ABSTRACT

Fuel cells are an attractive alternative for residential stationary applications because of their high power generation efficiency, low-emissions, and low-noise characteristics. The ratio of thermal to electric energy output for fuel cell systems matches the residential base needs far better than conventional internal combustion engine technology.

While PEMFC systems are being pursued for residential applications, SOFC systems may be more attractive in these applications. SOFCs operate at higher electrical conversion efficiencies, do not require CO removal, do not require humidification of the anode and cathode gases, and generate higher quality waste heat that can be better used for fuel reforming, space heat, or domestic hot water applications. The higher electrical efficiencies of SOFCs translate to lower fuel costs, meaning that they are allowed higher capital costs while still being economically competitive. While PEMFCs have shorter start-up times than SOFCs, a PEMFC system that includes methane reforming has a start-up time comparable to that of SOFC because both are governed by the transient response of the fuel processor.

INTRODUCTION

Fuel cells are an attractive alternative for stationary applications because of their high power generation efficiency. In addition, their low-emission and low-noise characteristics allow them to be installed at or near the end-user's location. In these distributed generation applications, fuel cells avoid expensive transmission and distribution costs and the alleged EMF problems related to transmission lines, thus providing environmental benefits beyond just reduction in emissions. As with any developing technology, fuel cells face the typical commercialization dilemma; in order to significantly penetrate the market, the production costs must be reduced. However, in
order to achieve significant cost reduction, the cumulative production must be greatly increased, implying that significant market penetration must occur.

One approach to minimizing the financial and technical risks associated with fuel cell commercialization involves the initial market entry of small-scale systems into high-value stationary applications (1). Small scale systems achieve rapid cost reductions from the economies of production (i.e., the manufacture of large number of identical units) as opposed to the economies of scale. One such small-scale, high-value application is residential cogeneration, generally in more expensive homes. A number of companies have been pursuing the development and commercialization of small scale proton exchange membrane fuel cells (PEMFC) for residential application. However, to date the bulk of the solid oxide fuel cell (SOFC) development efforts have focused on the larger-scale distributed generation market. Because the SOFC runs efficiently at high temperatures, it is quite suitable for combined heat and power residential applications as well.

The objective of this paper is to determine the advantages (if any) that SOFC-based systems might have in residential cogeneration applications. To do this we first identify the overall market requirements, especially from a customer perspective. Then we specify the technical performance requirements. Finally, we carry out an analysis to assess the suitability of SOFC-based systems in this application. This includes a comparison with PEMFC systems.

RESIDENTIAL COGENERATION REQUIREMENTS

From a residential customer’s perspective, a fuel cell based system should have the same attributes as current electric and thermal service. Its cost to the residential customer should be equal to or less than current service. It should have comparable performance in meeting the residential customer’s electric and thermal loads. It should have the same reliability as utility grid-connected service. It should have low emissions and negligible noise and vibration. Its volume and footprint should be commensurate with residential HVAC systems.

General Requirements

One aspect of fuel cells that is particularly advantageous is its low NOx emissions. The trend in emission regulations is towards increasingly rigorous standards. For example, the emission standards for small engines under 50 horsepower in southern California require NOx emission under 40 ppm. By comparison, typical uncontrolled internal combustion (I.C.) engines have NOx emissions in excess of 1000 ppm (@ 15% excess oxygen) while highly controlled units are in the 50 to 100 ppm range (2). It is expected that on site cogeneration system emissions would have to be no worse than those of gas furnaces and water heaters (e.g., 20 ppm for the low NOx units). By comparison, fuel cell power units have NOx emission levels of less than 5 ppm.

Cogeneration systems should not have noise and vibration levels in excess of current HVAC equipment; noise levels should be no higher than 60 dB. I.C. engines have
inherently high noise/vibration levels, although the developers have done an excellent job of minimizing this aspect by appropriate packaging (insulation) of the equipment. Fuel cell systems are inherently quiet, typically below 60 dB, with negligible vibration.

In residential applications there also will be practical limitations on the size and weight of the systems. There will likely be limitations imposed on size due to the need to move equipment through building doorways. The equipment should have size/weight characteristics in the same range as conventional HVAC equipment. Normalized volumes of conventional residential equipment are typically less than 7 ft³/kW.

The operation and maintenance (O&M) requirements for single family residences are more stringent than for commercial and multifamily buildings. Homeowners will not accept O&M requirements that require more than one service call a year (corresponding to 4000 to 8760 operating hours). In all likelihood, they would expect O&M performance comparable to current HVAC equipment, which is on the order of once every five years.

**Performance Requirements**

In assessing the potential of cogeneration systems for residential applications, it is necessary to take into account the daily and seasonal variations in both the electric and thermal loads. It would be convenient if the electric and thermal loads were coincident, since a cogeneration unit produces these two energy forms simultaneously and it is desired to make optimum use of the energy produced. Thus, the ratios of thermal to electric energy (i.e., T/E) needed by the residence and produced by the cogeneration unit are important parameters in assessing the relative fit of cogeneration for residential applications. To aid in this evaluation, it is instructive to separate the electric loads into 1) non-HVAC electric loads and 2) HVAC related electric loads. It is also instructive to separate the thermal loads into 3) domestic hot water (DHW) loads and 4) space heating and cooling loads.

The T/E of typical homes can range from as high as 9 in the winter (when the thermal loads for space heating are high, as shown in Figure 1) to less than 0.2 in the summer (when the electric loads are high for air conditioning and the only thermal loads are for hot water, as shown in Figure 2). Thus, the low (in the summer) and seasonally variable T/E ratios make sizing the cogeneration system difficult. On average, though, the electric loads (not including air conditioning) are about the same as the hot water loads, yielding a T/E of 0.6 - 1.0 (2,3).

For a single family residence, the average electric load (in the absence of air conditioning) is generally less than 1 kW, with the nighttime average loads being less than 500 watts. The average total daily use of electricity (including air conditioning) is about 15 kWh for a 1800 ft² house and increases to about 24 kWh for a 2400 ft² house. Generally, the reported electrical and thermal usage load profiles for a given type of building are averaged over the hour or half-hour. It is important to recognize that the hourly (or half-hourly) load profiles mask the large variations that typically occur in a house over the course of the hour. For example, during an hour when the average load might be less than 1 kW, the peak loads might be as high as 5 kW due to intermittent loads such as furnace blowers, hair dryers, and refrigerators/freezers. Thus, in designing a
Figure 1. Residential thermal and electric load profiles for the peak winter day in a northern climate (2).

Figure 2. Residential thermal and electric load profiles for the peak summer day in a northern climate (2).

system to meet the typical residential electric loads, it is necessary to allow for the capacity to handle these intermittent spikes.
SUITABILITY OF FUEL CELL-BASED SYSTEMS FOR RESIDENTIAL COGENERATION

Most cogeneration systems based on internal combustion (I.C.) engines are designed to meet the thermal load with the electric output as a byproduct. This is because typical I.C. cogeneration systems are only 25-30% efficient at converting fuel to electricity and have a relatively high T/E ratio (2 or greater). For example, the 5 kW residential cogeneration system developed by Kohler (3) had an electrical generation efficiency of only 23%, a T/E = 2.7 when operated in electric demand mode (13.4 kW thermal, 5 kW electric), and a T/E = 17.4 when operated in thermal demand mode (17.4 kW thermal, 1 kW electric). On average, I.C. engine driven cogeneration systems produce too much heat for residential applications, which explains why these systems have been restricted to niche applications, most of which have high hot water loads (e.g., hotels).

By comparison, current fuel cells operate at electrical generation efficiencies ranging from 40% for proton exchange membrane fuel cells (PEMFC) to 45% for solid oxide fuel cells (SOFC), based on the lower heating value (LHV) of methane. Fuel cell systems operating in this range have T/E ratios of approximately 1. As a result, the electric and thermal characteristics of fuel cell systems are much better matched with the base load requirements of residential applications than I.C. engine cogeneration systems. This makes their application less dependent on the size and consistency of thermal loads.

In assessing a fuel cell cogeneration system's suitability for residential application, it is necessary to define the manner in which it will be used. Will it be operated in a grid-connected mode or will it be grid-independent? If it is grid-connected, is there the potential for reverse metering if electricity in excess of that needed within the residence is fed back to the grid? Will it be operated in a base load configuration or will it be used as a load following power source? If it is grid-independent and operating in a base load configuration, what is the means of energy storage (e.g., battery storage) to handle the peak demands?

One of the advantages of fuel cells is their ability to operate efficiently at part load. In fact, in contrast to I.C. engines, which operate most efficiently at full load and show a rapid falloff in efficiency at part load, the overall efficiency of a fuel cell system incorporating a fuel processor tends to be constant between 50% and 100% of rated power and does not fall off until loads drop to less that 25-40% of full load (4). This constant system efficiency is a result of a trade-off in the efficiency of the fuel processor (which tends to have a lower efficiency at part load due to heat transfer losses and parasitic power requirements) and the efficiency of the fuel cell stack (which is higher at part load). Thus, because of its relatively flat efficiency-load curve, a fuel cell system would be better able to follow the electric load profile without incurring an economic penalty, unless it is consistently operating below 25% of its rated power. In addition to its relatively constant efficiency over a wide range of operating conditions, a fuel cell system also has a very fast reactive power response. This is advantageous in handling the instantaneous peaks when operating in peak following mode.
From the previous discussion it is clear that a fuel cell cogeneration system designed for base load operation would have a capacity of about 1 kW while one designed to address peak (or near peak) loads would need a capacity of about 4 - 10 kW (depending on whether it needs to handle only the hourly averaged peak loads or the full maximum peak loads). However, such a load-following system designed to handle the peak loads would be operating at only 25 - 10% of its capacity the majority of the time. One would pay a penalty in lower system efficiency as well as additional capital cost for operating at such a low capacity factor. This increased capital cost would need to be balanced against the cost of an energy storage device (e.g., battery) if operating in a grid-independent mode, or against the cost of electricity from the grid if operating in a grid-connected mode. Thus, it may be preferable to operate the fuel cell in a base load configuration.

**COMPARISON BETWEEN PEMFC AND SOFC-BASED COGENERATION**

In carrying out the analysis of alternative fuel cell-based residential cogeneration systems, we considered an SOFC-based system utilizing a steam reforming fuel processor with the system operating at 45% LHV electric conversion efficiency (based on the current demonstrated state of the art). We also considered two PEMFC-based systems: one utilizing a steam reforming fuel processor with the system operating at 40% LHV electric conversion efficiency (again, based on the current demonstrated state of the art) and one utilizing a catalytic partial oxidation (or autothermal reforming) fuel processor with the system operating at 35.8% LHV electric conversion efficiency. In all cases, we allowed for the recovery and use of the depleted anode gas as well as the waste heat generated by the fuel cell. A schematic of the fuel cell system is shown in Figure 3. The difference in the performance of the two PEMFC systems is attributable to the difference in the efficiencies of the fuel processors (5).

![Figure 3. Schematic of fuel cell power plant.](image)

A PEMFC-based system requires a fuel processor to convert the natural gas to hydrogen. This will either be a catalytic partial oxidation (POX) system, also referred to as autothermal reforming, or a steam reforming (SR) system. In both cases, it also requires sulfur removal, as the electrodes are easily poisoned by sulfur. Furthermore, the system requires CO removal, as the PEMFC anode catalyst is poisoned by CO levels above 10 ppm and the water-gas shift reaction is not able to achieve such low CO levels.
This can be accomplished using a preferential oxidation reactor or a palladium hydrogen separation membrane. As the proton exchange membrane performance is very sensitive to membrane dehydration, there is a need to humidify both the anode and cathode streams. The waste heat generated during the operation of the PEMFC is of low grade due to its relatively low temperature (70-90°C). As a result, its uses are limited to moderate heating of water to 50-55°C. This low grade waste heat is of little use in the fuel processor. In the case of the POX-PEM system, the unconsumed fuel in the depleted anode gas is available for further cogeneration use, such as space or domestic water heating. In the case of the SR-PEM system, the unconsumed fuel in the depleted anode gas is needed to help drive the endothermic steam reforming reaction. However, as the depleted anode gas does not contain enough energy by itself, it is necessary to combust a small portion of the natural gas feed to generate the remainder of the energy required to drive the steam reforming reaction. While PEM fuel cells themselves have relatively short start-up times, the start-up or transient response time of the PEMFC system is governed mainly by the response of the fuel processing system (which is limited by its thermal mass).

In comparison, an SOFC-based system can be operated with either an external reformer or it can reform the natural gas internally within the anode compartment. In either case, the reforming will employ steam reforming technology. As with the PEMFC-based systems, sulfur removal is required (although somewhat higher sulfur concentrations can be tolerated). However, an advantage that SOFC has over PEM is its ability to handle large quantities of CO, which participates in the water-gas shift reaction taking place in the anode compartment. In addition, water management is not an issue in the SOFC-based system as the performance of the solid electrolyte is not dependent on the presence of water. In contrast to PEMFC, where water is produced by the electrochemical reaction at the cathode, the SOFC produces water at the anode where it is subsequently consumed by reaction with CO during the water-gas shift.

Because the waste heat generated during the operation of the SOFC is at a high temperature (650-1000°C), the high quality waste heat can be used to aid in providing the energy necessary to drive the endothermic SR reaction as well as for domestic hot water and space heating. As was the case for the PEM systems, the unconsumed fuel in the depleted anode gas exiting the SOFC is available for use in reforming or for space heating or domestic hot water. While it is generally accepted that SOFCs have an inherently longer start-up time than PEMFCs due to their higher operating temperatures and larger thermal mass of the electrolyte, the start-up time of the SOFC-based system is comparable to that of the PEMFC-based system, both of which are governed by the transient response of the fuel processor. In addition, tubular SOFCs are less susceptible than planar SOFCs to damage from thermal shock or rapid start-up or thermal cycling. A summary of the comparison of the PEMFC and SOFC-based systems is given in Table 1.
Table 1. Comparison of issues for PEMFC and SOFC.

| Issues            | PEMFC                                      | SOFC                  |
|-------------------|--------------------------------------------|-----------------------|
| Operating Temperature | Fuel Cell: 80-100°C  | 650-1000°C            |
|                   | Reformer: 650-1000°C                    |                       |
| CH₄ Reforming     | External                                  | External or Internal  |
| CO Management     | CO is an anode poison                    | Participates in water-gas shift reaction in anode compartment |
|                   | Requires CO removal to reduce to <10 ppm levels |                       |
| Sulfur Management | Sulfur is an electrode poison             | More tolerant to sulfur but sulfur removal still required |
|                   | Requires sorbent bed to reduce to <5 ppm levels |                       |
| Water Management  | Membrane performance sensitive to dehydration.   | Not an issue.            |
|                   | Humidification required for anode and cathode streams | Water generated in anode compartment participates in water-gas shift reaction |
| Cogeneration      | Low grade waste heat                     | High quality waste heat |

It is widely perceived that SOFCs are ill-suited to residential applications because their lifetime can be shortened by thermal cycling. Indeed current SOFCs are often carefully brought up to temperature and cooled down over a period of hours. In practice, this will not be a problem, as most houses have a continual electric power draw. Appliances such as refrigerators, TV's, computer monitors, stereos, and HVAC fans operate 24 hours a day, independent of whether a house is occupied. Thus, as it is generally advantageous to supply power directly from the fuel cell whenever possible (rather than through a battery in which there is a 5% charge/discharge loss) the fuel cell will rarely face a no-load situation, and if it does, the no-load period will likely be short. Thus, there is very little penalty for operating the system in such a manner that the stack is always maintained at operating temperature.

From the perspective of the residential end user, the PEMFC and SOFC-based cogeneration systems (represented as “black boxes” with fuel input and electricity and heat outputs) differ in their capital costs, their fuel usage and in the quality of the recovered waste heat. The SOFC system has a larger amount of higher quality, high temperature waste heat available for cogeneration applications. In addition because of the higher operating efficiency, the SOFC system has a fuel usage that is 80% of that of the POX-PEMFC system and is 89% of that of the SR-PEMFC system. Assuming a cost of natural gas of $4/MMBtu (6), this translates to a lower fuel cost for the SOFC system (3.04 cents/kWh for SOFC, 3.41 cents/kWh for SR-PEM, and 3.82 cents/kWh for POX-PEM). The differential between the fuel costs and the U.S. average cost of electricity (8.57 cents/kWh (6)) gives us a basis to calculate the allowable capital and O&M costs for each system to be competitive with current delivered electricity. The bulk of this allowable cost will be for capital costs as O&M costs should be low due to residential expectations of one service call every five years. In addition, this allowable cost includes
the cost of energy storage (e.g., batteries) if the fuel cell is used for base load and the battery is used for peak load.

Assuming a fifteen year lifetime of the system, this translates to an allowable combined capital and O&M cost of $3376 for the SOFC system, $3150 for the SR-PEM system, and $2900 for the POX-PEM system. If the fuel cells are used for load following (with no energy storage) and as a result a higher capacity fuel cell is needed (i.e., 4 - 10 kW), this sets stringent limits on the allowable cost per kW for the fuel cells (290 - 850 $/kW). However, if the fuel cells are used for base load operation and are integrated with battery storage to handle the peak load, then a 1 kW fuel cell may be acceptable. Assuming that the cost of battery storage is the same for all systems, this implies that the base load SOFC system has a higher allowable capital cost than that of either PEM system to be competitive with grid-delivered electricity.

**SUMMARY**

In summary, fuel cells are an attractive alternative for stationary applications because of their high power generation efficiency, low-emissions, and low-noise characteristics. While a number of companies are pursuing the development and commercialization of PEMFC systems for residential applications, SOFC systems have advantages that make them more attractive in residential applications. SOFCs operate at higher electrical conversion efficiencies, do not require CO removal, do not require humidification of the anode and cathode gases, and generate higher quality waste heat that can be better used for fuel reforming, space heat, or domestic hot water applications. While it is perceived that PEM fuel cells have shorter start-up times than SOFCs, a PEMFC system that includes reforming of methane has a start-up time that is comparable to that of SOFC because both are governed by the transient response of the fuel processor.

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