

# Hybrid Fuel Cell Gas Turbine System Design and Optimization

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*Ultrahigh efficiency, ultralow emission fuel cell gas turbine (FC/GT) hybrid technology represents a significant breakthrough in electric power generation. FC/GT hybrid designs are potentially fuel flexible, dynamically responsive, scalable, low-emission generators. The current work develops a library of dynamic component models and system design tools that are used to conceptualize and evaluate hybrid cycle configurations. The physical models developed for the design analysis are capable of off-design simulation, perturbation analysis, dispatch evaluation, and control development. A parametric variation of seven fundamental design parameters provides insights into design and development requirements of FC/GT hybrids. As the primary generator in most configurations, the FC design choices dominate the system performance, but the optimal design space may be substantially different from a stand-alone FC system. FC operating voltage, fuel utilization, and balance of plant component sizing has large impacts on cost, performance, and functionality. Analysis shows that hybridization of existing fuel cell and gas turbine technology can approach 75% fuel-to-electricity conversion efficiency.*  
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## 1 Introduction

The world faces a pending energy revolution. The current means by which transportation, residential, and industrial energy needs are met will not sustainably power the economy into the future. The lack of a national energy policy has stalled many promising technologies, due to uncertainty in fuel costs, environmental liabilities, foreign oil security, and public policy. Three desirable features for future energy solutions are diversity in primary energy sources and generation technology, improved efficiency in energy conversion and use, and optimally matching energy technologies and resources to specific uses.

Energy technologies of the future require high efficiency, low emissions, scalability, and dispatchability. Fuel cell gas turbine (FC/GT) hybrid technology meets these requirements with demonstrated fuel-to-electricity conversion efficiency as high as 56% (lower heating value (LHV)) [1,2] and theoretical plant efficiencies exceeding 75% [3]. FC/GT hybrids designs are fuel flexible, dynamically responsive, scalable, low-emission generators [4,5].

Fuel cell-gas turbine (FC/GT) hybrid technology has demonstrated the ultrahigh efficiency, ultralow emissions, and fuel flexibility necessary to achieve local, state, and federal targets for future energy conversion [6–9]. Integration of fuel cell and gas turbine technologies into a single symbiotic system represents a breakthrough in electric power production technology. Gas turbine performance limitations result from the Carnot limit governing all heat engines, but a fuel cell extracts work directly from the chemical potential energy, bypassing the entropy-generating combustion process entirely. However, a fuel cell cannot fully utilize the fuel or all of its chemical energy, severely hindering overall system efficiency. Hybrid FC/GT systems capture and oxidize the anode off-gas to drive turbomachinery and produce additional electricity and air compressor power. Molten carbonate and solid oxide fuel cells are well-suited for hybridization with a gas turbine generator [10,11]. Both operate at high temperature and can be manufactured at scales congruent with existing turbomachinery.

Physical demonstrators are expensive to build and operate; thus, physical models must be employed to conduct design and

performance studies that may justify a novel technology, such as FC/GT hybrids. Accurate simulation of FC/GT behavior can only be achieved with a methodology meeting the following guidelines:

- Physical, chemical, and electrochemical processes that govern each component must be resolved from first principles, with the exception of compressor and turbine components, whose behavior is well characterized by empirical maps. Detailed electrochemical and heat transfer models are necessary to capture the effects of temperature, oxidant concentration, or fuel utilization changes [2].
- Dimensional models are superior to bulk models for their ability to capture detailed spatial information, accurate temperature and concentration profiles, and physical behavior unrepresented by equivalent circuit models. Bulk physical models are computationally efficient and useful for first approximations in the design phase but not for dynamic studies.
- Accuracy is paramount for the heat transfer in a nodal model. Physical parameters, such as wall thickness, channel dimensions, and material properties, are critical in determining the convective and conductive surface areas between nodes. The principle means of heat transfer throughout the stack is conduction through the solid materials and must be determined as accurately as possible.

Simulating a specific FC/GT hybrid for a design study and simulating a generic FC/GT hybrid for dynamics and control studies requires different parameter specifications. Designing a scalable model based upon several dimensionless parameters leads to robustness and versatility. Flexibility and scalability can be used to simulate any existing or future system, employing one of four design methods: (1) sizing the turbomachinery to meet the air flow needs of a given fuel cell system, (2) sizing the FC system to integrate smoothly with an existing turbine, (3) scaling both fuel cell and turbine to meet a desired system output, or (4) modifying operating conditions, simulating off-design performance, to integrate a fully specified FC and gas turbine combination. To achieve high efficiency and robust performance using the final method requires the two primary systems to be extremely well suited for each other. Some flexibility in the operating conditions, heat exchangers, recirculation, and bypass loops allows integration of

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some existing off-the-shelf technologies to function well in a hybrid FC/GT, but achieving ultrahigh efficiency typically requires specific design attention to both the FC and GT components. The methodology developed for this study can apply to any of the above design scenarios; results presented will focus upon a completely flexible design of the components, because this provides a fair basis of comparison and requires only a specification of power output. The process used in the current work is as follows:

- (1) Specify the FC type, physical dimensions, geometry, and electrochemical properties. These parameters can be calibrated to an existing physical system or taken from the literature and are then held constant throughout the design process.
- (2) Simulate the fuel cell by specifying four of the following eight conditions and solving for the remaining four under steady operating conditions: air flow; fuel flow; cell power; voltage; inlet temperature; average temperature; temperature gradient; and fuel utilization. The method chosen was to specify power, average temperature, temperature gradient, and fuel utilization and then determine the remaining operating and outlet conditions. These four were chosen for the likelihood of being reported as a common comparison basis by manufacturers as performance features or operating constraints.
- (3) Simulate the balance of plant components using the outlet conditions specified by the fuel cell simulation. Depending upon the precise hybrid configuration, different design parameters will be available for modification. In the current system configuration studied, five of the following ten parameters must be specified: net system power; FC stack size; GT mass flow; FC air flow; FC inlet temp; recirculation; pre/postcombustor fuel; fuel/air preheater size; and turbine inlet temperature (TIT). The five design parameters specified were net system power, FC air flow and inlet temperature (from FC simulation), and the amount of additional fuel supplied to a pre- and post-FC combustor (zero).
- (4) Combine the dynamic fuel cell and dynamic balance of plant components into a single model with the sizing and operating conditions specified by their respective individual models, and confirm that the steady-state performance arrives at the desired operating temperature and power output conditions.
- (5) Apply a control strategy to physical inputs, such as valves, fuel flow, and blowers, to test the dynamic response to perturbations, including ambient temperature, fuel chemical content, and electric load changes.

Steps 2–4 have been repeated for a parametric design study that yields valuable insights regarding design parameters for consideration when developing hybrid systems. Figure 1 specifies the optimization process for specific design parameters. Three distinct computational models were used to converge to an optimal configuration. The parameters shown in Table 1 specify the design point, average operating temperature, operating power density, voltage, and temperature rise across a single cell. The flexible turbomachinery model can utilize ten different compressor and turbine maps relevant to a variety of turbine designs: radial or axial and single or multispool. Generic performance maps of mass flow rate, pressure, shaft speed, and efficiency are employed, but calibration to manufacturer data is possible. Figure 2 shows an example single spool, axial, compressor, and turbine map operating near its design point.

## 2 Background

The primary synergy of an FC/GT hybrid is that the FC waste heat drives the gas turbine, which in turn supplies the air flow necessary for stack cooling plus additional electricity. The effectiveness of hybridizing an electrochemical device with a heat engine

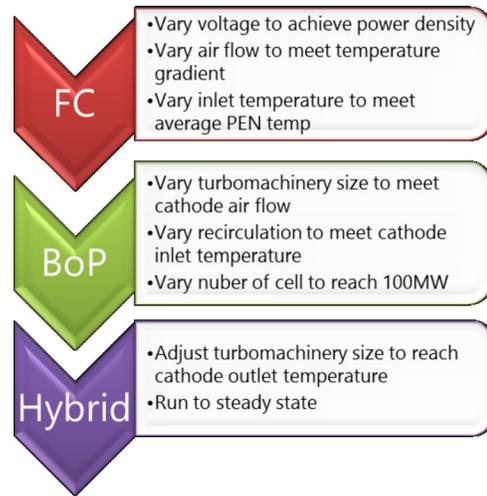


Fig. 1 Hybrid design methodology

relies on a precise balance between heat generation and exchange with electric power production. The primary components must be sized appropriately for the specific cycle configuration and operating conditions. The tradeoffs in system efficiency, cost, complexity, and robustness must be carefully balanced in the design phase.

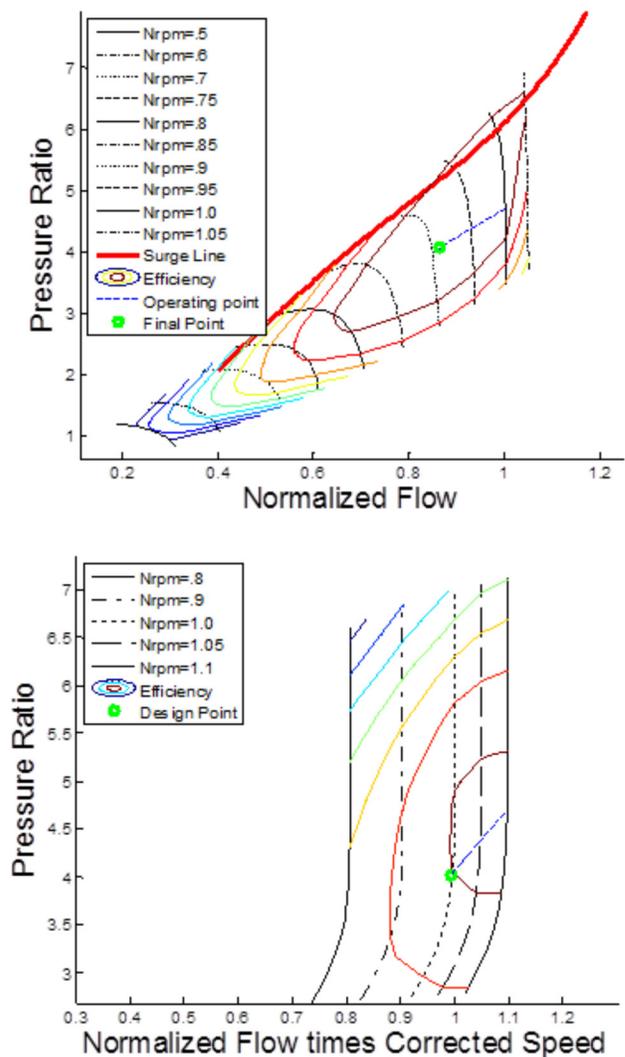


Fig. 2 Empirical compressor and turbine maps

**Table 1 Fuel cell operating requirements**

Fuel cell type	SOFC
Operating power density	100–700 (mW/cm <sup>2</sup> )
Average operating temperature	700–850 °C
Limiting stack temperature rise	50–100 °C

**Table 2 Fuel heating values**

Fuel	Lower heating value (LHV) (kJ/kmol)	Higher heating value (kJ/kmol)
CH <sub>4</sub>	802,952	890,835
H <sub>2</sub>	240,424	284,469
CO	305,200	305,200

Varying the cell dimensions, stack size, operating pressure, fuel utilization, and a host of other parameters can potentially improve integration [12]. A key difference in hybrid technology compared to stand-alone FC systems is that the optimal fuel utilization may be substantially lower, due to the ability to convert a portion of the generated heat into electricity through the turbomachinery. In addition, the desired system operating temperatures may differ due to the potential of using an established temperature difference to drive the heat engine [4]. In a hybrid FC/GT, additional fuel can reduce fuel cell losses while providing thermal input to the turbine [13].

Investigations of integrated FC/GT hybrid system dynamics have been ongoing at the National Fuel Cell Research Center (NFCRC) for over 10 years. Early collaborative work with the National Energy Technology Laboratory determined that creative control strategies would be required to protect sensitive equipment during perturbations. This initial work included carbonate fuel cell models previously validated on the ability to simulate internal reformation of methane [14]. Each laboratory independently developed individual models and control strategies.

Recent work extended previous capabilities with simulation of a variable speed compressor. This allowed for an additional control input for maintaining cathode inlet temperature that both lab models showed decreasing in the previous work [15,16]. The results presented in this study showed improvements in the controllability of the stack temperature. It was noted that the load shed resulted in a lower fuel cell power, lower GT power, and slightly higher efficiency.

Despite excellent efficiency and emissions specifications, the market success of FC/GT systems is limited by high capital costs. Niche applications, such as natural gas pipeline pressure reduction stations, present possible market entry points for high-temperature fuel cell systems [17]. Most solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems demonstrated to-date have operated in a very narrow range suited to maintain steady fuel cell temperature and operation while minimizing dynamics and degradation [1,3,10,18]. Burbank et al. [19] introduce two additional degrees of control by utilizing a variable-geometry nozzle turbine and an auxiliary combustor that can provide additional heat to the turbine inlet stream. This new system configuration allows for a system-wide turndown ratio of 5:1, meaning the system can safely operate at 20% of its rated power production capacity [19]. No bypass or bleed flow paths were needed to accomplish this turndown. The system performs best, 63% efficient, at 30% power and operates at 53% efficiency at full power.

Higher level analyses have also sought to characterize off-design performance of hybrid systems. System level analysis is capable of determining a suite of operating conditions that can be plotted into performance maps, characterizing the system under off-design conditions [20].

The world's first pressurized SOFC-GT hybrid prototype was tested at the University of California, Irvine. A Siemens–

Westinghouse tubular fuel cell system producing 180 kW was paired with a 75-kW Ingersoll–Rand gas turbine. The resulting hybrid system was capable of producing up to 220 kW during its 2900 h of testing at the NFCRC. The data gathered validated modeling approaches developed at the NFCRC [18]. The system achieved fuel-to-electricity conversion efficiencies of 53%.

The use of FC-GT hybrids is not limited solely to terrestrial power generation applications. Interest has arisen from the aerospace industry for an efficient power generation device to meet the increasing electrical demands of commercial aircraft and unmanned aerial vehicles. NASA and the NFCRC collaborated to model different configurations of the SOFC-GT system that would be suitable for aerospace applications [21].

The SOFC-GT cycles investigated in this detailed design analysis work are only a few of the many configurations that have been proposed. A similar design with an intercooled gas turbine was previously studied at the NFCRC [12]. The simulation was conducted for a steady-state optimization by varying the pressure, moisture content, excess cathode air, and ratio of low-pressure to high-pressure compressors. The study determined optimal conditions that produced 75% electrical efficiency based on LHV of natural gas with 55% excess air. The authors were able to conclude that higher operating pressures increase efficiency at the expense of additional development cost [12].

The current study differs significantly from previous hybrid FC/GT design studies, in that it fully considers the impacts of seven major design parameters on performance and optimizes the balance of plant integration with each specified fuel cell operating condition. Internal fuel cell temperature, current, and species distributions allow for consideration of additional heat transfer pathways between the fuel cell and cathode air stream. A fully dynamic turbomachinery model capable of resolving off-design performance and mass flow determines the turbomachinery response to different inlet temperatures and flow rates. A detailed physical heat exchanger model is scaled to achieve optimal thermal integration of the fuel cell and turbine in the specified hybrid configuration. The detailed physical description of each component justifies the predicted direct and indirect impact each operational specification has on net system performance.

### 3 Model Development

Many FC/GT hybrid configurations have been proposed. This work focuses on one of the most promising designs for high efficiency, controllability, and fuel flexibility. The use of ceramic SOFC technology permits the design of a pressurized topping cycle, as shown in Fig. 3, due to the high temperature, solid state, and oxygen ion conduction nature of the technology. This cycle configuration was chosen based upon its simplicity, performance, and controllability. The current analysis, which focuses on the design aspects of the FC/GT hybrid system, utilizes a set of fully dynamic, spatially discretized, physical models. These models have been developed for simulation of experimental test data, control studies, and off-design analysis and comprise a set of ten individual component models for the following: compressor; turbine; shaft; fuel cell; heat exchangers; blower; oxidizer; plenum and mixing volumes; external reformer; and control valves. This section presents the assumptions and high-level derivation; precise programming details are proprietary. The components can represent a variety of different FC/GT cycles by integrating in a variety of configurations. A methodology for determining the size of each device for a given set of operating conditions was developed and used to parametrically compare the rated performance of the specified cycle under eight changing parameters. It was determined that nine system parameters could be used to completely specify the outputs and state points of the SOFC-GT topping configuration. A fixed system power output provided a basis for sensitivity analysis of design and operating conditions. The 100-MW scale was selected for the application of ultrahigh efficiency power generation from coal in an advanced integrated gasification



significant electrical hardware to convert mechanical energy to electricity and prepare for interconnection with a utility grid network. This study employs a simple torque balance shaft model with appropriate rotational inertia; however, this analysis limits its scope to fixed shaft speed performance, and thus complete explanations of the dynamics are omitted.

Hybrid FC/GT system configurations often require high-temperature heat exchangers manufactured from stainless steel and/or ceramics. A quasi-2D heat exchanger model is constructed that discretizes the heat exchanger length into ten control volumes, each comprising a hot gas, solid, and cold gas volume. This method develops a spatial temperature profile and avoids effectiveness limitations of bulk models. Total surface area, adjusted by varying the number of plates, determines the heat transfer rate and net effectiveness. This method approximates the required heat exchanger surface area and neglects complex geometric considerations of some heat exchanger designs in favor of computational efficiency to enable dynamic simulation. Conservation of energy analysis for the heat exchanger model is detailed in Eqs. (11)–(13).

$$\frac{dT_{\text{hot}}}{dt} = \frac{(\dot{h}\dot{n})_{\text{in-out}} - h_c A \left( \frac{T_{\text{in}} + T_{\text{out}}}{2} - T_s \right)}{c_v \cdot \nabla_{HX\text{node}} \cdot C} \quad (11)$$

$$\frac{dT_{\text{cold}}}{dt} = \frac{(\dot{h}\dot{n})_{\text{in-out}} - h_c A \left( \frac{T_{\text{in}} + T_{\text{out}}}{2} - T_s \right)}{c_v \cdot \nabla_{HX\text{node}} \cdot C} \quad (12)$$

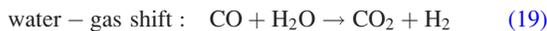
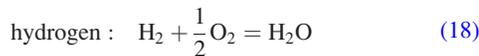
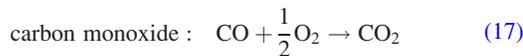
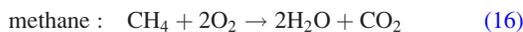
$$\frac{dT_{\text{solid}}}{dt} = \frac{\begin{bmatrix} h_c A \left( \frac{(T_{\text{in}} + T_{\text{out}})_{\text{cold}}}{2} - T_s \right) \\ h_c A \left( \frac{(T_{\text{in}} + T_{\text{out}})_{\text{hot}}}{2} - T_s \right) \\ k_c A (T_{n+1} + T_{n-1} - 2 \cdot T_s) / L_{\text{node}} \end{bmatrix}}{c_v \cdot \nabla_{HX\text{solid}} \cdot \rho} \quad (13)$$

An oxidizer or combustor combines the anode and cathode off-gas to react the remaining fuel. A successful hybrid FC/GT design maximizes the use of heat generated by the FC stack and by the combustion of anode off-gas to drive the turbine, power the compressor, and produce additional electricity. A combustor can also be fired with additional fuel, and some designs use a combustor to increase turbine inlet temperature, control the system, and/or dynamically increase system output. This typically reduces system efficiency and should be limited to start-up and shut-down procedures, if high efficiency is important. The mixing of anode and cathode off-gas in the oxidizer is expressed in Eqs. (14) and (15).

$$\dot{n}_{\text{out}} = \sum (+(\dot{n}X_i)_{\text{fuel}} + (\dot{n}X_i)_{\text{off}}) \quad (14)$$

$$x_{\text{out},i} = \frac{(\dot{n}X_i)_{\text{air}} + (\dot{n}X_i)_{\text{fuel}} + (\dot{n}X_i)_{\text{off}}}{\dot{n}_{\text{out}}} \quad (15)$$

The combustion modeled in this work accounts for the same seven species as the remainder of the model and considers four reactions in Eqs. (16)–(19).



Once again, a control volume conservation of energy approach is employed to balance the energy flowing into the combustor, the energy flowing out of the combustor, the heat lost to the environment,

and the heat generated by the combustion process. The heat release of each of the four chemical reactions occurring within the fuel cell and combustion chamber are calculated from the standard heating rates presented in Table 2.

$$\frac{dT_c}{dt} = \frac{\begin{bmatrix} h_c \cdot A \cdot (T_c - T_{\text{amb}}) + (\dot{h}\dot{n})_{\text{air}} \\ + (\dot{h}\dot{n})_{\text{off}} + (\dot{h}\dot{n})_{\text{fuel}} \\ - (\dot{h}\dot{n})_{\text{out}} - Q_{\text{ion transfer}} \end{bmatrix}}{C_p \frac{P_{\text{comb}} \nabla_{\text{comb}}}{R U T_{\text{comb}}}} \quad (20)$$

Both MCFC and SOFC hybrid systems may utilize recirculation and/or bypass flows. The mixing of the primary and recirculated streams is modeled with a perfectly stirred and nonreacting plenum volume. Continuity and conservation of mass account for species flow rate and determine the exiting composition. Conservation of energy determines the exit temperature of the mixed gas and accounts for ambient losses with a separate energy balance for the mixing chamber.

$$\dot{n}_{\text{mix}} = \sum ((\dot{n}X_i)_1 + (\dot{n}X_i)_2) \quad (21)$$

$$X_{\text{mix},i} = \frac{(\dot{n}X_i)_1 + (\dot{n}X_i)_2}{\dot{n}_{\text{mix}}} \quad (22)$$

$$\frac{dT_{\text{mix}}}{dt} = \frac{\begin{bmatrix} h_c \cdot A \cdot (T_{\text{mix}} - T_{\text{pipe}}) \\ + (\dot{h}\dot{n})_1 + (\dot{h}\dot{n})_2 - (\dot{h}\dot{n})_{\text{mix}} \end{bmatrix}}{c_p \frac{P_{\text{mixer}} \nabla_{\text{mixer}}}{R U T_{\text{mix}}}} \quad (23)$$

A blower operates similar to a compressor, often with significantly lower pressure rise. The current analysis treats the blower as a compressor with fixed isentropic efficiency and calculates the parasitic power consumed by the blower for any particular operating condition. Cathode exhaust recirculation is simulated, with an analysis accounting for energy lost to inefficiencies and cooling. Here, the subscript *re* defines the recirculated gas stream, and once again, *s* and *a* represent the solid and ambient conditions. The blower power is calculated using the following energy balance, wherein the sensible enthalpy under isentropic conditions,  $h_{\text{isen}}$ , is found as a function of the isentropic temperature:

$$\frac{dT_{\text{re}}}{dt} = \frac{\dot{W}_B + (\dot{h}\dot{n})_{\text{in-out}} + h_c A (T_s - T_{\text{re}})}{C_p \frac{P_{\text{out}} \nabla}{R U T_{\text{re}}}} \quad (24)$$

$$\frac{dT_s}{dt} = \frac{h_c A (T_{\text{re}} - T_s) + \varepsilon \sigma A (T_a^4 - T_s^4)}{c_p m} \quad (25)$$

$$\dot{W}_B = \dot{n}_{\text{out}} \left( \frac{h_{\text{isen}} - h_{\text{in}}}{\eta_{\text{isen}}} \right) \quad (26)$$

$$T_{\text{isen}} = \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\gamma-1/\gamma} \quad (27)$$

Electrical power is generated in the FC, the turbine generator, and a steam bottoming cycle generator, if a bottoming cycle is employed. Similarly, fuel may be provided to the system at different points: an air preheater, reformer, FC, or post-FC combustor. All sources must be accounted for when calculating the net power and efficiency of the system. The system efficiency is found using known heating values for the fuel, multiplying by the fuel flow rates, and dividing the net power produced by this quantity as follows:

$$\dot{W}_{\text{Net}} = \dot{W}_{\text{TurbGen}} + \dot{W}_{\text{FC}} + \dot{W}_{\text{SteamGen}} \quad (28)$$

$$\eta_{\text{cyc}} = \frac{\dot{W}_{\text{Net}}}{\dot{n}_{\text{fuel}} HV_{\text{fuel}}} \quad (29)$$

#### 4 Steady-State Design Performance Results

A parametric study is conducted for seven design parameters that span the range of the available technology for SOFC and turbine technology. These parameters can often be found on manufacturer specifications sheets (power density, utilization, compression ratio, or operating temperature) or derived from the specified state points (temperature gradient or compressor/turbine efficiency). The seven design parameters are:

- (1) temperature differences across the fuel cell stack
- (2) fuel cell operating power density
- (3) fuel cell fuel utilization
- (4) fuel cell stack air preheating
- (5) peak compressor/turbine efficiency
- (6) system operating pressure
- (7) fuel cell trilayer average operating temperature

An important design feature of the SOFC topping cycle studied is the size of the air preheater. A larger heater reduces the amount of cathode recirculation, which increases efficiency, but lowers the turbine inlet temperature (TIT), which reduces system efficiency. The combined effects of these design parameter choices depend upon the part-load efficiency of both the blower and turbine. Use of a heat exchanger with a bypass loop at this point of the cycle allows for substantial controllability. The heater bypass generates increased air flow at constant temperature by cooling the heater exhaust and relying upon additional recirculation heating of the cathode inlet stream. Table 3 presents a comparison of design operation with different heater sizes for 80% fuel utilization, 200 °C temperature rise across the stack, and a power density of 500 mW/cm<sup>2</sup>. The 200 °C heater represents the baseline design, to which subsequent figures have been normalized.

**4.1 Stack Temperature Rise.** Stack temperature gradient and overall temperature rise plays a determining role in system efficiency and fuel cell durability. Manufacturers often specify a maximum thermal stress sustainable by the system to be met at design and during off-design performance. Intuitively, a greater temperature rise across the stack requires less air flow and thus smaller turbomachinery, resulting in higher system efficiency. The model supports this but to a lesser extent than expected. Figure 4 presents the results of this sensitivity analysis. Thirteen important design variables are evaluated as either better or worse than the baseline system design. For some features, higher values indicate a better design, efficiency, voltage, compressor size, turbine % power, stack power, generator power, and TIT; for others, a lower value is an improvement, recirculation, blower power, stack and heat exchanger sizes, and trilayer (sometimes called PEN for positive electrode, electrolyte, negative electrode) temperature gradient. Each variable has been scaled to its maximum

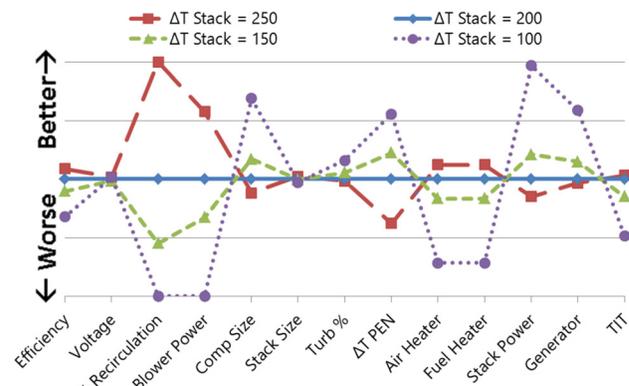


Fig. 4 Design impact of stack temperature profile

deviation from the mean value in the sensitivity analysis, thus allowing sensitivity comparisons among all of the design parameters.

Reducing the temperature gradient across the cell 50 °C reduces efficiency 1.2%, but may substantially improve system durability and lifespan. The lower than anticipated reduction in efficiency is due to the additional cathode preheat effectiveness, which captures more exhaust heat from a lower temperature turbine exhaust to reach the same pre-recirculation temperature. This additional heat capture offsets the negative impact of a larger turbine and additional recirculation necessary to achieve a 30% increase in airflow. A 25% increase in recirculation reduces the additional airflow requirement on the turbomachinery to less than 10%. One could not capture this design impact without the detailed manifolded heat transfer model that is able to accurately correlate internal temperature distributions, air flow rates, and inlet and exhaust states of the cathode stream. The additional recirculation reduces the oxygen concentration and increases the blower parasitic, both contributing to the slight reduction in system efficiency. The efficiency loss is doubled an additional 2.4% for a further 50 °C reduction in cell-temperature gradient.

**4.2 Fuel Cell Operational Power Density.** The second operating condition studied was fuel cell power density. Variations in operating power density present a clear trade-off between cost and efficiency. Fuel cells operate closest to their ideal efficiency at low power densities, but cost per kW of capacity is inversely proportional to power density. Stand-alone fuel cell systems exhibit efficiency behavior closely mirroring the polarization curve and are typically designed to operate at power densities that balance efficiency with power production or cost. A hybrid system, however, has the luxury of capturing a portion of the fuel cell-generated heat, thereby reducing the negative impact of operating at higher power densities. The balance of efficiency and power production (cost) in a hybrid system should thus tilt towards higher power density operation than that one would choose for the same fuel cell operated in a stand-alone system. Additionally, operating at high pressure permits even higher power densities with the same electrochemical loss and heat generation. The impact of increasing or decreasing the fuel cell power density is shown in Fig. 5.

Figure 5 affirms that lower operating power densities result in higher efficiencies; however, the change is less for a hybrid system than for the FC itself. The operating voltage is directly proportional to FC efficiency and exhibits a greater differential drop with increasing power density than the hybrid system efficiency. Reducing power density from 600 mW/cm<sup>2</sup> to 200 mW/cm<sup>2</sup> increased efficiency from 63% to 70% LHV, yet required a three-fold increase in stack size to achieve the same system power. An interesting attribute of FC technology is the capability to achieve higher efficiencies at reduced power. This holds true for the hybrid system as well, and dynamic studies indicate a greater

Table 3 Initial design results

Air preheat		0 °C	100 °C	200 °C
Voltage	Volts	0.855	0.863	0.866
ΔT trilayer	°K	101.7	100.4	96.8
Stack size	Cells	306,400	303,700	302,200
Stack power	MW	84.1	83.5	83.4
Gen power	MW	16.6	17.1	17.0
Blower power	MW	0.70	0.55	0.40
Efficiency	%	65.0	66.1	66.4
Comp size	kg/s	74.4	87.7	107.2
Turbine %	%	16.5	17.0	17.0
Air heater	Plates	0	891	2762
Fuel heater	Plates	1042	1898	2270
Turbine inlet	K	1332	1220	1095
Recirculation	%	64.09	55.54	42.28
Peak temp	K	1072	1072	1071
Cath outlet	K	1061	1061	1061

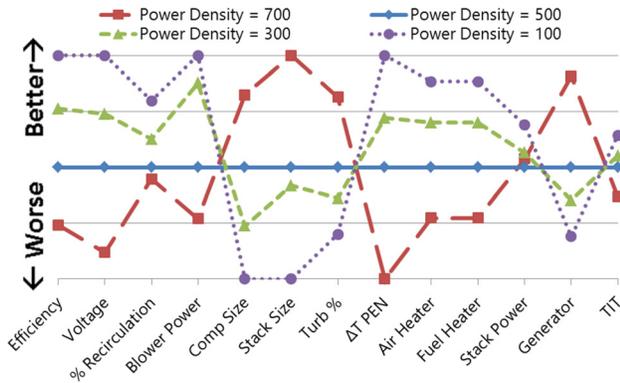


Fig. 5 Design impact of stack power density

capability to load follow compared to a stand-alone fuel cell system. This off-design behavior is superior to most electrical-generating technologies that often exhibit steep performance drops when operating at reduced output.

Figure 5 shows an inverse relationship between voltage and compressor size and a positive relationship between voltage and trilateral temperature gradient. This indicates that the higher FC efficiency (i.e., higher voltage) reduces air flow requirements and necessitates a smaller turbine. Similarly, the higher voltage generates less heat, causing lower temperature rise across the cell. Interestingly, the TIT rises at lower power density. The same amount of anode off-gas oxidizes with less air flow, producing higher temperatures (and lower mass flow) entering the turbine.

**4.3 Fuel Cell Operational Fuel Utilization.** The next operating condition investigated was fuel utilization. Other authors have hypothesized that operating at reduced fuel utilization in the fuel cell would increase the turbine inlet temperature and produce more energy from the turbomachinery. Despite the fact that the fuel is underutilized in the more efficient of the two devices, the fuel cell, these authors argue that the benefits to the stack voltage and TIT outweigh the efficiency penalty of reduced fuel utilization [23,24].

The results presented in Fig. 6 show a steep decline in system performance, from 67% to 52% LHV, with decreasing fuel utilization. This system efficiency decline occurs despite the rise in fuel cell operating voltage and TIT, as others have predicted. Operating this hybrid cycle at reduced fuel utilizations does provide some interesting side benefits. The stack size is reduced due to the greater amount of power derived from the turbine generator, the compressor size and trilateral temperature gradient are reduced due to the higher operating voltage, the parasitic blower power is reduced due to the reduction in cathode air flow, and the fuel heater size is reduced due to the higher TIT at which heat is

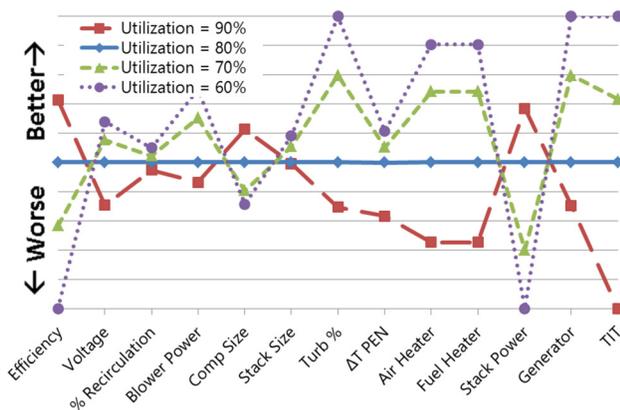


Fig. 6 Design impact of stack fuel utilization

exchanged. It is expected that, for a particular configuration of FC and GT, where the turbine was slightly oversized, reduced fuel utilization could be beneficial to supply sufficient thermal energy to the turbine; however, in an optimized design, the higher efficiency component, the FC, should be designed to generate the maximum amount of power possible from the supplied fuel, as shown in Fig. 6.

**4.4 FC Air Preheat.** The performance of a thermodynamic cycle can often be improved with heat recuperation. Advanced Brayton cycles employ intercooling and staged compression, with large and efficient heat exchangers recovering the heat for use elsewhere in the cycle. Applying a recuperative heat exchanger to the SOFC-GT hybrid allows use of post-combustor or post-turbine exhaust gases to preheat cathode inlet air. This reduces the cathode recirculation required, raising oxygen concentrations and improving system efficiency. The design analysis demonstrated little benefit from heat recuperation of the combustor exhaust, which is unexpected but indicative of the design, which already captures combustor exhaust heat in the turbine. Analysis identifies an improvement from 65% to 66% LHV with 200 °C of preheating rather than none. Reduced recirculation increases required turbomachinery size, while lower turbine inlet temperature reduces efficiency. Thus, despite the obvious improvements in parasitic load and oxygen concentration, the net system output remains quite similar for the case of adding recuperation to the design.

Figure 7 would seem to indicate the inclusion of an air preheater provides little benefit to the system performance and should not be part of the design. However, the inclusion of an air preheater allows for an additional bypass loop. Bypassing the air preheater serves to cool the cathode inlet air stream, requiring additional recirculation to preheat the air. This boosts the air flow rate, providing more cooling to the fuel cell stack when necessary. Even a well-designed system will require additional cooling under instances of increased ambient temperature, decreased ambient pressure, and some fuel perturbations. In addition, including a heat exchanger and bypass valve allows independent control of inlet temperature and flow rate, which is often required for control purposes. Finally, such a design may also provide required flexibility for coping with long-term cell degradation.

**4.5 System Pressure.** Table 3 and the Fig. 7 show air preheat positively affects system efficiency, if only minimally. Air preheat can be achieved through heat exchange with fuel cell off-gas or by additional compression. This provides motivation for operating a hybrid system at higher pressures. Raising system pressure from 5 atm to 10 atm yields significant improvement in fuel-to-electricity conversion performance from 65% to 69% LHV. Operating at 8 atm rather than 5 atm raises efficiency to 68% and may be more

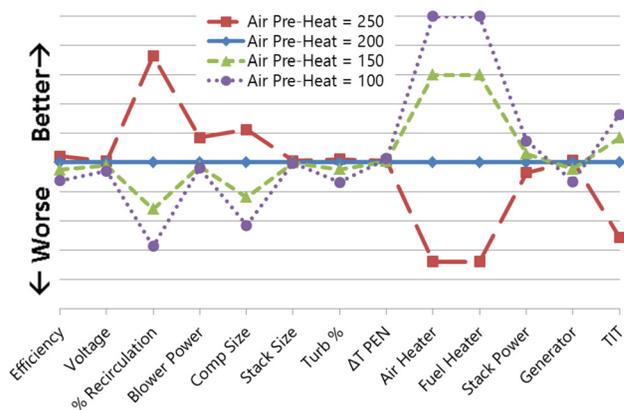


Fig. 7 Design impact of air preheating

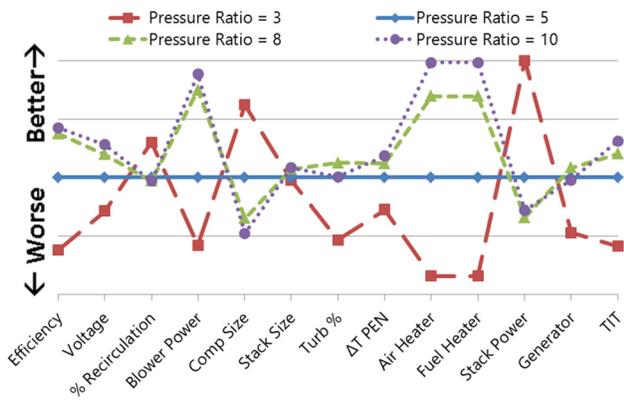


Fig. 8 Design impact of system pressure

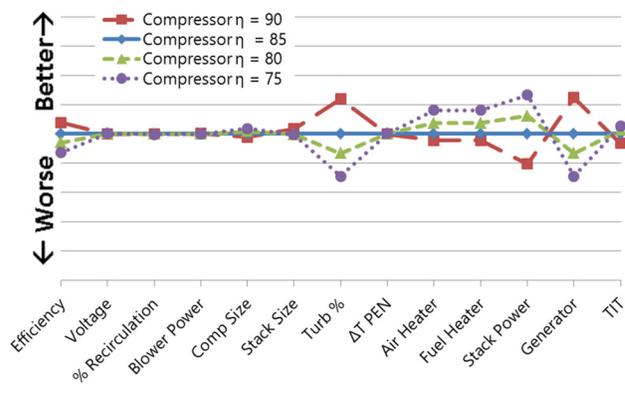


Fig. 10 Design impact of compressor efficiency

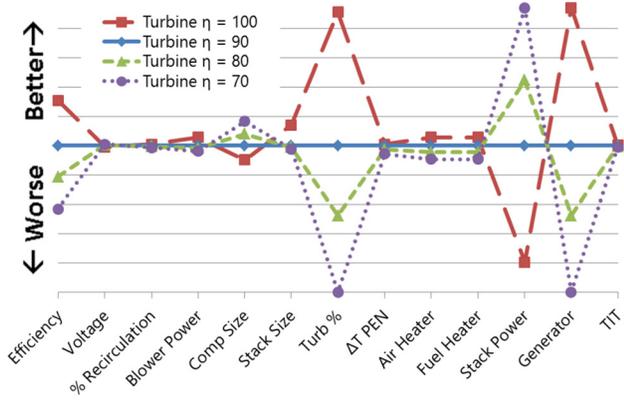


Fig. 9 Design impact of turbine efficiency

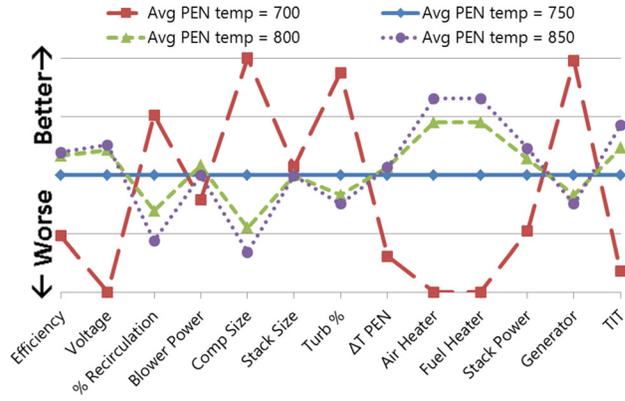


Fig. 11 Design impact of average cell temperature

feasible in the near term than 10 atm. The voltage gains and reduced blower power requirements shown in Fig. 8 are largely responsible for these improvements.

**4.6 Turbine Efficiency.** Proper sizing of the two major components is a key factor in integrating a fuel cell and gas turbine. The previous analyses showed fuel cell operating voltage and efficiency produced large variations in optimal compressor size. Efficiency of the turbomachinery also impacts performance and the relative sizing of the two primary components. The peak efficiency for the characteristic map is investigated between 70% and 100%, with most real turbines operating between 85% and 95% efficiency.

The turbomachinery only produces 15% of the net power of a hybrid, but Fig. 9 demonstrates the large impact of turbine efficiency on overall system performance. A significant portion of turbine power drives the compressor, operating at a fixed load. Thus, a 10% reduction in turbine power reduces net gas turbine power by 25% and overall hybrid system power by 4%. Net turbine power diminishes quickly as the turbine operating point shifts away from the high-efficiency island of the performance map. This sensitivity highlights the importance of matching the turbine to the fuel cell, since an oversized turbine will operate well below peak efficiency.

Compressor efficiency is also highly dependent upon the operating position of the turbomachinery and thus can compound the impact of an improperly sized system. The effect of diminishing compressor efficiency does not impact system performance as greatly as turbine efficiency (see Fig. 10). Since the air flow passes through at a lower temperature in the compressor, inefficiencies of compression do not produce the same amount of energy loss as in the turbine. However, by looking at the generic axial compressor map, one might suppose efficiency drops off

quicker when operation moves away from the compressor design point, resulting in similar system losses during off-design operation.

**4.7 Fuel Cell Operational Temperature.** Average fuel cell operating temperature was the final design consideration investigated in this parametric sensitivity study (Fig. 11). The overpotential parameters used in this study, particularly Ohmic losses, are sensitive to operating temperature. The resulting higher voltage at higher temperatures improves system performance by lowering cooling demands, shrinking the necessary turbomachinery, and thereby increasing the portion of power produced in the fuel cell. Heater size requirements are reduced, since heat transfer is more effective at the higher cathode exhaust temperatures. The hotter exhaust and smaller heat exchangers result in an increased TIT, thereby improving the turbomachinery efficiency as well. Increased fuel cell operational temperature primarily reduces the area-specific resistance and increases cell degradation. The current results suggest that, if two fuel cell systems are capable of similar performance and lifespan, the higher temperature system is more amenable to hybridization. This is one of several reasons why high temperature SOFC technology should be pursued for this application over the slightly lower temperature molten carbonate technology.

## 5 Observed Trends

Choosing a design point for a FC/GT hybrid represents a complex trade-off between cost and performance. Additionally, individual components may have different performance characteristics when integrated into any particular hybrid configuration. Figure 12 presents the performance impact each independently studied parameter has on total system performance. Each colored

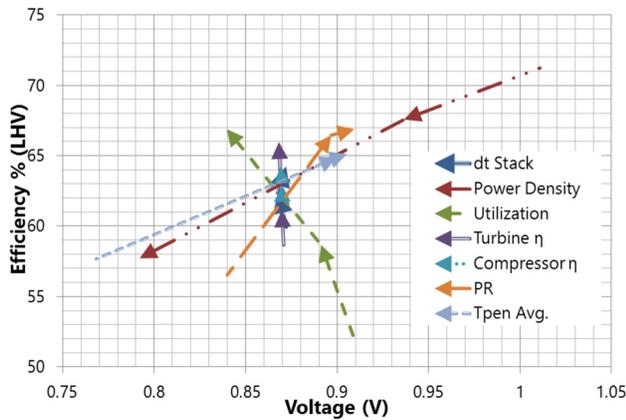


Fig. 12 Voltage and efficiency as dependent variables

arrow represents the variation of a single parameter within the range of values outlined previously. This chart seeks to illustrate the relative impact of each design parameter on complete system performance. Figure 12 illustrates that power density and average trilateral temperature affect both voltage and efficiency, where compressor and turbine efficiencies affect only system efficiency. What is interesting about this chart is that the typically direct relationship between voltage and system efficiency in a FC device is skewed by the impact on the integrated system, particularly for fuel utilization and system pressure. Combining the effects of changing several system parameters may be used to achieve optimum configurations for cost, efficiency, or durability. The curvature of each arrow implies nonlinearity in the application of each design choice; however, the trends toward increasing efficiency, voltage, recirculation, or turbine power fraction (as will be seen in the next figures) will remain fixed. The combined manipulation of multiple design parameters may exhibit interacting benefits that may compound or contradict the trends, as shown in Figs. 12–14.

Turbomachinery efficiencies of the compressor and turbine have little to no effect on voltage but a small effect on system efficiency. Figure 12 also shows the larger impact that turbine efficiency has on performance. This impact is due to the fact that the power production in the turbine is much greater than consumption in the compressor, and thus, 10% of additional losses in the turbine accounts for a greater total system energy loss than 10% losses in the compressor. This may be important when selecting turbomachinery that will operate at off-design conditions, noting that it will be more important to maintain the expander near its highest rated efficiency.

Figure 13 illustrates the relative impact each design consideration has on the necessary amount of cathode recirculation, assum-

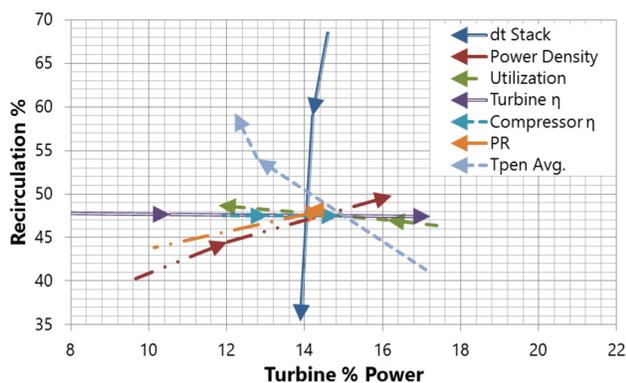


Fig. 13 Recirculation and turbine % power as dependent variables

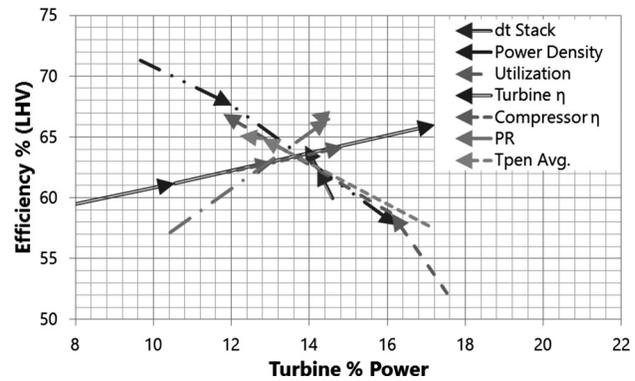


Fig. 14 System efficiency and turbine % power as dependent variables

ing a recuperating heat exchanger is not used, and the portion of total power provided by the gas turbine. This relationship is important at the design stage for appropriately sizing the turbine and blower or designing an ejector. The amount of cathode recirculation will also largely determine the margin of controllability of the inlet temperature when using a variable air flow-rate turbine.

Interestingly, Fig. 13 illustrates a decoupled behavior, meaning that some design choices affect primarily the amount of recirculation, while others affect the portion of power derived from the turbine. Increasing power density and decreasing fuel utilization both raise the turbine inlet temperature, having a similar effect as increasing turbine efficiency. Increasing the temperature rise across the FC reduces air flow and preheating needs that were accomplished through cathode recirculation. The excess energy given off by the FC remains nearly constant; therefore, the turbine output is unaffected. Operating temperature provides an interesting exception, which impacts both recirculation and turbine output by requiring additional preheating through recirculation and providing less energy to the turbine, due to reduced Ohmic losses. Recirculation controls the air flow rate and temperature of the cathode. A change in stack temperature gradient requires a change in recirculation only and minimally affects turbine size and power. A system change that reduces FC efficiency typically increases turbine output through additional heat generation that becomes available to the turbine. Examples of this include increases in power density and fuel utilization and decreases in average operating temperature. Optimally sizing the turbomachinery for the hybrid application is extremely important, but the relationship between turbine size and fuel cell size is complicated. A slightly oversized turbine can be throttled back to achieve a near optimal design, but a subscale turbine cannot provide the air flow necessary to meet the stack requirements.

It is therefore clear from Fig. 14 that the turbine should be expected to output nearly 20% of the rated power of the FC stack. A compatible turbine must match the flow rate, inlet temperature, and power output specified by the hybrid configuration and the nominal fuel cell output. Precisely matching all three conditions is unlikely. Thus, the turbine will typically operate off-design, either by derating pressure, turbine inlet temperature, or both. The turbine selected for hybridization should be sized to provide at least 120% of the air flow required by the FC, less any recirculation. This will often correspond to a low-pressure turbine nominally producing ~20% of the rated fuel cell output. Reaching the specified turbine inlet temperature can be achieved with additional post-FC oxidation, but the turbine should nominally be rated for 200 °C greater than the operating temperature of the fuel cell.

Figure 14 illustrates two seemingly contradictory trends toward improving system efficiency. Those design features that would improve the turbine efficiency will improve system efficiency as well as the portion of power contributed by the turbine. Those system parameters that increase the FC efficiency will decrease the energy available to the expander and thus decrease the turbine

contribution while increasing system efficiency. To achieve optimal efficiency, the higher efficiency device, the FC, should contribute the greatest to the system output. This does not imply that using a smaller compressor will make a hybrid system perform better; often this would cause the hybrid to fail completely. What this trend implies is that designing a system that requires less air flow, and therefore a smaller compressor, implies an increase in FC efficiency. From a capital cost perspective, the turbomachinery will be cheaper, per kW, than the FC stack and related components, and therefore, designs maximizing the power from the turbine will likely reduce the initial system cost.

## 6 Conclusions

The primary considerations when designing a hybrid FC/GT system are stack-power density, operating temperature, stack temperature rise, system pressure, fuel utilization, and the relative size of the turbomachinery. These design selections and the FC structure and material set, determine the operating voltage and therefore the operating efficiency of the FC. These decisions, in turn, determine the air-flow requirements and heat available to drive the turbomachinery, with the difference in preheating and air flow provided by the cathode recirculation. High voltage, typically achieved by operating at low power density, resulted in the highest achievable system efficiency but the largest necessary FC stack size. Higher system pressure improves voltage and efficiency but requires sturdier components and applies mainly to large systems utilizing axial flow turbomachinery. Typical axial turbines are designed for high-pressure ratios, but utilization of the low pressure spool only could produce system pressures amenable to SOFC integration. System pressures between 4 and 8 atmospheres would bring the design within the operating regime of existing hardware. Higher fuel utilization actually has a negative impact on fuel cell voltage for the configurations considered here but improves system performance by employing more fuel in the electrochemical reactions. It is important to note that the efficiency penalty associated with reduced fuel utilization is less in a hybrid system than in a stand-alone FC system. It is extremely likely that the optimal operating condition for a specific FC stack will be at lower fuel utilization when hybridized with a gas turbine. The side benefits of lower fuel utilization include reduced degradation effects, less chance of fuel starvation, more even spatial current and temperature distributions in the stack, and greater dynamic operating flexibility. Higher operating temperatures reduce ionic resistance, increase the turbine inlet temperature closer to nominal conditions, and raise overall hybrid system efficiency. The drawbacks of high temperature operation include accelerated voltage degradation and the requirement of potentially exotic interconnect and sealant materials. An optimal system may be able to achieve ultrahigh fuel-to-electricity conversion efficiency but fall short of economic viability. The fuel cell stack represents the single largest capital cost, so that minimizing the stack size requirement reduces cost significantly. Achieving size reductions primarily occurs by raising power density. In the current study, increasing power density from 400 to 500 mW/cm<sup>2</sup> reduces the stack size by 25%, with only a 2.6% efficiency penalty. Eliminating the air preheating heat exchanger reduces the cost significantly but may diminish the ability to sufficiently control stack operating temperature. Replacing air preheating with additional compression heating raises efficiency if the fuel cell can safely handle the pressure without cracking. Increased pressure improves power density, allowing for additional trade-offs between efficiency and reducing stack size even further. Optimizing the system with cost-minded design choices can produce a highly efficient (65% LHV or better) system with a substantially higher specific power output than a stand-alone FC system.

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## Nomenclature

$A$  = area  
 $C$  = thermal capacitance  
 $C_{p,v}$  = specific heat (constant pressure, constant volume)  
 Flow = turbomachinery flow rate  
 $h$  = enthalpy  
 $h_c$  = convection coefficient  
 $k_c$  = conduction coefficient  
 $m$  = mass  
 $M$  = Mach number  
 $N$  = normalized turbomachinery parameter  
 $P$  = pressure  
 $PR$  = pressure ratio  
 $Q$  = sensible enthalpy of ions  
 RPM = shaft speed  
 $R_u$  = universal gas constant  
 $T$  = temperature  
 $V$  = velocity

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