Challenges and Opportunities for Fuel Cells in Stationary Power Generation

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ABSTRACT

Fuel cell power systems are considered attractive for a wide range of stationary power generation applications including residential, commercial, and industrial distributed generation, as well as large utility power plants. The current interest in fuel cell systems stems from their potential for high efficiency (lower heating value (LHV) efficiencies of 35-70 percent, depending on technology and system capacity). In addition, fuel-cell technology has demonstrated very low (truly negligible) emission levels and has noise characteristics similar to air-conditioning systems (i.e., mostly air-moving equipment). Routine maintenance of fuel cells has the potential for being minimal even in low-capacity systems because there are no heavily loaded mechanical subsystems required (unless compressors are required for pressurized operation).

Four primary fuel cell technologies are being developed for stationary applications.

- Polymer Electrolyte Membrane Fuel Cell (PEMFC);
- Phosphoric Acid Fuel Cell (PAFC);
- Molten Carbonate Fuel Cell (MCFC); and
- Solid Oxide Fuel Cell (SOFC).

The past two decades have seen impressive advancements in the science and technology of these fuel-cell power systems. Excellent discussions of the science and technology of all the major types of fuel cells, recent developments and remaining technical challenges can be found in

references [1-2].

We address the end-user economics of fuel cell systems for stationary applications using planar, 5-kW anode-supported SOFC technology as an example. Planar SOFC is receiving a great deal of attention as part of both government—the Solid State Energy Conversion Alliance (SECA) program—and industry initiatives. The increasing interest in planar SOFC is the result, in large part, to technology developments (anode-supported thin-film electrolyte designs) in which the total ohmic resistance of the stack is significantly reduced allowing for lower-temperature operation (650°C-800°C rather than 1000°C) than was previously the case.

We also discuss the important cost elements that determine the cost of electricity from fuel cell power systems including factory, material, installation, and operating and maintenance (O&M) costs. We assess the impact of success in ongoing R&D programs on the cost of electricity.

COMPONENTS OF A FUEL CELL POWER SYSTEM

Figure 1 shows a schematic of a 5-kW SOFC power system that operates on fossil fuels. In addition to the fuel-cell stack, a large number of balance of plant (BOP) components are required. The BOP components shown in Figure 1 include the fuel processor, high-temperature recuperators, fuel pump, and air compressor. BOP components not shown, but those that might be required for stationary systems, include power conditioning electronics, grid interface equipment, safety systems, and energy storage.

SYSTEM INSTALLED COSTS

The system installed costs are determined by the system factory cost, corporate overheads, the value-chain mark-ups, and installation costs (inclusive of permitting and interconnection costs). TIAX has developed proprietary cost models for estimating the factory costs of power systems such as that shown in Figure 1 [4-8]. The overall cost of a 5-kW SOFC system in high-volume production is shown in Figure 2.

Addition of the value-chain markups and installation costs could result in an installed cost that is two to three times the system factory

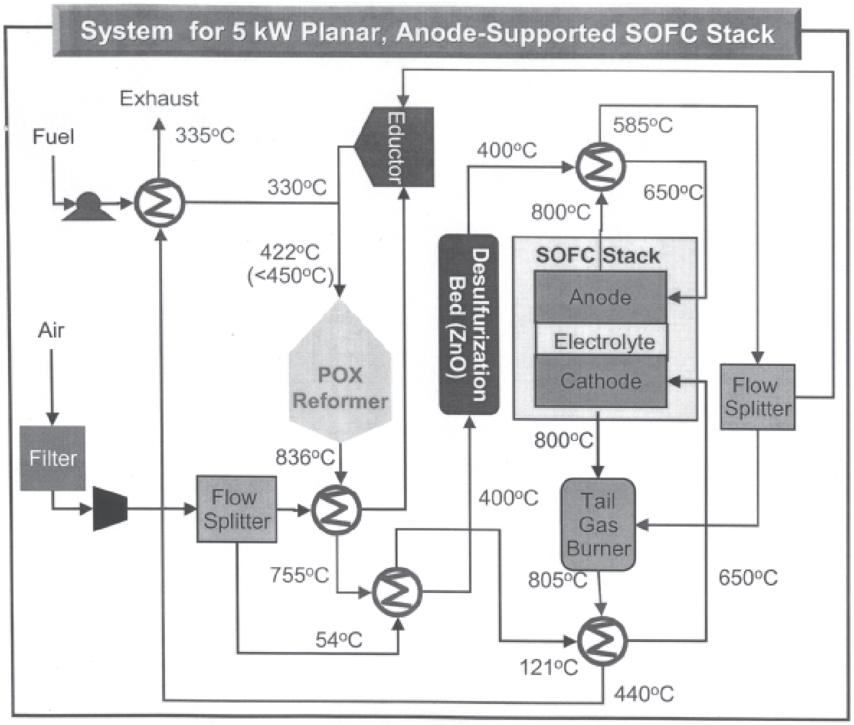

Figure 1. System schematic for a 5-kW SOFC power system based on planar solid oxide fuel cell technology. Balance of plant components not shown here but those that might be necessary for stationary applications include: power conditioning electronics, grid interfacing equipment, energy storage system [4].

cost. Note that the value chains for fuel cell systems are still developing. At this stage, one has to draw analogies with value chains for similar types of equipment to estimate the value-chain mark-up.

NON-FUEL O&M COSTS

Non-fuel operating and maintenance (O&M) costs are rarely discussed in the fuel cell literature and, as shown below, might become significant depending on the operating life characteristics of the system. The main components of the non-fuel O&M costs include the equipment

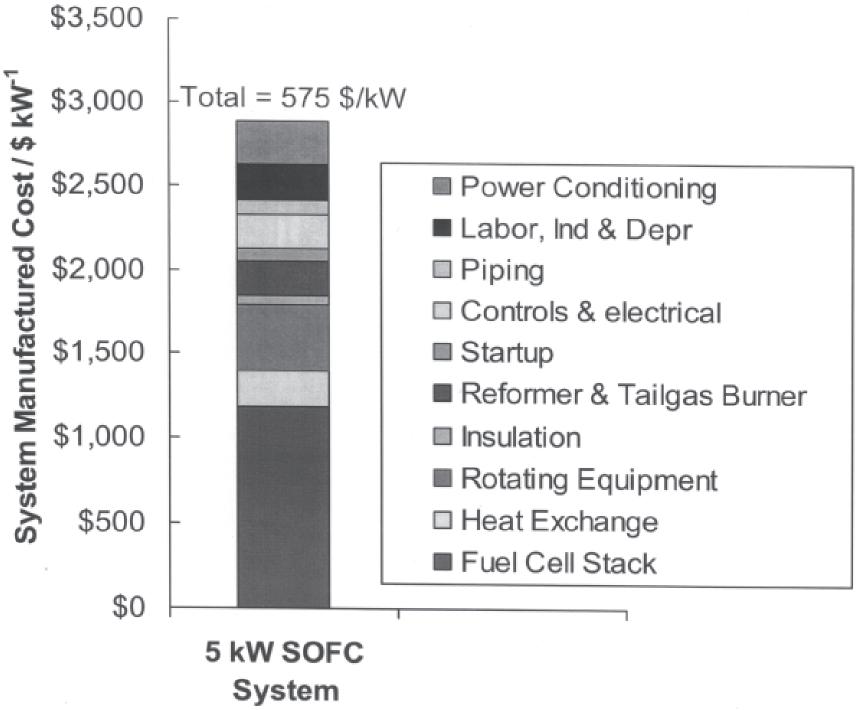

Figure 2. Breakdown of the system factory costs for a 5-kW anode-supported SOFC system. Additional costs might include the cost for grid interconnection equipment or battery energy storage device [4].

replacement costs, the labor for equipment replacement, and regular maintenance costs.

The replacement costs are determined by the life or the degradation rate of the equipment. In a SOFC system, the main uncertainty with life is associated with the SOFC stack. SOFC developers are targeting a stack life of 40,000 hours for stationary applications. Performance stability over the useful life of the system is important as well. For example, the performance of fuel-cell stacks degrades with time even during steady-state operation because of materials degradation. Assuming that 20-percent performance degradation is acceptable over a 40,000 hour period, the degradation rate of fuel-cell stacks must not exceed 0.5% per 1000 hours of operation.

To date operation of planar stacks has been demonstrated only for thousands of hours. In most demonstrations, the performance degradation rate has been unacceptably high. In contrast, the Siemens-Westinghouse tubular SOFC stacks have been tested for ~ 20,000 hours in a 200-kW system with less than 0.5% performance degradation. Single tubular cells have been tested for more than 60,000 hours with negligible performance degradation. Current and future efforts will be directed towards improving the SOFC stack life.

Figure 3 shows the impact of stack operating life and capacity factor on the non-fuel O&M costs. Clearly, a long stack life is preferable to reduce the non-fuel O&M costs. In addition, high-duty cycle operation is key to maintaining low O&M costs.

FUEL COSTS

Fuel costs are directly related to the system efficiency. Although the efficiency of a fuel cell stack can itself be quite high, the overall system efficiency is reduced by balance-of-plant inefficiencies. A major parasitic loss in a SOFC system is the power associated with the air compressor.

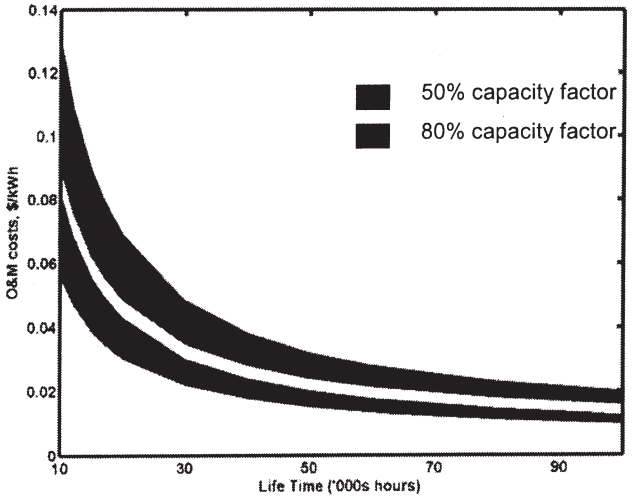

Figure 3. Effect of SOFC stack life and capacity factor on the non-fuel O&M costs for a 5-kW anode-supported SOFC system. The non-fuel O&M costs include the stack replacement costs, routine maintenance costs, and their associated labor costs [3]. The lifetime here refers to the period of time that the stack is at operating temperature.

SOFC stacks are air-cooled. For a typical planar SOFC, the air flow for cooling the SOFC stack is nearly seven times the stoichiometric air flow requirement. For a 5-kW system, the parasitic power for air movement represents about 15% of the total system power [4].

The overall system efficiency is influenced by the system capacity and the load profile that must be served.

For example, for base-load operation, a compact, cost-effective 5-kW system can be designed to operate at ~ 37 to 40% efficiency [4] and a 250-kW system designed to operate at ~50 to 54% efficiency [6]. At larger capacities (> 3 MW), fuel cell gas turbine hybrid systems can be designed to operate at ~ 65% efficiency [9].

On the other hand, for a system designed to follow house-hold loads, the overall system efficiency can be lower than the efficiency of the US electricity grid (Figure 4). The efficiency of the fuel cell system alone is about 38%. However, the power electronics that were sized for 9-kW peak loads (supplied by the fuel cell and battery), operate on average at about 10% of rated capacity. The resulting low average efficiency of the power electronics contributes significantly to the low energy efficiency of 29% [5].

Figure 5 shows the effect of efficiency on the fuel costs for a base-loaded 5-kW system, assumed to operate at a constant efficiency at 50% capacity factor. In this analysis, natural gas fuel costs were estimated at $6.75 per MMBtu, which is a typical value for commercial and industrial users. Residential users may pay a higher price. System efficiencies higher than 35% are required if the cost of electricity is to be less than 7.5¢/kWh, even if the capital cost and non-fuel O&M costs were zero.

COST OF ELECTRICITY: OPPORTUNITIES FOR COST REDUCTION

Significant resources worldwide are focused towards SOFC research and development. Developers of planar SOFC technology are primarily focusing on obtaining repeatable, reliable performance from stacks and systems based on conventional materials and architectures. In parallel, fundamental research worldwide is focusing on development of new materials and advanced architectures. Although it is impossible to precisely predict future technology developments, we can assess the impact on the system cost if the research targets are achieved.

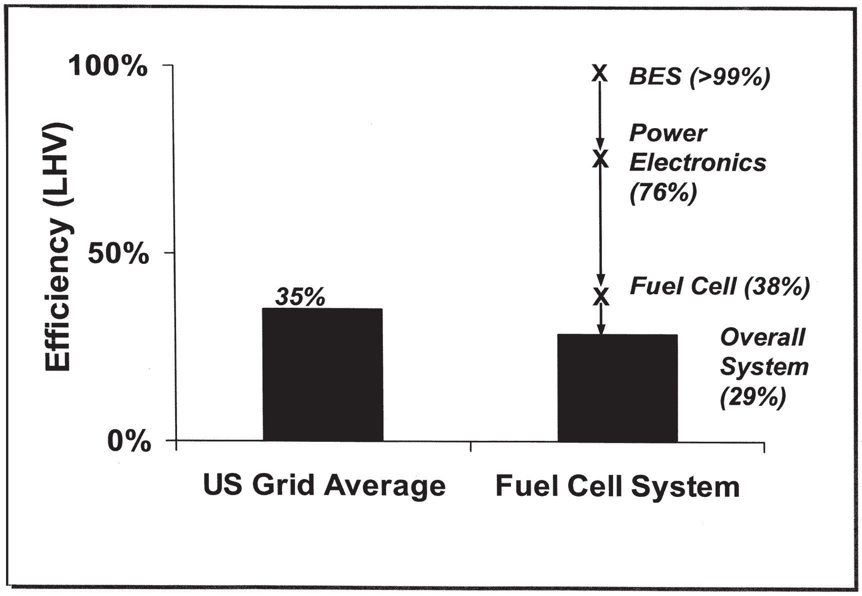

Figure 4. Annual efficiency of a grid-independent 4-kW SOFC system designed for serving household loads compared with the US grid electricity generation efficiency[1,2] [5].

1 U.S. grid average efficiency = 31.7% (based on higher-heating value (HHV)) for year 2000, from DOE's 2001 BTS Core Databook; July 13, 2001; Table 6.2. Corresponds roughly to 35% (based on lower-heating value (LHV)) efficiency.

2 BES = Battery Energy Storage. Round-trip BES efficiency is 85 %, but only a small fraction of energy delivered passes through the BES, resulting in an annual efficiency of >99%.

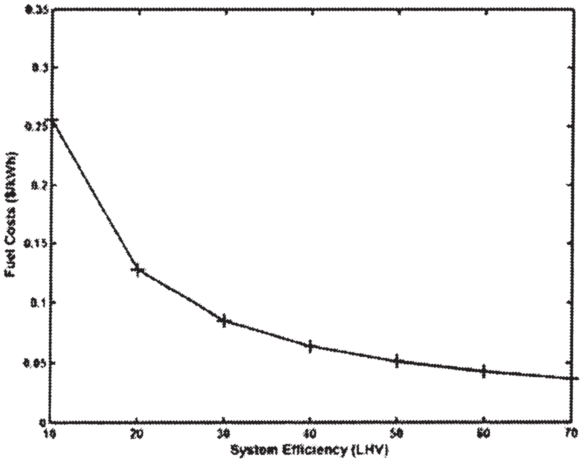

Figure 5. Effect of fuel cell system efficiency on fuel O&M costs for 50% capacity factor and $6.75 per million Btu.

The following summarizes some of the key developments that might reduce the fuel cell system costs. The potential effect of these improvements on the performance metrics are summarized in Table 1. The impact of these developments on the cost of electricity is summarized in Figure 6, which shows the cost of electricity at 0.12 $/kWh for the near term scenario dropping to 0.09 $/kWh for the long term scenario. In these Figures, near term refers to success in the current development programs with conventional materials and architectures, and long term refers to success in advanced development programs.

System Costs

Developers are focusing on improving the stack power density (which would lead to reduction in the materials costs) through a combination of better engineering of the stack and advances in stack materials. One option being pursued is a reduction in the stack operating temperature through advancements in stack materials. Also, improved heat rejec-

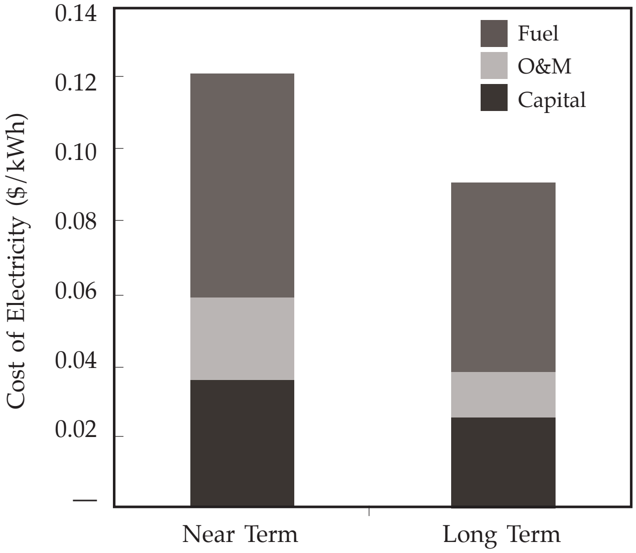

Figure 6. Comparison of the cost of electricity for near term and long term SOFC scenarios corresponding to the assumptions listed in Figure 6. Additional assumptions include: installed cost of system is two times the factory cost, capital recovery factor of 0.15, 50% capacity factor, and fuel costs of $7 per million Btu.

Table 1. Summary of assumed near term and long term performance characteristics of SOFC systems used for estimating the cost of electricity.

Performance Metric	Near Term	Longer Term	Assumed Performance Improvements for Longer Term Performance Projections
Stack power density	300 mW/cm^2, 0.7 V, 90% fuel utilization	600 mW/cm^2, 0.7 V, 90% fuel utilization	• Improved electrode microstructures • Reduced stack contact resistance • Better seals
Operating temperature range	650 to 800°C	500 to 650°C	• Improved cell performance resulting from materials development • Better cell and stack thermal management
Fuel reforming	~30% internal reforming/direct oxidation	~70 to 100% internal reforming/direct oxidation	• Optimized anodes • Better stack thermal management • Results in simplified balance of plant
Product life	Up to 30,000 hrs	Up to 50,000 hrs	• Lower temperature reduces degradation rates
System factor costs	~$525/kW	~$360/kW	• Improved stack power density, reduced recuperator sizes and reduced size of the air compressor
System efficiency	~35% to 38%	~40 to 45%	• Reduced parasitic losses from lower air flow, better thermal integration, internal reforming/direct oxidation

tion from the stack can help reduce the costs associated with air movement equipment and high temperature recuperators. Enhanced heat rejection can be achieved by the use of on-anode steam reforming of the fuel, direct oxidation of fuel on the anode, and use of more robust cell materials.

Non-fuel O&M Costs

There is little information in the literature to project the life of planar SOFC stacks or systems, consequently the life assumptions in Figure 6 should be regarded as place-holders only. Current focus for most developers is to obtain repeatable, reliable performance of SOFC stacks and systems, and long term performance data is scarce. However, the stack durability might be expected to increase with reduction in the operating temperature of the stack.

Fuel Costs

The fuel cell system efficiency can be improved through better thermal management of the stack and better thermal integration in the system. Use of on-anode steam reforming of the fuel, direct oxidation of fuel on the anode, and more robust cell materials can help reduce the coolant air flow required and hence improve the system efficiency.

CONCLUSIONS

End-user economics of fuel cell systems for stationary applications are dependent on the installed costs, non-fuel O&M costs, and fuel costs. The complete system inclusive of the required BOP components must be considered while evaluating these costs. Although non-fuel O&M costs are not typically discussed in the fuel cell literature, they can become significant if the system does not meet the life/reliability criteria. Our activities-based manufacturing cost models allowed an assessment of the impact of current and proposed technology developments on the end-user economics.

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Suresh Sriramulu, Jason Targoff, Stephen Lasher, Eric Carlson, and **Robert Zogg** each work for TIAX LLC. TIAX LLC (www.tiaxllc.com) is a premier technology, product development, and technology-based consulting firm operating at the intersection of business and technology. TIAX is the former Technology & Innovation division of Arthur D. Little, works with clients on the development and implementation of new technologies and products across a wide cross-section of industries, including the energy industry. As part of their focus on the energy sector, the company works in conjunction with the U.S. government and various commercial organizations to assess and analyze fuel cell development, examine the benefits of fuel cell use, explore the costs associated with fuel cell technology and investigate the proposed manufacturing and utilization of fuel cells. TIAX is ISO 9001 registered and has more than 50 research and development laboratories.

Dr. Suresh Sriramulu is an associate principal in the Hydrogen and Fuel Cells unit at TIAX, LLC. His specialization includes fuel cells, heterogeneous catalysis, and chemical reaction engineering. At TIAX (and previously at Arthur D. Little, Inc.) he has been involved in a wide range of fuel cell related projects including: performance modeling of fuel cell stacks and systems, technology due-diligence, market assessments, cost assessments, and experimental evaluation of fuel cells. In addition, he has been involved in the simulation and evaluation of emission control systems for stoichometric and lean-burn engines. Dr. Sriramulu has a Ph.D. in chemical engineering from the University of Washington, Seattle, M.S. in chemical engineering from the University of Wyoming, Laramie, and B. Tech in chemical engineering from the Indian Institute of Technology, Madras, India.