

Considerations in the Design and Application of Solid Oxide Fuel Cell Energy Systems in Residential Markets

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ABSTRACT

This paper examines aspects of fuel cell system design for application in stationary residential markets. The development of fuel cell systems for sub-10 kW stationary applications involves consideration of sizing, fuel processing, operating point selection, fuel cell operating capabilities, system integration, and load management strategies. Each of these considerations is discussed, and strategies are presented for matching the electrical and thermal energy demands of a residence with a solid oxide fuel cell power system. Efficiency considerations for configuring fuel cell, DC-to-AC inverter, and electrical energy storage components for conditioning of DC power generated by the fuel cell stack are also given. Recommendations are made on the potential opportunities for solid oxide fuel cells in small-scale stationary power applications.

INTRODUCTION

In the U.S., residential and commercial sectors together are responsible for over 35% of the total annual energy consumption (EIA 1996). Of this fraction, over 50% is used for low-efficiency space heating, domestic hot water, air-conditioning, and refrigeration (EIA 1995). Modern residential furnaces operate with second law efficiencies of less than 15%, leaving substantial room for improvement. Nearly all energy conversion technologies in the various end-use sectors (transportation, industrial, and utility) attain higher efficiencies than residential heating applications. The low cost of heating fuels (natural gas, propane, and fuel oil) has allowed continued use of inefficient direct-fired heating systems. However, increasing national and international pressure to

reduce greenhouse gas emissions (primarily CO₂) coupled with concerns of finite energy resources are providing renewed impetus toward improving fuel conversion efficiencies (Grubb 1999; Oberthuer and Ott 1999). Additionally, electric utilities and independent power producers nationwide are studying ways to meet the increasing energy demands in a competitive environment through the use of distributed generation resources.

Research and development in the area of fuel cell technology has gained momentum during the past decade. Ongoing efforts in this area offer a timely opportunity to achieve significant improvements in energy conversion efficiency and reduction of energy-related emissions. Although fuel cells themselves have been studied extensively, primarily from materials and electrochemical viewpoints, a considerable gap exists in the area of application techniques to maximize benefits of fuel cell systems for both electrical energy generation and thermal energy utilization.

In this paper, we present design and operating approaches that will achieve optimal performance for solid oxide fuel cell (SOFC) systems in small-scale (1-10 kW) stationary applications, with particular focus on single-family detached dwellings. The paper begins by discussing application requirements for single-family residential dwellings. Next, design considerations for SOFC systems that provide residential heat and power are examined. The effect of design cell voltage on fuel cell thermal-to-electric ratio, cost of electricity, and value of thermal energy are quantified and reported. The paper concludes with recommendations to achieve variable thermal-to-electric ratios for grid-connected residential end-use and a short commentary on the outlook of fuel cell technology.

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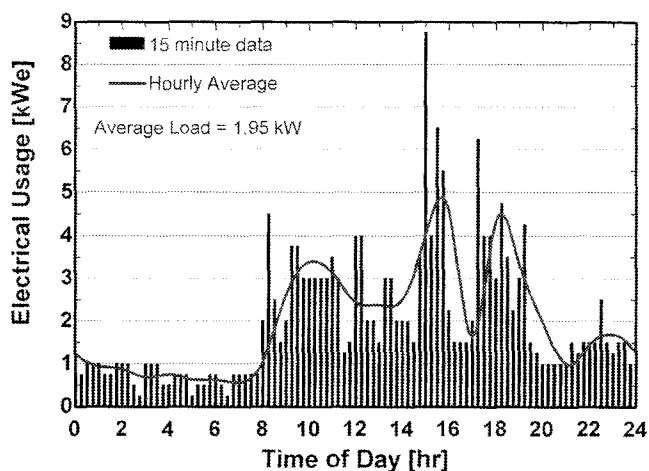


Figure 1 Diurnal electrical energy demand of a household (adapted from Bos 1994).

RESIDENTIAL APPLICATION REQUIREMENTS

The electrical energy demand in residential dwellings varies widely over the course of a day. Figure 1 illustrates an example of the diurnal electrical energy usage of a single-family household on both fifteen-minute and hourly time-average bases. Fifteen-minute load data better illustrate the peak electrical demands associated with cycling electrical appliances on and off. The magnitude of these demands ranges from a 0.3 kW base load to a 9 kW peak load. It is expected that short-term demands (on the order of seconds) of 15 kW or more during motor starts frequently occur (Bos 1994). Figure 1 provides some indication of the transient load-following characteristics that would be required by a stand-alone fuel cell power generation system for a residence. For instance, to follow the load variation in the fifteenth hour of the day would require the fuel cell power system to modulate at a ramp rate better than 0.5 kW/min. To truly follow the power demand associated with the cyclic operation of various appliances, the stand-alone fuel cell power system would have to be capable of responding to load steps on millisecond time scales.

Figure 2 depicts the hourly average residential energy demands for a 242 m² (2,500 ft²) single-family detached dwelling in Madison, Wisconsin, during winter and summer days. Electrical load data were obtained from Krist and Wright (1999) and account for lights, appliances, and HVAC power; domestic hot water (DHW) demand data from Mutch (1974) and space heating data were generated using an hourly building simulation model (Klein et al. 2000) driven by typical meteorological year weather data. As the residential energy load profiles in Figure 2 show, both the timing and magnitude of household energy demands are widely disparate; however, the annual average hourly electric load for the house is approximately 1.0 kW, and the annual average hot water load is also about 1.0 kW_{th} (3412 Btu/h).

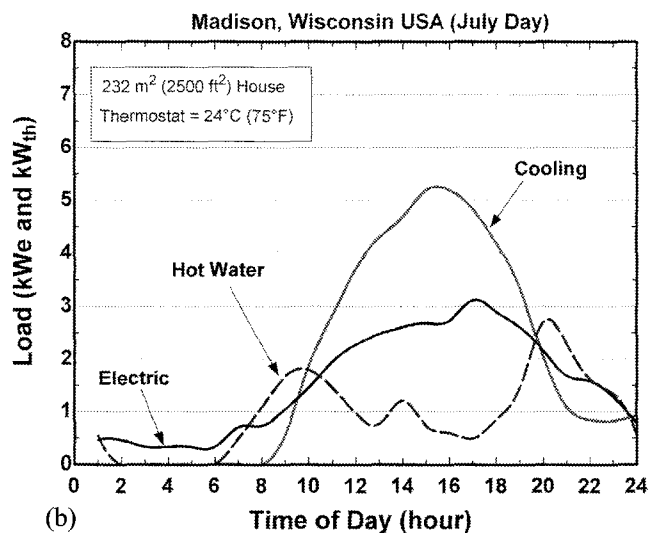
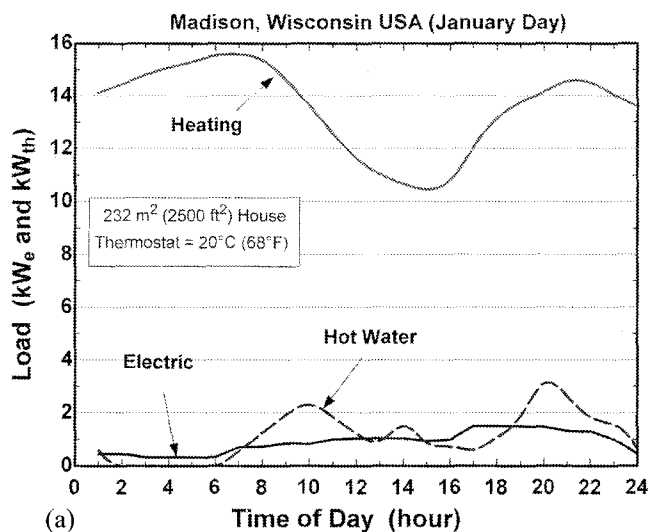


Figure 2 Winter (a) and summer (b) residential load profiles.

Household thermal energy demands also vary significantly over 24-hour periods. Figure 3 presents the hourly average residential hot water and space conditioning loads in terms of the thermal-to-electric (TER) ratio, that is, the residential thermal energy demand over the residential electrical energy demand. The hot water and space heating demands assume that electricity is not used for heat pumping. A peak hourly domestic hot water heating TER of less than 2.75 and a base value near 0.4 are apparent in the figure for a typical January day. The peak hot water TER for a July day is about 1.6 with a base value near 0.2. Also, note both the magnitude and rate of change in hot water TER during the early hours of the day. The annual hourly average domestic hot water TER is about

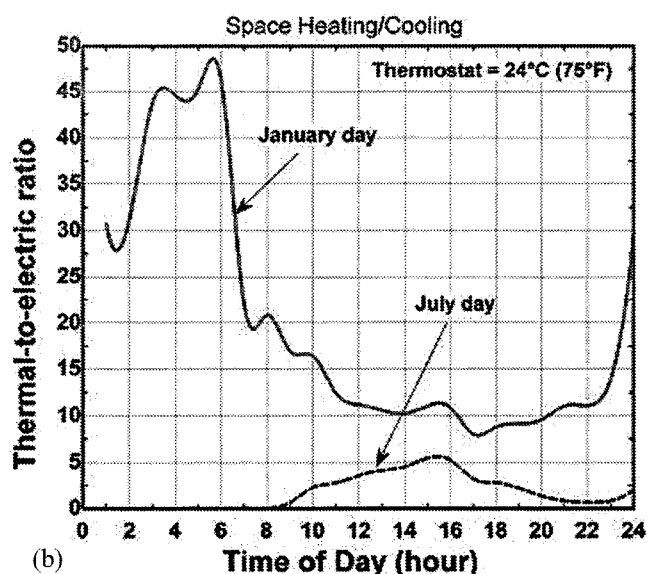
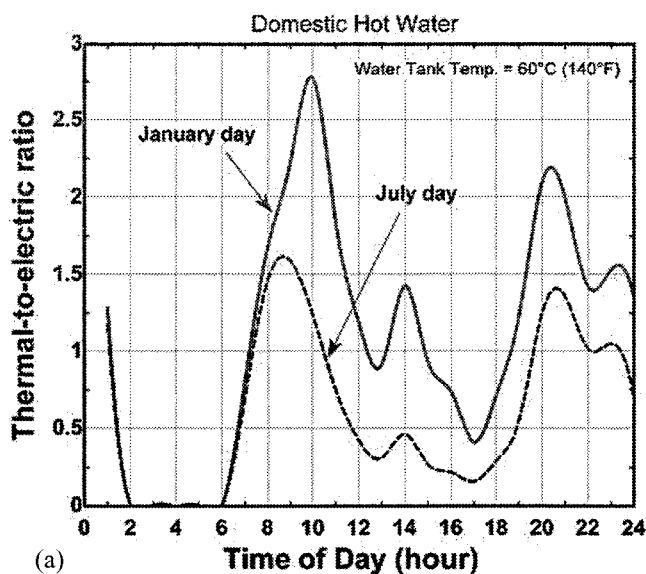


Figure 3 Domestic hot water (a) and space heating/cooling (b) diurnal thermal-to-electric ratios.

1.0, and this value is typical of most households in the U.S. In contrast to domestic hot water heating, the TER data for space heating is substantially higher with a peak hourly TER demand near 50 and a base load of 7. The cooling TER registers a maximum of about 5 during late afternoon hours. Since fuel cell systems typically operate with TERs between 1 and 2, their application is best suited for domestic hot water heat recovery.

Given the slow transient response capability of SOFCs and end-use load diversity, both thermal and electrical energy storage concepts may be required. In the case of grid-connected, single-family residential dwellings, electrical energy storage can be avoided by using the grid for peak power and fast dynamic power response.

FUEL CELL SYSTEM DESIGN CONSIDERATIONS

A schematic diagram of a conceptual natural gas-fueled SOFC system with external reforming and heat recovery is shown in Figure 4. Necessary components, in addition to the fuel cell stack, are the fuel processing (compressor, pump, desulfurizer, steam ejector, and reforming reactor) and heat recovery (boiler, air preheater, heat exchanger) equipment. Natural gas entering the plant is pressurized, stripped of sulfur, and mixed with superheated steam. The fuel-steam mixture is delivered to the integrated fuel preheater/steam-methane reformer where the endothermic reforming reactions are driven by the fuel cell stack exhaust gases to produce a hydrogen-rich fuel mixture suitable for delivery to the fuel cell anode. Methane is reformed to produce hydrogen according to the highly endothermic reaction,

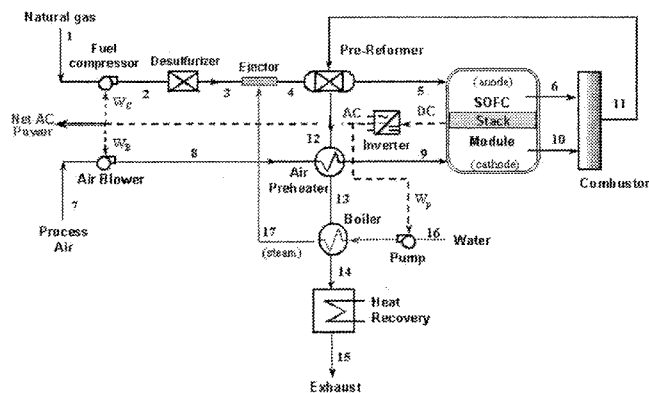
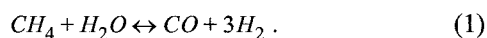
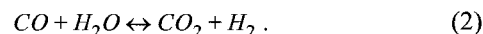
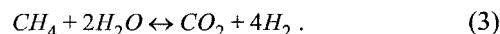


Figure 4 Schematic of a natural gas-fueled SOFC CHP system with external reforming (adapted from Riensche et al. [1998]).

Additional hydrogen is produced via the mildly exothermic shift reaction,



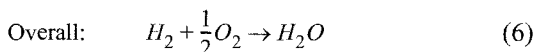
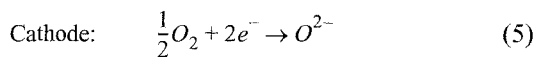
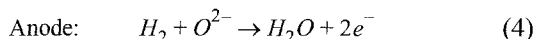
The overall reforming reaction is endothermic,



The reactants (hydrogen-rich reformat and air) are heated to a temperature approximately 50°C (122°F) below the nominal cell-stack operating temperature of 800°C (1472°F) prior to delivery to the fuel cell module to prevent thermal shock to the stack. Once delivered, the reactants are distributed through a manifold to the anode and cathode

compartments of the individual cells. Air is provided in excess (~100% to 600%) of the stoichiometric requirements of the electrochemical reactions to maintain the operating temperature of the solid oxide fuel cell.

Inside the cell, the hydrogen in the fuel gas is drawn to the anode where it is oxidized, and the oxygen in air is drawn to the cathode where it is reduced according to the following reactions:



After electrochemical oxidation of hydrogen and reduction of oxygen, the direct current (DC) power produced in the process is converted to alternating current (AC) by the inverter. A portion of the electrical power produced is used to serve ancillary equipment, such as the fuel compressor and air blower (W_c and W_B , respectively). Not all of the hydrogen delivered to the cell stack is reacted since doing so would unacceptably lower the stack voltage and threaten the integrity of the cell. The unreacted fuel exiting the fuel cell stack is oxidized in an afterburner with the depleted air exiting the cathode manifold. A portion of the anode cell exhaust (station 6) can be recycled to the anode inlet (station 4) to provide the steam for reforming. Recycling of the depleted anode fuel gases will alter the amount of fuel utilized in the cell stack and, hence, the stack efficiency. The term *fuel utilization* is commonly used to quantify the proportion of fuel electrochemically oxidized. Overall fuel utilization generally runs in the range of 75% to 90% for SOFCs. Oxidation of any unused fuel exiting the anode must be carried out in a catalytic combustion process due to its low heating value content. The products of the catalytic afterburning process are then recovered for use in fuel processing and air preheating before being made available for external heat recovery in the form of hot water, steam, or warm air.

Fuel type and fuel processing details can have a considerable impact on the efficiency and performance of a fuel cell system. Residential solid oxide fuel cell systems fueled with natural gas or another hydrocarbon-based fuel type will employ either internal or external reforming methods to generate the hydrogen needed for fuel cell operation. The steam required for methane reforming (see Equation 1) is supplied by either a waste heat boiler or by recycled fuel cell reaction products. Other hydrogen production processes, such as catalytic partial oxidation or autothermal reforming, are also available. The choice of one fuel reforming process over another is dependent on factors that include cost, efficiency, transient response, and technology readiness. The focus of this paper is on steam-reforming-based SOFC systems. Additional process design considerations, such as cathode gas recycle, separate

air and fuel gas loops, fan and compressor selection, etc., are also important but are more pertinent to cost and product performance optimization, i.e., design trade studies.

The addition of the fuel processing equipment adds complexity, capital cost, maintenance, and inefficiency to the system, but this equipment is necessary in any practical system operating on readily available hydrocarbon fuels. The fuel reforming processes for fuel cell system design, operation, and optimization are of major importance, since the overall system efficiency is heavily dependent on the hydrogen production efficiency.

Efficiency improvements in second generation SOFC systems will likely be realized by the use of direct-internal reforming at the anode, as well as other advanced gas processing concepts, such as anode gas recirculation, cathode gas recycling, and integrated fuel processing. The use of cathode gas recycling lowers the air preheater heat exchange duty and, depending on how the recycling effect is achieved, can lower the blower parasitic power. Integrated fuel processing can include combining fuel preheating and fuel cell exhaust gas afterburning steps or fuel pre-reforming, coupled with fuel cell exhaust gas afterburning, together in a single component. Advanced SOFC cell stacks are also likely to exhibit high power density performance, which can increase the challenge of providing cost-effective cell stack air cooling.

There are several alternative approaches for recovering thermal energy from fuel cell exhaust gases. The temperature of the useful waste heat product depends on where the heat is extracted in the system. In Figure 4, heat extraction immediately downstream of the combustor produces the highest grade of heat, whereas heat recuperation after the steam boiler will produce the lowest grade of heat, which is more than sufficient for producing domestic hot water. In addition to the application requirements, another consideration for heat extraction design is that high-temperature heat recuperation can lower temperature differences in the downstream heat exchangers, thereby increasing their size and the associated capital cost (Riensch et al. 1998).

CONSIDERATIONS FOR POWER CONDITIONING AND ELECTRICAL ENERGY STORAGE

Most residential applications require 120 volt single-phase AC power, so the DC power produced by a fuel cell system will require power conditioning. Residential fuel cell systems can be configured as stand-alone or grid-connected. In stand-alone systems, batteries or other energy storage devices are used to meet dynamic and peak loads. In a grid-connected configuration, the need for batteries or other energy storage methods depends on the utility net metering plan and grid-connection charges, as well as the dynamic capability of the fuel cell system (in particular, that of the fuel processing subsystem).

In either grid-connected or stand-alone scenarios for residential applications, inverters are required to convert the high current, low DC voltage from the fuel cell to a 60Hz, single-

phase split 120V/240V output suitable for domestic stationary applications. Desirable inverter characteristics include high efficiency and low total harmonic distortion (<5% on a standard test). The efficiency of currently available sine wave inverters ranges between 87% and 96%, depending on the output voltage of the fuel cell. The maximum efficiency is typically reached at relatively small power outputs (20% of design capacity) and is maintained over the remainder of the power range (Ulleberg 1998).

The fuel cell may set its operating point based on a control signal from the inverter. The time constant of an SOFC can be 30 seconds or more (Achenbach 1995), resulting in a required time of one to two minutes for the fuel cell system to adjust to a new control setting. If the power demanded by the inverter during this transient is not matched by the power output from the fuel cell, there will be either a power deficiency or surplus.

In the case of a call for more power, the current is increased, resulting in a decrease in cell voltage accompanied by excess production of oxygen anions (O^{2-}) at the cathode. Changes in current demand (or power) can occur on millisecond time scales. The fuel supply to the anode compartment is not likely to follow such short time scale transients. Thus, the oxygen anions that migrate across the solid electrolyte are likely to arrive at the anode where no fuel is available for oxidation. When such a loss of fuel supply occurs, these highly reactive anions can then oxidize the nickel in the anode, thereby shortening cell life. To avoid shortened life, power system control sequences that ensure the cell stack is not exposed to the condition in which current demand exceeds production are required.

In the case of a decrease in power demand, unoxidized fuel will exit the cell and reduce the system efficiency. There are additional concerns for loss in electric load beyond an efficiency loss. For system designs where a catalytic combustor is positioned downstream of the fuel cell stack to oxidize unused

fuel, a fuel excess may lead to a large heat release in the unit, generating large temperature gradients. Large temperature gradients lead to the potential for damaging combustion catalysts via sintering. Worst-case scenarios in fuel overrun could result in critical failure to the combustor and/or cell stack. The level of hardware safety concern for such loss in load is proportional to the magnitude and duration of the load excursion from the previous steady-state operating point. Unless such issues can be resolved with control measures, load buffering (or energy storage) with a battery or other methods will be needed for stand-alone power systems.

In addition to the choice of energy storage technology (e.g., flooded or valve-regulated lead-acid battery, ultracapacitor, or flywheel), the strategy for the integration of the electrical energy storage medium into the power conditioning system design of a stand-alone fuel cell system can significantly affect the net fuel cell system efficiency. Figure 5 depicts a power conditioning system layout that could be used for power systems employing battery storage. The battery storage in this scheme is shown on the low-voltage side separated from the fuel cell by the DC boost (or charger). A SOFC may convert the raw fuel entering the plant to DC electrical energy with a conversion efficiency of about 50% (on an LHV basis). The fuel cell, system electric, and cogenerative efficiencies used in this paper are defined as follows:

Cell-stack efficiency

$$\eta_{stk} = \frac{\text{Gross electric DC power}}{\text{Heating value of fuel}} = \frac{P_{DC}}{(\dot{n}_{fuel,in} \cdot LHV_{fuel})_{system\ feed}} \quad (7)$$

Net system electric efficiency

$$\eta_{sys,e} = \frac{\text{Net AC electric power}}{\text{Heating value of fuel}} = \frac{P_{net,AC}}{(\dot{n}_{fuel,in} \cdot LHV_{fuel})_{system\ feed}} \quad (8)$$

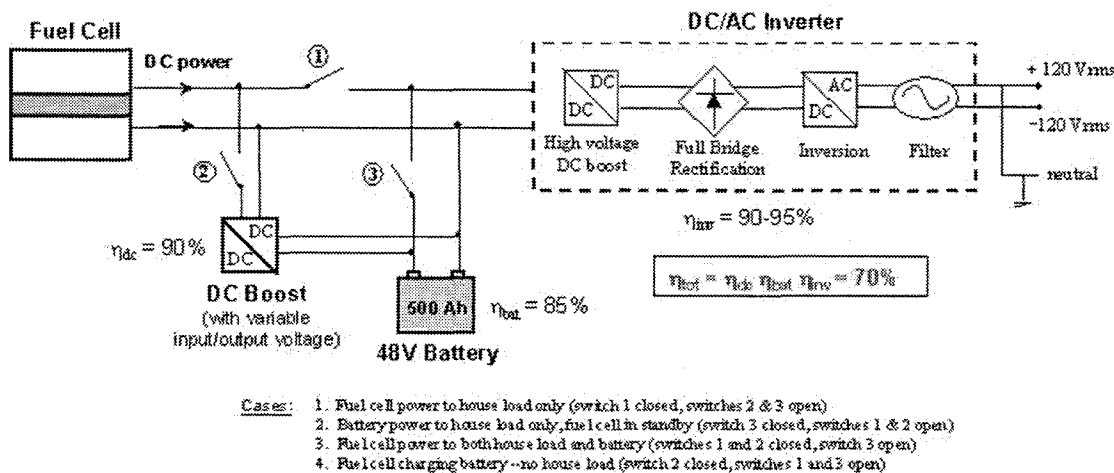


Figure 5 Power conditioning system topology for fuel cell electric power conditioning-
stack generation

System cogeneration efficiency

$$\eta_{cogen} = \frac{\text{Electric and thermal power}}{\text{Heating value of fuel}} = \frac{P_{net,AC} + \dot{Q}_{rec}}{(\dot{n}_{fuel,in} \cdot LHV_{fuel})_{system\ feed}} \quad (9)$$

where P_{DC} is the gross cell-stack DC power, $P_{net,AC}$ is the net system AC power, \dot{Q}_{rec} is the amount of thermal energy recuperated, $\dot{n}_{fuel,in}$ is the molar system fuel flow rate, and LHV_{fuel} is the lower heating value of the fuel.

If the fuel cell power is sent directly to the inverter, only about 10% of the DC power is lost in the inversion process, resulting in a net system efficiency of 45%. However, routing the power to the battery via the DC boost before inversion can incur a 30% loss for a net efficiency of 35%. Such a scenario could occur if the fuel cell was configured to only charge the battery with the battery always discharging to the load (i.e., fuel cell-converter-battery-inverter are placed in series). Alternatively, one could use a higher voltage battery after the DC/DC converter in the inverter section, thereby eliminating one boost stage during battery discharge and a source of inefficiency. Such considerations are necessary for optimal design and application of stand-alone fuel cell systems.

CONSIDERATIONS IN SELECTION OF FUEL CELL DESIGN OPERATING POINT

Changes in cell design parameters will yield varying thermal-to-electric ratios, as well as balance-of-plant¹ (BOP) component sizing, system economics, and overall performance. Solid oxide fuel cell system design parameters include operating cell voltage, temperature, and fuel utilization. As the fuel cell design operating voltage is altered, system process temperatures and the quantity of thermal energy available for domestic hot water production will vary. To investigate the impact of the average single cell operating voltage on cell stack and system performance, a one-dimensional counter-flow SOFC model, with direct internal reforming capability, was developed, verified, and incorporated into a system simulation model, complete with hot water storage (Braun 2002). The simulated system concept is identical to that shown in Figure 4. Figure 6 shows the predicted impact of design cell operating voltage on the gross cell-stack DC power, net system AC power, and air blower parasitic power for a 73-cell SOFC stack operating at 800°C (1422°F) and 78% fuel utilization. As the fuel cell design voltage is lowered, increasing cooling air is required to maintain the SOFC operating temperature due to lower efficiency operation. The increase in cooling air translates into increases in heat exchanger duties and blower power. The figure shows the dramatic difference between fuel cell stack DC power and net system AC power performance. The fuel cell stack can theoretically approach 5.5 kW of power

production; however, the net system power output can never achieve that level in practice due to increasing BOP (blower and compressor) parasitic loads.

The system TER increases with decreasing voltage in Figure 4, ranging from 0.40 to 1.65 in the design voltage range of 0.55 to 0.8 V. Because residential applications require instantaneous TERs of 2 or more, thermal storage can be used to more effectively satisfy domestic hot water needs. The integration of thermal energy storage decouples the production of hot water from the demand for its consumption to increase the fraction of waste thermal energy recoverable. A more complete investigation of selection of optimal fuel cell design parameters is presented in Braun et al. (2004a, 2004b).

A cost model that incorporates production cost estimates for SOFCs has been developed previously (Braun 2002). The model makes use of component costs, utility costs (grid electricity and natural gas), interest rates, expected return on investment, and system efficiency and calculates the system life-cycle costs, expressed as either cost of electricity (COE) or simple payback. The fuel cell COE may then be utilized as an optimization parameter for system design.

In an electric-only application, the COE is a function of capital and maintenance costs, fuel costs, system electric efficiency, electric capacity factor, and discount rate.

$$\text{Electric only:} \\ COE_1 = k_1 \cdot \frac{(R_F \cdot C_{sys,1} + M_C)}{C_F} + k_2 \cdot \frac{F_c}{\eta_{sys,e}} \quad (10)$$

In a combined heat and power (CHP) system, the net cost of electricity is influenced by the amount of thermal energy recovered. This amount is referred to as a "heat credit." The COEs (expressed in ¢/kWh) for electric-only and CHP systems can be determined from the contributions of capital and operating costs as shown by Ellis and Gunes (2002).

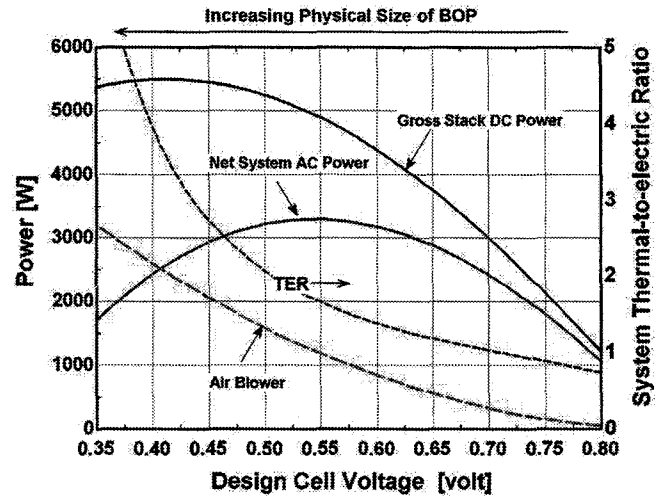


Figure 6 Influence of design cell voltage on system power and TER.

¹ The balance-of-plant is defined here as all system components except the SOFC cell stack.

Table 1. SOFC System Capital Cost*

System Size	Cogen.	Electric-only
(kW)	(\$/kW)	(\$/kW)
1	2170	2030
2	1630	1645
3	1425	1490
5	1250	1355
10	1050	1225

* Adapted from literature data (Lundberg 1989; ADL 2001)

$$COE_2 = \underbrace{k_1 \cdot \frac{(R_F \cdot C_{sys,2} + M_C)}{C_F}}_{\text{capital and maintenance cost}} + \underbrace{k_2 \cdot \frac{F_c}{\eta_{sys,e}}}_{\text{fuel cost}} - \underbrace{k_2 \cdot \frac{F_{th} \cdot \epsilon_H \cdot F_c}{\eta_{sys,e} \cdot \eta_R}}_{\text{thermal energy credit}} \quad (11)$$

where R_F is the capital recovery factor, $C_{sys,1}$ and $C_{sys,2}$ are the unit fuel cell system costs for electric-only and cogeneration systems in \$/kW, respectively, C_F is the electric capacity factor, M_C is the unit annual maintenance cost in \$/kW, F_c is the unit fuel cost in \$/MMBtu, $\eta_{sys,e}$ is the fuel cell system electric efficiency (lower heating value basis), ϵ_H is the heating or thermal energy recovery efficiency, F_{th} is the fraction of thermal energy from the fuel cell system that can be used, η_R is the efficiency of the thermal source that is displaced by the exported thermal energy of the fuel cell system, and k_1 and k_2 are unit conversion constants. ϵ_H is equivalent to $(\eta_{cogen} - \eta_{sys,e})$, where η_{cogen} is the system cogeneration efficiency. Transmission and distribution costs do not factor into the cost of electricity for onsite distributed power generation. Electric-only and CHP system capital costs were estimated and are summarized in Table 1. The values shown in Table 1 were computed for high manufacturing volume (0.2-2.5 GW/yr) scenarios.

Figure 7 depicts the influence of design cell voltage on the system cost of electricity² for a fixed design of 3 kW net AC power in a grid-connected scenario. The analysis results presented in Figure 7 assume that the efficiency of the thermal source that is displaced by the fuel cell system is 80%. As the design operating voltage is increased (increasing fuel conversion efficiency), the cell-stack costs begin to increase at a rate greater than operating costs because the lower current densities demand larger cell areas to deliver a 3 kW output. As the fuel efficiency increases, the fuel cost savings cannot offset the increase in fuel cell capital cost; consequently, the selling price of electricity must rise to compensate. The minimum electric-only cost of electricity occurs at a design cell voltage of 0.70 V, and the estimated cost of electricity (including a heat credit for exported useful thermal energy in the form of hot water) is

2. The COE is computed using a methane (estimated from natural gas) price of \$7.0/MMBtu, a capacity factor of 0.8, 20% discount rate, 0.5¢/kWh maintenance cost, cell-stack life of five years, and system BOP life of twenty years.

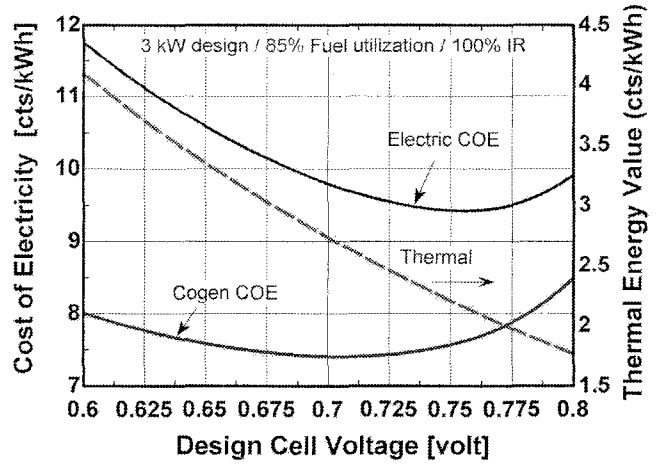


Figure 7 Influence of design cell voltage on cost of electricity.

7.4 ¢/kWh. The unit system capital cost³ associated with a 0.70 V design cell voltage is about 1500 \$/kW.

Interestingly, as the design cell voltage is increased, the electric-only COE decreases more rapidly than the cogeneration COE, reaching an optimal value of 0.76 V. The optimum for either cost is established by the same mechanism of competing fuel and capital costs; however, the location of the optimum is altered as fuel savings for recuperated thermal energy from the system are not realized.

Since the cost estimates remain uncertain for fuel cell systems, a capital equipment cost uncertainty of $\pm 30\%$ was applied to the present analysis. The COE resulted in a fixed value of 7.4 ± 1.3 ¢/kWh. The operating costs were estimated to contribute 56% of the cost of electricity at the 0.7 V design condition. Of this percentage, annual fuel cost accounted for 51% and operation and maintenance for 5%. The remaining 44% of the COE was distributed among the BOP (32%) and the SOFC cell stack (12%) capital costs. The fuel cell capital cost estimates were given for a high-volume production scenario (i.e., mature) and have a 33% salvage value at the end-of-life. For the mature mass production situation, fuel and balance-of-plant (BOP) costs dominate the total system life-cycle costs.

Figure 7 also presents the value of thermal energy recovered, as defined in Equation 11, as a function of design cell voltage. The plot shows a nearly linear decreasing value of thermal energy with increasing design cell voltage. The higher the cell voltage, the higher the system electric efficiency and the less thermal energy is available for DHW.

Figure 8 illustrates the economy of scale associated with balance of plant hardware that can be realized when varying the system power rating for a cell stack operating at 800°C (1422°F) with an average cell voltage of 0.735 V and a system

3. The unit system capital cost does not include installation, shipping, or contingency fees.

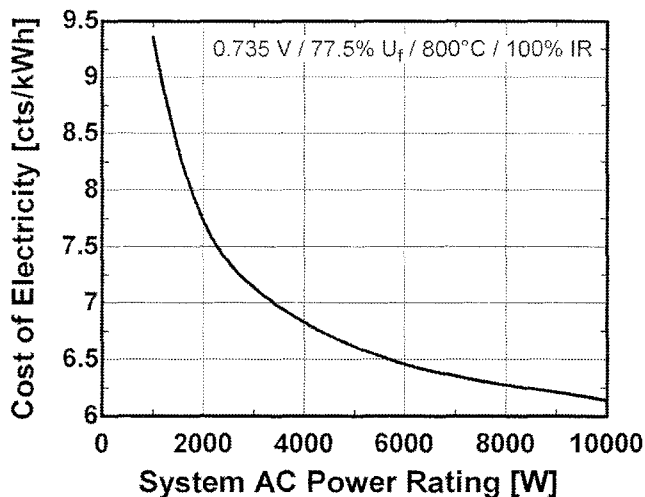


Figure 8 Influence of system power rating on life-cycle costs.

fuel utilization of 77.5%. As the size of the SOFC system increases, the cost of electricity decreases from a COE of 9.4 ¢/kWh at 1 kW to 6.1 ¢/kWh at 10 kW. Clearly, SOFC system capacities are more economical at 5–10 kW than at 1 kW, suggesting that competitive application of the technology would be in multiple-family dwellings rather than single-family, detached dwellings. It should be noted that Figure 8 only includes the economy-of-scale associated with the balance-of-plant hardware and not with the costs of the solid oxide fuel cell stack, which are more sensitive to economies of production.

DESIGN STRATEGIES FOR VARIABLE THERMAL-TO-ELECTRIC RATIOS

The most significant application requirements for residential fuel cell power systems are the required transient response, magnitude of the electrical loads, and the thermal-to-electric ratio (TER). The transient response and the magnitude of the electrical loads are not as significant for grid-connected SOFC systems where short-term load transients (and peak demands) can be met by the electric grid. Since residential applications require flexibility in operating modes, designing a system with variable TERs is a desirable objective.

Solid oxide fuel cell systems have difficulty in following the dynamic electrical load due to both the response time of the fuel delivery system (seconds) and cell-stack thermal response (minutes). The SOFC will eventually modulate up or down in power output in a relatively slowly changing manner, while the instantaneous power demand is served by the electric grid (or battery in stand-alone systems). Thus, the most difficult residential energy demand characteristic to meet with a fuel cell system is the high thermal/low electrical load condition. With this in mind, the following engineering design strategies have

been conceived to address meeting the quasi-instantaneous thermal (hot water)-to-electric load ratios.

Strategy 1—Net Metering

Many states in the U.S. offer the possibility to sell electricity produced from a home power generation system back to the utility through a net metering program. In such a case, the SOFC system could be designed to produce a fixed electric power with excess power sold back to the utility. The fuel cell TER could then have flexibility in matching the residential (or other end-use) TER. However, most net metering programs only buy back power at retail rates as long as the net kWh of the residence, as registered on the utility meter, are greater than zero for the billing cycle. The merit of this design and operating strategy from the customer perspective is explored further in Braun et al. (2004b).

Strategy 2—Hot Water Storage Tank System

This strategy makes use of the off-peak thermal energy recuperation by storing it to serve peak demands at another time. It is the simplest of the available options to meet demand and may be integrated with a conventional hot water heater if demands cannot be met solely by waste heat recovery. An SOFC system with a two-tank hot water system is simulated and results are presented in Braun et al. (2004b).

Strategy 3—Use Excess Fuel Cell Electrical Energy Generation for Electric Water Heating

The electrical demand of the application could be increased by use of a combination of electric and thermal energy recuperative hot water heating. In this scenario, both the fuel cell electrical and thermal output could increase, with only the resistive heating element as the additional system capital cost. However, higher SOFC load factors need to be weighed against cell life and durability issues, as well as the impact on operating costs.

Strategy 4—Integration with Heat Pump Systems

The capacity of the fuel cell can be increased to supply an electric-driven heat pump that would serve both the heating and cooling loads of the household. The fuel cell system could provide auxiliary heat and/or domestic hot water heating. For example, if the electrical demand of the household was 5 kW (where the heat pump provides 3 kW of heat), the total “heating” system (fuel cell plus heat pump) could provide 8 kW of thermal energy. Such a scenario might be limited by the economics associated with geographic variables (utility costs and weather) and an additional waste heat recovery heat exchanger for space air heating, but it deserves further investigation as the potential benefit is to meet a large fraction of the energy loads of a residence with the fuel cell heat pump system.

Strategy 5—Low Fuel Utilization Operation

This strategy involves operating the SOFC system at a higher fuel flow rate than required (low fuel utilization) and

sending the unused fuel to the catalytic combustor (after-burner). The lower operating fuel utilization would simultaneously increase the cell stack efficiency due to higher reactant partial pressures in the electrode compartments and the increased efficiency of the combustion process through preheat of the fuel and combustion air. Several additional design considerations, such as thermal limits of the catalytic combustor, combustor turndown capability, fuel feed composition flexibility, and reduction of fuel reformation load, are necessary. Alternatively, a fraction of the unused fuel could also be directed to the hot water burner.

In the present analysis, it is assumed that peak electric loads are served by the electric utility grid. However, there is at least one design strategy where the daily (or even hourly) average household electric load can be met at any time of the year without significant increases in capital and operating costs.

Strategy 6—High Voltage Stack Sizing, Low Voltage BOP Sizing

In this strategy, the stack size is based on a high voltage/high efficiency operating condition to meet the annual hourly average electric load. However, as noted in Figure 6, maximum cell power occurs at relatively low cell voltages/efficiencies. If the lower capital cost balance-of-plant components were sized to accommodate the larger gas flows at low voltage/high power conditions, cell stack power could be doubled depending on the original design voltage condition and operating current density limits. Thus, hourly average electric loads could be met most of the time with high-efficiency operation, but during the summer months, high power output could be achieved to serve an air-conditioning load. The disadvantage with this strategy is that higher system power turndowns are required, and rotating equipment (blower, compressor, and pump) will be operating at lower efficiency, off-design conditions for most of the year.

Battery storage was considered an unattractive option for grid-connected systems due to both high first costs and significant maintenance costs. In addition to proper sizing of fuel cell/battery combinations to avoid deep battery discharges, system design complexity increases in terms of control and proper electrical-side design topology for maximum net system efficiency.

SUMMARY OF RESULTS

Fuel cell-based power generation systems offer the potential for realizing more efficient use of primary resources to deliver electricity and thermal energy in stationary end-use applications. This paper has focused on small-scale stationary applications using solid oxide fuel cells, although many of the considerations necessary to achieve cost-effective design and application of this new technology are applicable to medium and large capacity installations, as well as to other fuel cell technologies, such as phosphoric acid, molten carbonate, and proton exchange membrane cell types. The following summarizes key findings reported in this paper:

- Residential applications generally require an average of only 1 kW of electrical energy.
- Due to BOP economy of scale, the lowest fuel cell cost of electricity is achieved with 10 kW systems, suggesting that a more competitive application of SOFC CHP systems in residential markets may be for multi-family dwellings. Additional investigation should be performed to evaluate the merits of SOFCs in this type of application.
- Considerations in cost-effective design and efficiency maximization include operating point selection, balance-of-plant design, and power conditioning system designs.
- Due to the large mismatch of TERs for space heating in northern U.S. climates, cogeneration to supply domestic hot water is the best option.
- Several methods to improve the match between fuel cell and residential TERs are possible, including integration with heat pump systems, and they should be examined in further detail.
- The value of heat is dependent on design cell voltages (as well as fuel prices and cost of capital) and has been shown to range from 1.7 to 4.2 cents/kWh of electricity generated.

CONCLUSIONS

The high level of optimism surrounding the “imminent” entry of fuel cell technology into many energy-use sectors is tempered by recognition of significant commercialization hurdles. The primary hurdles are component durability and system cost. Fuel cell design lifetimes are targeted at 40,000 hours with minimal cell voltage degradation⁴ between beginning and end of life, but development must continue if these lifetimes are to be achieved. In addition to cost and durability, fuel cell commercialization has been significantly impeded by fuel processing demands. The numerous steps involved to produce a hydrogen-rich fuel gas add complexity and inefficiency to the system. The use of catalytic reactors in fuel processing can also introduce operability and durability concerns as the reactors must allow flexible operating conditions and avoid deactivation of the beds while providing sufficient operating lifetimes. Hydrogen has been considered by many to be the fuel of the future. However, substantial issues in the production, storage, and distribution of hydrogen exist as barriers to achieving a hydrogen economy (cf. Eliasson and Bossel 2002). Fortunately the futures of fuel cell technologies and hydrogen are not necessarily intertwined. SOFCs can, theoretically, operate using methane directly, and research is underway to make this viable (see Gorte et al. [2002]); however, they are more efficient when operating off hydrocar-

4. Acceptable voltage degradation over the lifetime of the cell stack is typically targeted at $\leq 0.5\%$ mV drop per 1000 hours operation or $\leq 20\%$ drop in operating cell voltage from beginning of life to end of life (Hirschenhofer et al. 1998).

bons than hydrogen, primarily due to improved thermal management when using internal reforming (see Braun [2004a]), and relatively tolerant to fuel impurities.

The ultimate measure of success for fuel cell systems will be whether the technology can compete with other power generation technologies in terms of total cost, total life performance, and reliability. In many instances, the perceived "value" of the system is not only related to first cost but to avoided cost; for example, where expansion of the transmission and distribution infrastructure can make the alternative, distributed generation technology more attractive. The "value" of fuel cell technology may also be enhanced when compared to conventional generating technology in CHP applications. It has been noted (see Ellis and Gunes [2002]) that widespread application of CHP systems in buildings has been limited because conventional technology tends to (1) be most efficient in large sizes and when operating near full-load, (2) require a larger and more skilled maintenance staff, and (3) be limited in new plant siting due to environmental restrictions on noise and emissions. Fuel cell technology has the potential to overcome all of these limitations while offering enhanced efficiencies and lower chemical and acoustic emissions than conventional power producing and heating equipment.

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