FEMP

Technology Installation Review

A New Technology Demonstration Publication

DOE/EE-0311

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Assessment of Packaged PEM Fuel Cell CHP Systems

Grid-connected, packaged fuel cell systems provide clean, quiet, reliable heat and power

Introduction

Packaged fuel cell systems are technically attractive for distributed generation because they are very efficient, quiet, and have the potential for very low waste-stream emissions. Packaged fuel cell systems have been commercially available for about 10 years. Although still expensive, the cost, reliability, and performance of these systems have been improving steadily. This document describes the technology, its application niche, and what a potential user needs to consider when making procurement decisions.

Why Combined Heat and Power (CHP) Distributed Generation (DG)?

The motivations for distributed power stem from our increasing reliance on electrical devices, from the high costs of expanding central generation capacity and transmission and distribution (T&D) capacity, and from the technical barriers to using central plant waste heat effectively. By adding distributed generation instead of central plant capacity, the need to expand T&D capacity is reduced or eliminated. By situating DG at facilities where waste heat can be put to good economic use (the premise of CHP), the prohibitive costs and inefficiencies of heat transmission are avoided. In some applications, the primary motivation is power reliability; the redundancy inherent in grid-connected DG achieves this objective.

Technology Description

Fuel cell development for transport and DG applications has increased remarkably in the past decade. There are a number of fuel cell technologies that appear to be viable in one or more applications, as indicated in Table 1. Note that the proton exchange membrane (PEM) technology, at its current stage of development, has the best efficiency and power density of all the technologies that run on air at low temperature. High temperature, such as with the molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC), and pure O_2, such as with the alkaline fuel cell (AFC), are considered safety concerns.

The fuel cell CHP systems demonstrated at Fort McPherson in Atlanta, Georgia, and at the 4th District U.S. Coast Guard Station, New Orleans, Louisiana,[1] are built around one main package that houses a fuel processor, PEM cell stack, power conditioning, recovery heat exchanger, and controls (all discussed below). An additional heat exchanger and pump may be required in the facility that will use the recovered heat. In most cases, an external water treatment unit is also required.

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future where energy is
clean, abundant, reliable,
and affordable

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[1] Fort McPherson was selected initially based on special interest by the Public Works office of U.S. Army Southeast Regional Public Works Office. The Coast Guard site was added because it has significant heat load. The ESCO for both sites, LoganEnergy, agreed to provide access to the on-line performance data.

U.S. Department of Energy
Energy Efficiency
and Renewable Energy

Internet: www.eere.energy.gov/femp/

Table 1. Summary of technical characteristics by fuel cell type

	Phosphoric Acid Fuel Cell	Alkaline Fuel Cell	Molten Carbonate Fuel Cell	Solid Oxide Fuel Cell	Proton Exchange Membrane (PEM)	Direct Methanol Fuel Cell
T^{cell} (°C)	200	80	650	1000	90	80
Efficiency*	42%	70%	50%	40%	45%	25%
Conducting Ion	H^+	OH^-	CO_3^{2-}	O_2^-	H^+	H^+
Cathode Gas	Atmospheric	Pure O_2	Atmospheric	Atmospheric	Pure O_2 and Atmospheric	Atmospheric
Catalyst	Pt	Pt, Ni/NiOx	Ni/LiNiOx	Ni/Perovskites	Pt	Pt
Fuel	H_2	H_2	H_2 and CH_4	H_2 and CH_4	H_2 (pure or reformed)	CH_3OH
Power Density	220 mW/cm³	4000 mW/cm³	150 mW/cm³	240 mW/cm³	300 mW/cm³	20 mW/cm³
Electro-Chemical Challenges	Hydrogen electro-catalysis, cathode corrosion	Hydrogen electro-catalysis, cathode corrosion	Oxygen electrode, cathode corrosion	Expensive component layers, high temperature	Oxygen electro-catalysis, water management	Methanol electro-catalysis, anode poisoning
Applications	Onsite cogeneration, transportation	Space Vehicles, transportation	Power generation, cogeneration	Power generation, regenerative fuel cell	Transportation, space defense, standby power	Transportation, remote power, standby power

*Electric only based on lower heating value of fuel, no inverter or reformer power penalties, under ideal conditions.

PEM cell stack. The proton exchange membrane (PEM) fuel cell uses a polymer electrolyte in the form of a thin sheet or membrane. The PEM blocks electrons but allows positive ions preferentially (more protons than electrons) to pass, as shown in Figure 1. Hydrogen is supplied at the anode and air is supplied to the cathode. A platinum catalyst promotes electrolytic reaction at the cathode.

The half-reaction at the anode (-) is:

$$2H_2 \rightarrow 4H^+ + 4e^-$$

The half-reaction at the cathode (+) is:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

Each cell generates 0.7V and a stack of 70 cells in series is used to generate power at about 50 volts. Because the polymer softens with temperature, the stack is limited to 80°C (175°F). This makes the efficiencies of PEM fuel cells somewhat less than those of higher temperature technologies, such as solid oxide fuel cells (SOFC) and molten carbonate fuel cells.

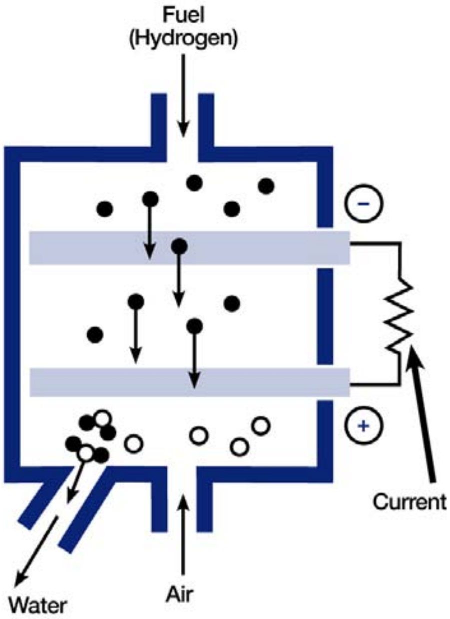

Figure 1. PEM fuel cell.

Reformer. Two reactions convert steam (H_2O) and natural gas (mostly CH_4) into hydrogen and carbon-dioxide (CO_2). The first produces some hydrogen and carbon-monoxide (CO) as an intermediate product:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

The second reaction converts CO and steam to CO_2 and more hydrogen:

$$H_2O + CO \rightarrow CO_2 + H_2$$

Residual CH_4 and residual CO are the two main perpetrators of cell stack poisoning.[2] Therefore, they are selectively burned ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ and $2CO + O_2 \rightarrow 2CO_2$) at low temperature in the presence of a catalyst before entering the cell stack. This extends cell stack life.

Waste heat comes from the burning of residuals and from the cell stack reaction. With current practical implementations, the overall efficiency of natural gas to electrical conversion without heat recovery is less than 30%. Some of the conversion heat (e.g., inverter heat) is

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[2] Poisoning refers to accumulations of compounds that reduce the efficiency of cathode, anode, or electrolyte.

not easily recoverable. Even with heat recovery, the maximum overall efficiency for the demonstration unit (total of heat plus power) is about 65%.

Inverter. The inverter converts 48Vdc to 120/240Vac and provides the necessary grid interface (power-factor and frequency following control). An approved[3] transfer switch is built in—and two external connections, main power and emergency power, are provided. When main power fails, the inverter is disconnected from the main panel to prevent back feed but may continue to feed an emergency power subpanel with no interruption. Field installation requires only two simple disconnects—typically one of these, the emergency panel breaker—already exists. Some utilites may have special requirements for grid connected DG.

Battery. The battery stores enough energy to carry the machine through load fluctuations encountered during emergency load service (grid outage) or in off-grid operation and to start the machine (cold boot) without grid power. The battery is not used when the unit is operating at a fixed (electric kW output) setpoint. A battery life of 5 years or more can therefore be expected in installations that run mainly in grid-connected constant-setpoint mode.

Controls and utility interface. The utility interface has two modes, on-grid and off-grid. In on-grid mode, the inverter tracks utility frequency and supplies current in phase with utility voltage to maintain a predetermined or remotely adjustable fuel cell power output. The demonstration unit develops up to 5kW continuous, but most units have been operated at 2.5kW continuous. The best mode of operation is site-specific to strike a reasonable balance between rate of payback (best at around 4kW) and stack life (decreases with increasing power level).

In off-grid mode, the inverter maintains voltage and frequency according to its internal references, and satisfies the real and reactive power of the aggregate local or emergency load by continuously adjusting the load. Time-varying control of capacity may be appropriate in off-grid installations.

Water Supply and Discharge. The reformer feed-stocks mentioned above are methane and water. Although the reformer and cell stoichiometry yield more water than is consumed, the current design requires a separate source of high purity water. Plug Power's purification unit uses a 3-step process: rust/scale filtering, reverse osmosis (RO), and ion exchange. Water requirements vary in directly with power output. At 2.5kW, the PEM unit requires 50 gallons per day (gpd) of pure water and produces about 100 gpd of waste water. The water plant and feed line must be protected from freezing.

Heat recovery. The reformer and fuel cell produce electricity from natural gas at 24% to 26% efficiency based on lower heating value (LHV) of the gas. Better overall efficiency can be obtained by making use of the 3.3 to 6.7 kW_{th} of heating produced in the reformer and cell stack. In most CHP installations, the heat byproduct is transferred to a domestic water heater or similar load, as shown in Figure 2. When the load is satisfied, tank temperature at the base of the dip tube will approach the fuel cell operating temperature (about 170°F). The heat byproduct will then have to be discharged via waste water and ambient air, and overall efficiency will revert to the machine's efficiency as an electrical power source.

Characteristics of Demonstration Package

A package that integrates the reformer, cell stack, heat recovery, battery, and inverter has been deployed at federal sites as part of a demonstration program. The product specifications of the package are documented in Appendix A.

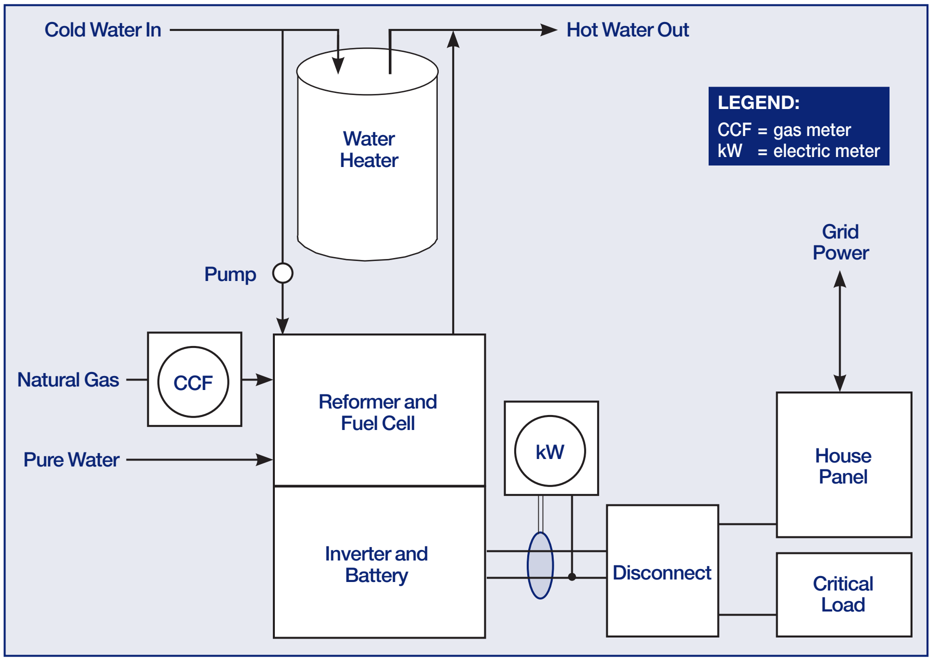

Figure 2. High-level CHP schematic. Heat transport design is site-specific; a system with one pump and no heat exchanger is shown.

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[3] Canadian Standards Association listing, which is recognized in the United States.

The performance data are summarized in Table 2, and the PEM fuel cell in-place at Fort McPherson is pictured in Figure 3.

Over twenty package fuel cell units of this type have been installed in the demonstration program as of January 1, 2005. Most of the demonstration sites produce heat as well as power. For the two demonstration sites reported here, the thermal output is used to heat domestic water and an intermediate loop carries ethylene glycol for freeze protection. A heat exchanger at the water heater transfers heat from the glycol loop to the potable water loop whenever heat is needed (potable water below 140°F) and available (fuel cell operating such that glycol loop temperature is greater than potable water temperature). In addition to a heat exchanger approved for potable water use, a differential temperature controller and two pumps are required to implement this heat recovery scheme. Excess heat is rejected to the waste water stream and to ambient air when the domestic water heating load is satisfied. Most of the demonstration units feed power to the grid during normal operation and keep emergency loads in operation when grid power fails. The characteristics of the products deployed in the demonstration program and the performance observed at two of the sites are described below.

Table 2. Performance specifications for federal demonstration package

kWe set point	2.5	4	5
Generation Efficiency (kWe/LHVkW)	26	25	23.5
Overall Efficiency ((kWe+kWth)/LHVkW)	60	65	55
Fuel Use (LHV kBtu/hr)	31.6	54.6	73
Water Use (gallon/hr)	3.33	5.67	7.33

Figure 3. Demonstration PEM fuel-cell-based CHP unit (left) at Fort McPherson.

O&M. The complexity of this technology could be said to lie between that of unitary HVAC equipment and that of an automobile. However, because the technology is less mature, the maintenance expectations are correspondingly higher. Although considerable design attention is devoted to ongoing improvements to reliability and simplicity of O&M, the user should be aware of the current basic maintenance needs.

Batteries. Batteries require no periodic maintenance. However, battery life is finite, depending largely on load magnitude and frequency of large load variations during off-grid operation. Replacement at roughly 5-year intervals can be expected at a cost of roughly $500.

Air Filters. Cathode air filters require replacement , typically every 12 months.

Radiator. Coolant flush and replacement service intervals are typically longer (>5 years) than for an automobile. Air side surfaces should be cleaned yearly or more often under dusty conditions (i.e., less often than for the outdoor unit of an air conditioner).

Periodic stack replacement. The fuel cell stack must be replaced every 7,000 to 10,000 operating hours. The cost of stack replacement is roughly $10,000 and is covered under the typical maintenance contract.

Water supply. The current design's requirement for very pure de-ionized (DI) water defines the most labor-intensive elements of site maintenance. In hard water locations, a water softener, with its attendant maintenance requirements, is needed. All installations require an RO filter and a resin bead cartridge for ion-exchange. Service intervals for these items range from 1 to 4 months.

Assessment Checklist. Before investing in fuel cell technology, a buyer should carefully evaluate the costs and benefits. A representative cost analysis is presented in Appendix B. In addition, the following technical issues should be considered.

Load characteristics should correspond to DG/CHP capabilities:

Peak electrical load and load factor

Thermal load and load factor; thermal storage requirement, cost, space

Logistical support:

O&M – understand required capability, commitment, and cost

Training – buyer's technician must attend manufacturer's two-week training program

Source of DI water – site must provide for warm water discharge

Freeze protection – heat recovery loop and water supply must be protected.

Life-cycle cost – In remote and critical power applications, there are often several options or combinations of options for satisfying peak- and base-load load requirements. For each option, one must evaluate the following cost elements:

Annual cost of fuel(s) and delivery thereof

Annual cost of maintenance including cell stack renewal

Annual value of displaced existing electrical and thermal source energy

Amortized costs (equipment, installation, design, administration, commissioning)

Acceptance Tests. Before taking ownership of the CHP system, it is important that the owner confirm proper operation and performance. This activity is a good step in familiarizing local maintenance person(s) with the new technology and the monitoring equipment. The monitoring equipment is essential to ongoing tracking of its operating condition and diagnosis of problems, should they occur. A basic acceptance protocol should include the following:

Controls: check responsiveness and calibration of sensors and actuators

Capacity: measure peak capacity for 1 hour

Noise: check fan noise and vibration

Emissions: check for NO_x and CO

Start-stop cycle: demonstrate start-stop cycle and 8 hours continuous operation

Leak check: reformer, cell stack, water, heat rejection; all feed and discharge lines

Efficiency: measure gas input and kWh and Btu output for 8-hour run at planned capacity.

Demonstration Results

A large number of residential-scale PEM fuel cell installations have been made for the DOD Fuel Cell Demonstration Program (Binder, Taylor and Holcomb 2001). Two representative sites are at Fort McPherson, Atlanta, Georgia, and the 4th District Coast Guard Station (CGS), New Orleans, Louisiana.

The demonstration sites were provided with basic performance verification metering consisting of residential-type gas and electric meters, as shown for Fort McPherson in Figure 4.

Heat recovery was measured at Fort McPherson using volumetric flow rate and temperature sensors. A programmable logic control system was configured to monitor and communicate the data to a server that provides web access to all stakeholders.

The Fort McPherson and CGS sites are both configured to provide constant electric power with any difference between the power set-point and local load being absorbed or supplied by the grid.

Figure 5 shows that the electric power output at Fort McPherson in July 2004 was 2.5 ± 0.1kW about 98% of the time. In grid independent mode, the fuel cell output is modulated to track the local emergency load. However, there were no grid outages to show

Figure 4. Residential-type meters to record gas input and electrical output.

during the July test period. Heat generated by the fuel cell and reformer is determined by the unit's electrical power output, not by the local thermal load. Any shortfall in heat output by the fuel cell unit is provided by auxiliary heat plant (domestic water heater) and any excess heat is dissipated to ambient via the waste water stream and/or the unit's cooling fan.

The thermal load at Fort McPherson turned out to be much smaller than the CHP capacity at even the lowest fuel cell operating point (11.2 kBtuh at the 2.5 kW setpoint). Figure 5 shows the average load to be about 1 kBtuh with a diurnal cycle that exhibits morning and evening peaks of 2 to 5 kBtuh. The average electric production efficiency (LHV basis including all parasitic loads) in July 2004 was 28.5% and the CHP efficiency was 43%.

In the case of the CGS, thermal loads are substantial but still have a diurnal variation, as shown for July 2004 in Figure 6. Figure 6 illustrates a base load of about 8 kBtuh, which is well matched to the 11 kBtuh available with a fuel cell operating point of 2.5 kWe. The diurnal fluctuations in thermal load are small—typically less than 2 kBtuh. In short, this is an ideal thermal load for this DG/CHP application. The dropouts on July 27 to 29, 2004, represent fuel cell downtime rather than the absence of thermal load. Electric and CHP efficiency cannot be calculated for CGS because the electric meter is reading only the emergency panel portion of electricity production.

Future Developments

Package DG/CHP fuel cell technology is evolving rapidly. In addition to understanding the current state of the technology, a potential user should consider technology advances that may be in the pipeline. A few possibilities, some of which are slated to appear by the 4th quarter of 2005, are outlined below.

Control. In many cases, it makes sense to configure the plant either to satisfy a dedicated load (load tracking) or to maintain a constant output of power,

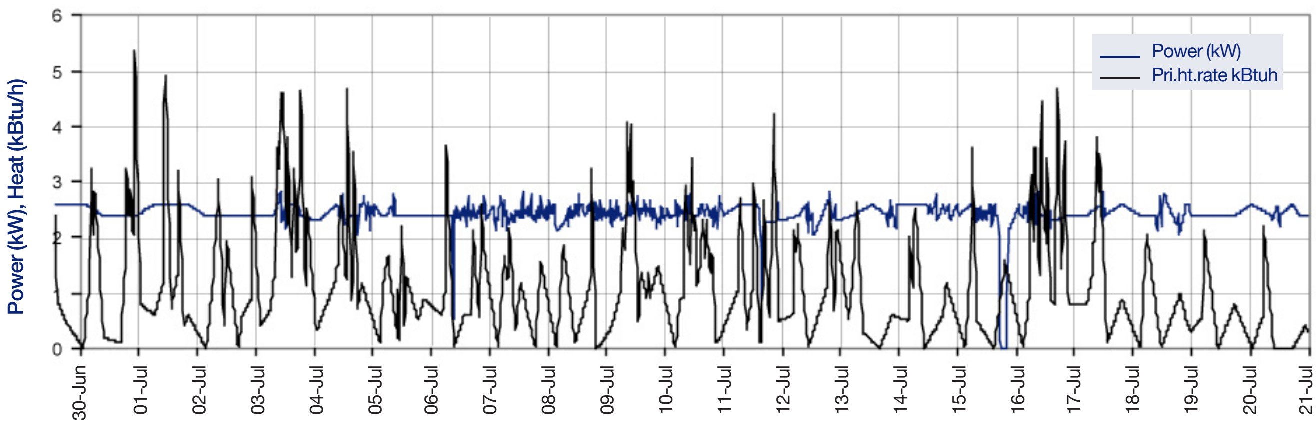

Figure 5. Heat and electric power output by Fort McPherson demonstration unit, July 2004.

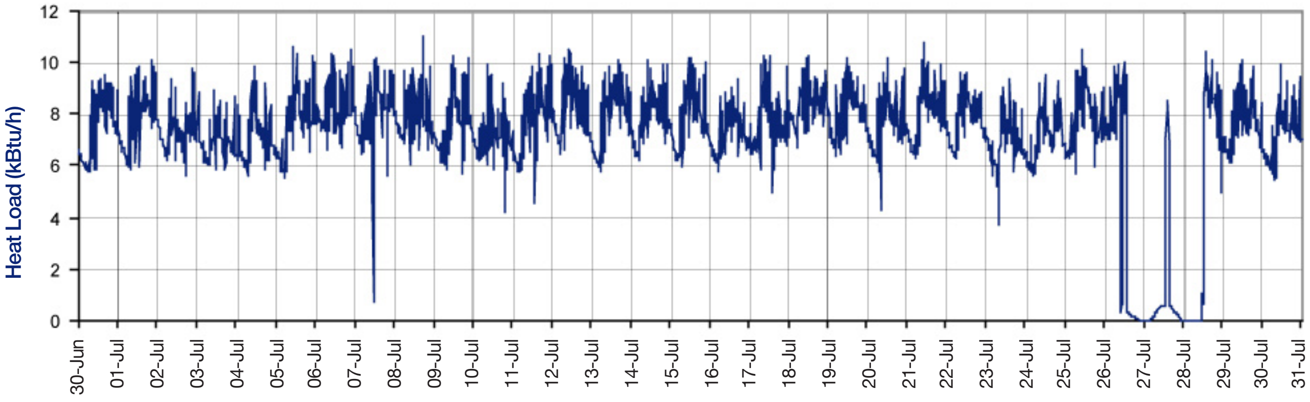

Figure 6. Heat output by the CGS demonstration unit, July 2004.

part of which may feed a critical load while the balance sold to the grid. However, in other cases, there can be significant benefits to a more sophisticated control strategy. Such cases may involve control based on time of use rates, real-time rates, or response to a utility curtailment program. In some cases, optimal or mission-critical operation may require load tracking of the thermal load or real-time switching between electrical and thermal load tracking.

Site approval. The demonstration unit satisfies California Air Resource Board (CARB) standards for small, low-emission DG and DG/CHP plants, as indicated in Appendix C. However, until installations become commonplace and familiar to building inspectors and other regulators, the site approval process is likely to present challenges for some sites. Some possible issues are water supply, hot waste water, utility interface, and emergency access (paved driveway).

High water use. The next-generation package is expected to have zero net water use. This would eliminate much of the expected maintenance as well as some of the potential site approval hurdles involving backflow prevention and hot water emissions. With balanced water management, hot water emission would be approximately halved and cold water emission would be zero.

High cost. Product cost is certainly one of the important drivers but second to maintenance. Currently, there is enough of a market in remote and critical power to justify the high cost, low volume production. This can be expected to gradually improve as competition and market volume increase.

Maintenance burden. Package designs are evolving steadily based on manufacturing and field experience. The two main maintenance costs are cell stack replacement and water supply (improved design and reliability).

On-line data. The demonstration unit has an embedded data acquisition system used by the manufacturer to gain valuable performance and diagnostic data. However, key M&V data are not collected. It would be more attractive to many end-users if internal meters for cumulative gas input, inverter output, and heat recovery output were offered as factory options than to have this equipment installed externally on-site, as is current practice. The power meter option is a particular need because one meter between the inverter output and internal transfer switch can handle both the main and emergency panel loads; two meters, or a meter that can accommodate the two load feeds (e.g., through the eye of a current transformer) are required to properly measure the power externally.

Benefits

Fuel cells have been shown to be capable of unattended operation in combined heat and critical power applications selected for the DOD fuel cell demonstration program. Although it has not been explicitly demonstrated in the program, the technical potential for DG to serve as a peak-shaving resource certainly exists. What has been demonstrated is the ability for fuel-cell based DG to provide “hot” back-up for mission-essential loads in commercial and residential applications. CHP addresses the common wasteful practice of producing of low-grade heat by direct burning of fossil fuel. Currently, the reliability and availability statistics are in need of improvement. In the long term, fuel cell technology could become one of the cornerstones of distributed generation, wherein low-energy buildings approach zero net electricity use by producing most of their own power needs from photovoltaic collectors, natural gas, or hydrogen.

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Appendix A

Manufacture’s Specification for the DG/CHP fuel cell package demonstrated at Fort McPherson.

Specifications

Physical	Size (L X W X H):	84 1/2” X 32” X 681/4”
Performance	Power rating:	5kW continuous
	Power set points:	2.5kW, 4kW, 5kW
	Voltage:	120/240 VAC @ 60Hz
	Power Quality:	IEEE 519
	Emissions:	$NO_X < 5ppm$
		$SO_X<1ppm$
		Noise < 70 dBa @ 1meter
Operating Conditions	Temperature:	0°F to 104°F
	Elevation:	0 to 750 feet
	Installation:	Outdoor/CHP
	Electrical Connection:	GC/GI
	Fuel:	Natural Gas
Certifications	Power Generation:	CSA International
	Power Conditioning:	UL
	Electromagnetic Compliance:	FCC Class B

Dimensions

Length	84 inches
Width	32 inches
Height	68 1/4 inches

Operating Requirements

Fuel Type	Natural Gas
Temperature	0°F to 104°F

Outputs

Power Output	5kW
Voltage	120/240 VAC @ 60Hz
Noise	< 70 dBA@ 1 meter

Certifications

CSA International	Fuel Cell System
UL	Power Conditioning Module

Appendix B

Initial life-cycle cost estimates for the Fort McPherson PEM fuel cell demonstration are contained in the Initial Project Description Report available on the DOD Fuel Cell web site at http://dodfuelcell.cecer.army.mil/res/InitialReport_FtMcPherson.pdf. More up-to-date performance information is available at http://dodfuelcell.cecer.army.mil/res/site_summary_statistics.php4?site_id=15.

Assuming the fuel cell operates at an average 2.5 kW capacity with an average availability of 90%, the following life-cycle cost analysis results from using BLCC version 5.1.

NIST BLCC 5.1-02: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Baseline

Alternative: PEM Fuel Cell

General Information

File Name:	C:\My Documents\McPherson Fuel Cell Analysis.xml
Date of Study:	2004
Project Name:	Fort McPherson Fuel Cell Assessment
Project Location:	Georgia
Analysis Type:	MILCON Analysis, Energy Project
Analyst:	J. Doe
Base Date:	April 1, 2004
Beneficial Occupancy Date:	April 1, 2004
Study Period:	10 years 0 months (April 1, 2004 through March 31, 2014)
Discount Rate:	3.2%
Discounting Convention:	Mid-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$83,825	-$83,825
Future Costs:			
Energy Consumption Costs	$13,663	$11,737	$1,926
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$71	-$71
Routine Recurring and Non-Recurring OM&R Costs	$0	$128,672	-$128,672
Major Repair and Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	$0	$0
Subtotal (for Future Cost Items)	$13,663	$140,480	-$126,817
Total PV Life-Cycle Cost	$13,663	$224,305	-$210,642

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	-$126,817
- Increased Total Investment	$83,825
Net Savings	-$210,642

Note: Meaningful SIR, AIRR and Payback can not be computed unless incremental savings and total savings are both positive.

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	Average Annual Consumption			Life-Cycle Savings
	Base Case	Alternative	Savings	
Electricity	19,710.0 kWh	0.0 kWh	19,710.0 kWh	197,019.1 kWh
Natural Gas	62.0 MBtu	258.9 MBtu	-196.9 MBtu	-1,967.8 MBtu

Energy Savings Summary (in MBtu)

Energy Type	Average Annual Consumption			Life-Cycle Savings
	Base Case	Alternative	Savings	
Electricity	67.3 MBtu	0.0 MBtu	67.3 MBtu	672.3 MBtu
Natural Gas	62.0 MBtu	258.9 MBtu	-196.9 MBtu	-1,967.8 MBtu

Appendix C

California Air Resource Board Certified Technologies

Once an Executive Order of DG Certification is issued to a manufacturer, it is posted on the CARB website: http://www.arb.ca.gov/energy/dg/dg.htm. Below are Executive Orders for DG Certification issued as of January 2005.

Company Name	Technology	Standard	Executive Order	Expiration Date
United Technologies Corporation	Fuel Cells 200 kW, Phosphoric Acid Fuel Cell	2007	DG-001	29-Jan-07
Capstone Turbine Corporation	60 kW, C60 MicroTurbine	2003	DG-002	31-Dec-06
FuelCell Energy, Inc.	FuelCell Energy, Inc. 250 kW, DFC300A	2007	DG-003	7-May-07
Ingersoll-Rand Energy Systems	70 kW, 70LM Microturbine, version C	2003	DG-004-A	31-Dec-06
Ingersoll-Rand Energy Systems	70 kW, 70LM Microturbine, version WD (CHP)	2003	DG-005	31-Dec-06
Plug Power Inc.	5 kW, GenSys™ 5C Fuel Cell	2007	DG-006	16-Jul-08
FuelCell Energy, Inc.	1 MW, DFC1500 Fuel Cell	2007	DG-007	13-Sep-08

Log on to FEMP's Web site for information about New Technology Demonstrations

www.eere.energy.gov/femp/

You will find links to

- A New Technology Demonstration Overview
- Information on technology demonstrations
- Downloadable versions of publications in Adobe Portable Document Format (pdf)
- A list of new technology projects under way
- Electronic access to a regular mailing list for new products when they become available
- How Federal agencies may submit requests to us to assess new and emerging technologies

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