated. The design first focused on the SOFC stack subsystem architecture. The study determined that a 19.9 MW SOFC stack subsystem operating at a pressure of 5 atm would be required for the 25 MW plant. The subsystem architecture included multiple stacks placed in pressurized modules. An individual stack size was determined through cost and reliability studies while factoring in power electronics constraints.

The study identified that the size of individual cells in a stack and the number of cells in a stack can be determined independently of each other. The cell size is found through a stack cost and reliability optimization. Using projections of the circular planar cell manufacturing technology capabilities, the stack cost as a function of cell diameter was found to be minimized over a wide range of cell diameters, 30-60 cm (12-24 inches). Reliability considerations favor large cell diameters and a smaller cell count. However the cell reliability may decline rapidly with the cell diameter thus placing a constraint on the cell size. Due to the lack of available reliability data on large cells operating in a stack, the cell size constraints were not quantified, and instead the cell size of 45.7 cm (18 inches) in the middle of the cost-minimizing cell range was chosen for the remainder of this study. The number of cells in a stack was determined through was determined through the optimization of the SOFC power conversion subsystem. The optimal maximum stack voltage of 400V was identified, which translates into the optimal number of cells per stack of 400. Given the cell size and the number of cells per stack, the optimal stack building block for the 25 MW plant was estimated to have a nominal power rating of about 320 kW.

Plant level reliability analyses were performed on the 25 MW hybrid plant including the selected plant architecture and the stack building block. This analyses identified that an operability scheme with eight active and two redundant modules each containing eight stack building blocks would achieve the reliability targets of the product specification. Therefore, pressurized modules of eight stacks were chosen for the 25 MW plant SOFC subsystem architecture.

The 25 MW plant factory cost and performance analyses were conducted next. The factory cost was determined to be about $7.9M, or $317/kW, compared to the product specification target of $400/kW. The calculated plant efficiency of 66% on natural gas also exceeds the product specification target of 65%. The plant projected layout shows that the projected plant footprint area is about 1580 $m^2$ (17000 $ft^2$), about twice the size of comparable combined-cycle plants. The plant design is also suitable for operation with coal gas with minimal design modifications. With coal, plant power was de-rated to 18 MW, and the efficiency on coal gas was determined to be about 69%. This translates into a gasified coal plant efficiency of 48-55% after factoring in the efficiency of a gasifier.

The 25 MW hybrid plant design developed in the study can be scaled to both higher and lower power levels using the same stack building block. Power plants of higher size can be built from the same eight-stack pressurized modules used in the 25 MW plant design. A 250 MW hybrid plant was projected to have 67.6% plant efficiency and $260/kW plant factory cost. Both parameters exceed the 25 MW plant capabilities due to plant economies of scale. A 5 MW hybrid plant can use the same 320 kW stack building blocks as the 25 MW hybrid plant, however the stacks would have to be arranged in smaller pressurized modules, with two stacks per module. The 5 MW hybrid plant projected efficiency and cost were projected to be 65.1% and $512/kW respectively.

In conclusion, the study developed a 25 MW SOFC-gas turbine hybrid power plant design for central power generation on natural gas. The projected plant performance, cost and reliability exceed the product specifications. The plant design is modular and can be scaled to higher and lower power ratings. To realize this plant concept, several technology goals must be met, primarily in the SOFC stack, including the cell scale-up and high-temperature stack seals. In addition, the turbomachinery and balance of plant (BOP) components will require significant re-engineering.

## EXPERIMENTAL

No experimental work was performed as part of this task.

## RESULTS AND DISCUSSION

# 1 INTRODUCTION

## 1.1 Background

The Solid Oxide Fuel Cell (SOFC) technology is regarded as one of the most promising future power generation technologies. The SOFC technology is perceived to have a range of advantages over competing technologies including high electrical efficiencies, low emissions, modularity, potential for low cost, etc. SOFC-based products are considered for a variety of applications, such as distributed power generation, auxiliary power units for transportation, combined heat and power for residential and commercial use. Most of these applications focus on products of low power rating due in large part to the challenges of scaling up existing development efforts to larger sizes. The study presented in this report explores the possibility of the SOFC technology to challenge the technologies that dominate the central power generation market, the combined gas turbine-steam turbine cycle and the traditional coal powered steam plant.

The products that the study targets will have to be an integral part of the existing electrical transmission and distribution system. This system was designed to take advantage of the steam power plant economies of scale, which drive the power plant size requirements into tens and even hundreds of megawatts. As the transmission and distribution system is an infrastructure of an enormous size that is unlikely to be modified, the SOFC products for central power generation must have a similar power-rating requirement. A minimum plant size of 20 MW was chosen for this study.

## 1.2 Program Objectives

The objective of the SOFC scale up program is to develop credible scale up strategies for large SOFC- GT hybrid systems. In particular, the task is designed to understand the effects of system and stack architecture on plant scale up and performance.

The task focuses on three inter-related areas: system architecture, stack building block, and cell size. System architecture has a significant impact on the SOFC subsystem and therefore on scalability and modularity of the SOFC stacks. Consequently, after determining the top-level plant requirements, several system architectures or concepts are to be considered. These concepts are then evaluated based on their ability to meet the plant requirements and their implications on the stack. A down selected system concept is to be used for further analysis.

Subsequently, plant performance, cost, and reliability are considered on the down selected concept to evaluate the optimum cell size. Simultaneously, cell size ranges that allow plant requirements to be met are determined.

Finally, the above analysis is integrated to ascertain whether a common stack building block suitable over a range of plant sizes can be identified. The optimum building block stack is estimated and the range of plant sizes over which this building block is applicable is evaluated.

The above approach necessitates a plant product focus. This study is limited to plant sizes in excess of 20 MW that are applicable to central station power generation applications. The system is also required to meet or exceed the Solid State Energy Conversion Alliance (SECA) factory cost goal of $400/kW and to target system efficiencies in the 55-75% (LHV) range.

Since SOFC stack and system scalability strategies are driven by the functional requirements of the end user, in this case the power generation industry, the first task in this study is to develop a functional product specification that would form the basis for all subsequent trade studies. Within the bounds of this product specification, system architectures that exploit planar SOFC technology are identified, and the SOFC stack scale up and technology development risks are discussed. For example, the minimum cell size and modular stack building block size are estimated based on performance, cost, and reliability considerations. Conversely, the applicable plant power range is estimated for a particular stack building block size. Finally, stack technology gaps are articulated, and a top-level technology development strategy is developed.

### 1.2.1 Product Specification

As mentioned above, the approach to this task is product focused. This focus is driven through the use of a functional product specification that was drafted at the start of the task and maintained through the duration of the task.

The functional product specification is a document that lists all the necessary top-level technical requirements of the plant. The product specification consists of a list of variables that are critical to the quality (CTQ) of the plant. The range over which each requirement can vary is also provided.

The product specification is typically determined by interacting with the end user or customer of the plant. Since this approach was not practical for this study, the product specification was established based on the performance standards of competing GE products. The product specification was also further divided into two sections. The top section, titled “Contractual Requirements” lists the plant attributes that are necessary to meet the contractual requirements of this task. In particular, the three attributes in this section included the power output, the plant efficiency, and the plant manufactured cost. The second section, titled “For Information Only” lists the plant attributes that are seen to be necessary for the plant to be competitive and successful in the targeted market but which are used in this study for guidance purposes only. Due to scope limitations of this study, system analysis is restricted to a conceptual level, and several attributes in this section cannot be determined with low variability at this level of analysis. They are listed to ensure that system concepts that are considered and down selected have the capability of achieving levels of performance listed in this section of the product specification.

As mentioned above, centralized power applications are the primary target of this study. This application is particularly pertinent to fuel cell studies since it necessitates base-loaded operation at low cost or high system efficiencies.

# 2 SYSTEM TRADE STUDY

## 2.1 System Concept Selection

System architecture has a significant impact on the design of the SOFC stack and consequently, on the scalability and modularity of SOFC stacks and hybrid systems. The system concept must be selected to maximize the advantages of integrating SOFC stacks with gas turbines while satisfying the product requirements. Therefore, the system concept selection process started with brainstorming concepts having high probability of satisfying the product requirements. The initial long list of concept ideas was then reduced to a few most promising concepts based on top-level system analyses and engineering judgment. The remaining concepts were then analyzed in more detail to determine the final hybrid plant conceptual design that has the highest potential to satisfy the product requirement. The plant conceptual design was then used as a starting point of plant-level trade studies to find an optimal plant design solution.

### 2.1.1 Initial Concepts

SOFC stacks operate at high temperatures, generally above 650$^{o}$C, due to the ionic conductance characteristics of the electrolyte. A mixture of hydrogen, carbon monoxide and methane can be used as the fuel, while air usually supplies oxygen. Though very efficient power producers, SOFC's still generate much by-product heat that needs to be removed to avoid overheating the fuel cell. In high-temperature fuel cells, such as the SOFC, systems are normally designed so that the by-product heat is removed with airflow through the fuel cell. Usually, the cooling requirement imposed on the airflow results in a much higher airflow rate than that required for the fuel cell reaction, due to the poor heat transfer characteristics of air and, equally importantly, the inability of the SOFC stack to withstand large temperature rise from stack inlet to stack exhaust due to thermal stresses. The presence of the large temperature gradients is detrimental to both structural integrity and reliability of the stack.

Therefore, the stringent heat rejection and SOFC thermal gradient constraints result in high airflow requirement and a necessity to preheat the air to a temperature nearly equal to the stack temperature before it enters the stack. Efficient, reliable and inexpensive airflow thermal management is thus the key to SOFC system design. Other important considerations may also affect the system design, such as the choice of the fuel pre-reformer and its thermal integration as well as water management.

The system size is an important factor in system design. Technological limitations for both the cell size and number of cells in a stack, discussed later in the report, result in a feasible stack power in order of hundreds of kilowatts, while the system power requirement is above 20 MW. Hence, a number of stacks, rather than a single stack, have to be integrated into the system. This fact poses both a challenge and an opportunity to the system designer. On the one hand, the air and fuel flows between the multiple stacks have to be managed to achieve high system efficiencies while maintaining reasonable system cost and reliability. On the other hand, the system may be designed to offset the air preheat and heat rejection requirements between multiple stacks, thus enabling high system efficiencies.

The large system size requirement provides an opportunity to integrate SOFC stacks with a gas turbine to achieve high system efficiency. As the SOFC stacks convert the chemical energy of fuel to electrical energy, it generates by-product heat that can further be converted to electricity. In the SOFC simple cycle, this thermal energy is rejected as waste heat. In a hybrid system, however, the thermal energy is recovered within the gas turbine generator, which converts thermal energy into electrical energy. A 4-5 MW gas turbine would provide a good match for a 20 MW hybrid system design. Gas turbines in this power have reasonable component efficiencies and are available commercially. Therefore, system designs considered in this study were focused on hybrid designs due to their high efficiency potential.

A large number of system and stack concepts were evaluated to address issues discussed above. Some of the ideas explored are noted as follows

- Due to the challenging system cost target, system design simplicity was stressed during concept evaluation. Concepts with multiple gas turbines and complex air preheating schemes were eliminated early due to their limited low-cost potential.
- SOFC stacks can be arranged either parallel or in series with respect to the airflow. In the parallel flow arrangement, flow is split equally among all the stacks. In the series or staged flow arrangement, the exhaust of one stack is the inlet to a subsequent stack. The staged arrangement potentially results in higher system efficiencies with a small cost penalty, as the by-product heat of the upstream stage is used to preheat the subsequent stack air inlet. A combination of staged and parallel arrangements is also possible.
- Solid-carbon-producing reactions limit the extent of internal reforming. When the ratio of molar concentrations of carbon and water reaches a certain limit (that depends on pressure and temperature), the chemical equilibrium shifts towards solid carbon, severely limiting the SOFC performance.
- Similarly, SOFC stacks can be arranged either parallel or in series with respect to the fuel flow. A staged arrangement may result in a high fuel utilization in the stacks even when each stack's fuel utilization is low, thus resulting in a high system efficiency.
- Both recuperated and un-recuperated systems were considered. A recuperator placed at the turbine exhaust to heat the gas turbine compressor outlet may improve the system efficiency. It is unlikely that the recuperator by itself can heat the compressor outlet to the SOFC operating temperature. Therefore, additional air preheat means is required.

- The additional means of air preheat to the SOFC operating temperature can be accomplished by burning additional fuel in the SOFC air inlet or using the by-product heat of the SOFC reaction.
- Different kinds of fuel reformers were also considered, namely steam reformers, partial oxidation fuel processors and auto-thermal reformers.
- Steam is required for fuel processing (both steam reformers and auto-thermal reformers). There are three options for steam supply: (1) outside water supply with steam generation; (2) a water pump with a steam generator providing steam from a water tank with a condenser at the system exhaust; and (3) recycling of the SOFC anode outlet containing product water to the reformer. Option 2 and 3 maintain water neutrality and are preferred if the plant site has fresh water supply limitations.

Over twenty system concepts were generated using the ideas outlined above. These concepts were ranked consistent to the criteria outlined in the product specification using simple conceptual analyses and engineering judgment.

#### 2.1.2 Results of Initial Screening

The results of initial screening analyses and some general observations are outlined below:

- A considerable amount of internal reforming within the SOFC stacks is desirable to achieve high system efficiency. Internal reforming occurs within the SOFC stacks when methane is present in the SOFC stacks fuel inlet. The reaction product water can be used for converting the methane to hydrogen and carbon monoxide. The methane reforming reaction is endothermic and absorbs the SOFC reaction by-product heat, thus lowering the gas turbine airflow requirement and improving the system efficiency. The fuel processor does not have to convert 100% of the inlet fuel to hydrogen and carbon monoxide and therefore becomes a pre-reformer.
- Steam reformers require no airflow and therefore result in higher system efficiency than that of systems that contain partial oxidation and auto-thermal reformers. The power required to pressurize the pre-reformer airflow reduces the auto-thermal-reformer-based system efficiency by about 5 percentage points below the steam-reformer-based system. Similarly, partial oxidation reformers result in a 10-percentage point efficiency disadvantage compared to steam reformers. Since there is no clear cost or reliability advantage for any of the reformer types, steam reformers are a better choice for hybrid systems.
- Air thermal management design can drive the SOFC stack design requirements, and vice versa.
- There is likely a limit of the number of SOFC stack stages in staged arrangements. This limit may be driven by either the minimum pressure drop

through SOFC stacks or the minimum reactant concentration required for stack operation.

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### 2.1.3 Down Selected Concepts

Considering the initial screening observations outlined above, four concepts were selected for further analyses to identify the system with the best chance of meeting the product requirements. All concepts incorporate multiple SOFC stacks with a steam reformer and a gas turbine (Figure 1). The gas turbine compressor supplies pressurized air to the SOFC stacks. The air is preheated to the SOFC operating temperature. All systems are recuperated. Steam reformers partially convert the fuel to a hydrogen-containing gas (so-called reformate) and supply it to the SOFC stacks. The differences between the concepts are in the ways each of them accomplishes air pre heat and water management.

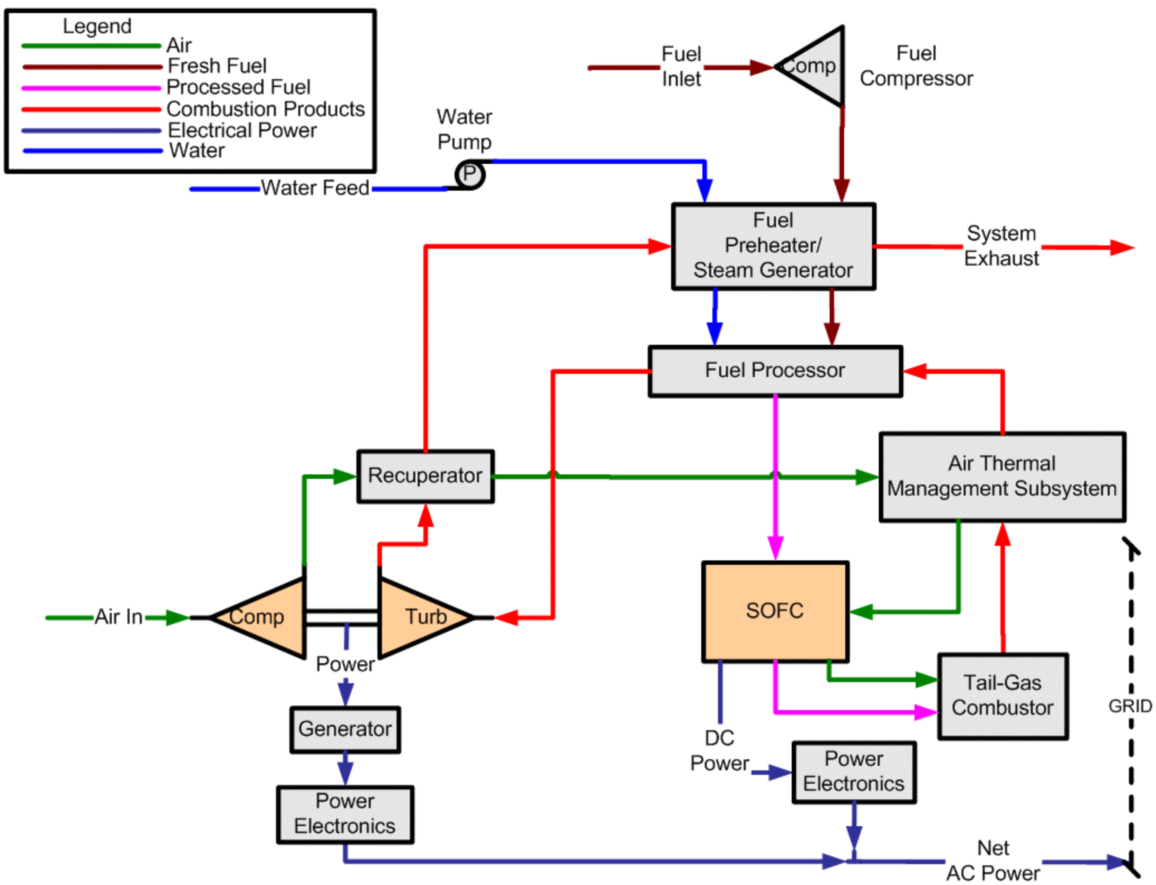


Figure 1 Generic SOFC-GT hybrid system

### 2.1.4 System Analysis Approach

#### 2.1.4.1 Performance Modeling

Thermodynamic performance models were developed for all four concepts using Aspen Plus™, a thermodynamic and chemical processes analysis tool. The thermodynamic performance models calculate the heat and material balances around each system component with appropriate component performance parameter assumptions and integrate the components into the system flow sheet. The performance model outputs are the calculated system efficiency and component performance specifications. The latter serve as the inputs to the system cost and reliability models. The component performance assumptions are outlined below.

##### 2.1.4.1.1 SOFC Stacks Performance Assumptions

The SOFC stack performance assumptions are based on GE's experience in the development of SOFC stacks. The assumptions are as follows.

- SOFC stacks are constructed out of planar fuel cells. The cells are ceramic tri layers with metallic interconnects and flow fields.
- The maximum air temperature rise through the stack is fixed. This assumption drives the airflow requirement through the stack. The air temperature rise is measured from the stack inlet air manifold to the stack outlet air manifold. The air temperature rise is usually limited by the cell temperature gradients. The relationship between the air temperature rise (or the airflow) and the maximum allowable cell temperature gradient is highly dependent on the stack and cell design.
- Maximum SOFC air outlet temperature is kept at a fixed value.
- Single-cell voltage at full load is 0.7V. The single-cell voltage drives the SOFC stack and the overall system efficiency. The single-cell voltage must normally be traded with the SOFC power density (or current density) to achieve the most favorable system efficiency-system cost balance. This trade-off requires knowledge of the SOFC stack polarization curve, showing the average single-cell voltage as a function of average current density. This polarization curve is a reflection of the cell technology and stack design. Rather than predicting what the stack polarization curves will be at the time when the SOFC technology matures to the point that a 20MW+ plant sizes are feasible, we chose in this study to fix the average cell voltage and determine the required power density to achieve the system cost goal. The single-cell voltage of 0.7V at full load is a reasonable assumption based on GE's previous SOFC system designs and other benchmark activities.
- SOFC subsystem air pressure drop is 5% of the total system pressure. The SOFC subsystem includes the SOFC stacks and the associated valves and piping.

- SOFC subsystem heat loss is equal to 2% of the SOFC power output. This is a relatively conservative assumption for a large system. This assumption will be revised in the detailed plant design phase.
- The concepts proposed in this study consider two types of SOFC stacks: stacks that use cells with cathode-to-anode exhaust seals, and stacks designed without these seals. We assumed that stack performance assumptions do not differ between the sealed and seal-less stacks. The stack designs for sealed and seal-less cells could potentially be drastically different. However, there are two reasons to believe that the performance assumptions should be identical for both stack types from the system perspective. First, while there can be significant differences in performance entitlements between the two types (for example, the fuel utilization entitlements), the performance assumptions made in this study are likely to be sufficiently below the entitlements that identical assumptions should be made. Second, the stack designs at high power levels considered in this study have not been developed. It is unclear which tack type will result in a higher entitlement for each particular assumption, therefore an identical assumption for both cell types should be made.
- The assumed baseline power density as a function of pressure was assumed. An assumption was made that the power density at 5 atm is 0.5 W/cm$^2$.

2.1.4.1.2 Gas Turbine Assumptions

Gas turbine compressor and turbine efficiencies are assumed to be functions of component size. For recuperated cycles, the recuperator operating conditions in the hybrid cycles under consideration are likely to be similar to those in the gas turbine cycle. Therefore, the recuperator effectiveness and pressure drops through the cold and hot sides are assumed to be similar to the values observed in typical gas turbines.

2.1.4.1.3 Pre-Reformer Assumptions

There are several options for sizing the fuel pre-reforming subsystem: (1) one central pre-reformer feeding all stacks in the system; (2) one pre-reformer per group of stacks; or (3) one pre-reformer per stack. The most appropriate configuration should be determined through performance-cost-reliability trade offs. Other assumptions are as follows.

- All pre-reformers are steam reformers.
- Pre-reformers are assumed to be in chemical equilibrium.
- Pre-reformers require minimum amount of steam in feed that corresponds to a steam-to-carbon (S/C) ratio of 1.5. The S/C ratio is defined as (mole flow of water in the pre-reformer feed)/(mole flow of carbon atoms in the pre-reformer feed). For example, the S/C ratio is $S/C = \frac{M_{H2O}}{M_{CH4} + 2 \cdot M_{C2H6} + M_{CO} + M_{CO2}}$ in the case of the pre-reformer feed being a mixture of steam, methane, ethane, carbon monoxide, and carbon dioxide. This requirement ensures that reactions that can

lead to carbon deposition in the pre-reformer are prevented. The minimum S/C value of 1.5 is consistent with empirical data.

#### 2.1.4.2 Cost Analysis Approach

The scope for all the costing is manufactured cost and not installed cost. A manufactured-cost model has been developed for the four system concepts presented earlier. The system cost model consisted of component cost models that were parameterized to allow analyses of component costs with respect to their duties. This modeling approach makes system cost model parametric to allow studies of the effects of system design and size on cost. It was assumed that all the system components, with the exception of the SOFC stacks, are acquired at their market prices at a volume corresponding to an annual production volume of 50 system units per year. The SOFC stack cost is analyzed separately with an SOFC stack cost model that is described in Section 4.2.3.2. Since the component cost models are duty-based, sensitivity studies, such as the effect of system pressure, effect of amount of recycle, various levels of internal reforming, etc., can be performed.

#### 2.1.4.3 Reliability Analysis Approach

The approach to modeling the system reliability is to develop component roll-up tools, followed by detailed redundancy studies. For the purposes of trade studies between the concepts presented above, the same redundancy scenario was selected for all concepts. The optimal reliability scenario was then determined by system reliability and cost trade studies on the down selected concept.

Mean Times Between Failures (MTBF) and Mean Times To Repair (MTTR) numbers for all the system components, except the SOFC stack, were collected from published data (ref. 1). Required SOFC stack MTBF and MTTR numbers are outputs of the analysis that are found from the condition of satisfying the availability and reliability targets. Component MTBF and MTTR numbers were then combined on the system level into the plant MTBF and MTTR using the selected redundancy scenario.

A reliability analysis tool for the hybrid SOFC plant has been developed. The model was designed to serve as a trade-off tool, so that the sensitivity of plant reliability to various design parameters could be studied.

##### 2.1.4.3.1 Approach

A two-part modeling approach was undertaken:

1. A detailed model was set up that could investigate the effect of stack arrangement, part load, maintenance intervals etc. This model concerned only the SOFC stack subsystem.
2. A roll-up tool was developed that included the stack assembly results from the first model, combined that with reliability data of the Balance Of Plant (BOP), and calculated the plant reliability and availability as a result.

The first model was done using the commercial software BlockSim™ while the second model was implemented in FORTRAN.

2.1.4.3.2 Definitions and assumptions

The term reliability is generally used to indicate the ability of a system to continue to perform its intended function (ref. 1). The key parameters in defining system reliability are MTBF and MTTR. The MTBF is defined as the mean exposure time between consecutive failures of a component. The MTTR is defined as the mean time to repair or replace a failed component.

The following are the major assumptions in the analysis.

- Only the principal failure mode of each component is considered
- Effects of specific failure modes are not investigated
- The failure rate is constant
- Failure is defined by stack outage, not de-rating

The last bullet requires explanation. In the context of reliability, failure needs to be adequately defined. For the purpose of this study, failure was considered at two levels: (1) the failure of the plant, and (2) the failure of the individual stacks that make up the SOFC subsystem of the plant. The two are not necessarily the same, since the plant could have redundant stacks, and thus the failure of one stack does not cause a plant failure. Plant failure is defined as the inability of the plant to provide the output power, within a margin of the rated power (25 MW). The margin is not explicitly defined in this study. It should be noted that for the purpose of this study, the plant power is being guaranteed, and not the plant efficiency.

Stack level failure is harder to define. It is a well-known fact that fuel cells degrade in power over their lifetime, and SOFC is no exception. The level of degradation, usually expressed as a percentage of power loss for every 1000 hr operation, is a known quantity for any specific fuel cell design. Since it is known, within a margin of uncertainty, degradation is accounted for in the plant operation. Certain failure modes might cause the stack to produce lesser power than what the degradation schedule allows for. If this power reduction is small in magnitude, it will not warrant repair till the next scheduled repair opportunity. However, if the power reduction is large then immediate attention will be warranted. This last event is termed a stack failure.

Figure 2 summarizes this effect. The blocks to the right entitled “fmN” refer to the probability of individual failure modes. In a well-designed stack the failure modes that cause outage will have very small probabilities.

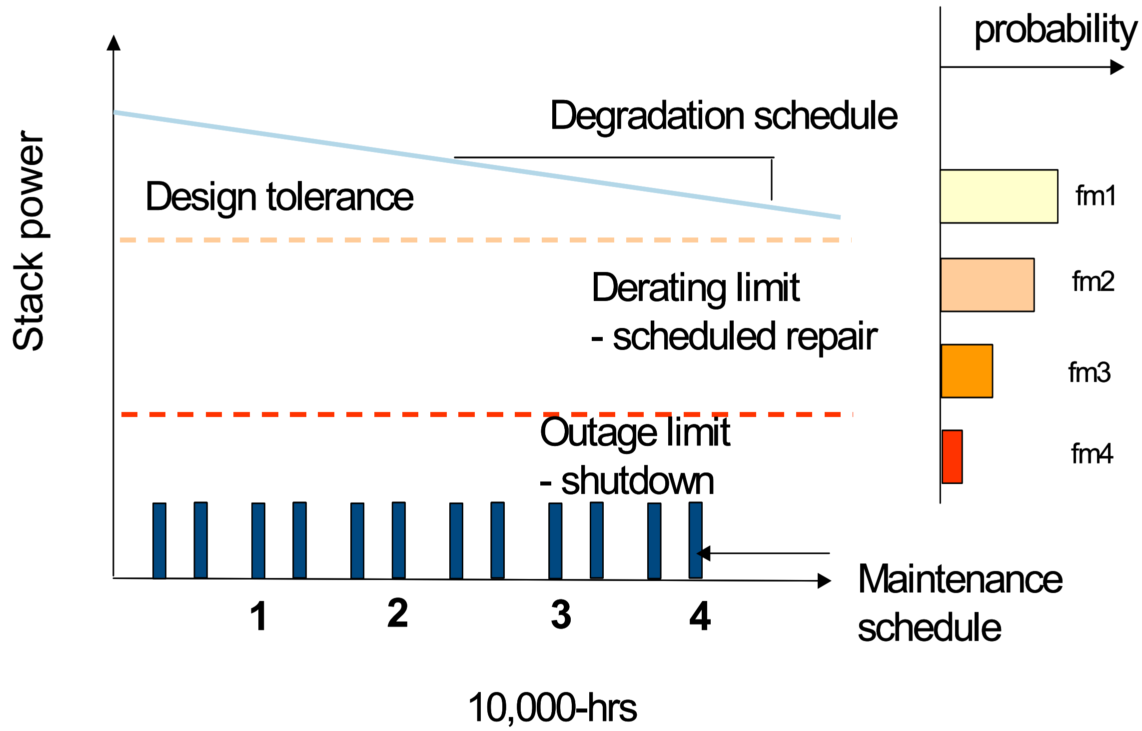


**Figure 2 Stack failure definition**

2.1.4.3.3 BOP Reliability Assumptions

The data shown in Table 1 have been used for reliability calculations. The data source is the standard IEEE STD 493 –1997. The SOFC stack mean time between failure (MTBF) data are scarce. An MTBF of 13,400 hrs has recently been reported (ref. 2). The MTBF numbers for SOFC stacks are expected to improve as the technology is developed. In this study, SOFC stack MTBF was varied to achieve the required reliability and thus is considered a study output.

| Components | MTBF (hrs) | MTTR (hrs) |
|---|---|---|
| SOFC Stack | Variable | 150 |
| Pre-reformer | 40000 | 150 |
| Pipe inside pressure vessel | 40000 | 36 |
| Hot pipe | 40000 | 36 |
| Cold pipe | 40000 | 36 |
| Hot valve | 40000 | 72 |
| Cold valve | 40000 | 72 |
| Inverter | 200000 | 126 |
| Transformer | 200000 | 130 |
| Step - up transformer | 200000 | 130 |
| Mass addition | 50000 | 72 |
| Heat exchanger | 40000 | 72 |

**Table 1 Expected mean time between failure (MTBF) for system components**

### 2.1.5 Results of Analyses of Down Selected Concepts

Concepts 1-4 were analyzed for performance, cost, and reliability with the goal of selecting the best concept based on these three measures. The analysis used the parameterized performance, cost and reliability models to identify the concept with the best chance of meeting the product requirements. The analyses assumed that the initial hybrid plant power is 25 MW to account for possible power degradation.

The comparison function for each concept was formed based on the analysis results:

$$S = \frac{\eta}{0.65} + \frac{\$400/kW}{C} + \frac{R}{0.985} + \frac{MTBF}{4380hrs}$$

where S is the dimensionless concept score used to compare concepts against each other, h is the system efficiency, C is the concept manufactured cost in $/kW, and R is the system reliability. Each concept was then optimized with respect to the system operating pressure to find the maximum score S, and the system with the highest score was then selected for further plant optimization analyses.

Analyses showed that the four concepts optimize approximately at the same system operating pressure of about 5 atm. This result is expected because similar recuperated gas turbine cycles optimize in efficiency at about 4-5 atm. The addition of manufactured cost as an object function to the optimization problem shifts the optimal value of the operating pressure to the upper end of this range.

Table 2 below shows the results of the concept analyses. These results will be used to select one concept for the plant optimization analyses.

| **Parameter** | **Concept 1** | **Concept 2** | **Concept 3** | **Concept 4** |
|---|---|---|---|---|
| System Power (kW) | 25000 | 25000 | 25000 | 25000 |
| Fuel Cell Power (kW) | 20315 | 18656 | 19811 | 19959 |
| Gas Turbine Power (KW) | 6083 | 7557 | 5664 | 5348 |
| System Efficiency, $\eta$, % | 65.53 | 60.54 | 67.19 | 66.69 |
| Cost | $13,385,686 | $13,990,218 | $13,633,862 | $13,551,625 |
| Specific Cost, *C*, $/kW | $535 | $560 | $545 | $542 |
| Reliability, *R* | 94.75% | 94.75% | 94.75% | 94.75% |
| MTBF, hrs | 1258 | 1258 | 1182 | 1146 |
| Total Score, *S* | **3.0045** | **2.8954** | **2.9990** | **2.9876** |

**Table 2 Results of preliminary analyses of selected concepts**

### 2.1.6 Final system concept selection results

Based on the assessment and analysis of the various concepts, Concept 1 was selected for further planned design.

## 2.2 Hybrid System Design

### 2.2.1 Plant description

The system concept down selected for plant design consists of the following subsystems:

- Gas Turbine;
- SOFC Stack;
- Fuel Delivery;
- Thermal Management;
- Water Management;
- Power Electronics and Controls.

SOFC Stack Subsystem is made up of several modules. A module contains SOFC stacks, pre-reformers, and the associated piping and valves. The modules operate at an elevated pressure, and therefore they must meet the requirements of pressure vessels.

The main characteristics of the conceptual design presented are as follows:

- A number of steam reformers for fuel pre-reforming;
- A recuperator is used to transfer heat from the turbine exhaust to the compressor exhaust.

During the detailed analysis phase, this conceptual design was optimized for performance, cost and reliability.

The system lay out is shown in Figure . The approximate footprint area of the plant is 1580 $m^2$ (17000 $ft^2$). The footprint is about twice the area of a combined cycle plant with a comparable power rating.

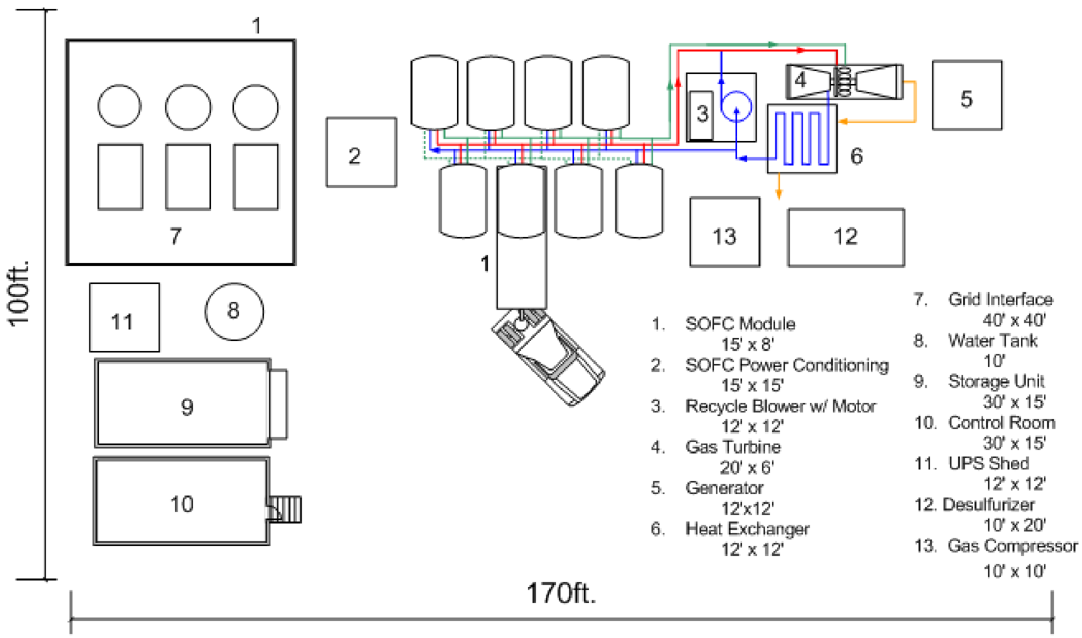


**Figure 3 Twenty-five MW SOFC-GT hybrid plant layout**

### 2.2.2 25 MW plant performance projections

The plant conceptual design is based on Concept 1Detailed plant design is an iterative process because the outputs of the performance analysis serve as the inputs to the cost and reliability optimization studies, however the results of the cost and reliability optimization studies can also have an effect on the plant performance analysis through changing pressure drop, heat loss and other performance parameters. This subsection presents the final plant performance analysis results.

The Aspen Plus™ plant performance model developed in the previous sections was again used in the plant performance analyses. The performance assumptions for a 25

MW plant are listed in Table 3 below. The assumptions are similar to those defined during the concept down selection process. One notable exception is the SOFC heat loss assumption that was re-calculated given the results of the module sizing analyses. The updated heat loss calculations given the SOFC stack module size and assumed levels of thermal insulation resulted in about 100 kWth of total system heat loss, which is about 0.4% of the system power and is below the 2% value assumed in the system down selection calculations (the change would not have had any effect on the concept down selection results).

| **Variable** | **Value** | **Comment** |
|---|---|---|
| Cell Design | Planar | |
| | | |
| Single-cell voltage at full load | 0.7V | Will not be optimized through performance-cost analyses because stack polarization curve is unknown |
| Stack fuel utilization | 70% | |
| System operating pressure | Optimized | |
| SOFC subsystem pressure drop | 5% of system pressure | |
| Total system heat loss | 100 kWth | Computed based on projected module size and length of hot piping |

**Table 3 Performance model assumptions**

The results of the pressure optimization study are shown on Figure 4. Note that the maximum efficiency occurs at the system pressure of between 5 and 6 atm. The combined system efficiency-cost optimization leads to approximately the same optimal pressure, as the cost gains from the fuel cell cost improvements are almost offset by the higher cost of balance of plant.

The maximum system efficiency of the 25 MW plant is equal to about 66%. Figure 4 also shows the effect of the SOFC subsystem pressure drop assumption on the system efficiency. The pressure drop assumption drives the SOFC stack flow field design and, as Figure 4 illustrates, has a major effect on system efficiency. In fact, if the stack pressure drop is reduced to 1.5% of the total system pressure then the maximum efficiency point moves to a slightly lower pressure, between 4-5 atm, and the maximum efficiency is 68%, almost 2 percentage points higher than the 5% pressure drop case. The uncertainty of the optimal pressure selection is quite small, and it appears that the optimal pressure is around 5 atm. Hence, we chose this value as the system operating pressure. Additionally, electrical power loads produced by the system power producers (SOFC stacks and the gas turbine) and consumed by major power parasites are shown in Table 4.

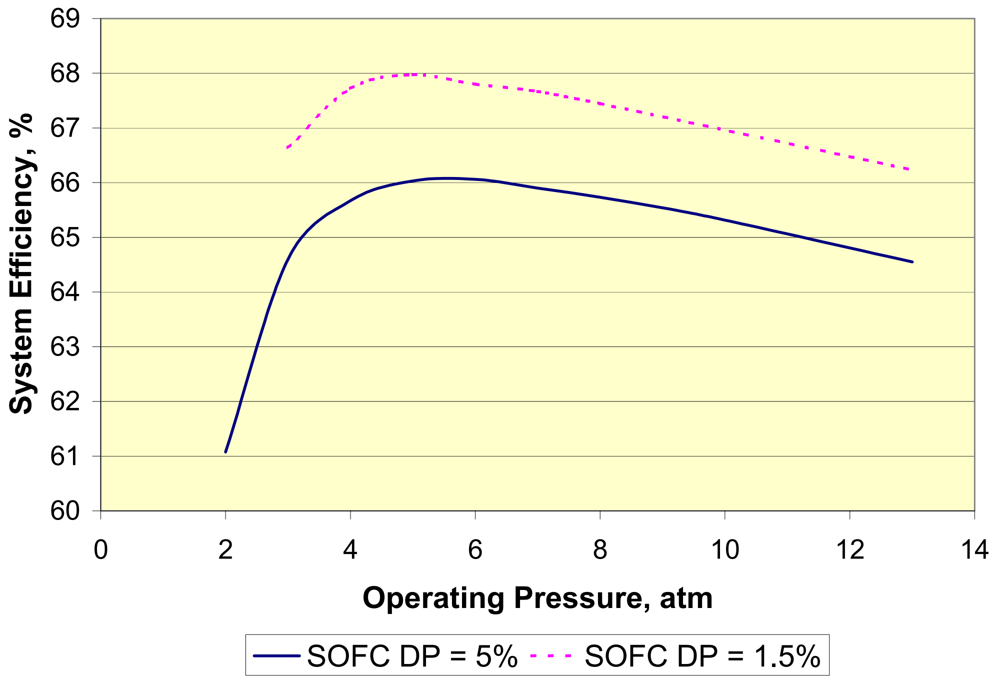


**Figure 4 Results of 25 MW plant performance optimization**

| **Component** | **Power Produced (Consumed), kW** |
|---|---|
| SOFC Stacks | 19941 |
| Gas Turbine | 7779 |
| Blower | (1554) |
| Natural Gas Pump | (1159) |
| Net | 25008 |

**Table 4 Power produced and consumed in the 25 MW plant**

2.2.3 25 MW plant SOFC building block design

The SOFC subsystem of the 25 MW plant design has a power output of 19.9 MW as shown in Table 4. It is impractical from a cost and reliability standpoint to build a 19.9 MW SOFC stack. Therefore, multiple stacks will be involved in the system configuration. The following chapter discusses an approach to determine the optimal number of stacks in the 25 MW plant and the associated stack power.

2.2.3.1 Approach

The approach to determining the optimal number of stack and the stack size undertaken in this study looks at stack size effects on the performance, cost and reliability of the plant. A bottoms-up analysis of the stack performance, cost and reliability results in an explicit dependence of the system cost, efficiency and reliability on the cell size, and number of cells in the stack. An optimization problem is then set up to minimize cost and maximize efficiency and reliability by varying the cell size and the number of cells. The stack size is the solution of this optimization problem.

Note that this problem appears to be under-defined, as three dependent variables are optimized with only two dependent variables. This is a reflection of the fact that system level parameters cannot be optimized with just stack level variables, as the rest of the system will affect the system level dependent variables. For example, stack grouping methods and redundancy scenarios will also have an impact on the system cost and reliability. In this study, some system level constraints will be unknown or uncertain due to the uncertainty of many assumptions and available data. Therefore, the solution for the stack size is not necessarily a fully optimized solution but rather an approximate solution and a guide to future system design efforts.

2.2.3.2 SOFC stack cost model

The cost model for this program was based on SECA stack cost model. This a complete cost estimation tool that uses a series of performance inputs and design assumptions and generates a breakdown of materials, equipment, labor and facilities costs associated with SOFC stack manufacturing.

The stack cost model has been designed to accommodate sensitivity analyses through flexibility, modularity and user-friendliness. It is therefore an easily modified tool, where progresses can be recorded as the design matures. Ultimately, a manufacturing cost, including equipment, labor and facility costs, is generated and is added to the materials cost to yield the total stack costs.

2.2.3.2.1 Stack Configuration

The GE SECA conceptual stack configuration was assumed in the study.

2.2.3.2.2 Assumptions

Material cost assumptions were based on DOE recommendations for the SECA program stack cost.

The stack manufacturing process was divided into two parts: (1) cell manufacturing, and (2) stack assembly. Yields were assigned to both sub-processes. Cell manufacturing yield is assumed to vary from 90% to 60% for a cell size variation of 15-50 cm (6-20 inches), Figure 5. These values are based on typical yields of mature ceramic manufacturing processes observed in the industry. Therefore, the cell yield assumptions are subject to the condition that the cell manufacturing process has a similar entitlement to existing ceramic processes.

Generally, ceramic process manufacturing yields are usually described with a Weibull distribution similar to the blue line on Figure 5. The cell manufacturing process yield however may not be accurately predicted with the Weibull distribution, and a more conservative yield distribution was chosen. Because of the uncertainty of the yield assumption, the impact of a lower yield was also examined.

Stacking yield was varied from 95% to 75% for the same cell size variation, Figure 6. Similarly, it was assumed that a straight line describes the yield distribution as a function of cell size. Sensitivity to a lower stacking yield assumption was also analyzed.

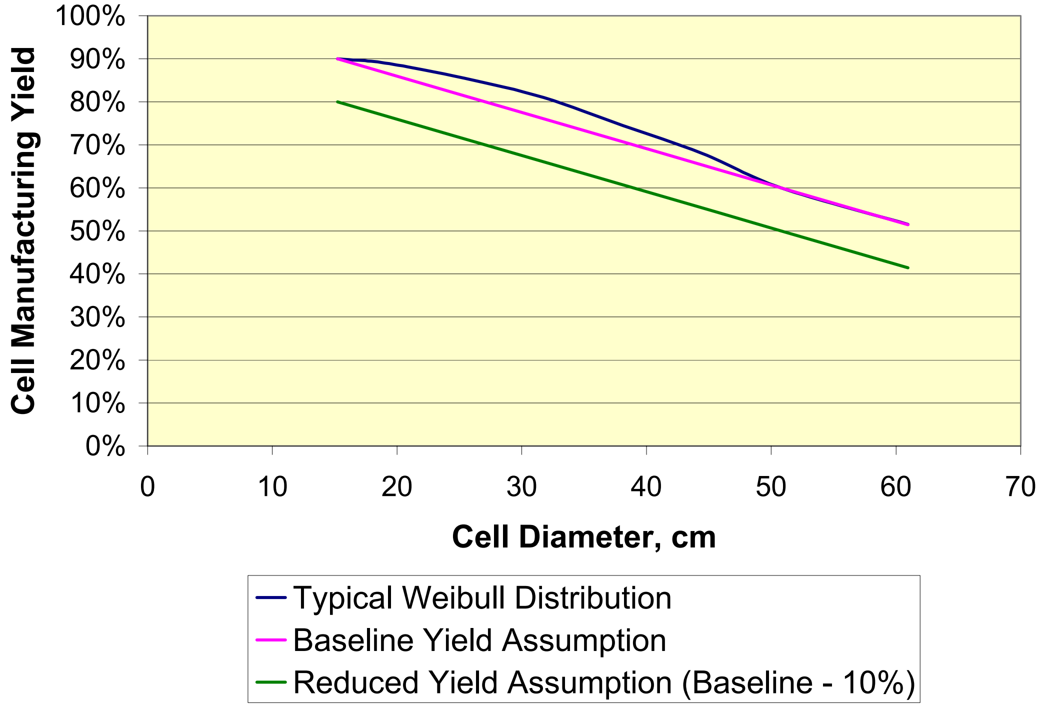


**Figure 5 Cell manufacturing yield assumption**

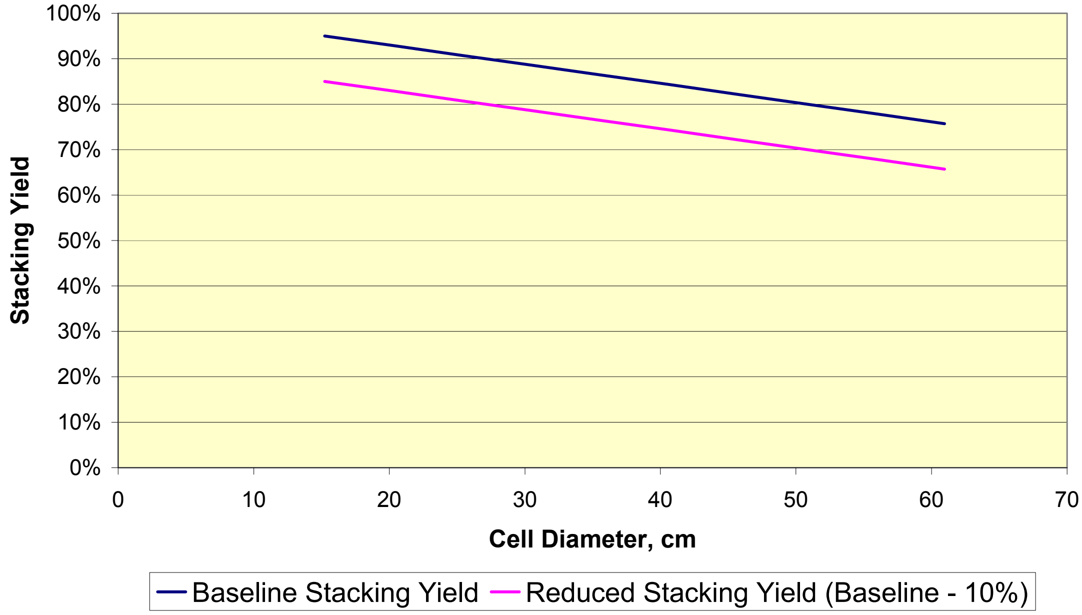


**Figure 6 SOFC stacking yield assumption**

2.2.3.3 Optimal cell size selection

Stack cost analysis results showed that the stack cost is a strong function of the cell size, Figure 7, in the 15-30 cm range. This result is intuitively obvious, since the cell-manufacturing yield (Figure 5) is expected to be a strong function of cell size. However, stack cost is a weak function of the number of cells in the stack, if the number of cells is over 50, because the cost of non-repeat parts in the stack, such as current collector plates, is much lower than the cost of repeat parts, such as cells, manifolds and flow field assemblies.

This is an important result to optimal cell size selection because it leaves the stack cost a function of the cell size only. Since the system cost is a weak function of number of stacks, as will be shown later in chapter 4.2.6, the system cost is also only a function of cell size and not number of cells in the stack. Therefore, the problem of determining the optimal cell size reduces to a simple minimization problem of the stack cost. Note that system reliability considerations may also become

Figure 7 shows that the stack cost has a minimum around cell diameter of 50 cm (about 20 inches). In fact, the stack cost function is relatively flat in the 30-60 cm (12-24 inches) region. Varying yield assumptions reduces optimal cell diameter values to about 40 cm (about 16 inches). Since the yield assumptions are highly uncertain, a range of acceptable cell diameters should be specified rather than an optimal value. From Figure 7, the 30-60 cm (12-24 inches) range appears to be acceptable, since the stack cost function is flat in this region for a variety of yield assumptions.

The reliability analyses discussed below favor larger cells and therefore, a smaller cell count in the system. This result argues for the selection of cells of 60 cm in diameter or even larger. However, cell reliability as a function of cell size is not well understood, and a safer cell size should be chosen. In the following system cost and reliability projections, a cell diameter of 45.7 cm (18.0 inches) was assumed in all calculations for illustration purposes.

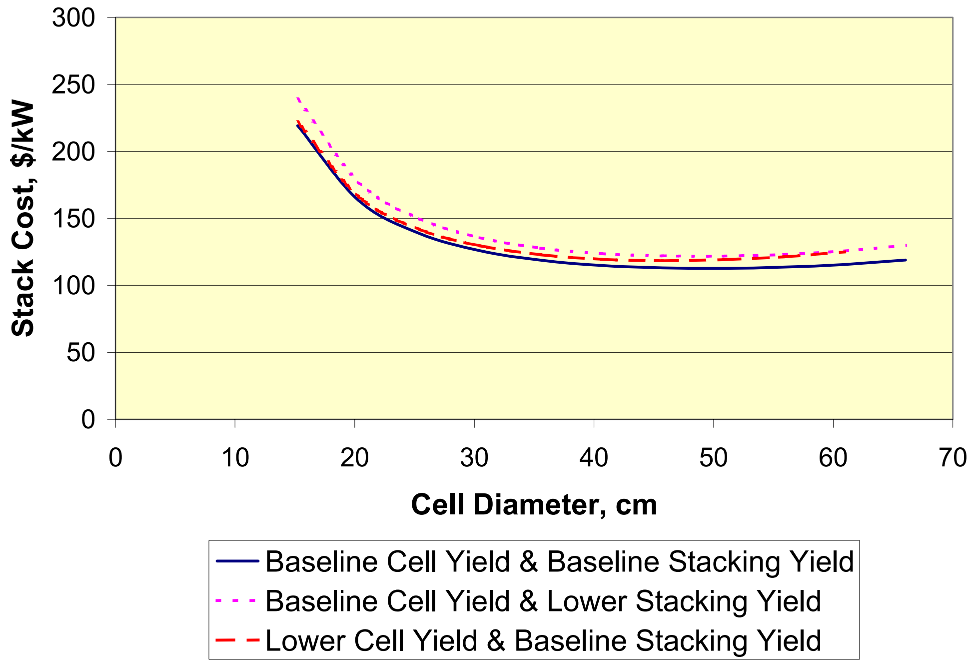


**Figure 7 SOFC stack cost as a function of cell diameter**

2.2.3.4 25 MW power electronics subsystem description

2.2.3.4.1 Power electronics design

For the design of stationary, utility-grade power conversion equipment, efficiency and availability are the predominant design requirements. The power conversion system linking the fuel cell stacks and the grid provides voltage and frequency transformation, galvanic isolation, and control over the power flow, but excludes grid interconnection. For a 20 MW SOFC stack subsystem as part of the hybrid 25 MW power generation plant, the low voltage, high current DC power provided by the fuel cell stacks must be converted to a balanced, three-phase medium voltage AC power. Uni-directional DC-to-AC power conversion is required. The specific electrical characteristics and requirements of the SOFC and utility grid must be considered while designing the conversion system. Since only base-loaded applications are being considered, energy storage is not required. The power converters feature small energy storage elements to balance instantaneous fluctuations in the equilibrium of input power and output power.

2.2.3.4.2 Semiconductor Technology

The choice of the stack voltage level will affect primarily semiconductor technology and voltage class choices. Both, technology and voltage class will ultimately influence the converter losses and the converter efficiency.

For a given voltage class, higher or lower power can be converted using more or less parallel connected devices. As long as the current density in each device remains the same losses scale linear with power. The same holds true for the losses in the bus bar arrangements.

This section presents an optimization in terms of efficiency for the stack and converter voltage level. The grid voltage level is solely affected by the transformer design and will not be further discussed. Any medium voltage grid voltage level can be achieved by an adequate transformer design. State-the-art semiconductors are silicon based and are generally manufactured with uni-polar or bipolar device structures. Nominal blocking voltages of 100V, 200V, 300V, 600V, 1200V and 1700V are the pre-dominant voltage classes for low voltage power conversion systems. Blocking voltage ratings other than these values exist but are not included in the comparison. Devices up to 500V feature primarily a uni-polar structure (MOSFETs), devices starting at 600V are typically of bipolar structure (IGBTs, IGCTs, GTOs, thyristors). Devices that use one single semiconductor chip to obtain large current ratings are latching devices, such as thyristors, GTO's and IGCTs. Blocking voltages start above 800V. The maximum voltage/current ratings commercially available are summarized in Figure 9 for device structures mentioned above. Short circuit current turn-off capability of the non-latching devices, e.g. MOSFET or IGBTs, is advantageous in case of a converter shoot-through. Latching devices such as IGCTs or GTOs require additional di/dt limiters partially eliminating the on-state loss advantages in comparison to non-latching devices.

The availability of device blocking voltages in discrete steps in combination with the maximum device utilization prescribes a unique number of cells for each semiconductor device class. For a maximum DC bus voltage equivalent to 70% of the device blocking voltages, i.e. an over-voltage margin of (1.0/0.7) = 1.42 the optimum number of cell is shown in Figure 8 up to a device blocking voltage of 1700V. The over-voltage margin is needed to prevent a device breakdown during short circuits and is influenced by the stray inductances in the converter set-up, the dc bus and intrinsic device capacitances.

For the optimum voltage level selection, the calculation of the specific losses, i.e. the losses per unit power converted, are analyzed for various voltage levels. The source current is kept constant at rated current density of the fuel cells. Roughly the same device current margin, a ratio between the nominal device current and the rms output current, of IC ~ 1.3 Irms is installed for all sample device voltage classes. The modulation indices and displacement power factors are equal assuming the transformer winding ratios are adjusted adequately. Figure 9 shows the specific converter losses as a function of the switching frequency and device blocking voltage capabilities, which in turn is set by the number of cells. For switching frequencies between 2 and 4 kHz, i.e. at typical PWM converter switching frequencies, the optimum device blocking voltage is 1200V. At low switching frequencies typical for the multi-pulse concept a higher DC bus voltage is preferable. Power conversion efficiency can be increased by ~0.5% if the stack is extended from 400 cells to 800 cells allowing a transition from 600V to 1200V devices. The effective commutation voltage at rated current is only ~ 49% of that of the device blocking voltage capability. This is given by the over-voltage margin needed for no-load operation plus the intrinsic cell voltage drop at rated current.

Individual semiconductor devices for IGBTs are manufactured up to a nominal current rating of ~ 50A. Larger current ratings are achieved by paralleling these individual chips in semiconductor modules. Semiconductor losses are unaffected by the current of the fuel cell stack

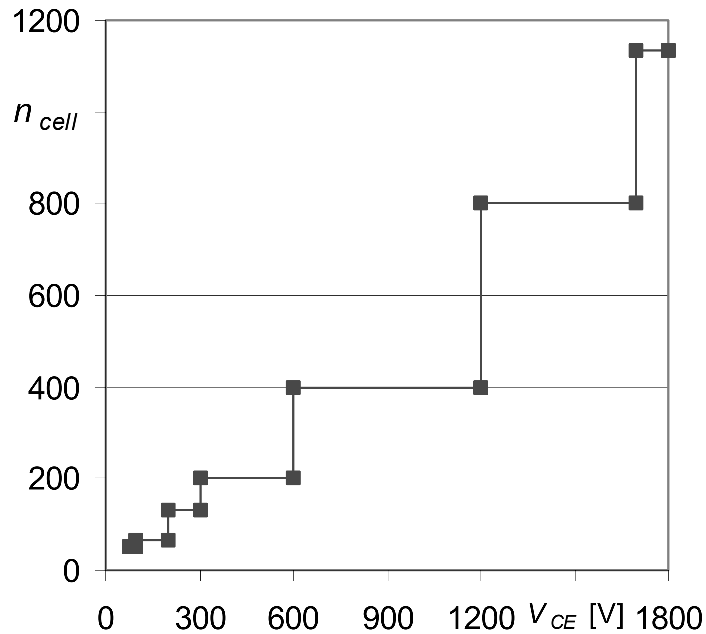


**Figure 8 Number of cells per SOFC stack as a function of device voltage with over-voltage margin of 1.42**

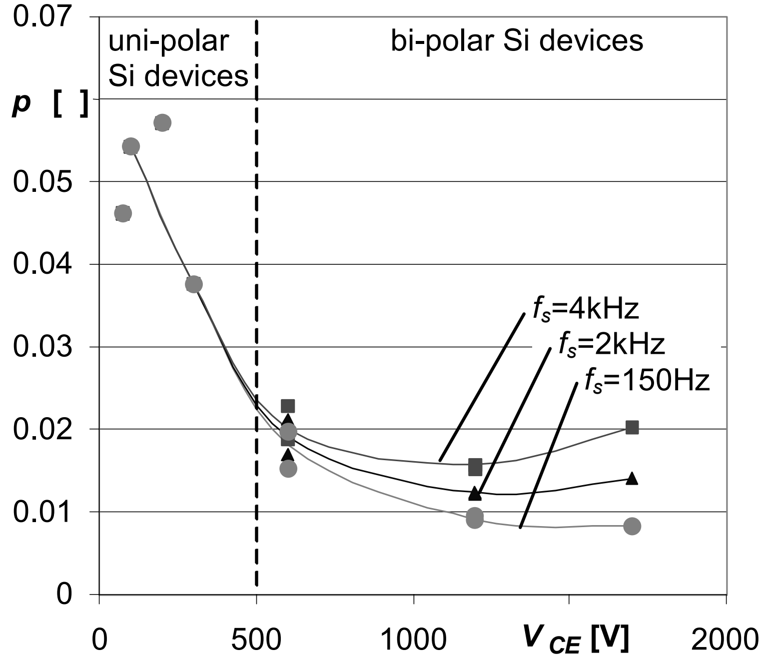


**Figure 9 Specific semiconductor losses for various converter switching frequencies (Vdc = 0.5 VCE)**

| Device Type | Device Voltage Class | Device Name | Device Current Rating at 75/80C | # parallel per switch position |
|---|---|---|---|---|
| MOSFET | 75 | VWM 350-0075P | 250 | 6 |
| MOSFET | 100 | VMM 650-01F | 500 | 3 |
| MOSFET | 200 | VMM 580-02F | 430 | 3 |
| MOSFET | 300 | VMM 300-03F | 220 | 6 |
| IGBT | 600 | BSM150GB60DLC | 150 | 9 |
| IGBT | 600 | CM200DU12F | 200 | 7 |
| IGBT | 1200 | FS450R12KE3 | 450 | 3 |
| IGBT | 1200 | CM200DU24F | 200 | 7 |
| IGBT | 1700 | FS450R17KE3 | 450 | 3 |

**Table 5 Device technologies**

2.2.3.4.3 Converter Design

The following section describes a single stage power conversion design avoiding the high stack input voltage requirements, eliminating conventional pulse width modulation, providing the minimum number of components in the conduction path, retaining full AC rms voltage controllability, and providing a modular structure for high volume production.

SOFC stacks change their internal impedance during their operational life. In order to avoid circulating currents in differently aged stacks each stack must be connected to an individual converter. A central DC bus configuration cannot be implemented without a second power conversion stage.

A single-stage directly coupled dc-to-ac power conversion derived from the multi-pulse GE Battery Energy Storage Systems (BESS) design is proposed. The new system is based on a separation of the DC bus into multiple DC bus channels such that independent DC sources can be connected, an adjustable DC bus voltage for optimum conversion efficiency and system availability, an unique transformer design that can be used for all conversion channels, and state-of-the-art trench gate IGBTs. At least six channels per multi-pulse system, resulting in a 36-pulse system, are needed to comply with existing utility power quality requirements. A higher number of converter channels forms a higher order multi-pulse system improving the power quality. Several multi-pulse systems can be connected in parallel.

The electric diagram of a six channel, independently sourced multi-channel systems is shown in Figure 3. The primary windings of the polygon transformers are connected to individual converter channels. The secondary windings of the polygon transformers are connected in series. There is no additional AC filter needed.

The control over the line harmonics is achieved by the phase-shifted transformers in combination with an adequately phase-shifted square wave converter voltage featuring dedicated phase delays for each converter channel. Control over the output voltage is achieved by (i) controlling the dc bus voltage or (ii) by introducing a notch in the modulation function reducing the effective volts-seconds. A control over the phase angle of the entire system is achieved by shifting the entire phase reference system on which the individual channels derive the phase information.

The controls described above are sufficient to adjust real and reactive power flow (magnitude and direction) as well as the harmonic content of the voltage at the medium voltage side of the transformer.

The details of the converter and the fuel cell interconnection are shown in Figure 4. The fuel cells may be linked to the DC bus converter via a protective circuitry. Details of the over-current and reverse voltage protection circuits are yet to be determined. The selection of the dc bus voltage is based on efficiency and availability criteria. The transformer ratios of the polygon transformers can be adjusted for any desired transformation ratio. Galvanic isolation is intrinsically provided.

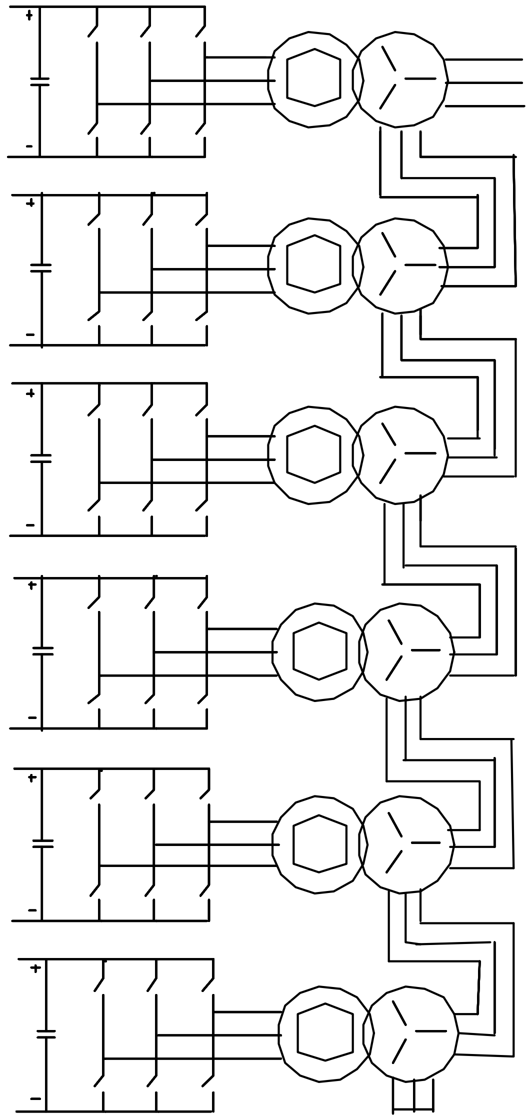


**Figure 3 Six-channel, independently sourced multi-pulse converter**

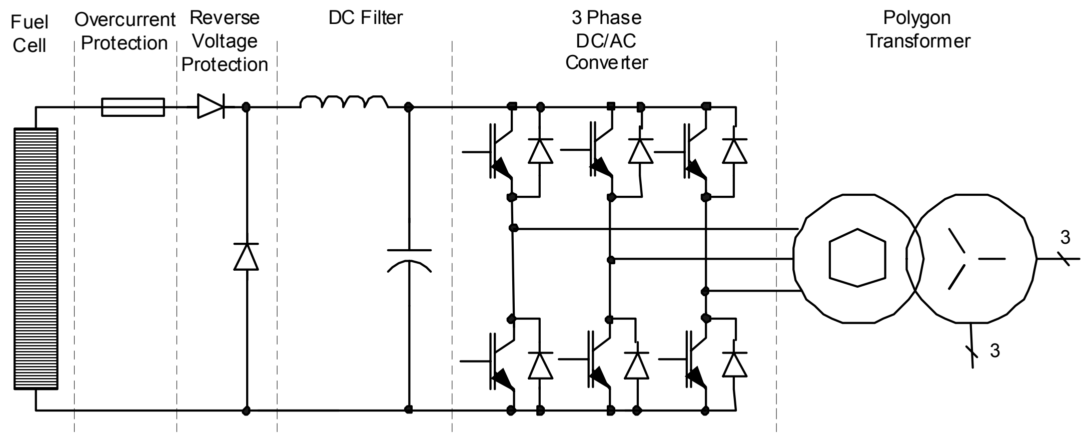


**Figure 4 Primary conversion stage associated with each SOFC stack**

2.2.3.4.4 Plant level layout

The integration of the multi-pulse converters into the 25 MW SOFC hybrid architecture is shown in Figure 5. The system is highly modular, can be installed in phases, and can easily be expanded to higher power levels if grid capacity is available.

At the predicted conversion efficiency, each multi-pulse converter associated with one fuel cell module is designed to provide 1.8 MW of real power (with 6 stacks per module). The maximum apparent converter power capability is 2.1 MVA.

On the turbine side, a gear-less high-speed turbine generator provides the approximately 5 MW. The high-speed generator requires a dedicated DC/AC power converter capable of providing 5 MW power at 300 to 800 Hz fundamental frequency. Partially bi-directional power flow is needed for start-up purposes. Various design options exist for the power converter architecture, the discussion of which are beyond the scope this report. Figure 5 depicts one power conversion system using a similar multi-pulse converter system for the grid connection and a parallel configuration of rectifiers on the generator side. The converter rating is set to 6MVA to support capacitive or inductive power needs.

Each multi-pulse converter system associated with one SOFC module and the high-speed turbine are separately connected to the medium voltage grid. Each generation unit can be disconnected for maintenance. Medium voltage grid voltage and frequency can freely be chosen based on the local needs (10kV to 34.5kV, 50Hz/60Hz). The entire system can only handle base load operation. The ramp up times for both the fuel cell and the gas turbine are too large to follow quick load changes.

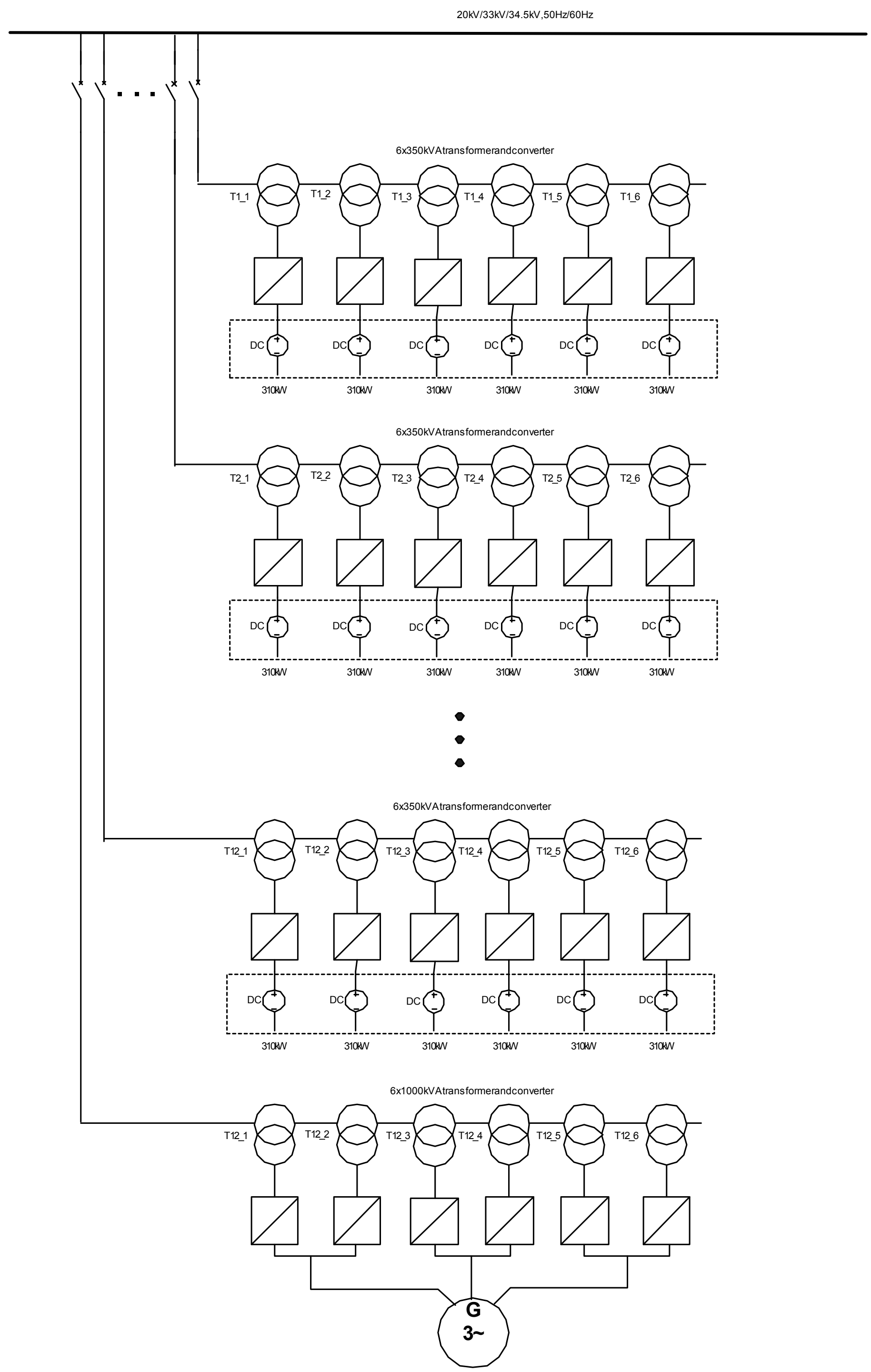


**Figure 5 Power conversion arrangement of one sub-module using multi-pulse converter**

2.2.3.5 25 MW plant stack building block selection

Summarizing the results of stack cost optimization and power electronics subsystem loss studies, the optimal SOFC stack configuration for a 25 MW hybrid plant has 400 cells 45.7 cm (18 inches) in diameter. Assuming cell power density of 0.5 W/cm$^2$, this SOFC stack size translates into a 320 kW stack power. Given the 20 MW total SOFC stack subsystem power requirement, a minimum of 62 stacks will be required to construct the 25 MW hybrid plant. Assuming that the SOFC stack subsystem will be divided into modules of 8 stacks each, a minimum of 8 modules will be required for the 25 MW hybrid plant.

Note that the stack cost optimization study showed that the stack cost is relatively flat in the 30-60 cm cell diameter range. This translates into a 135-550 kW SOFC stack building block power range and a 5-19 range for the number of the eight-stack modules.

2.2.4 25 MW plant reliability projections

As a base-loaded, multi-megawatt power generator, the hybrid SOFC power plant has high reliability and availability requirements. The plant specifications call for 98% reliability and 97% availability. This requires careful system design with reliability in mind. The plant is divided into multiple power generating blocks. The multiplicity provides challenges for control system design, but it could be advantageous from the reliability viewpoint. Redundancy could be added in the plant, providing slightly most cost but enormously more benefit in terms of reliability, availability and maintainability.

2.2.4.1 Operability scenarios

Given the multi-stack nature of the power plant, one obvious way to design for reliability is to add redundant stacks in the plant. The stacks are pressurized, and hence located inside pressure vessels. For cost reduction, multiple stacks are placed inside one insulated and pressurized container. A number of stacks inside a single pressure vessel is called a module. In the present designs, the air entering the module and exiting the module is provided with on-off valves, which could be used to isolate a module hermetically from the rest of the plant. Once inside the module, the air is distributed in and out of the stacks by large diameter manifolds. No additional valves are provided in the air path, in order to reduce costs. The air could be used to provide a source for pressurization and heating for the stack. The fuel flow, on the other hand, is individually controlled in this design. Thus, the amount of fuel that flows in and out of each stack is controlled. So when a stack does not produce power, little or no fuel could be flown through it. This flexibility provides enough opportunity to draw different redundancy scenarios with the extra stacks.

Three practical redundant configurations along with maintenance schemes are described below. These three schemes were considered for this analysis. To make comparisons meaningful, each of the following power plant configurations consists of the same number of fuel cell stacks; i.e., 72 fuel cell stacks, distributed equally in a pressure vessel (fuel cell module).

Other redundant designs can be formed with combinations of these 3 schemes.

2.2.4.1.1 Scheme A – Standby Redundancy

The configuration is shown is the following Figure 6.

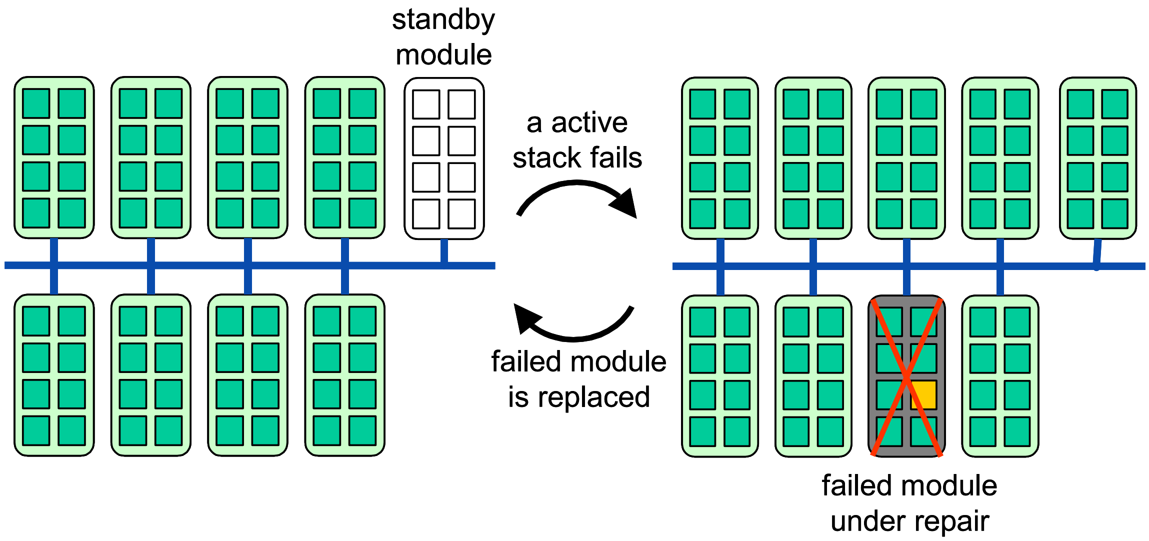


**Figure 6 Standby redundancy (Scheme A)**

Eight fuel cell modules (each of which is made up of 8 fuel cell stacks) operate fully and 1 fuel cell module is powered off or in standby in the normal operation mode. An outage of any stack in any active module will lead to switching off one entire working module and starting/switching in the standby module. The failed module will be under restoration immediately.

This scheme is said to be operating in an N+I redundancy mode if there are N active modules and I stand-by modules.

2.2.4.1.2 Scheme B – Parallel Redundancy

This design is shown in the following Figure 7.

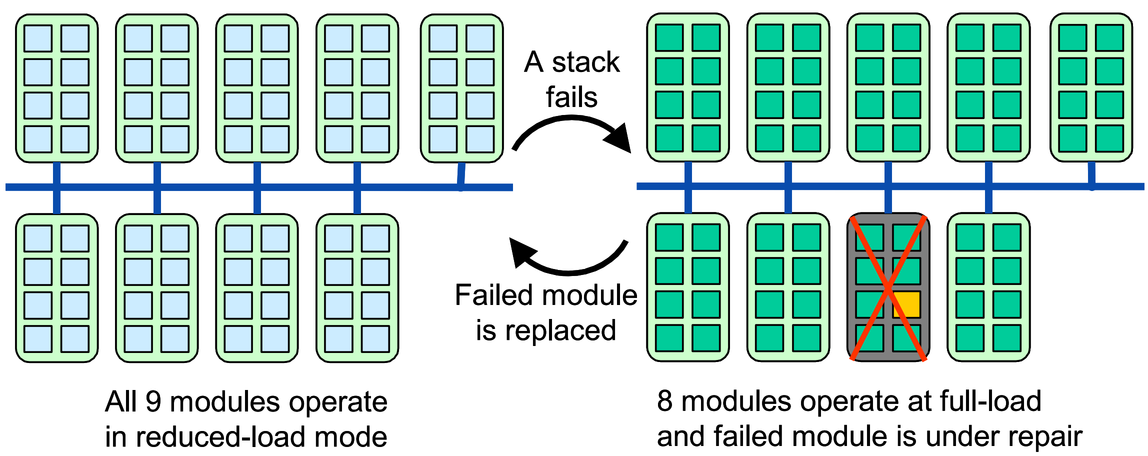


**Figure 7 Parallel redundancy (Scheme B)**

All 9 modules are powered up, but operate in a reduced-load mode, during normal operations. Whenever a fuel cell stack fails, the entire module will be switched off and the remaining 8 modules will be fully loaded to compensate for the deficit from the failed module. The failed stacked is under repair immediately and put back once it's fixed. After that, normal reduced load operation is resumed.

This scheme is said to be operating in an N+I redundancy mode if the required number of modules is N but the number of active modules in the normal operating mode is N+I.

2.2.4.1.3 Scheme C – Enhanced Module

Instead of having a redundant module as shown in the designs above, an extra fuel cell stack is put into each module. System configuration is shown in the following Figure 8.

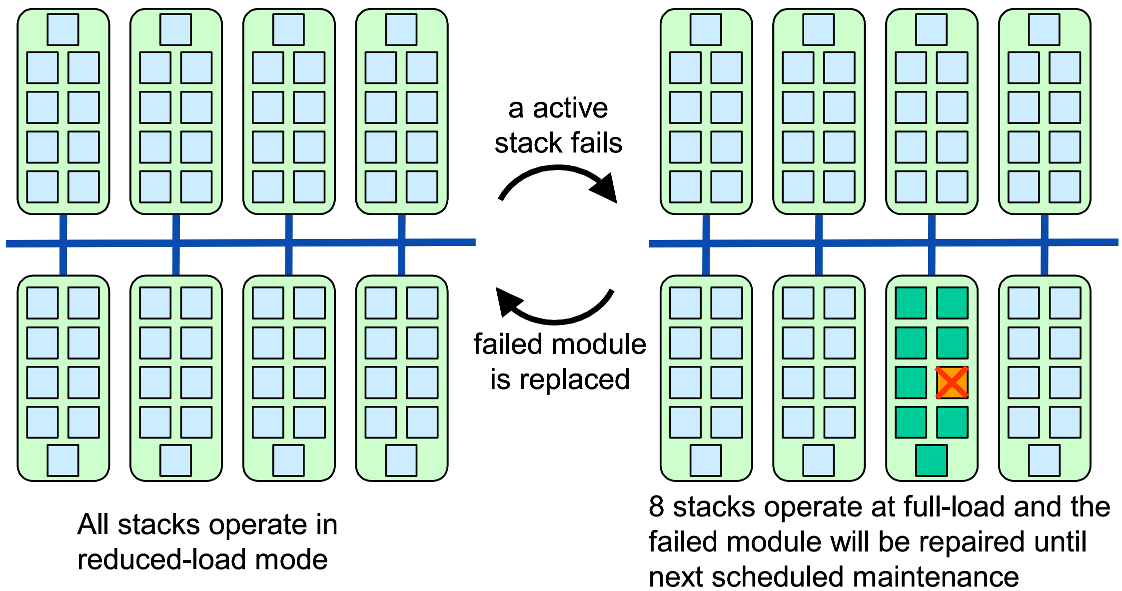


**Figure 8 Enhanced redundancy (Scheme C)**

All stacks normally operate in the reduced load mode. The failure of a stack leads to the remaining stacks in that degraded module working at full load, and failed stack will be replaced upon next maintenance interval. After being fixed, it will be put back into service.

This scheme is said to be operating in an N+I redundancy mode if the required number of stacks per module is N but the number of active stacks per module in the normal operating mode is N+I.

2.2.4.1.4 Reliability Comparison

The power plant reliability of 3 schemes above have been modeled precisely and analyzed, using the commercially available software BlockSim™. To compare the three scenarios, only the assembly of fuel cell stacks are considered – the balance of plant or the bottoming cycle is not considered at this stage. The assumptions for the analysis are given as follows.

- A fuel cell stack has a MTTF of
    - 40,000 hours at full load,
    - $MTTF\_stack \propto load^{-1}$ or 45,000 hours at 8/9 full load
- MTBF is not a function of anything other than the stack power level
- Average repair time is 72 hours
- Scheduled maintenance interval is 6 months
- Stacks within a module operate independently
- Modules are independent of each other. There are no common failure modes across the modules.
- Both “time to fail” and “time to repair” are exponentially distributed

2.2.4.1.5 N+1 redundancy results

The MTBF of 3 scenarios are listed below in Table 6. It should be kept in mind that this is the MTBF of the assembly of the stacks, arranged in modules. To that extent, these numbers are artificial, but they do help distinguish between the scenarios.

| | Power Plant MTBF (hours) |
|---|---|
| Scheme A - Standby Redundancy | 4,647 |
| Scheme B - Parallel Redundancy | 6,054 |
| Scheme C - Enhanced Module | 3,151 |

**Table 6 Mean time between failure (MTBF) for N+1 redundancy case**

From the results it is seen that

- Scheme B is the most effective way to introduce redundancy with maintenance schedules among these 3 configurations.
- The absolute MTBF is rather small for all the three scenarios. More degrees of redundancy are needed to achieve the desirable reliabilities.

Since the Scheme B is the most efficient way of redundant arrangement, the rest of report will focuses on this scheme only.

2.2.4.1.6 N+2 redundancy results

To further improve the plant reliability, N+2 level redundancy has been investigated. The following Table 7 shows the MTBF at different redundancy levels, using the previous assumptions. Only Scheme B is reported.

| | Power Plant MTBF (hours) |
|---|---|
| N+0 (no redundancy) | 625 |
| N+1 redundancy | 6,054 |
| N+2 redundancy | 105,927 |

**Table 7 Redundancy trade study**

The N+2 level of redundancy shows a significant jump in plant reliability from the N+1 level. With 2 extra modules in place and a repair made immediately after a failure, a power plant maintains a redundant configuration almost all the time. The plant is down only if at least 3 modules fail within a repair-time window, which has a very low probability unless there is a common failure cause. In short, the Scheme B with a N+2 level of redundancy may be able to provide a SOFC power plant with a satisfactory level of reliability.

2.2.4.2 Reliability optimization and cost effects

Having selected Scheme B with N+2 redundancy as the best candidate for a 25 MW class hybrid SOFC power plant, several trade-off studies could be performed.

2.2.4.2.1 Number of modules in plant

A 25 MW plant would need several building blocks, defined as stacks of a certain nominal power output. These stacks must be divided in modules to lower capital costs. Based on reliability considerations, the optimum number of stacks per modules, and hence modules per plant, could be determined. A schematic of this grouping procedure is shown in Figure 9 below.

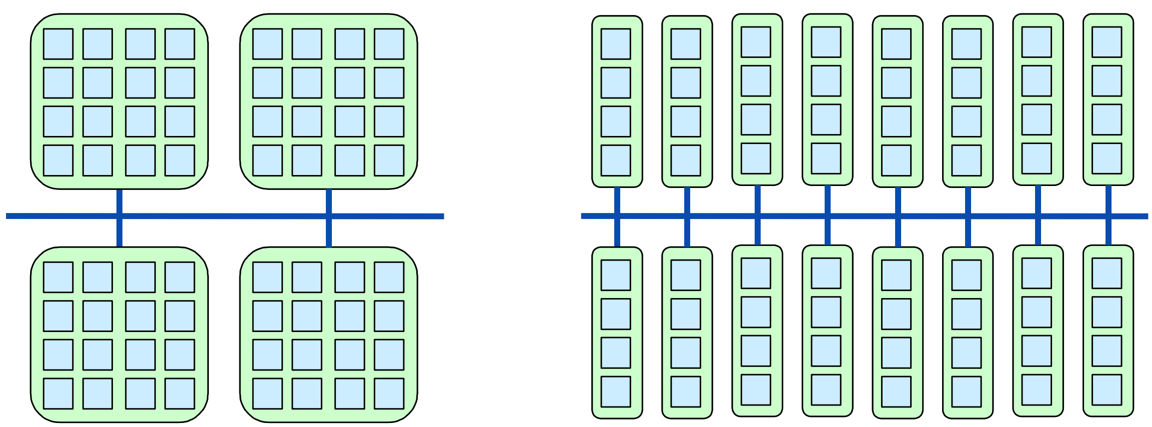

**Figure 9 Building block grouping scenarios**

Thus, a 64-stack plant could be divided in 4 modules with 16 stacks each or 16 modules with 4 stacks each, amongst other possibilities.

Results for stack assembly MTBF for different sized modules are given in Figure 10 below. These results correspond to Scheme B, using the same data as the previous section. Both N+1 and N+2 redundancy situations are shown.

It appears that there is an arrangement that maximizes the MTBF for the stack assembly. This is intuitively clear, as seen in the figure above. In Scheme B, failure of one stack requires the shut down of the whole module containing the failed stack, while raising the load in the operational stacks. In the left hand side scenario, this means a much-increased load for the remaining stacks, since a large number of stacks have to be shut down. On the right hand side scenario, however, there are too many modules, so the probability of all of them working at the same time is relatively smaller. Thus, there is an optimal arrangement.

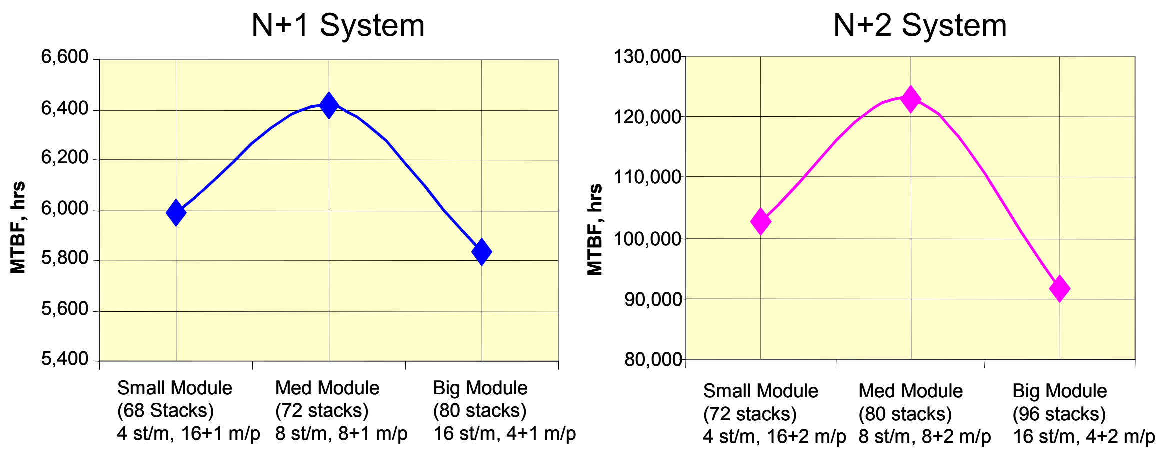


**Figure 10 MTBF analysis for N+1 redundancy cases**

2.2.4.2.2 Cost penalty of redundancy

Increasing the number of redundant modules improves the system reliability but at the same time increases the cost as shown in Table 8, below. The choice of 2 redundant modules in the base case meets the cost requirements and at the same time provided satisfactory system reliability.

| Number of redundant modules | Cost/kW | Total cost (M$) |
|---|---|---|
| 0 | 292.76 | 7.319 |
| 1 | 305.08 | 7.627 |
| 2 | 317.40 | 7.935 |
| 3 | 329.72 | 8.243 |

**Table 8 Cost of redundancy**

2.2.4.3 Cell reliability effects on optimal cell size selection

The plant MTBF strongly depends on the stack MTBF. However, stack MTBF could depend on cell size, since the number of defects in ceramic components is expected to depend on the component surface area. Most, but not all, of the defects are caught during cell QC and are accounted for in the stacking yield. Thus the failure mechanisms are cell area dependent, causing the MTBF to decrease with the cell area. Better understanding of failure mechanisms may lead to stack designs that could diminish the dependence of cell MTBF on cell size

No experimental data is currently available for proving how the reliability assumptions matter for the cell size selection. In order to investigate the impact of the cell size on the stack MTBF we assumed the following 4 scenarios:

- MTBF independent of the area
- MTBF increases 5% with the cell area
- MTBF decreases 15% with the cell area
- MTBF decreases 26% with the cell area

Figure 11 shows the assumed dependence of the stack MTBF as on the cell size for the above scenarios.

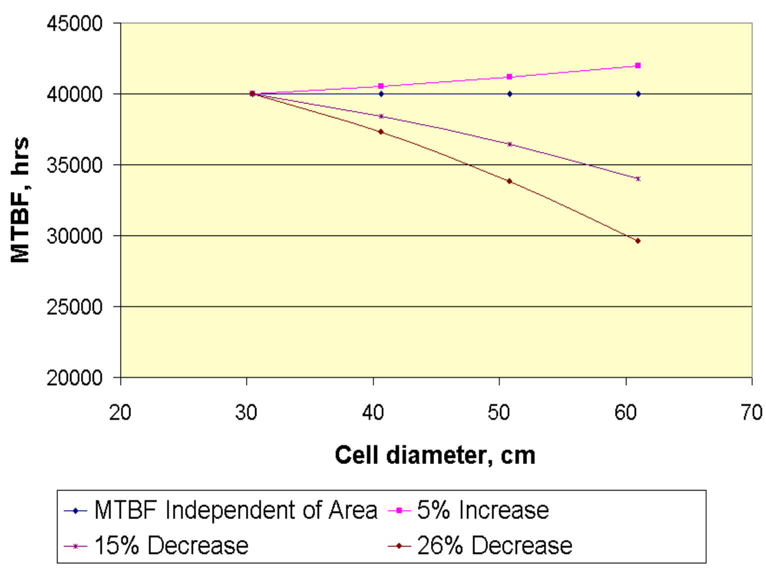


**Figure 11 Stack mean time between failures as a function of cell diameter**

Using the above assumptions, stack MTBF could be rolled up into plant MTBF. The impact of cell size on overall plant reliability for Scheme A (no redundancy) is shown in Figure 19.

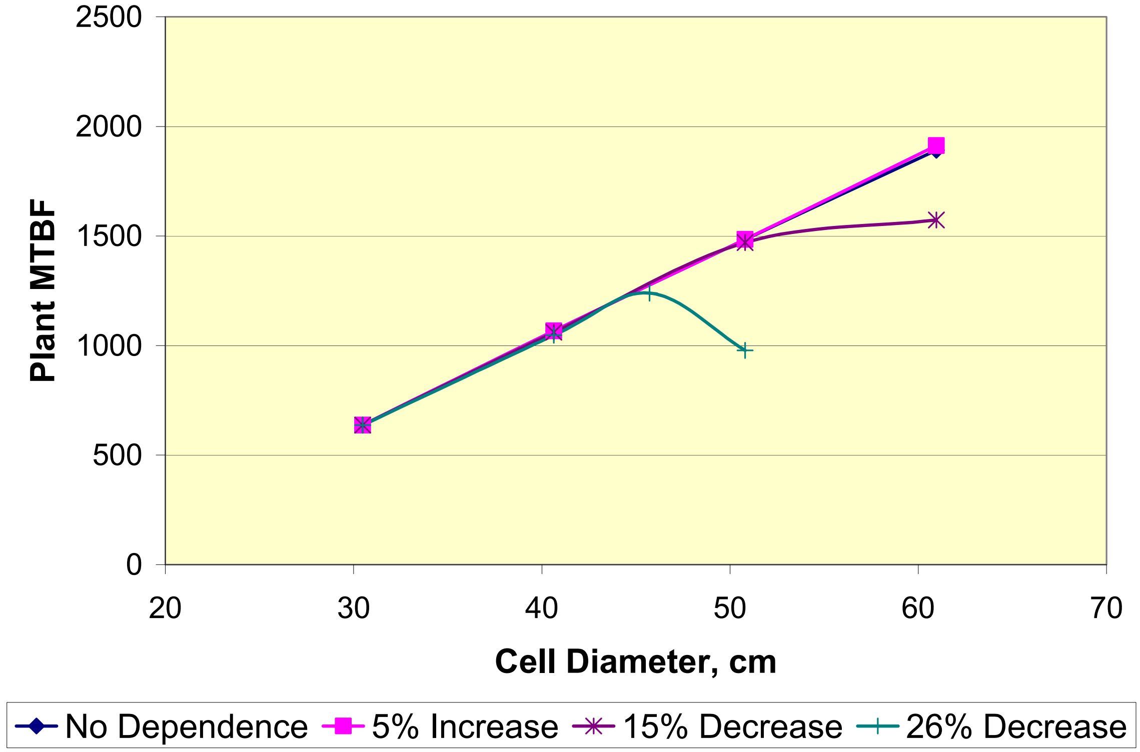


**Figure 19 Plant mean time between failure as function of cell area results (assuming a 25 MW plant with no redundancy using scheme A)**

As cell size increases, the number of stacks needed in the plant to produce 20 MW decreases. This is the main reason why the plant MTBF increases with cell size. In fact, if the cell reliability is independent of the cell size then the cell size should be chosen as large as the system cost goal allows. However, the cell reliability may be a strong function of the cell size. Therefore, beyond a certain size, the stack MTBF could be low enough to have a negative impact on the plant MTBF, as shown in Figure 19.

Recall that the optimal cell size was determined solely by minimizing the SOFC stack cost. Other constraints however may limit the cell size. In particular, Figure 19 shows that there can be reliability constraints on the cell size. For example, if the cell MTBF falls by more than 26% from cell diameter of 30.5 cm (12 inches) to cell diameter of 60.96 cm (24 inches) then cell diameter of 45.7 cm (18 inches) is sub-optimal because it leads to sub-optimal plant MTBF in Scheme A. Since there is very limited data on cell reliability in the size range of our interest, it is impossible to factor the cell reliability constraints into the cell size selection process. However, it must be recognized that the size reliability effects must be taken into account when the cell reliability data is available.

A similar study was done on the down selected arrangement of Scheme B with N+1 redundancy, with MTTR=72 hrs, Figure 12.

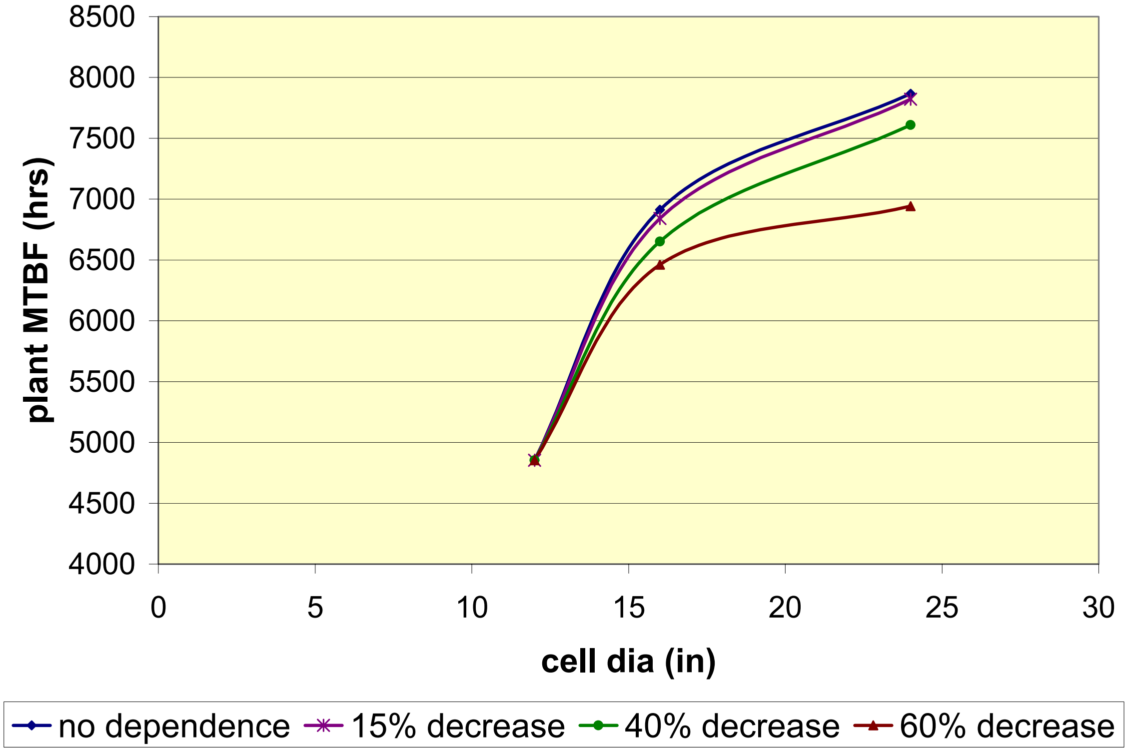


**Figure 12 Plant mean time between failure verses cell area results (assuming 25 MW plant with N+1 redundancy using scheme B)**

It could be seen that even with a 60% decrease in stack MTBF, the plant MTBF does not decrease with cell size. This is a further testimony that Scheme B is more robust than Scheme A.

### 2.2.5 25 MW plant component selection

Table 9 presents a list of major components of the 25 MW plant design. The performance, cost and reliability studies of the 25 MW hybrid plant have yielded the optimal cell, stack and module sizes. The gas turbine and balance of plant components were sized using the design point analysis. Some additional considerations were taken into account as follows.

- One gas turbine per system is preferable because the gas turbine component efficiencies and costs both improve with increasing size.
- Pre-reformers have economies of scale that result in one pre-reformer per system being the preferable configuration. However, reliability Scheme B selected in the study calls for an isolation of the module with a failed stack and subsequent maintenance. The procedure requires that fuel flow to the failed stack be temporarily cut off. The most efficient way to isolate individual stacks is to use a cold-temperature valve at the inlet of the pre-reformer that feeds the failed stack, which requires one pre-reformer per stack. Even though there is a

cost penalty associated with building many small pre-reformers rather than a fewer number larger pre-reformers, the savings from placing cold-temperature valves on the natural gas side instead of high-temperature valves on the reformate side make up for it.

| Part | Quantity | Comments |
| --- | --- | --- |
| Gas Turbine & Auxiliaries | 1 | |
| Recuperator | 1 | |
| Pre-Reformer | 80 | One per stack |
| Blower | 1 | |
| Ejector | 80 | Part of pre-reformer |
| SOFC Stack | 80 | |
| Pressure Vessel | 10 | One per module |
| Burner | 1 | |
| DC-AC Inverter | 80 | One per stack |
| Small Transformer | 10 | One per module |
| AC-AC Inverter | 1 | |
| Cathode Isolation Valves | 10 | |
| Anode Isolation Valves | 10 | |
| Start up Valves | 2 | |
| Fuel Preheater | 1 | |
| Water Pump | 1 | |
| Water Tank | 1 | |
| Steam Generator | 1 | |
| Fuel Compressor | 1 | |
| Desulfurizer | 1 | |
| Main Fuel Shut-off Valve | 1 | |
| Switch Gear | 10 | One per module |
| Control Box | 1 | |
| Start up Auxiliaries | | |
| Instrumentation | | |
| Cold Piping | | |
| Hot Piping | | |

**Table 9 List of major components for 25 MW SOFC-gas turbine hybrid plant**

2.2.6 25 MW plant manufacturing cost projections

Our analysis with baseline yield assumptions and a 45.7 cm (18”) diameter cell results in a $317/kW system manufactured cost, Figure 13, which is significantly below the $400/kW goal. SOFC stacks are the main driver of the system cost reduction, as they comprise 36% of the system cost. Recall that a 0.5 W/cm$^2$ was assumed in cost analyses. In fact, the fuel cell power density can be as low as 0.305 W/cm$^2$ and still enable the system design to achieve the $400/kW cost target. Figure 14 shows the system cost breakdown for the 0.305 W/cm$^2$ case that results in a $400/kW system cost.

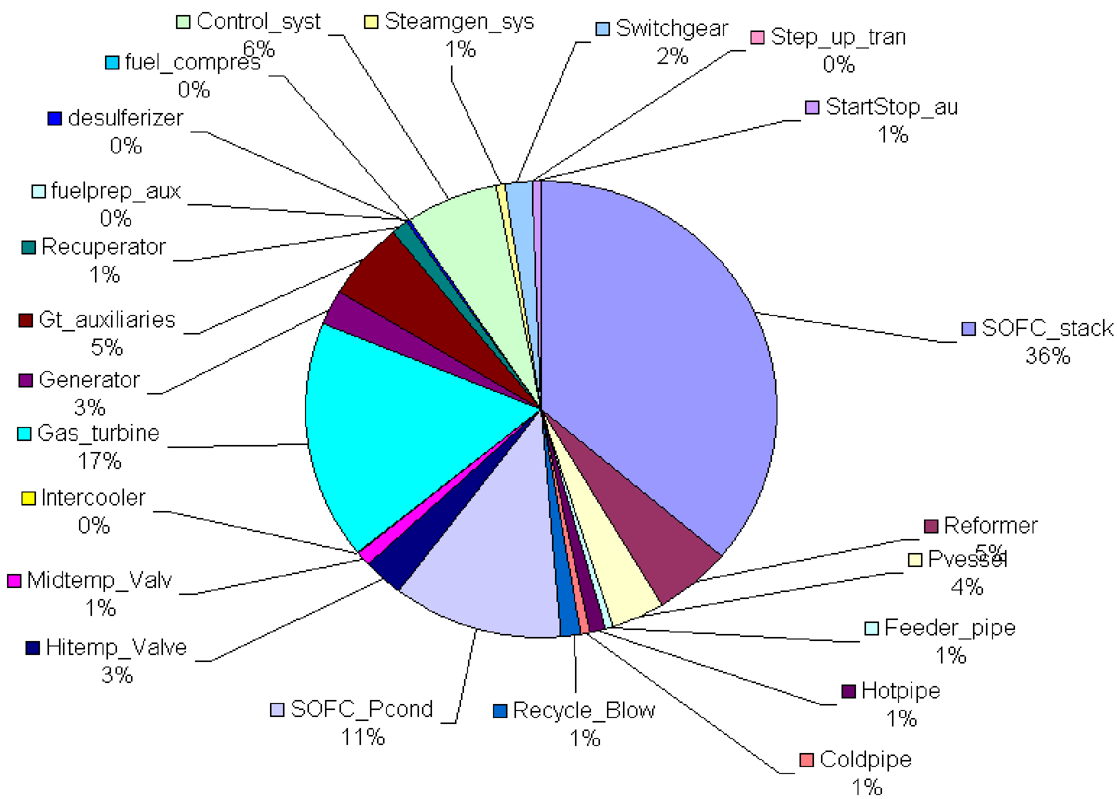


**Figure 13 Plant cost breakdown assuming 25 MW hybrid plant with baseline cost assumptions and cell current density of 0.5 W/cm$^2$, system specific cost = $317/kW**

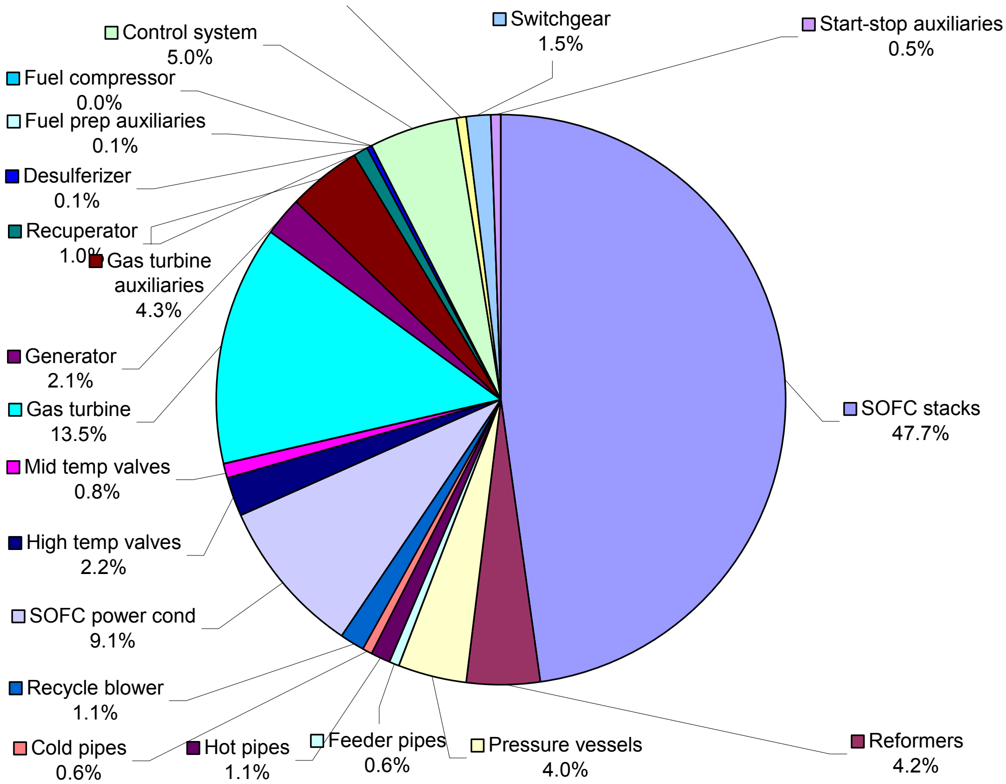


**Figure 14 Plant cost breakdown assuming 25 MW hybrid plant with baseline cost assumptions and cell current density of 0.305 W/cm²**

### 2.2.7 Discussion of system size effects

The discussion has so far concentrated on the 25 MW plant design. The design methodology is likely applicable to a range of system sizes. Note that the product specification was adopted from the central power generation market application and is valid for a range of system sizes up to hundreds of megawatt. The next section will address the applicability of the SOFC building block design to the system power rating range 5-250 MW. System performance, size and reliability effects in this range will also be analyzed.

#### 2.2.7.1 SOFC stack building block selection

The analysis in section 4.2.3 identified the optimal stack size for the 25 MW hybrid plant. The optimization process found the cell size that minimized the stack cost and the number of cells per stack that minimized the power conditioning losses while addressing stack reliability issues. These two optimization problems are independent of each other and, more importantly, independent of the system size. The stack cost will be minimized independent of whether the system power rating is 25 MW or 250 MW. Similarly, the power electronics loss per stack is minimized independent of the system size. However, a minimized stack cost and power electronics loss-per-stack do not necessarily mean that the system cost and system power electronics are minimized with the same stack building block. The differences between the smaller and larger systems need to be examined.

For example, let us consider a 250 MW hybrid plant. If the same stack and module building block sizes as those in the 25 MW hybrid plant are assumed, then the 250 MW hybrid plant would have ten times the amount of hot piping. As Figure 13 and Figure 14 show, hot piping comprises only about 1% of total system cost, which is dominated by the SOFC stack subsystem cost. Therefore, the increase in hot piping length with system size increase should not significantly affect the optimal cell size that minimizes the SOFC stack subsystem cost and hence, the system cost. The stack block of 400 cells 45.7 cm (18 inch) in diameter is still the optimal stack building block for the 250 MW plant as well.

Similarly, a 5 MW hybrid plant can also use the same stack design as the building block. In fact, the smallest system size for which the module block of eight 320 kW stacks can be used as a building block is about 1.3 MW. The 1.3 MW plant however will only have one module and therefore, the operability Scheme B cannot be applied to this system. Reliability and operability considerations will determine the minimum system size for which the stack and module blocks can be used. Section 4.2.7.3 will examine system size effects with respect to reliability.

#### 2.2.7.2 Performance size effects

Hybrid plant performance at the design point depends on component efficiencies, pressure drops, and heat losses. The component efficiencies are generally functions of component size. The pressure heat losses usually decrease with system size because the system component surface area increases more slowly than the system component volume.

The hybrid plant SOFC efficiency does not change with the system size because the stack and module building blocks do not vary with the system size. The gas turbine component efficiencies on the other hand do depend on the system size. In general, the compressor and turbine efficiencies increase with size. Similarly, natural gas compressor efficiencies also increase with component size. Using GE's projected components efficiencies, it can be shown that the efficiency of a 250 MW hybrid plant is 67.7%. This efficiency is about 1.7 percentage point higher than the 25 MW plant efficiency due to higher turbomachinery component efficiencies and a lower heat loss.

Similarly, the system efficiency of a 5 MW plant will be lower than that of the 25 MW plant. A system performance analysis shows that the 5 MW plant efficiency is about 65.1%, about one percentage point lower than that of the 25 MW plant due to lower component efficiencies and a higher heat loss.

#### 2.2.7.3 Reliability projections

The proposed layout of 6 or 8 stacks per module and 12 or 8 modules in the plant is specific to the 20 MW plant size, which needs about 64 standard sized (320 kW) stacks, plus 16 redundant stacks. For a smaller plant, the building blocks or the stacks will stay the same in size. This is because the considerations that led to the selection of this specific stack size (power electronics and cost considerations) are not linked to the plant size. However, the layout for a smaller plant will be different. Given that N+2 redundancy is needed to meet the availability criteria, smaller plants would tend to have fewer stacks per module.

Let us consider a 5 MW class hybrid power plant, where about 3.5 MW of power is generated by the SOFC stacks. This plant would require about 12 standard sized stacks in full load operations. If there are 4 stacks per module, the plant would have a total of 20 stacks, including redundancy. On the other hand, for 2 stacks per module, the plant would have only 16 stacks, including redundancy. Although the cost of the pressure vessels and pipes would be larger in the later arrangement, the savings in the stacks, which tend to be the biggest cost item in the plant , would largely offset this additional cost. For very small systems (1 MW or less), if the availability criterion is relaxed, it is conceivable that the whole set of stacks would be contained in a single pressure vessel to keep cost to a minimum.

Similar reasoning could be applied for larger systems. The building blocks stay the same in size. The stack count in the module would tend to go up for optimal cost. However, a limit might be reached in terms of power conditioning capability. In the power electronics layout proposed in this study, there is a single transformer per module. For a large number of stacks per module (10 plus), this transformer would be required to handle very large currents, which would lead to high costs. Correspondingly, the cost of the insulated pressure vessel, which scales with the vessel volume, would keep going up. Thus, beyond about 10-12 stacks per module, the cost benefits from stack arrangement would be offset by rising BOP costs.

#### 2.2.7.4 Cost projections

The SOFC stack subsystem of larger hybrid systems consists of the same stack and module building blocks as the 25 MW hybrid system's SOFC stack subsystem. A hybrid system with the power rating larger than 25 MW is built by adding more SOFC modules. Since the cost of SOFC stack modules dominates the SOFC stack subsystem cost, the SOFC stack subsystem shows no economies of scale, i.e. its cost per kW stays virtually constant with varying system power. The same cannot be said however about the gas turbine and balance-of-plant components, which generally show strong economies of scale. For example, the system cost analysis of a 250 MW shows that the system specific cost declines to $260/kW (Figure 23).

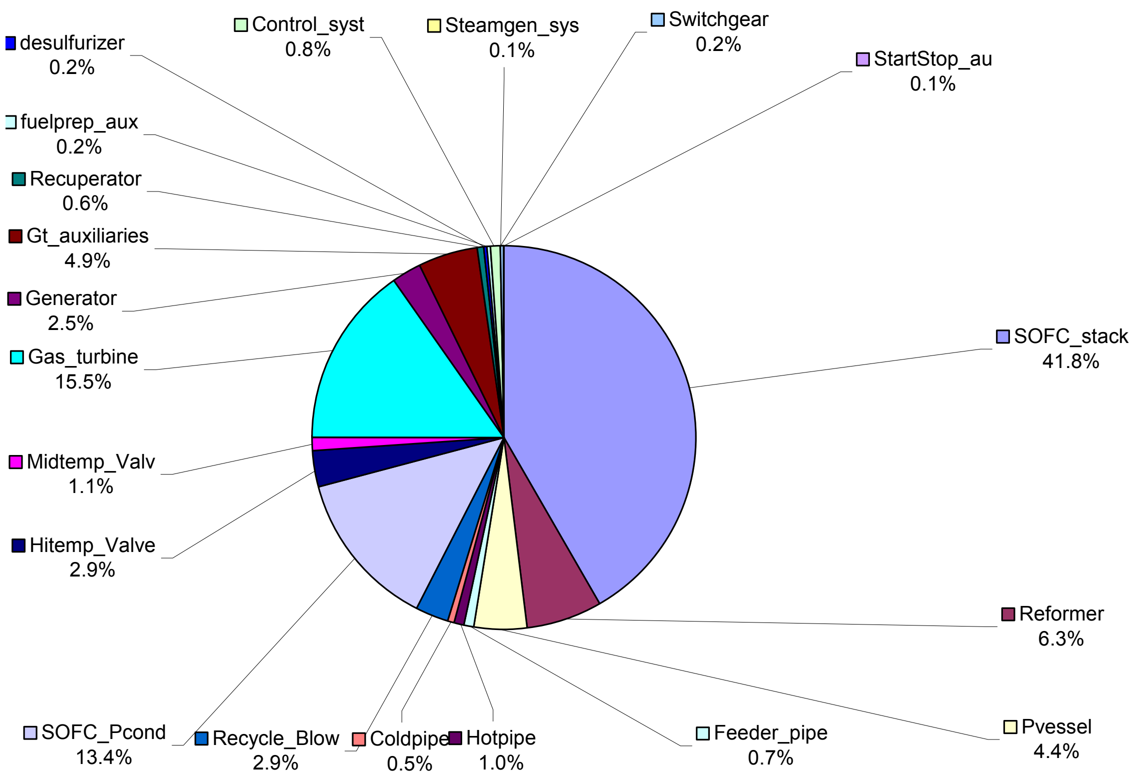


**Figure 23 System cost breakdown for a 250 MW hybrid plant, plant manufactured cost = $260/kW**

Similarly, the specific cost of a hybrid system with the power rating of lower than 25 MW is higher than that of the 25 MW hybrid system. For example, Figure 24 shows that the system specific cost of a 5 MW hybrid system is $512/kW.

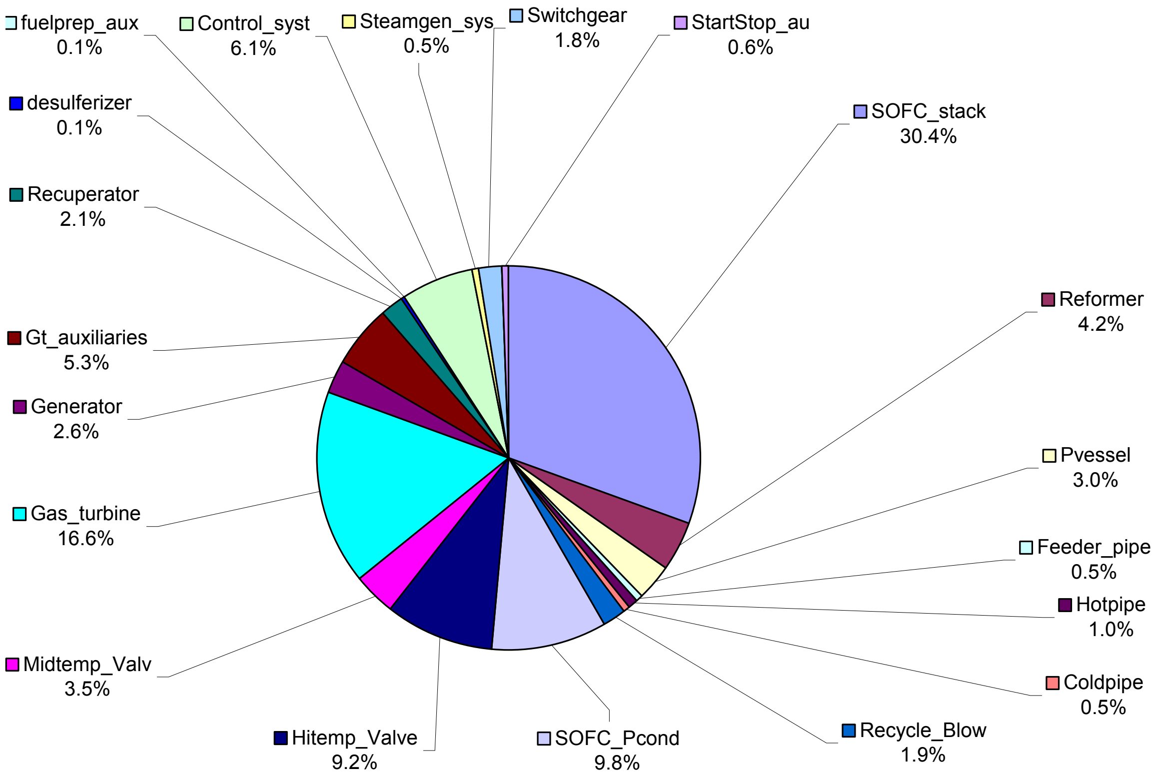


**Figure 24 System cost breakdown for a 5 MW hybrid plant, plant manufactured cost = $512/kW**

### 2.2.8 25 MW hybrid system operation on coal gas

The 25 MW hybrid system design permits operation on coal gas with some modifications to the plant. The coal gas may be supplied from an outside coal gasification system. A typical coal gas composition is shown in Table 13. Since the coal gas contains methane in concentrations acceptable to SOFC, there is no need for additional fuel reforming. Therefore, pre-reformers and the associated piping and valves can be removed from the plant and replaced by coal gas piping and interfaces. The rest of the hybrid system design, including the SOFC stack subsystem and the gas turbine, requires no modification. The amount of coal gas flow to the hybrid plant is limited by the cooling capacity of the air supplied by the gas turbine compressors. In the analysis presented in this section, the coal gas flow to the system was adjusted to meet but not exceed the SOFC stack subsystem air temperature rise and temperature out constraints.

The result of a performance analysis of such a plant is shown in Table 14. The analysis shows that the power produced in the SOFC stack subsystem is lower than that of the natural-gas-fueled 25 MW hybrid plant, 11.2 MW vs. 20 MW. The drop-off in the SOFC power can be attributed to the following two factors. (1) The SOFC single-cell voltage drops below the design assumption of 0.7 due to lower concentration of usable fuel in coal gas. Our calculations showed that the single-cell voltage for the coal gas composition shown in Table 13 declines to 0.6V. The lower single-cell voltage results in a lower SOFC power. (2) The coal gas methane concentration at the SOFC stack inlet is only 3.1% compared to 16.1% for the natural-gas-fueled system. The internal reforming reaction of methane in the SOFC stacks serves as an additional cooling mechanism and reduces the cooling requirement imposed on the cathode air. For a fixed gas turbine size and therefore cathode airflow, the smaller amounts of methane in the fuel inlet translates into a lower amount of the total fuel flow that the SOFC stack subsystem can convert to electricity without violating the SOFC stack subsystem air temperature rise and temperature out constraints. Hence, the system operating on coal gas has a lower capacity to convert useful LHV in the fuel stream into electricity than the natural-gas-fueled system due to a lower stack-inlet methane composition, resulting in a lower SOFC stack power.

Table 14 shows that the gas turbine power in the coal-gas-fueled hybrid is 9.5 MW compared to 7.8 MW in the natural-gas-fueled hybrid plant. The reason for this increase is a higher turbine mass flow in the coal-gas-fueled hybrid plant compared to the natural-gas-fueled hybrid plant due to a higher concentration of $CO_2$ and water in the fuel composition, resulting in a higher turbine mass flow.

The coal-gas-fueled plant efficiency is about 69%. Note that this efficiency does not include the losses for converting the fuel (coal) to the SOFC stack subsystem fuel feed. Coal gasifiers typically have efficiencies in the 70-80% range, where the gasifier efficiency is defined as (LHV of gasifier output)/(HHV of coal feed). Factoring in the gasifier efficiency, the total coal-fueled plant efficiency of the plant is in the 48-55% range.

| Stream Component | Molar Fraction |
|---|---|
| $H_2$ | 0.0348 |
| $H_2O$ | 0.293 |
| $N_2$ | 0.0224 |
| $CO_2$ | 0.445 |
| $CH_4$ | 0.0314 |
| CO | 0.173 |

**Table 13. Coal gas composition (BGL gasifier output on Pittsburgh 8 coal)**

| **Component** | **Power Produced (Consumed), kW** |
|---|---|
| SOFC Stack Subsystem | 11186 |
| Gas Turbine | 9353 |
| Blower | (1549) |
| Fuel Compressor | N/A |
| Net Power | 17977 |
| **System Efficiency** | **69%** |

**Table 14. Performance analysis results of a 25 MW hybrid plant fueled by coal gas**

# 3 TECHNOLOGY GAPS AND DEVELOPMENT STRATEGY

The hybrid plant design developed in this study requires cell size scale up, stack pressurization and operating plant components at high temperatures. It is not feasible, at present, to realize the plant concept presented in this report because significant technological gaps exist in certain areas, primarily in SOFC technology. Moreover, in other areas, existing products must be extensively re-engineered to achieve the desired objectives. This section lists the gaps and development requirements that must be closed to enable feasibility of the plant concept.

## 3.1 Technology gaps

### 3.1.1 SOFC Seals

One of the biggest risks embedded in the system design presented in this report is the availability of the SOFC seals. The seals are essential to enable the cathode and anode recycling that significantly increases the system efficiency and reduces the plant cost. The seals must operate at temperatures above 1400°F. Analyses show that seal leakage must be limited to less than 10% of fuel flow rate. No feasible seal solution exists today, a significant effort is required to develop seal materials and cell and stack designs that would satisfy the sealing requirement.

### 3.1.2 SOFC Power Density

With the current set of materials widely in use, YSZ for electrolyte, LSM-YSZ for cathode and Ni-YSZ for anode, the entitlement for reaching the power density target of 300 $mW/cm^2$ or higher at 0.7 V exists without a doubt. However, improved understanding of materials and microstructures is needed to meet or exceed the performance goals. For instance, optimizing the composition and microstructure near the interfaces for improved electrochemical activity can help reduce activation polarization at the electrode/electrolyte interfaces. Though the pressure helps in improving the diffusion polarization, work needs to be done to engineer the microstructure for better gas access to the electrodes. Another area of significant importance that needs better understanding and improvement is the ohmic drop across various interfaces, especially the interconnect/electrode interfaces. Concentrated efforts need to be made to reduce the ohmic drop across these interfaces for improved performance as well as reliability. Possible studies include new interconnect materials with low degradation rates and improving the characteristics of current collection layers at the interconnect/electrode interfaces.

### 3.1.3 Cell Size Scale up Feasibility

Present study indicates that a cell size of 45.72 cm (18 inches) diameter is needed for optimized stack cost. Reported state-of-the art in cell size for planar stacks tested worldwide is as follows: Mitsubishi Heavy Industries, Japan (20 cm x 20 cm); Fuel Cell Energy, USA (15 cm or 5.9 inch diameter); Julich, Switzerland (20 cm x 20 cm); Ceramic Fuel Cells Limited, Australia (13 cm diameter); General Electric, USA (20.32 cm or 8 inch diameter); and Indec, Switzerland (15.6 cm or 6.13 inch diameter). The cell size needs to be scaled up more than 100% from the best one available today. As cell size scales up, the influence of cell area on mechanical properties and electrochemical properties need to be understood. General Electric has recently demonstrated cell size scale up to 30.48 cm (12 inches) diameter on anode-supported cells using the tape calendering method but more effort is needed to understand the yield, strength and performance of these large area cells. Interconnect supported cells using deposition techniques have also been proposed but much gap remains to be filled regarding the cost and performance. Efforts need to be directed in electrochemical and stress and thermal modeling to define cell configurations capable of high electrochemical performance and strength. For electrochemical performance remaining the same, yield data needs to be collected as a function of cell size to validate/refute the cost model assumptions used in this study. With the help of modeling, process development efforts would be needed in the area of cell manufacturing to demonstrate the feasibility of manufacturing large size cells. To reduce labor costs, this study further assumes continuous manufacturing as opposed to batch manufacturing that is currently being used in the industry. Hence, routes to continuous manufacturing of SOFC cells need to be explored to achieve the cost targets.

### 3.1.4 Stacking Improvements

For this study, a stack design currently in use for the DOE SECA program was chosen for concept down selection. However, for a stack building block of 320 kW using large cells, many stack design issues, such as stresses, pressure drop, leakage and thermal gradients, need to be understood as a function of cell size. For instance, the interconnect design and/or cell-to-cell manifolds may need to be optimized to take care of differences in temperature gradients and gas flow rates at larger cell sizes. Design efforts are also needed to understand the stresses generated during assembly and operation of large cells. This information can then be used in cell manufacturing to design and fabricate cells with strength higher than that governed by the design stress. Appropriate quality control methods will need to be developed to screen out defective cells and/or other defective parts not meeting the specifications. As cell size increases, the area over which seals are needed also increases. Seal materials that can withstand pressurized operation over large areas and for stack sizes in the range of few hundred kW are not proven at present and will merit further investigation.

### 3.1.5 Reliability

This study assumes different scenarios of system reliability as a function of cell size. However, to reduce variability of system study results, statistical data on the stack/system reliability as a function of cell size needs to be generated. For example, stack MTBF was assumed to be inversely proportional to stack power. Although most experts assume a dependence of MTBF on the power output, there is a strong need for experimental data to find the right relationship between the two. The same statement could be made about the effect of stacking (number of cells per stack) on the stack MTBF. The failure mechanisms that cause de-rating and outage in large stacks are also poorly understood, and must be investigated carefully.

### 3.1.6 Degradation

Degradation in fuel cell systems is universally accepted as a major issue. Long-term stack degradation is poorly understood, both in terms of the fundamental mechanisms as well as its repercussions for the system. Degradation affects all aspects of system design, performance, reliability, operability and cost. This study focused on the system scalability, thus no assumptions regarding degradation was made. The effects of stack degradation on a hybrid plant should be carefully studied.

## 3.2 Engineering development needs

The following engineering development needs have been identified in the course of the study. Unlike the technology barriers discussed in the previous section, these areas bear a much lower development risk and lower investment needs.

- Most of the plant layout surrounding the SOFC stack modules is novel and untested.
- No gas turbine presently exists with the particular combination of pressure ratio, flow rate, and low firing temperature called for by this design. Additionally, this

design requires 100% of the compressor air to be piped to the fuel cell modules before returning to the combustor and turbine. Engineering development is needed to develop compressor and turbine plenums with low pressure losses.

- Large number of stacks, along with redundant stacks, operating at full load and part load need robust design of control systems. This is especially important given the high availability requirements of a hybrid SOFC plant. Integration of gas turbine and fuel cells, with very different transients, would also be a challenge in control system design.
- The power conditioning topology proposed in this study is untested. Given the critical role power conditioning plays in determining system efficiency, further modeling and simulation is needed. Effects of ripple, fault tolerance and similar issues need to be dealt with in detail. Similarly, the integration of a hybrid SOFC plant with the grid could pose design challenges that need to be studied.

Plant start-up and shut down was not covered in this study at all. This is an important subject, which has cost and reliability impacts on the plant. More focus is needed on this topic.

## CONCLUSIONS

The study developed a system design that satisfies the product specification and a SOFC stack development strategy. The system design of a 25 MW plant showed that system efficiencies of over 65%, system cost of under $400/kW, and system reliability of over 98% are feasible.

The plant SOFC subsystem is constructed from a 400-cell stack building block. A wide range of the cell diameter is acceptable: the system cost does not vary significantly in the cell diameter range 30-60 cm (12-24 inches), with the corresponding stack building block power in the 140-570 kW range. Reliability considerations favor large cell diameters and a smaller cell count, however the cell reliability may decline rapidly with the cell diameter. Cell reliability dependence on cell size can put additional constraints on the cell size and stack building block selection and must be studied for the 30-60 cm (12-24 inches) cell diameter range. Due to the lack of available reliability data on large solid oxide fuel cells operating in a stack, the cell size constraints were not quantified, and instead the cell size of 45.7 cm (18 inches) in the middle of the cost-minimizing cell range was chosen, which translates into a stack building block power of 320 kW.

The 25 MW hybrid plant design developed in the study can be scaled to both higher and lower power levels using the same stack building block for wide range of system sizes, 5-250 MW or larger.

High-temperature stack exhaust seals are the highest system and stack development risk for the recommended system design. The stack and system risk mitigation strategy should first address this risk. Cell scalability and yield and reliability improvement efforts at large cell sizes must be addressed parallel to the high-temperature seal development to prove the feasibility of the hybrid system design.

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