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Program Evaluation

207-R

Assessment of Solid Oxide Fuel Cells in Building Applications

Phase 1: Modeling and Preliminary Analyses

November 2001

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Report Summary

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Assessment of Solid Oxide Fuel Cells in Building Applications

Phase 1: Modeling and Preliminary Analyses

November 2001

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Report Summary

This document is a summary of an Energy Center of Wisconsin (ECW) funded project entitled, *Assessment of Solid Oxide Fuel Cell Energy Systems for Building Applications, Phase I*. The complete report can be obtained from the ECW library.

The primary objective of Phase 1 was to develop a solid oxide fuel cell (SOFC) system model for use in simulation studies aimed at exploring the design, operation, and control of building-integrated fuel cell systems. The model has been used to select the optimal operating point of the cell stack module, calculate system cost-of-electricity, study waste heat utilization schemes for meeting total building energy demands, and simulate a 2-kW solid oxide fuel cell system integrated with a domestic hot water heater for a residential application.

A product of this research effort is a simulation tool suitable for assessing several critical aspects of fuel cell use in residential and commercial buildings. The preliminary information from residential analyses illustrates some of the technical and economic hurdles for viable systems in these types of applications. Ultimately, when all research phases are complete, they will provide a base of information for understanding the key benefits, issues, and impacts of employing advanced fuel cell power systems in both small and large commercial applications.

Introduction

The combination of market forces (utility deregulation) and recent trends in the development of energy-efficient electric generation equipment, such as fuel cells, will change the manner in which energy is generated, utilized, and supplied in all end-use sectors within the next twenty-five years. Since capital costs for these new electrical generation technologies will likely decrease, their entry into the commercial marketplace is expected to accelerate over time.

Electrochemical fuel cells have the potential to convert fuel directly to electricity (with heat as a byproduct) at efficiencies greater than any single conventional energy conversion technology. Their modular nature coupled with their ability to generate electricity in a clean and efficient fashion make them attractive for a wide variety of applications and markets. There are six different types of fuel cells that have received varying degrees of development attention. Presently, the 80°C proton exchange membrane fuel cell (PEMFC) and the 700-1000°C solid oxide fuel cell (SOFC) have been identified as the likely fuel cell technologies that will capture the most significant market share (Braun, Klein, and Reindl, 2000; Schafer, 1996). As these two fuel cell types are targeted for early commercialization in the residential (1-10 kW) and commercial (25-250 kW) end-use markets, system studies in these areas are of particular interest.

The basic components of a fuel cell power plant consist of a fuel processor, fuel cell power module, power conditioning equipment for dc-to-ac inversion, and process gas heat exchangers. Depending on the operating temperature, fuel cells produce varying grades of waste heat that can be recovered for process heating, gas compression requirements, or exported for cogeneration (or trigeneration) purposes. The utilizability of this waste heat can significantly impact system efficiency, economics, and environmental emissions.

The provision of both electricity and heat (cogeneration) for an application is a significant development objective for fuel cells. The ability of the fuel cell type to meet the building energy demands will depend on both its electrical and thermal performance characteristics and the coincidence of the residence’s demands. One measure of a thermal-electric system’s ability to provide both heat and electricity is its thermal-to-electric ratio. It has often been stated that the characteristically high thermal-to-electric ratio of the SOFC makes them attractive for providing the thermal requirements of various end-use applications. The high-grade waste heat produced in a solid oxide fuel cell can be utilized for space heating, process steam, and/or domestic hot water demands. The type of heat recovery used is dependent on the application requirements and the resulting cogenerative efficiency will depend on the design.

A significant issue surrounding the use of highly efficient fuel cells in residential applications is their ability to meet the highly non-coincident electric and thermal loads in either grid-connected or stand-alone configurations. That is, in either base load operation or electric load-following conditions, electricity and/or heat may be available when it is not needed or vice-versa. Additionally, either higher or lower fuel efficiency and different proportions of electric and thermal output is derived from the fuel cell system depending on where the fuel cell stack is operated on its voltage-current characteristic. As a result, both the *system* design point and off-design point operating characteristics are dependent on 1) selection of optimal *fuel cell* design and operating point, 2) heat recovery design, 3) electric and thermal load management, and to a lesser degree 4) the performance characteristics of auxiliary hardware, such as inverters, pumps, compressors, controls, and external reformers (if any) These and other operating aspects require detailed study to elucidate and resolve implementation issues before commercialization of the technology, thereby enabling an accelerated realization of the inherently high efficiencies of fuel cell systems.

Objectives

The primary objective of Phase 1 of this project is the development of an SOFC energy system simulation model that is capable of answering the following questions:

- What is the optimal design point of the fuel cell for electric-only and cogeneration systems?
- How well does the respective fuel cell system meet the total energy demand of a building? What is the system operating strategy (base-load or load-following)?
- What are electrical and thermal storage requirements? Does heat pumping make sense?
- What are the fuel processing requirements?
- What are the respective environmental emissions of each system concept and what are the anticipated payback economics of mature SOFC-based residential systems?
- What advantages might the high temperature SOFC-based system possess for residential and commercial cogeneration applications compared to conventional systems and to other fuel cell types, such as the low-temperature PEM?

System Modeling and Simulation

Figure 1 shows an information flow structure from data input and component models to system simulation and performance output. Experimental weather, utility, and cost data are utilized for model development. Experimental and design data, such as cell area specific resistance, is input into the fuel cell model, which is one component of a larger thermodynamic system model. Similarly, manufacturing cost data for fuel cell stack, compressors, inverters, etc. are input into the cost model whose output, together with that of the thermodynamic system model, is used for the purposes of establishing a system design and parameterization of the power system performance over a range of load conditions. Weather data and building characteristics, such as a construction materials, are fed to the model which computes building hourly heating and cooling demands. The generated building loads are then employed in the annual simulation. In addition to gas and electric utility rate data, operating strategies (e.g., electric and thermal load-following vs. base-load) are provided. The annual simulator computes hourly and yearly fuel cell system efficiency, economic, and environmental performance from the various inputs. Feedback between the fuel cell system design, operating strategy, and simulation results is necessary to approach "optimal" application designs.

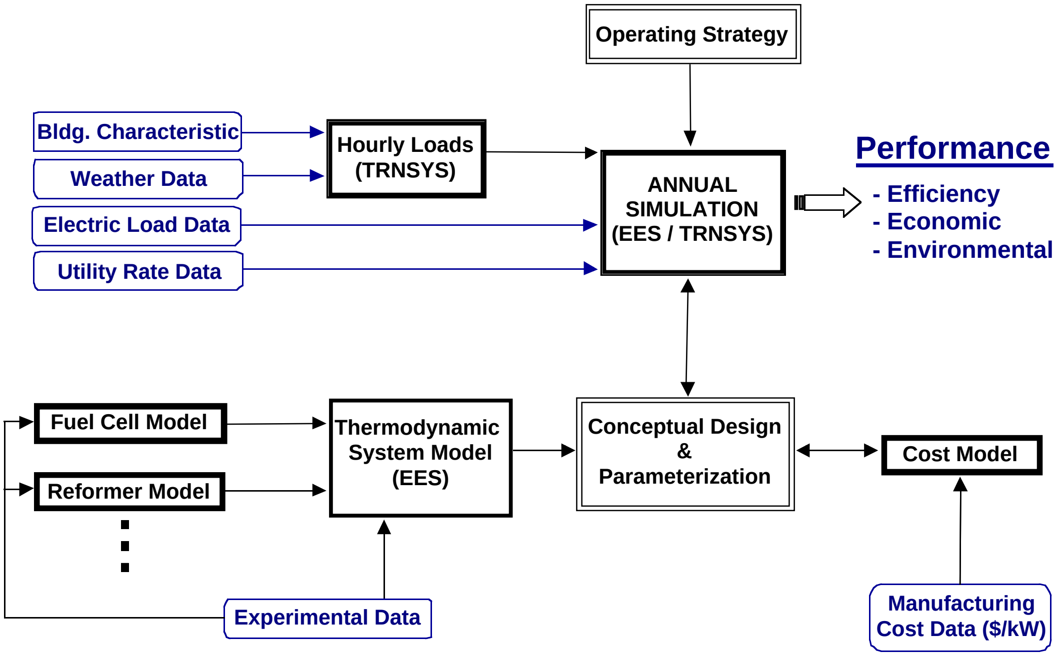


Figure 1: Model Information Flow Schematic

Fuel cell systems consist of fuel preparation, fuel cell stack, and power conditioning equipment. The primary fuel for the small applications (residential) is natural gas, necessitating a model for equipment that provides fuel reforming. A cost model that incorporates production-scale capital cost estimates for solid oxide fuel cells was developed. The model makes use of component costs, utility costs (grid electricity and natural gas), interest rates, and expected return-on-investment and calculates the system capital and operating costs. From this, a fuel cell cost-of-electricity (COE) is computed and used as an optimization parameter for system design. An annual simulation model was developed for residential building applications to investigate optimal system designs over a range of load conditions.

The balance of plant components for a fuel cell system are the fuel compressor, fuel desulphurizer, air blower, air and fuel preheaters, and dc-to-ac inverter. Depending on the type of installation, the fuel compressor may or may not be needed as city natural gas pressures are often stepped down through gas regulators. The natural gas used in this analysis was comprised of a mixture of 95% methane and 5% carbon dioxide with some low-level sulfur which must be stripped via a catalytic desulfurization process. The desulphurizer is a packed bed reactor in which catalytically promoted zinc oxide is used to remove sulphur compounds. The inverter technology in fuel cell systems is a solid state electronic device which allows for variable DC voltage input and outputs either a 120V or 240V, 3-phase alternating current. The efficiency for this class of inverter was 94%. The fuel compressor and air blower are centrifugal type units with isentropic efficiencies of 70% and 63%, respectively. Table 1 lists the component models needed to model fuel cell systems and their respective status.

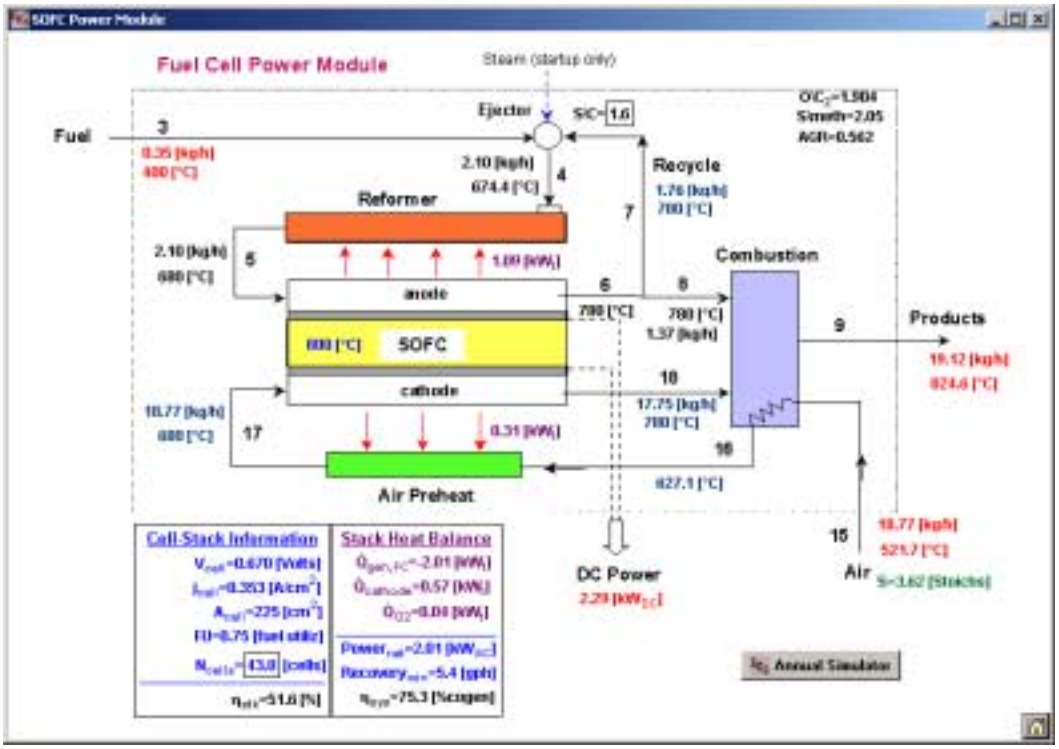
Table 1: System Component Models and Status

	Model Status	
System Component	**Complete**	**Future Effort**
Fuel cell stack	**X**	
External reformer		**X**
Fuel desulphurizer	**X**	
Steam ejector (jet pump)		**X**
Fuel compressor	**X**	
Fuel preheater	**X**	
Air compressor	**X**	
Air preheater	**X**	
DC/AC Inverter	**X**	
DC/DC Inverter		**X**
Hot water storage tank	**X**	
Lead-acid battery	**X**	

The modeling of each of the system components in Table 1 required a basic thermodynamic approach. The model is made up of a system of governing equations, the formulation of which is derived from: 1) boundary conditions, 2) conservation laws, 3) property relations, and 4) performance characteristics of the component. With this approach, a program was written using Engineering Equation Software (EES), a general purpose equation solver, to determine all the state point variables in the thermodynamic flowsheets. Mass and energy balances were written for each component in the system. Performance characteristics, such as cell voltage-current curves, blower and compressor efficiencies, and heat exchanger effectiveness or overall heat transfer coefficient were included in the analyses. See the complete report for a detailed description of these models.

Fuel Cell Design and Optimization Program

Figure 2 shows a program diagram window showing output and process flowsheet information for an indirect, internal reforming, 2-kW solid oxide fuel cell stack using anode gas recirculation. The display shows relevant temperature, mass flows, heat flows, DC stack power generated, and other stack performance information. The design and simulation programs are separate programs but are linked together and accessed through action buttons. An example of the program diagram window for a 2-kW residential system is shown in Figure 3.



Cell-Stack Information

V_{cell}=0.670 [Volts]

i_{cell}=0.353 [A/cm^2]

A_{cell}=225 [cm^2]

FU=0.75 [fuel utiliz]

N_{cells}= 43.0 [cells]

η_{elec}=51.6 [%]

Stack Heat Balance

$\dot{Q}_{gen,FC}$=-2.01 [kW_t]

$\dot{Q}_{cathode}$=0.57 [kW_t]

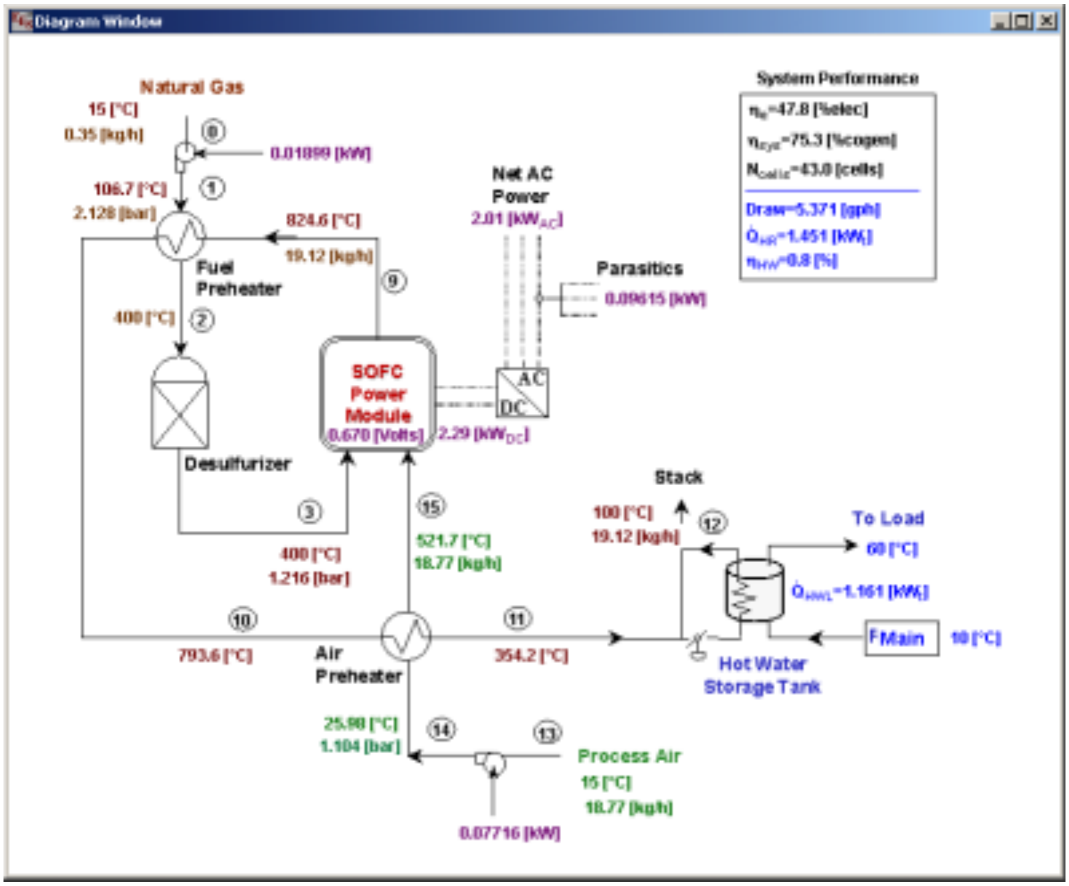
$\dot{Q}_{O2}$=0.08 [kW_t]

$Power_{net}$=2.01 [kW_DC]

$Recovery$=5.4 [gph]

η_{sys}=75.3 [%cogen]

Figure 2: Sample Program Window for 2-kW Fuel Cell Stack



System Performance

η_{el}=47.8 [%elec]

η_{sys}=75.3 [%cogen]

N_{cells}=43.0 [cells]

Draw=5.371 [gph]

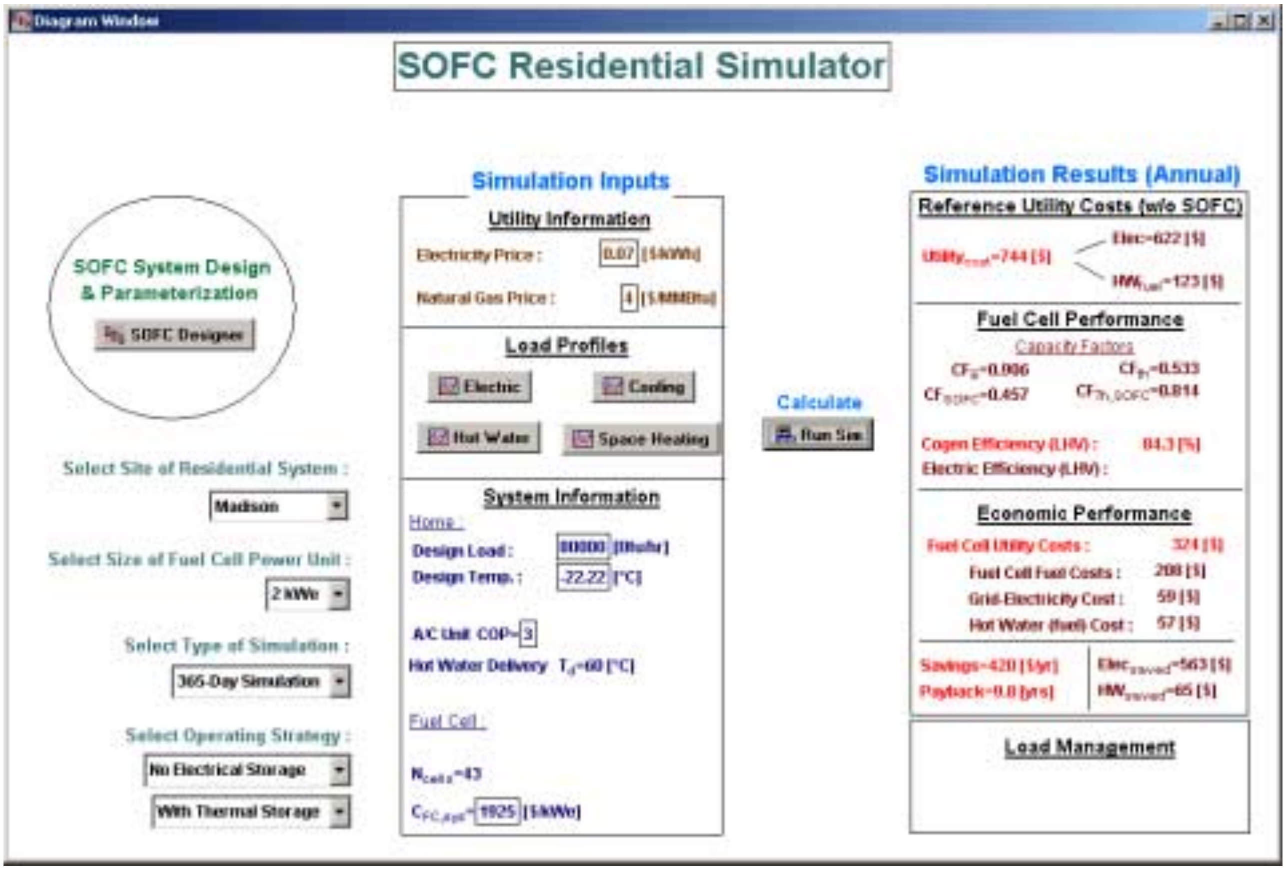
$\dot{Q}_{HR}$=1.451 [kW$_t$]

η_{HW}=0.8 [%]

Figure 3: Sample Program Window for 2-kW SOFC System with Thermal Storage

Once the fuel cell stack has been designed, heat exchanger parameters, stack size (number of cells for a fixed electroactive area), and reformer effectiveness are selected. With the selection of these values, power and process conditions may be predicted over the fuel cell operating range. The system performance is then characterized as a function of mass flow or power output. More specifically, the fuel cell power, stack current and voltage, cooling air flow, and exhaust gas temperature and composition are all functions of inlet fuel mass flow. The parameterization of these performance variables enables an annual (8,760 hours) simulation to take place relatively quickly. Utility rates, building loads, and system costs are input to the model.

The simulation program takes the respective inputs, and using simple control logic for load-management, calculates yearly natural gas and electricity consumption, utility costs, fuel cell power production, heat recovery, CO_2 emissions, and annual efficiency and utility savings realized by the fuel cell cogenerator. Figure 4 illustrates a user-interface window of the solid oxide fuel cell simulator. The simulation program also enables calculations to be made for a home in several U.S. geographic regions, including Madison, Baltimore, Tampa Bay, and Phoenix.



Select Site of Residential System : Madison

Select Size of Fuel Cell Power Unit : 2 kWe

Select Type of Simulation : 365-Day Simulation

Select Operating Strategy : No Electrical Storage; With Thermal Storage

Electricity Price : 0.07 [$/kWh]

Natural Gas Price : 4 [$/MMBtu]

Design Load : 80000 [Btu/hr]

Design Temp. : -22.22 [°C]

A/C Unit COP=3

Hot Water Delivery T_d=60 [°C]

N_{cells}=43

$C_{FC,spt}$=1925 [$/kWe]

$Utility_{cost}$=744 [$]

Elec=622 [$]

HW_{ref}=123 [$]

CF_E=0.906

CF_{th}=0.533

CF_{SOFC}=0.457

$CF_{Th,SOFC}$=0.814

Cogen Efficiency (LHV) : 84.3 [%]

Electric Efficiency (LHV) :

Fuel Cell Utility Costs : 324 [$]

Fuel Cell Fuel Costs : 208 [$]

Grid-Electricity Cost : 59 [$]

Hot Water (fuel) Cost : 57 [$]

Savings=420 [$/yr]

Payback=0.0 [yrs]

$Elec_{saved}$=563 [$]

HW_{saved}=65 [$]

Figure 4: Sample Window from SOFC Residential Simulator

Cost Model

A cost model that incorporates production cost estimates for solid oxide fuel cells was developed. The model, described in detail in the complete Phase I report, makes use of component costs, utility costs (grid electricity and natural gas), interest rates, and expected return-on-investment and calculates the system capital and operating costs. From these costs, a fuel cell cost-of-electricity (COE) is computed. The fuel cell COE is then utilized as an optimization parameter for system design.

The system capital cost is estimated from summing each of the component costs,

$$C_{sys} = C_{FC} + C_{FP} + C_{AP} + C_{INV} + C_{Blow} + C_{IC} + C_{HW} + C_{Bat}$$

where C_{FC} is the fuel cell stack unit cost, and C_{FP} is the fuel processing unit cost including fuel compressor, preheater, and desulphurizer. The desulphurizer requires the catalyst to be replaced every 4 years and this replacement cost is also included. Finally, C_{AP}, C_{INV}, C_{Blow}, C_{IC}, C_{HW}, C_{Bat}, are the unit costs for the air preheater, inverter, air blower, instrumentation and controls, hot water storage, and electrical storage battery, respectively. The unit costs are summarized in Table 2.

Table 2: System Capital Cost Data

Component	Unit Cost[1] ($/kW)		Cost Exponent[5]	
	1-5 kW	200kW	1-5kW	200 kW
Cell hardware[2]	$490/m^2	$490/m^2	0.0	0.0
Inverter	400	200	0.0	0.0
Air Preheater	202	106	0.8	0.75
Air Blower	99	43	0.8	1.0
Fuel Processing[3]	585	90	0.67	0.6
Instrumentation & Controls[4]	300	160	0.0	0.0
Hot Water Heater*	125	--	0.0	--
Battery*	50	--	0.0	--

* Residential cogeneration systems only

[1] 1999 USD

[2] 800°C cost shown. Cell costs are a decreasing function of temperature.

[3] Includes desulfurizer and catalyst, fuel preheat, and ejector.

[4] Includes startup burner and boiler.

[5] Costs for different capacities are scaled by the capacity raised to this exponent.

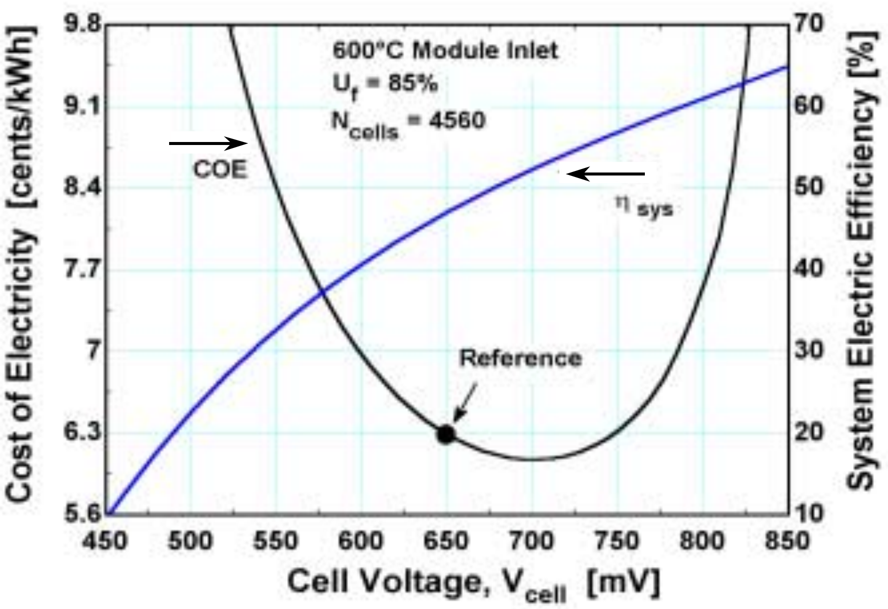
Results

The variables considered in the operating point study include operating temperature, cell voltage, and fuel utilization. For a given cell area specific resistance, these parameters dictate the power density and operating efficiency of the fuel cell stack module. The choice of the relevant performance parameters may maximize electric power or electric efficiency. In addition to a technical study of operating variables, the sensitivity of minimum life cycle costs to economic parameters, such as fuel and cell stack cost are also presented. Table 3 details the important system hardware specifications employed, including that of the base case, range of parameter variation, and fixed variables.

Table 3: Reference System Values and Parameter Ranges Under Study

Parameter	Ref. Value	Range Studied
Cell Temperature (°C)	800	700-1000
Cell Pressure (atm)	~1	Fixed
Cell voltage (mV)	650	500-850
Power Output (kW)*	200	May Vary
ASR (Ohm-cm^2)	.663	.278–1.01
Fuel Utilization (%)	85	60-95
Air Stoichs, S	4.2	2-6
Steam-to-Carbon Ratio	1.6	Fixed
Cell-Stack Temperature Rise (°C)	100	$\leq$ 100
Module Temperature Rise (°C)	250	200-450
Module Outlet Temperature (°C)	850	$\leq$ 850
Fuel Compressor Efficiency	70%	Fixed
Air Blower Efficiency (static)	65%	Fixed
Fuel Preheater Effectiveness	.415	Fixed
Air Preheater Effectiveness	0.70	Variable
Inverter Efficiency	4%	Fixed

The cell performance for a fixed stack size is investigated for 800°C operation and a fuel utilization of 85%. The effect of varying operating cell voltage on the cost of electricity (COE) and system electric efficiency is shown in Figure 5. At 650 mV operation, the reference COE is 6.3¢/kWh. The unit system capital cost (not including installation, transportation or contingency fees) associated with an average 650mV cell voltage is 1100 $/kW. As the operating voltage is increased (increasing fuel conversion efficiency), the cell-stack costs begin to increase at a rate greater than operating costs because lower current densities result and therefore larger cell areas



are required. Continued increases in fuel efficiency cannot pay for increases in capital costs, which are dominated by the fuel cell stack, and the selling price of electricity must then be raised to compensate. The minimum cost occurs at a cell voltage of 700 mV with a corresponding system efficiency of 52%. The effect of fuel utilization on COE also exhibits an optimum characteristic near a utilization of 90%. Increasing fuel utilization results in increasing capital costs due to the reduced average current density, but this cost increase is offset by decreasing fuel costs. This method of COE minimization was also employed to determine an optimal operating cell temperature of 800°C. Similar results were obtained for an analysis with fixed power output instead of fixed stack size.

Figure 5: Effect of Cell Voltage on Cost of Electricity and System Efficiency

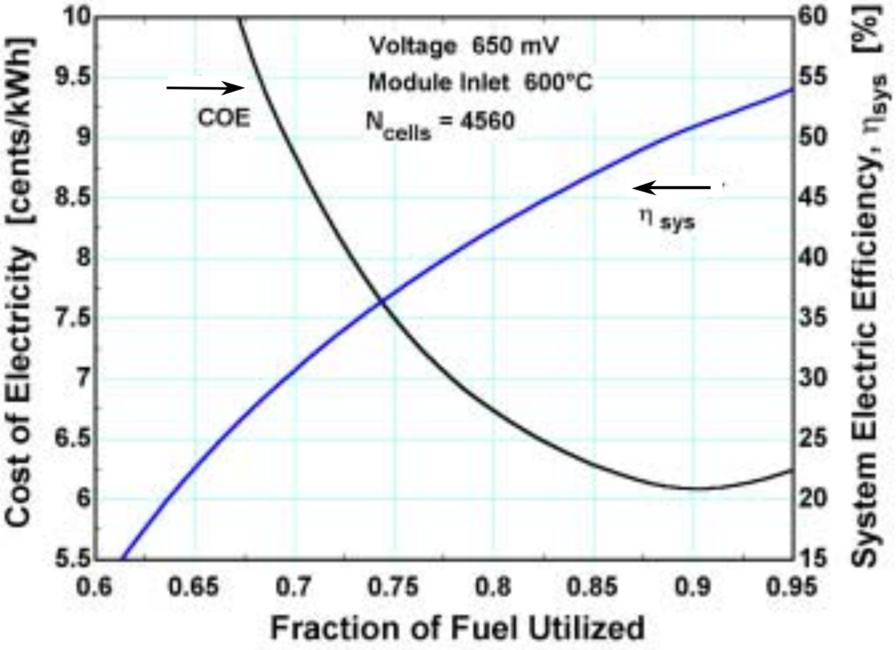


Figure 6: Effect of Fuel Utilization on Cost of Electricity and System Efficiency

A breakdown of costs indicates that fuel cost is dominant, followed by cell stack and balance-of-plant (BOP). The bulk of BOP costs (64%) are attributable to the inverter and start-up equipment, instrumentation, and controls. Aside from these costs, the air preheater accounts for 16%, fuel processing 15%, and air blower 5% of the total BOP cost.

The effect of varying fuel cell stack cost, area specific resistance (ASR), and fuel cost is illustrated in Figure 7. The stack costs are linearly dependent on cell operating temperature. The stack cost estimates utilized in this analysis are based on large manufacturing volumes (200 MW/yr). Early SOFC production units are likely to see higher costs, and as Figure 7 indicates, they must operate at lower voltages for increased power density. The cost of natural gas can vary greatly depending on geographic location. Increase in fuel costs necessitates higher electricity prices to achieve adequate payback, thereby boosting the required optimal operating cell voltage.

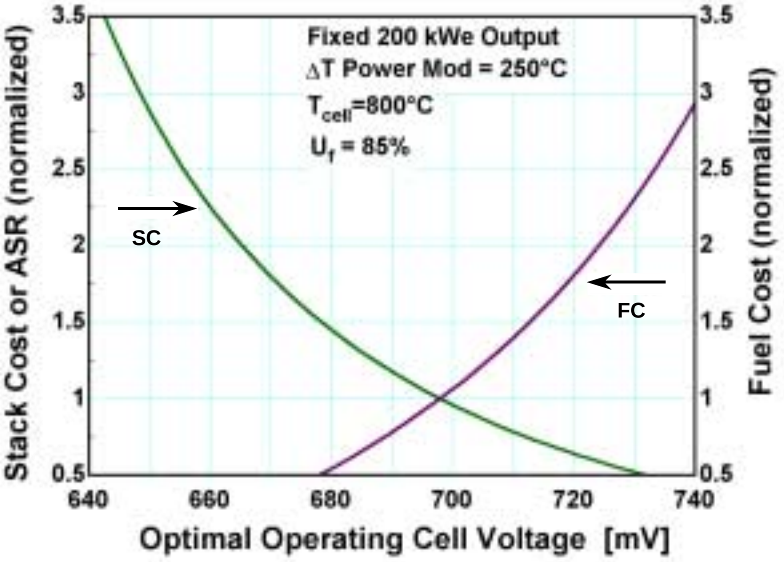


Figure 7: Effect of Stack and Fuel Costs on Optimal Operating Cell Voltage

To summarize, optimal operating voltage (0.7V), fuel utilization (89%), and operating temperature (800°C) were determined for both fixed size and fixed power analyses. System electric efficiencies as high as 55% are possible in these schemes. It was also recognized that the increases in temperature rise across the fuel cell power module had little effect on COE because of the heat sink effect of internal fuel reforming.

The analyses of optimal fuel cell design voltage were based on mature (i.e. high volume) stack cost estimates and relatively low natural gas prices. Economic sensitivities in these parameters suggest the following system design guidelines: 1) decreasing the optimal voltage when fuel cell stack costs are high, and 2) increasing the optimal voltage when fuel costs are high.

The results of the optimal operating point studies were of course dependent on cost estimates that have relatively large uncertainties, which makes calculation of absolute COEs difficult. However, while the precision of absolute numerical predictions may be low, the importance of the study lies in the *relative* change induced by altering an operating parameter.

A 2-kW rated SOFC system with a two-tank hot water storage configuration is shown in Figure 3. The optimal design parameters for this system (based on an electric-only analysis) were found to be 670 mV, 75% fuel utilization, and 800°C cell temperature. Operating at the design conditions, the system electric efficiency is 47.8% (LHV basis). The unit system capital cost for this design was estimated to be $1,925/kW. The total system capital cost, including the second hot water tank for waste heat recovery, was estimated to be $4100.

The conceptual system was designed for electric load-following and buffering of non-steady electrical demands by the grid. The two-tank hot water storage configuration allows for thermal buffering, that is, heat recovery during zero hot water draw situations. Cold water from the main enters the first hot water tank at 10°C. Depending on the amount of heat recovery and the tank temperature, the cold water can be heated from 10° to about 65°C. If the heated water leaves the first tank at a temperature lower than 60°C, a burner in the second tank accomplishes supplementary heating to the delivery temperature. A single node, lumped capacitance model is employed to simulate the hot water tank system. At rated power conditions, fuel cell waste heat gases enter the first hot water tank at 385°C where 1.6 kW of heat may be recovered before the gases exhaust the system at about 95°C. The corresponding steady-state thermal-to-electric power ratio is 0.8:1 at rated power conditions.

Electric load and water heating data were generated for a 242 m^2 (2,500 ft^2) home located in Madison, WI using TRNSYS (Klein, Beckman, and Duffie, 1999) and typical meteorological year (TMY) weather data. In winter, the maximum electric load is approximately 1.5 kW. The load data are represented by integrated hourly averages and therefore do not depict the shorter time scale peak power demands of 10 kW or more that characterize residential electricity consumption. The space heating thermal requirement can often be ten times greater than the electrical load. It can thus be seen that the use of residential fuel cell power systems to serve space-heating loads is difficult to achieve without other system concepts. In contrast, the domestic hot water demand illustrates a better match between the magnitudes of thermal energy available from the FC and the thermal energy required.

On a “typical” summer day, the electric load increases due to vapor compression air-conditioning systems. The peak power demand generally occurs in the afternoon hours and in this analysis, may range from 1.5–3.5 kW. Although the coincidence of the electric and thermal loads is not well matched, electrical and thermal storage opportunities exist.

The utility electricity price for this analysis was 7¢/kWh and the natural gas price was $4/MMBtu. Annual simulation of the fuel cell system without any maintenance shut down shows the annual fuel cell system cogeneration efficiency (LHV basis) to be 84.3%. Over the course of the year, the SOFC met 91% of the total house electric energy requirement. On the thermal side, the fuel cell system was able to provide 54% of the total annual domestic hot water energy requirements.

Table 4 summarizes the economic performance of the 2-kW SOFC residential power system against the base case of utility-provided electricity and gas. From a simple energy usage viewpoint (i.e., no fixed transmission and distribution costs), the use of the residential SOFC resulted in electric utility savings of $563, a 90% reduction. However, in the case where no heat was recuperated, the gas utility requirement increased 169% from $123 to $331 due to SOFC fuel consumption. A simple payback of nearly 11 years would result from an electric only operation. With cogeneration in the form of domestic hot water, the utility savings could be increased by nearly 20% over the electric-only system, achieving a 9.8 year payback.

The *electric* capacity factor of the fuel cell (defined as the kWh supplied by the fuel cell divided by the maximum kWh it could have supplied) is an important performance parameter, as it measures the total annual operating usage of the high capital cost component. The larger the capacity factor, the better the fuel cell payback economics. The electric capacity factor of the fuel cell indicates that a 2-kW size solid oxide fuel cell may be too large, as only 46% of its annual electrical energy production capacity was utilized. Employing a smaller fuel cell system of 1 kW could conceivably double the electric capacity factor to 92%. Other methods to increase the fuel cell electric capacity factor include the use of lead acid batteries, heat pumping, and where possible, selling electricity back to the grid for "net metering."

Table 4: Economic Summary of 2-kW SOFC Residential Cogenerator

System	Electric ($)	Gas ($)	Total Cost ($)	Payback (yrs)
Grid electricity; gas-fired water heater	622	123	745	(base case)
SOFC + grid backup; gas-fired water heater	59	331	390	10.9
SOFC + grid backup; cogeneration with gas-assist	59	265	324	9.8

The *thermal* capacity factor of the fuel cell, defined as the kWh recovered from the exhaust gas divided by the kWh that could have been supplied had the exhaust gases been reduced to the water main temperature, is also a useful measure. An 81% thermal capacity factor was achieved in cogeneration mode, displacing 4,800 kWh of thermal energy that otherwise would have been provided by the hot water heater. This high degree of waste heat recovery was possible due to the use of a 2-tank thermal storage configuration. Use of both electrical and thermal storage would effectively increase fuel cell electric and thermal capacity factors. Additionally, electrical energy storage may enable more high efficiency baseload operation strategies for the SOFC. In fact, such high efficiency operation may be necessary to offset the inefficiencies of power conditioning and electrical storage requirements of systems that include batteries.

Conclusion

Solid oxide fuel cell design and simulation programs were created and used to determine the optimal fuel cell design operating point for residential and commercial-scale systems and to simulate an SOFC-based residential cogenerator. A method for optimal fuel cell operating point selection for system design was presented. The results indicate that the optimal operating cell voltage for a 200 kW commercial class system is 700 mV and an optimal operating temperature of 800°C. This analysis showed an optimal fuel utilization of 89%, but further study of fuel utilization may be required. The results of the optimal operating point studies were dependent on cost estimates that have relatively large uncertainties. However, while the precision of absolute numerical predictions may be low, the importance of the study lies in the *relative* change induced by altering an operating parameter.

A 2-kW residential SOFC power generator system was simulated. Results indicated that an annual cogeneration efficiency of 84% and a ten-year simple payback were possible. The fuel cell system met both the electric and hot water loads with the help of a 2-tank hot water storage system. However, the value added by making use of the fuel cell waste heat for domestic hot water heating may be limited since the economic payback is reduced by only one year over an electric-only fuel cell configuration. The low electric capacity factor of 46% indicates that a 2-kW rating for the home in this analysis may be too large. Electrical storage, heat pumping, and net metering are conceivable options to boost electric capacity factor; however, optimal operating and control methodologies must be devised to maximize efficiency and economic performance.

The result of this research effort provides a simulation tool for assessing several critical aspects of fuel cell use in residential and commercial buildings. The preliminary information from residential analyses illustrates some of the technical and economic hurdles for viable systems in these types of applications. Ultimately, when all research phases are complete, they will provide a base of information for understanding of the key benefits, issues, and impacts of employing advanced fuel cell power systems in both small and large commercial applications.

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