Assessment of Fuel Cell Applications for Critical Industrial Processes

Dan Birleanu, Energy & Resource Solutions, Inc.
Mark D'Antonio, Energy & Resource Solutions, Inc.
Gary Epstein, Energy & Resource Solutions, Inc.
Alan MacDougall, Energy & Resource Solutions, Inc.

ABSTRACT

In the past few years there has been an increasing emergence and market penetration of new fuel cell technologies. Successful technologies are characterized by their high power reliability or availability, minimal environmental emissions, and potential for cogeneration. The most commercially available system is the phosphoric acid technology, but there has been significant progress with several other fuel cell system types. Installed costs for most of these fuel cell systems have made it difficult to achieve economically attractive installations in the absence of third party financial incentives. A higher level of success, however, has been observed for applications that require premium power, characterized by a near total absence of power quality and availability problems (over or under voltages, surges, outages, etc.).

The focus of this paper is on critical industrial process applications that require premium power and the fuel cell systems that can resolve problems associated with power reliability. The paper will present detailed discussions of fuel cell power output characteristics and the integration of the fuel cell system in the overall facility power and utility infrastructure. A comprehensive feasibility assessment methodology will be described that assesses baseline power quality and its impact on the process, costs associated with downtime and power quality deficiencies, fuel cell system design concepts, system costing, energy and demand impacts, environmental impacts, overall economic merits, and the enhanced sustainability of the application. A case study example will be presented that considers an industrial process application in the semiconductor crystal manufacturing industry. For such processes, there is considerable sensitivity to interruptions in process-specific and facility environmental energy systems. Brief downtime or power interruptions can result in product loss for the duration of the crystal growth period, frequently several days. Complete technical, environmental, and economic merits of this application will be described.

Introduction

Power quality is a "hot topic" for today's automated and highly computerized industrial and commercial environments. For many energy users the cost of productivity interruptions, lost product, as well as damaged equipment due to power quality issues can be substantial. In recent years, premium power has become a "must" for companies that suffer major impacts to operations or productivity if an electricity supply fault is incurred.

Industrial processes represent one of the most vulnerable applications for premium power. Power quality events that could result in lost production or data can be prevented by employing adequate power supply strategies. Fuel cells can play an important role in providing premium power supply since they are extremely reliable and yield clean power. The following sections will present a discussion of common power quality problems, sensitive applications requiring premium power, a description of the premium power equipment with an emphasis on fuel cells technologies, and a methodology to assess the feasibility of premium power systems. Additionally, a case study for an industrial process application in the semiconductor manufacturing industry is presented.

Power Quality and Critical Applications

Premium power is clean, uninterruptible, controllable and reliable. The ultimate goal of a premium quality power strategy is to provide all of the critical equipment with power that is free from outages, voltage transients and other distortions. The most common types of power events, related possible causes, and associated effects on electricity consuming equipment are described in Table 1.

Table 1. Summary of Power Events – Causes and Effects

Event	Possible Causes	Effects
High-voltage spikes and surges	▪ Lightning ▪ Utility-grid switching ▪ Heavy building-system equipment	▪ Equipment failures ▪ System lock-up ▪ Data loss
Low-voltage electrical noise	▪ Electronic equipment ▪ Switching devices ▪ Motorized equipment ▪ Improper building power system grounding ▪ Power-system protective devices, contactors and relays ▪ Copiers	▪ Building-system data corruption ▪ Erroneous command functions ▪ Variations in system timing signals ▪ Changes in building-system processing states ▪ Loss of building-systems synchronization ▪ Control instability ▪ False activation of protective devices
Harmonics	▪ High number and capacity of switch-mode power suppliers ▪ Uninterruptible-power supplies ▪ Variable frequency motor drives ▪ Electronic lighting ballasts	▪ High power-system neutral currents ▪ Overheated distribution and power equipment such as transformers, panel boards, neutral conductors
Voltage fluctuations	▪ Overburdened power distribution networks ▪ Power system faults ▪ Planned and unplanned brownouts ▪ Unstable generators	▪ System lock-up ▪ Motor overheating ▪ System shutdown ▪ Bulb burnout ▪ Data corruption and loss ▪ Reduced performance ▪ Loss of control
Power outages and interruptions	▪ Blackouts ▪ Utility fault ▪ Construction accident ▪ Extreme weather conditions ▪ Utility system overload ▪ Power distribution main system fault	▪ System crash or lock-up ▪ Battery discharge ▪ Lost data ▪ Loss of control ▪ Lost communication ▪ Complete shutdown

There are numerous applications that require premium power. These are not only industrial or industrial-related sites, but also medical, social and administrative facilities. A short list of different premium power applications include: medical treatment facilities; high-security facilities; communications and data centers; advanced manufacturing processes; electronics manufacturing processes; air traffic control facilities; research and testing facilities; and remote sites and field operations.

For these applications, the impact of power quality problems range from simply losing communication capability to irreversible loss of production and even to devastating impacts on human life if problems happen in highly sensitive or hazardous environments, like medical facilities or advanced manufacturing facilities. Subsequently, critical systems require protection against faults in the main supply source, which in typical cases is the utility power grid. This protection equipment is selected in accordance with the facility's need for reliable power, and can lead to significant increases in the capital and operating costs for the critical process.

Premium Power Equipment

In order to assure high quality power to critical applications, a premium power supply system must satisfy the following essential design elements:

- **Availability.** Should the primary supply system go offline, power must seamlessly be provided to the redundant system. This is realized by high-speed transfer systems that can assure a very rapid switch between primary and backup systems without introducing significant voltage or frequency distortions.
- **Reliability.** The system must be reliable and must offer the requested reliability under any circumstances. When an application specifies a reliability of 99.9999% (six nines), it is typical that multiple backup systems utilizing different technologies and different primary energy streams are incorporated.
- **Maintainability.** The system must be easily accessible for maintenance while maintaining the desired level of availability. For very critical applications, any risk is too high; therefore redundancy represents a key element.

Historically, energy storage technologies have been used to solve power quality problems. These technologies produce no net energy but can provide electric power over short periods of time. They are used to correct voltage sags, flicker, and surges, and provide an uninterruptible power supply (UPS) to compensate for utility outages.

In recent years, distributed generation has emerged as an alternative solution that provides quality power and high reliability at the same time. Generator sets have historically been used to provide back-up power for large facilities. For many critical applications, partial or complete segregation from the utility supply provides a solution to externally generated transients and outages. Along with reciprocating generation sets, the main alternatives include microturbines, small gas turbines, and fuel cells. These types of equipment can assure high reliability, come in many numerous form factors and capacities, and are highly adaptable to particular sites and applications. Installed together with energy storage systems, distributed generation can achieve reliabilities of “five to six” nines, often demanded by large critical facilities.

Fuel cells can provide a premium power solution for critical or semi critical loads that require higher quality and/or reliability than is typically provided by the electric utility grid. Depending on their configuration, fuel cells can provide continuous power while also serving as a backup or uninterrupted power supply.

Overview of Fuel Cell Technologies

A fuel cell is an electrochemical device, similar to a battery, which converts the energy from a chemical reaction directly into electricity and heat. When operated directly on hydrogen, the fuel cell produces this energy with clean water as the only by-product. Unlike a battery, which is limited to the stored energy within, a fuel cell is capable of generating energy as long as fuel is supplied.

Although hydrogen is the primary fuel source for fuel cells, the process of fuel reforming allows for the extraction of hydrogen from more widely available fuels such as natural gas and propane.

A variety of fuel cells are in different stages of development. The most commercially advanced includes: Phosphoric Acid Fuel Cell (PAFC); Proton Exchange Membrane Fuel Cell (PEMFC); Molten Carbonate Fuel Cell (MCFC); and Solid Oxide Fuel Cell (SOFC) – Intermediate Temperature (ITSOFC) and Tubular (TSOFC). Table 2 presents an overview of the current performances of the fuel cells and Table 3 presents a synthesis of the challenges facing the different fuel cell technologies.

Feasibility Assessment Methodology

Like other energy related assessments, the premium power feasibility assessment methodology is a highly comprehensive approach, addressing all aspects of critical systems and the impacts on overall operations of the facility including technical, economic, regulatory, reliability, and environmental components. The following section discusses a methodology that addresses premium power technologies application with a special emphasis on fuel cell technologies.

Table 2. Fuel Cells Overview

	PAFC	PEMFC	MCFC	SOFC
Size Range	100-200 kW	3-250 kW	250 kW - 10 MW	1 kW - 10 MW
Fuel	Hydrogen, Natural Gas, Landfill Gas, Digester Gas, Propane	Natural Gas, Hydrogen, Propane, Diesel	Natural Gas, Hydrogen	Natural Gas, Hydrogen, Landfill Gas, Fuel Oil
Capacity	0.1-0.3 W/cm^2	0.6-0.8 W/cm^2	0.1-0.2 W/cm^2	0.3-0.5 W/cm^2
Efficiency	36-42%	30-40%	45-55%	45-60%
Environment	Nearly zero emissions (when running on H_2)	Nearly zero emissions (when running on H_2)	Nearly zero emissions (when running on H_2)	Nearly zero emissions (when running on H_2)
Other Features	Cogeneration (Hot Water)	Cogeneration (Hot Water)	Cogeneration (Hot Water or Steam)	Cogeneration (Hot Water or Steam)
Estimative Cost	$4,000 per kW	$5,000 per kW	$2,000-$4,000 per kW	$1,300 per kW (Desired)
Commercial Status	Available	Pre-commercial	Pre-commercial	Pre-commercial
Strengths	Quiet Low Emissions High Efficiency Proven Reliability	Quiet Low Emissions High Efficiency	Quiet Low Emissions High Efficiency	Quiet Low Emissions High Efficiency
Weaknesses	High Cost	High Cost Need to Demonstrate Limited Field Test Experience	High Cost Need to Demonstrate	High Cost Need to Demonstrate

Source: California Energy Commission, 2002

Table 3. Fuel Cells Current Challenges

PAFC	▪ Reduction of manufacturing and operating costs ▪ Further improved durability and reliability ▪ Reducing space requirements ▪ Improving heat recovery potentials ▪ Staying economically competitive with other fuel cell technologies as they mature
PEMFC	▪ Reduction of manufacturing and operating costs ▪ Understanding the influences of operating conditions ▪ Understanding transient load response ▪ Improve fuel processing to accommodate different type of fuels ▪ Improve cold-start ▪ Catalyst loading
MCFC	▪ Reduction of manufacturing and operating costs ▪ Reducing the rate of cathode dissolution ▪ Improve retention of the electrolyte ▪ Improving resistance to catalyst poisoning
SOFC	▪ Reduction of manufacturing and operating costs ▪ Identifying configurations that require less stringent material purity specifications ▪ Use of less exotic alloys, which is directly related to the high operating temperature ▪ Maintenance of seals and manifolds under severe thermal stresses

Description of the Operation and Need for Premium Power

The effort to fully understand the nature of premium power requirements starts with the collection of all pertinent data describing the current facility operations and the way in which electrical energy is utilized throughout the critical processes. Issues and technical topics to be addressed include:

Applicable end uses and equipment. Specific equipment or processes for which premium, high reliability power is required should be investigated in depth for system characteristics and sensitivity to power quality fluctuations.

Utility usage. Comprehensive data on utility usage should be gathered, with additional focus on demand and energy use patterns for that specific equipment for which premium power is imperative.

Outage and low power quality history. Frequency and duration of incidents of power outages or power quality failures should be identified. End use systems and equipment that have been severely impacted by such incidents should be identified.

Cost impacts of outages and low power quality incidents. Information should be gathered that describes the cost impacts associated with outages and power quality problems.

Technical impacts of downtime. In addition to direct costs associated with power incidents, data on other technical impacts of power incidents should be gathered. This may entail discussion of processes for which it becomes necessary to discard product from incomplete process runs and time to setup for a new process run after a power incident.

Capital project financial and investment rquirements. Data on the financial resources and conditions associated with purchase of premium power systems should be gathered and assessed for economic feasibility.

Assessment of Power Quality

Critical equipment service lines should be investigated to characterize historical power incidents. All power quality data should be assessed to determine if monitored power quality issues are within the tolerance range of critical equipment, or if the power quality has the potential to jeopardize the integrity of critical equipment operation or product manufacturing.

Assessment of Economic Losses Associated with Power Reliability and Power Quality Problems

Based on data collected regarding frequency and duration of power reliability and quality issues, and the impacts of such disturbances on key identified equipment and processes, accurate estimates of the economic impacts of such events should be performed. A scenario should be developed that outlines the anticipated annual cost of power quality and reliability problems on equipment and systems that are being assessed for service by a premium power system. This technical economic scenario, and its economic impacts, will be used in all subsequent analyses of the benefit of the premium power systems.

Research and Review of the Premium Power System Technical Options

A comprehensive review of the premium power systems that may have the most suitable applicability for the specific operations should be performed. A discussion of the premium power technologies that will be under immediate consideration, along with a brief discussion of features and advantages, should be presented.

Preliminary Technical and Economic Screening of Options

Based on the findings and data from the prior tasks, preliminary calculations to determine those technical options that are most suitable for further study and feasibility assessment should be performed. This task is intended as a screening function and should not be a highly involved (investment grade) feasibility assessment. As such, initial (simplified) estimates of energy impacts, system costs, maintenance costs, and energy and operational cost savings should be used in the modeling efforts. Similarly, the analysis modules will not produce an exhaustive range of economic results, but will develop a comparative framework where one can identify the technology or technologies that could be the subject of detailed life cycle cost analyses.

It is important to note that in addition to generating screening level economic indices, a discussion and tabulation of the technical advantages and disadvantages of each system option should also be developed. Under consideration will be premium power system maintenance costs and requirements, technology life and needs for stack replacement, sizing and spacing requirements, and numerous other factors. The preliminary environmental impacts of different technologies should be assessed as part of the screening of the options.

Once preliminary screening results have been developed, one or more technologies will be identified that look attractive. The goal here is to review the economic merits, and other advantages or disadvantages of each technology option, and decide what should be considered for conceptual design, system cost estimation, and detailed economic evaluation.

Preparation of Conceptual Design for Cost-Effective Application

Once a technology and application site has been selected for rigorous feasibility assessment, the next step is to prepare a conceptual design for the system. Site-specific conceptual designs differ from full-scale designs in that drawings and system plans are developed schematically and all explicit layout and control details are not necessarily specified. Conceptual designs are intended to explicitly show all major equipment that will be required, types of connections between most major components, and the flows and services for all utilities and resources necessary to operate the equipment. Further, the conceptual design facilitates accurate estimates of installation costs, as well as operating costs and conditions. In contrast, a full engineering design goes well beyond conceptual presentation of the system and incorporates explicit drawings, details, and operations associated with all aspects of specific equipment installation and existing infrastructure.

For the conceptual design of the premium power system, all major components necessary to install the premium power system should be identified, including: primary systems; control and instrumentation; transfer switching; electrical and non-electric utility supply; and all input and output connections. Also, the desired location of the system will be identified, and any issues involved in installing the system at the desired location will be assessed. The conceptual design should be presented as a series of schematic and one line drawings inclusive of utility connection equipment, a listing of all primary and auxiliary systems, and a detailed operation requirements and strategy document. The conceptual design as presented will represent the basis for a bid process for engineering design, or for a design-build firm to use as a guide for turn-key design and installation.

System Cost Estimation

The conceptual design for the premium power system will provide the basis for developing accurate estimates of installed costs for the system. The costs estimates for the system that will address: Primary Equipment Selection; Controls and Instrumentation; Electrical Panels, Service Wiring, Switchgear, and Connections; Plumbing Connections; Large Component Rigging and Installation; System Installation and Connection; Design Services; and Project Management. The final cost estimate will represent one of the primary inputs for the detailed energy and economic analysis for the overall project assessment.

Detailed Energy, Environmental and Economic Analyses

This important task will result in a summary that presents feasibility of the premium power installation from quantitative and qualitative perspectives. The information gathered or developed through all prior activities will be used to perform a series of energy, environmental and economic modeling activities that will yield results and information to develop conclusions regarding the installation of the premium power system. Furthermore, these analyses will provide the basis for developing an action plan for the implementation of the project. The analyses performed in this task will incorporate factors such as: Energy requirements for critical energy and process systems; costs associated with power quality and reliability issues; potential energy savings of the premium power system; installation costs for the premium power system; system maintenance costs

Using this information, life cycle system costs should be developed to demonstrate the economic merits of the premium power installation. Economic results can be presented as net present value, internal rate of return, or any other economic indicator that would be useful for making a decision on installation of the premium power system.

Case Study

The following case study focuses on operations within a semiconductor crystal manufacturing complex, specifically the crystal growth facility, and the applicability of a fuel cell system as a premium power solution for the facility. This project is in the initial stages and subsequently we will discuss preliminary study findings, detailed descriptions of the technological process, proposed solutions, and preliminary results of the technical, economical and environmental benefits of the proposed solutions.

The crystal growth process at the analyzed facility is based on Molecular Beam Epitaxy (MBE). MBE is a one of the few techniques for growing thin epitaxial structures made of semiconductors, metals or insulators. In this process, a beam of atoms or, more generally, a beam of molecules, is directed in an ultra-high vacuum towards a crystalline substrate such that the atoms or molecules stick at the substrate's surface forming a new layer of deposited material. The typical rate of growth with MBE is around a single mono-layer per second. Although slow, this allows for abrupt changes in material composition. Under the right conditions, the beam of atoms will attach to the substrate material and an epitaxial layer will begin to form. The production process includes a series of critical systems. Any fault in operation of these systems could affect the production cycle or the quality of the final product:

- **Ultra-high vacuum system.** The ultra-high vacuum environment is used to guarantee formation of a molecular beam.
- **Heating system.** The entire epitaxial growth process takes place in a heated environment. Both, the beam of molecules and the substrate are kept at high temperature (above 1400ºF) by tightly controlled heaters.
- **Cooling system.** The cooling is used to control the process temperature, but also for keeping the ambient temperature in the facility within specified limits.

The critical electric loads are associated with the direct fabrication of semiconductor crystals and with the supporting equipment that provides process and environmental control to facilitate the crystal growth production. A loss of function of any of the following critical systems will result in a termination of the growth cycle and a complete loss of product for that cycle:

- The ultra-high vacuum environment is used to guarantee formation of a molecular beam. Without vacuum the beam can never be formed, and therefore the growth process would not take place.
- The growth process requires considerable power input to introduce heat into the crystal and is a very sensitive operation taking days of time to complete a cycle. The entire epitaxial growth process takes place in a heated environment. Both the beam of molecules and the substrate are kept at high temperature (above 1400ºF) by tightly controlling process heaters.
- Process cooling is required to control temperatures within a small range in order to achieve desired material properties and product quality. This is accomplished using a chilled water system supported by large centrifugal chillers. Additionally, these operations are conducted in a clean room environment with controlled temperature and humidity. HVAC systems that support the environmental conditions inside the clean room represent a significant additional load. The analyzed facility has a total cooling capacity of 1,700 Tons.

The loads in the areas proposed for study are considerable. The complex has a production load of 2.5 MW with a minimal sustaining load of 1.5 MW in the fabrication area. The complex is supplied with electrical energy from the local utility. The complex is electrically fed from to two different circuits offering some level of redundancy in case of power outages. The back-up system consists of UPS batteries, summarizing about 600 kW of capacity, and emergency generators, with a total capacity of 1.5 MW. Designated equipment incorporate UPS batteries that facilitate operation for limited durations in the absence of the main supply source. Energy consumption for the complex totals approximately 20 million kWh annually.

Even with the redundancies in the system, the complex has experienced seven separate episodes of power loss for a one-hour duration (or greater) over the last year. Also, a significant number of other incidents have happened, including voltage sags and over voltages. The existing power correcting equipment can correct minor voltage sags, but major sags can have a serious impact on the equipment leading to process shut down of the critical systems.

The cost and economic impact to the company due to these events is enormous. The labor costs alone for the complex are $50,000 per hour. Additionally, operational losses associated with the outages can impact the crystal growth processes for several hours. The losses incurred over the last year alone equate to millions of dollars in lost revenue for the company.

The scope of the project is to identify the available fuel cell technologies and to assess the feasibility of implementation of a fuel cell premium power system. As presented above, fuel cell technologies are in varying stages of developments. The study assesses the implementation of the four more commercially advanced technologies, and the different characteristics in respect to the specific application for the semiconductor facility. Table 4 presents the comparative assessment of the prevalent fuel cell systems.

Considering the comparative assessment shown below, the detailed analysis will be performed for the Phosphoric Acid Fuel Cell technology. For this technology, there are few manufacturers in United States that produce packaged systems with capacities up to 200 kW. One of these systems is PC25 produced by UTC Fuel Cells. The main characteristics of this unit, extracted from the product specification sheets, are: rated electrical capacity: 200 kW/235 kVA; voltage and frequency: 480/270. 60 Hz, 3 phases; fuel consumption: 2100 ft^3/h of natural gas at 4'-4" water pressure; efficiency (LHV basis): 87% total: 37% electric and 50% thermal; thermal capacity: 900,000 Btu/h at 140ºF; emissions: <2 ppmv CO, <1 ppmv NO_x and negligible SO_x (on 15% O2, dry basis); and noise level: 60dBA at 30 ft.

The proposed configuration of the premium power system at the facility will incorporate the integration of the fuel cells with the existing back-up systems. Eight units of 200 W each are proposed to cover the highly critical load of 1.5 MW. The utility network will still supply the balance of the load for the complex. In case of outage, the emergency generators and the UPS batteries can assure the necessary redundancy.

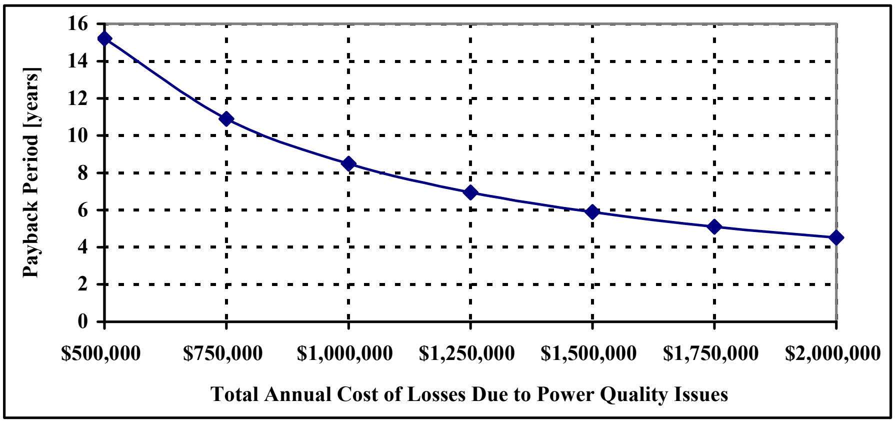
The total cost for installing the fuel cells and for integrating them with the existing systems is estimated to be $9,600,000. The preliminary results of the economic analyses are presented in Figure 1. The calculations are based on average prices of natural gas and electricity in the Northeast of $6.38/ccf and $0.0772/kWh. A total operating time of 8,000 hours/year was considered for the fuel cell plant. Cogeneration was not considered in the analysis.

Table 4. Case Study Comparative Assessment of the Fuel Cells Technologies

PAFC	▪ Proven reliability: installations in different locations all over the world with many hours of successful operation ▪ Commercially available in sizes that are attractive for the facility (200 kW) ▪ For premium power, requires a reliable source of fuel ▪ To make it highly cost-effective, requires cogeneration opportunities - which may not be present
PEMFC	▪ Not sufficiently proven for this application ▪ Commercially available in sizes too small (maximum 50 kW) ▪ For premium power, requires a reliable source of fuel ▪ To make it highly cost-effective, requires cogeneration opportunities - which may not be present
MCFC	▪ Not sufficiently proven for this application ▪ Still in the pre-commercial stage ▪ For premium power, requires a reliable source of fuel ▪ Can produce steam, which could be used in absorption chillers – would require chiller replacement
SOFC	▪ Not sufficiently proven for this application ▪ Still in the pre-commercial stage ▪ For premium power, requires a reliable source of fuel ▪ Can produce steam, which could be used in absorption chillers – would require chiller replacement

The figure below indicates that payback periods for the project become attractive as the lost costs associated with power quality events escalate. In the case of the analyzed facility, the losses are in the higher range of the scale and subsequently make the project potentially feasible.

Figure 1. Payback Period for the Fuel Cell System vs. Cost of Losses



Conclusions

Fuel Cells represent a potential solution to solve power quality problems and reliability concerns associated with utility power networks. This technology can provide clean and reliable power for critical applications and certain technologies, such as PAFC and

PEMFC, have worked successfully in hundreds of installations worldwide. Installation costs represent a considerable barrier to widespread commercialization of the available fuel cell systems. Technological improvements are still evolving and solutions to reduce system costs are actively being pursued. State and federal funding, through specialized programs for implementation of fuel cell systems, can encourage the future development of these technologies. Currently, only applications with premium power requirements that incur substantial losses during power quality events can justify the economics associated with fuel cell systems. Case study has revealed that, although technologically the fuel cells are a good option for the critical industrial applications, as they provide safe and reliable power, cost-effectiveness of the large fuel cell based premium power application rises in the probability that major events with high impact on company's revenues occur. Very critical operations, such as communication and data centers, financial transaction operations and high-tech manufacturing facilities represent the most suitable applications for future implementation of these systems.

References

Ahuja, Anil. 2001. *Problems with Power.* Pure Power, Spring 2002

Andrews, Nathan. 2002. *Poised for Growth: DG and Ride-Through Power.* Power Quality, January/February 2002

California Energy Commission. *California Distributed Energy Resource Guide.* Available at www.energy.ca.gov

Ceasar, Gerald and Warner, James. 1999. *ATP Focused Program: Premium Power*. Available on World Wide Web at www.atp.nist.gov

Energy Nexus Group. *Technology Characterization: Fuel Cells*. April 2002. Prepared for Environmental Protection Agency. Available at www.epa.gov

Flickinger, Thomas. 2002. *A Glossary of Power Events.* Pure Power, Winter 2002

Marshall, Alan. 2001. *Fuel Cells: Standby Power's Future?* Pure Power, Fall 2001

———. www.fuelcells.org

———. www.utcfuelcells.com

———. *The Business of Fuel Cells*, Issue 1, February 2002. Available at www.eyeforfuelcells.com