February 2002 • NREL/CP-710-31321

Conference Paper

Inspection and Short-Term Measurement of a National Park Service Photovoltaic/Fuel Cell Remote Hybrid Power System at Kirby Cove, California

Preprint

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To be presented at the American Society of Mechanical Engineers' Solar 2002 Conference
Reno, Nevada
June 16–20, 2002

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INSPECTION AND SHORT-TERM MEASUREMENT OF A NATIONAL PARK SERVICE PHOTOVOLTAIC/FUEL CELL REMOTE HYBRID POWER SYSTEM AT KIRBY COVE, CALIFORNIA

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ABSTRACT

This paper reports short-term performance measurement of a hybrid photovoltaic/fuel cell power supply system at Kirby Cove Campground in Golden Gate National Recreation Area, California. The system operated reliably for two years from June 1999 to June 2001. During this period, the campground host load was met with a combination of solar power and power from the fuel cell. In 2001, reports of power outages justified an in-depth investigation. Data is reported over 13.5 days from September 2 to September 15, 2001. Over this period, energy delivered by the photovoltaic array totaled 42.82 kWh. Energy delivered by the fuel cell totaled 1.34 kWh, and net (out-in) energy from the battery totaled 6.82 kWh. After losses in the battery and inverter, energy delivered to the campground host totaled 34.94 kWh, an average of 2.6 kWh/day. Photovoltaic efficiency was measured at 8.9%. Fuel cell efficiency was measured at 42%, which is a typical value, but fuel cell power output was only 35 W instead of the 250 W rated power. Replacing a burnt fuse restored fuel cell power to 125 W, but several cells measured low voltage, and the fuel cell was removed for repair or replacement. Ordinarily, load in excess of the PV capability would be met by the fuel cell, and 22 cylinders of H_2 (261 scf, 7,386 sl each) were consumed from April to August 2001. After failure of the fuel cell, load in excess of the solar capability resulted in discharged batteries and eight power outages totaling 48 hours in duration. Thus, overall system availability was 85% when relying only on solar power. This paper describes daily system operation in detail, presents component performance indicators, identifies causes of performance degradation, and provides recommendations for improvement.

INTRODUCTION

Kirby Cove Campground is a tent campground in Golden Gate National Recreation Area. Rather than replace an old power line with a new one, the National Park Service wanted to restore a hillside to its pristine appearance by removing the old line and installing a remote power system. Because of the proximity of the power supply system to campers' tents, the power supply system must be very clean and quiet. Other options included noisy, polluting, or expensive gasoline or diesel generators. In addition, zero pollution and high efficiency support the mission of the park to preserve natural resources and provide visitors with a high-quality experience. Photovoltaics (PV) were identified as the power source that could provide clean, silent power. To meet the load under prolonged cloudy periods, the size of the PV array is optimized by providing a clean, silent fuel cell as backup power. [1]. The only emission from the hydrogen fuel cell is water. As a bonus, the system serves as a demonstration model for rangers to interpret silent, pollution-free photovoltaics and fuel cells to park visitors. In June of 1999, Fully Independent Residential Solar Technology, Inc., installed the system in collaboration with H Power, Solar Depot, and Sun Pirates Inc. The system cost of $47,000 represents a savings for the Federal government of $113,000 over the cost of replacing the old power line with a new one.

NOMENCLATURE

$\Delta H^{o}{}_{f}$	enthalpy of formation (kJ/mol)
η	efficiency (-)
A_c	solar collector area
AC/DC	alternating current/direct current
I_t	incident solar radiation in plane of array (W/m^2)
P	power (W)
V_{H2}	volume flow rate (standard liters per minute, SLPM)

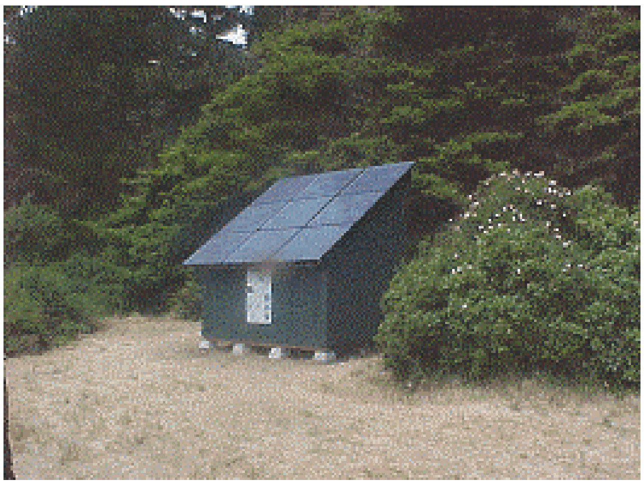

Figure 1. Photo of 1080 W PV array atop structure housing fuel cell, batteries, inverter and controls.

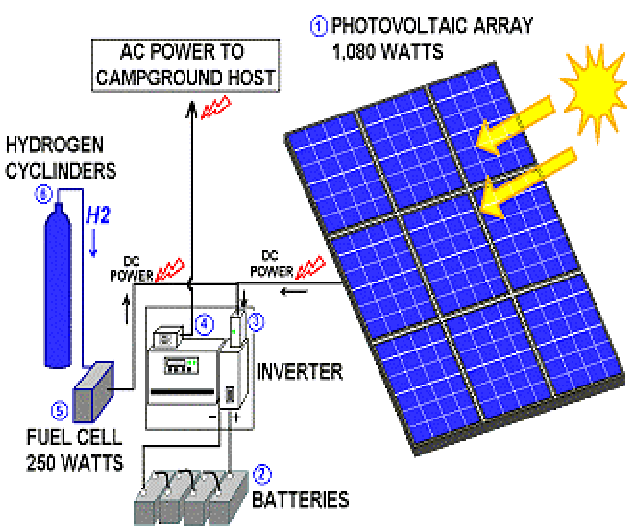

Figure 2. Schematic diagram of Kirby Cove Hybrid Photovoltaic/Fuel Cell System.

LOAD REQUIREMENTS

The site requires power for a campground host in a motor home 6 months of the year (from April 1 to September 30). Research into the electricity requirements presented by an average motor home indicates that the site would need 2 kWh per day. The host, and therefore the load, changes annually. The maximum expected demand for a motor home is 6 kW [1].

DESCRIPTION OF SYSTEM

The power station is installed in a 6 ft x 10 ft shed at the campground. The 1,080 W photovoltaic array is mounted on the roof of the shed, and the 250 W fuel cell system, DC-to-AC power inverter, and batteries are inside the shed. The array consists of nine Solarex MSX120 PV modules. They are made of polycrystalline silicon PV cells coated with antireflective titanium dioxide, ethylene vinyl acetate (EVA) laminated to a low-iron, tempered-glass superstrate with Tedlar backing. Frames are made of bronze-anodized aluminum alloy. Each module is rated for 120 W under standard rating conditions. The modules are configured for a 24 V DC array. Each module is 991 mm wide and 1108 mm long for an area of 1.09 m^2 per module and 6.59 m^2 for the array. In response to vandalism (two panels have broken glass but continue to function), co-extruded plastic covers were added to hide and protect the PV modules. These covers have a 90% transmissivity but screen out the ultraviolet, reducing PV panel output.

The fuel cell is an H-Power PS-250 Proton Exchange Membrane (PEM) fuel cell system rated for 250 W DC, which includes the pumps and controls required for operation. Fuel cells are electrochemical devices that convert chemical energy directly into electrical energy and heat. The PEM fuel cell uses a solid polymer membrane through which H nuclei (protons) carry a positive charge. The negative charge flows through an external circuit to deliver power. Fuel cells produce little or none of the emissions typically associated with power plants because the efficient electrochemical conversion process does not include combustion. The PEM is also silent, except for the slight noise of fans to cool the device and pumps to deliver fuel and air. Although fuel cells cost significantly more than conventional alternatives, their quiet operation, ultra-low emissions, and potential for heat recovery offer value in specific cases where reliable power quality is critical and environmental siting restraints are demanding. Fuel cells have been granted emissions exemptions by several California air quality management districts. This includes the Bay Area Air Quality Management District, the regional agency charged with developing and enforcing air pollution regulations in San Francisco and its environs.

The 24 V battery bank originally consisted of 18 kWh of storage in eight sealed, valve-regulated, deep-cycle batteries. Shortly after installation, an additional four batteries were added for a total battery storage capacity of 18 kWh. The inverter is a

Trace 4024 inverter mounted on a Trace Powerpanel with disconnects and charge controller. The hybrid power system provides 120 V AC power to a pedestal in the middle of Kirby Cove campground used by the campground host.

Figure 2 shows that the PV modules (1) generate 24 V DC power during the day, charging heavy-duty, deep-cycle batteries (2). A battery charge controller (3) shuts off the PV modules when the batteries are full. DC power from the batteries is converted to AC power by the inverter (4). If there is not enough solar power to provide power to the home, such that the battery voltage falls below a setpoint, the fuel cell (5) turns on, drawing hydrogen from the cylinders (6) and converting its energy to 24 V DC electric power to charge the batteries. When battery voltage reaches an upper setpoint, the fuel cell is turned off. The PV array and fuel cell operate together to provide power silently, reliably, and with zero on-site pollution.

HYDROGEN USAGE

Reforming a number of fuels, including natural gas, can produce hydrogen on site. But for this small system an industrial gas supplier delivers compressed hydrogen gas. The gas is stored in two pressurized cylinders in a special cabinet outside the shed. Each of the cylinders holds 261 scf (7,386 sl) of hydrogen at 2265 psia. Hydrogen is delivered to the fuel cell at 30 psia and reduced to 5 psia by a regulator inside the fuel cell enclosure. The fuel flow rate corresponding to full output of 250 W is 3.3 SLPM [2]. From mid-April to late August 2001, 22 cylinders were delivered, an average consumption rate of about 1 cylinder per week. The cost of the gas is $41.50 per cylinder, but with delivery charges and other fees the average price per cylinder delivered is $57.50. Each cylinder would supply the fuel cell for about 37 hours of operation, delivering 9.3 kWh of electricity per cylinder of hydrogen. This high cost of hydrogen indicates the value of limiting the load to that which can be met with solar power, and using the fuel cell only for backup when solar is insufficient. If hydrogen is used only for high-value backup to ensure reliability, not for provision of bulk power, the clean and silent nature of fuel cell generation justify the high cost in this tent campground.

MEASUREMENT OF PERFORMANCE

Instrumentation was installed on the system on June 8, 2001. Table 1 below lists the physical properties measured and the sensors used to measure each one. Measurements were made at 1-second intervals, and stored as both 10-minute and 60-minute averages. All measurements were made using a Campbell Scientific CR10 datalogger. Because it is difficult to retrieve data from the remote site, some data was lost as new data wrote over the full memory of the datalogger. On August 8, an out-of-range alarm was exceeded on the load current, and no useful data was collected after that date.

Table 1. Instrumentation

Measured	*Units*	*Sensor*
Current to batteries	amps	shunt
Current from PV array	amps	shunt
Current from hydrogen fuel cell	amps	shunt
Voltage across batteries, PV array, and fuel cell	volts	voltage divider
Power from inverter	kWh	kWh meter
Collector-plane solar radiation	W/m^2	LiCor pyranometer
Outdoor air temperature	deg C	thermocouple
PV module temperature	deg C	thermocouple
Hydrogen fuel flow (*)	lit/min	mass flow meter

*The hydrogen fuel flow meter may not be accurate, as it is reported to have a 2-second response time, and during startup the hydrogen appears to flow to the fuel cell in a batch mode, in a burst of about 1 second every minute. This behavior was unknown when the flow meter was ordered.

SYSTEM PERFORMANCE

Figure 3 shows power (P), to the load (P_{load}), power from the PV array (P_{array}), and power from the fuel cell ($P_{fuel\ cell}$) for each hour of the 14 days from September 2 to 15, 2001. The fuel cell often starts after days of reduced solar gain (clouds).

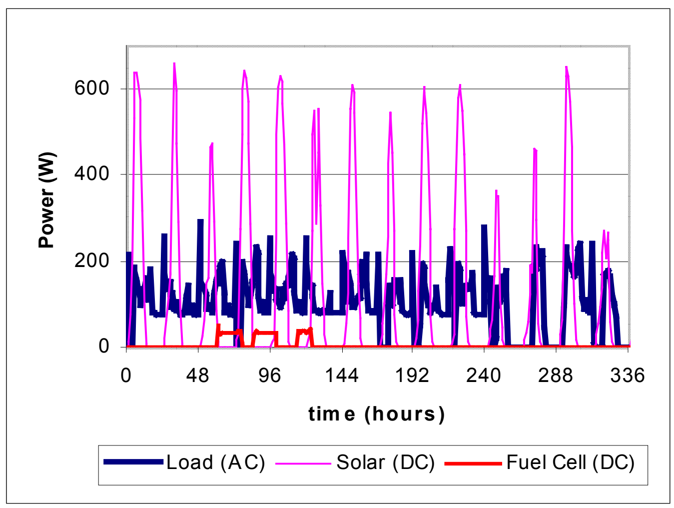

Figure 3. Power to load, power from solar array, and power from fuel cell for 14 consecutive days.

On eight days of this 14-day sample, the load was disconnected due to low battery voltage. This loss of load usually occurred early in the morning before the PV array began producing power, and occurred for 48 hours of the 330-hour sample. During such an outage, no power is supplied to the campground host.

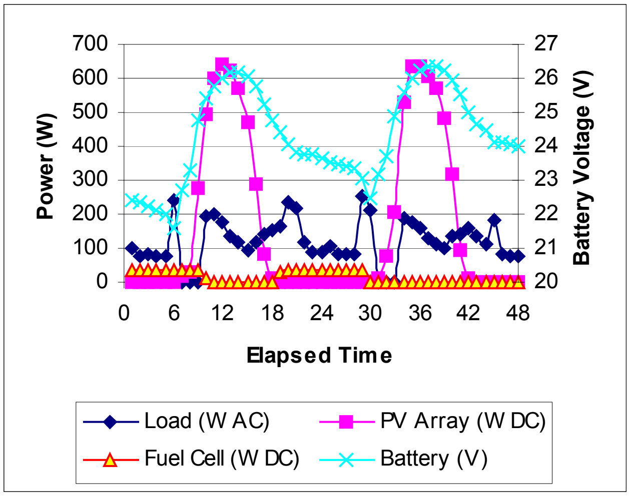

Figure 4. Hourly data for two days showing details of system control including fuel cell operation and low voltage load disconnect.

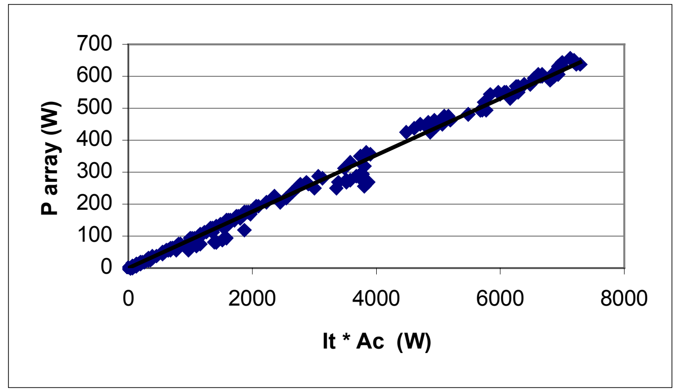

Figure 5. Hourly DC power from the array (P_{array}) as a function of incident solar power (I_t * A_c).

Figure 4 shows P_{load}, P_{array}, and $P_{fuel\ cell}$ and battery voltage for each hour of a two-day period. These two days were selected because solar gains were not sufficient to meet the load and fuel cell operation is illustrated. The finer resolution of Figure 4 shows two important details of system operation. First, notice that at night the fuel cell turns on when the battery voltage drops to less than 24.9 V DC, corresponding to a typical state of charge of 50%. Battery voltage continues to drop, because fuel cell output is not sufficient to supply the load. When the batteries are fully discharged, the load is disconnected. This disconnection of the load often occurs in the early morning, before the sun has come up. The fuel cell continues to charge the battery after the load has been disconnected. After the sun comes up the PV array begins to charge the battery. At about 9 am each day (hours 9 and 33 in Figure 4), the battery voltage has recovered to 24.9 V and the load is reconnected.

PV ARRAY EFFICIENCY

The electric power from the array is plotted against the radiant solar power incident on the array in Figure 5. The fit line has slope of 0.089 and a regression coefficient (R^2) of 0.992, indicating a very nearly constant array efficiency:

$$\eta_{array} = P_{array} / (I_t * A_c) = 0.089 \qquad (1)$$

FUEL CELL PERFORMANCE

An inspection of the fuel cell system was performed December 21 and 27, 2001. The following steps specified by the fuel cell manufacturer were followed.

VISUAL INSPECTION BEFORE OPENING

Ensure that the cylinder is hydrogen, not a mixture. Ensure that the hydrogen pressure is set above 20 psig (preferably in the 30-50 psig region). Ensure that the H_2 and air passages are not blocked. Ensure that the cooling air passages are not blocked. Measure the output voltage (should be 28 V at 250 W).

AFTER OPENING (IF NECESSARY)

Remove the top and check if: there are loose wires; the filter is clogged; the pump has degraded, or loose; the stack is loose. Visually check the stack, cell by cell, to check for anything unusual. Measure voltage, cell by cell, to see what the voltage is.

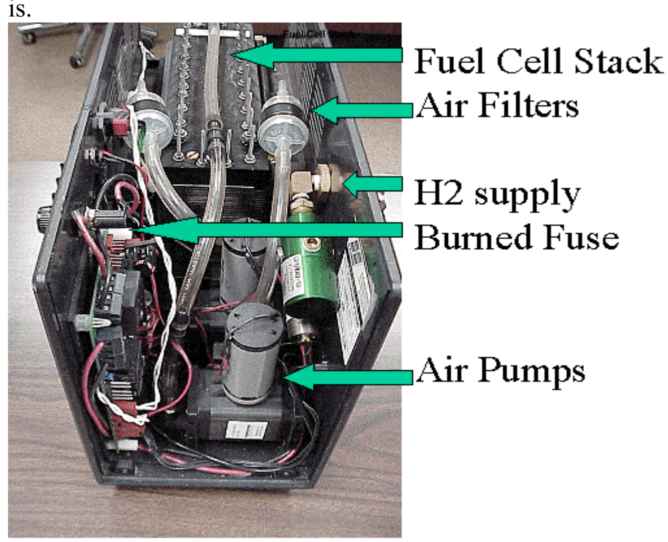

Figure 6. H-Power PS250 fuel cell stack, air pumps and inlet filters, pressure regulator, purge valve, and controls.

Upon trying, the fuel cell repeated its startup sequence over and over without continuous operation. The startup sequence includes purging the hydrogen side of the system. Both air pumps were generating suction at the inlet and both air filters looked clean. A fuse on the fuel cell faceplate was found to be burned and was replaced. After the fuse was replaced, the fuel cell completed its startup sequence and operated continuously. Stack voltage was measured at 25 V and output power was measured at 125 W. Most individual cell voltages in the stack were 0.7 to 0.8 V, but some were only 0.2 V, hampering the fuel cell's ability to charge a 24 V battery system. The fuel cell and its controller were removed for repair or replacement of the stack.

FUEL CELL EFFICIENCY

The combination of hydrogen and oxygen ions in a PEM fuel cell yields water and heat, and frees electrons to flow from the anode through an external circuit to the cathode, as governed by this simplified chemical reaction:

Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$ 2

Cathode reaction: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_20$ 3

Overall reaction: $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ 4

The efficiency of the fuel cell is the electric power output divided by the heat of formation of the overall reaction, ΔH^o_f (241800 J/mol) and by the molar flow rate of the fuel, n:

$$\eta_{\text{fuel cell}} = P_{\text{fuel cell}} / (\Delta H^o_f\, n) \quad 5$$

Figure 7 shows hourly electric power output as a function of hydrogen fuel consumption. The line that best fits this data is:

$$P_{\text{fuel cell}} = 76.375\, V_{H2} + 0.8412\ , \quad 6$$

where V_{H2} is the volume flow rate of the hydrogen gas in SLPM. Neglecting the intercept (0.8412) and using standard density and molecular weight, the efficiency equation becomes:

$$\eta_{\text{fuel cell}} = (76.375 \text{ W/SPLM})/(0.090 \text{ g/l})\ (2\text{g/mol})\ (60 \text{ s/min}) / (242 \text{ kJ/mol})$$

7

$$\eta_{\text{fuel cell}} = 0.419\ ,$$

which is within the published range (0.35-0.45) for PEM fuel cells [3]. So while the efficiency is high, both the hydrogen intake and power output of the fuel cell are less than specification values.

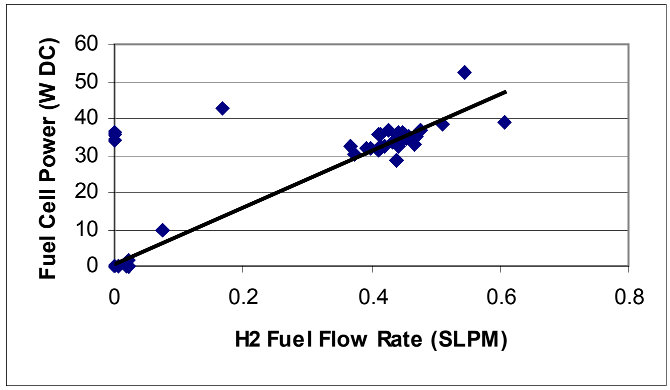

Figure 7. Fuel cell DC power output and regression line as a function of hydrogen fuel input (standard liters per minute).

INVERTER EFFICIENCY

Figure 8 shows 120 V alternating current power output of the inverter as a function of 24 V direct current into the inverter. The trendline has a slope of 0.859. The high R^2 of 0.963 corresponding to the curve fit indicates that efficiency is nearly constant over the small range considered here. Neglecting the intercept, the efficiency of the inverter is thus measured to be:

8

$$\eta_{\text{inverter}} = 0.859$$

The inverter operates at a low fraction of its rated output (4 kW) and measured efficiency of 86% is less than the rated peak efficiency of 94%. The tare loss of 1 W (search mode) or 16 W (no load) is visible on the axis of Figure 8, and averaging over an hour may hide short periods of low inverter load and consequent low inverter efficiency.

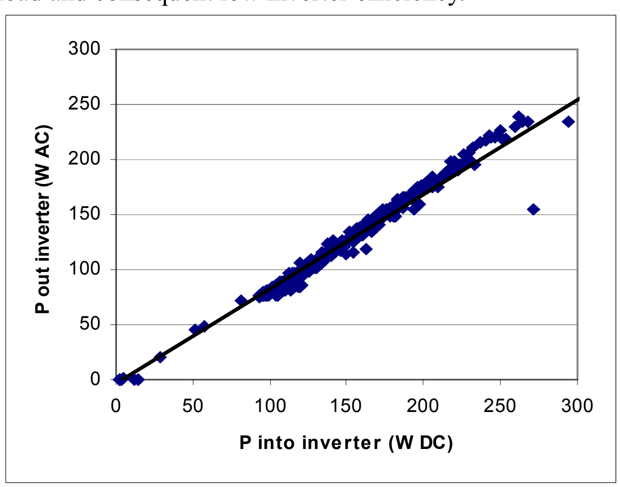

Figure 8. Hourly power output of the inverter (120 V AC) as a function of power into the inverter (24 V DC).

RESULTS

The photovoltaic/fuel cell hybrid system was inspected, and data from September 2 to 15, 2001, was collected, analyzed, and presented. Table 2 shows integrated values over the 14-day monitoring period. Over this period, the solar system provided 84% of the total energy input, the fuel cell provided 3%, and the battery provided 13% (because it ended the period at a lesser state of charge than it started with). Power output of the fuel cell was only 35 W, rather than the rated 250 W. Replacing a burnt fuse restored power to 125 W, but low cell voltages resulted in only 25 V output, too low to reliably charge the 24 V battery bank. Energy delivered to the host averaged 2.59 kWh/day, with a maximum of 3.2 kWh/day on July 30, 2001. Without the fuel cell, the PV array/battery/inverter system alone could not meet the load at all times. This resulted in low battery voltages, which caused eight system outages totaling 48 hours in duration (3 to 17 hours each). The eight power outages totaled 48 hours in duration over the 330-hour monitoring period, for an overall system availability of 85%.

Table 2. Energy, Solar Radiation and Temperature Summed or Averaged over the 14-Day Monitoring Period

Campground Host Load (kWh)	34.94
Energy from Photovoltaics (kWh)	42.82
Energy from Fuel Cell (kWh)	1.34
Net Energy from Battery (kWh)	6.82
Average Solar Radiation (kWh/m^2/day)	5.52
Average Ambient Temperature (°C)	14.3

Table 3. Timing and Duration of Power Outages due to Low Battery Voltage

Start Time/Date	*End Time/Date*	*Duration (hrs)*
7:00 am July 26	9:00 am July 26	3
7:00 am July 29	9:00 am July 29	3
7:00 am Aug 2	12:00 noon Aug 2	6
6:00 am Aug 3	9:00 am Aug 3	4
10:00 am Aug 5	11:00 am Aug 5	2
9:00 pm Aug 5	1:00 pm Aug 6	17
10:00 pm Aug 6	9:00 am Aug 7	12
6:00 am Aug 8	12:00 noon Aug 8	6

CONCLUSIONS

The system was designed to serve a 2 kWh/day load, but campground host use exceeds that. As a consequence, the fuel cell used more hydrogen than expected but met the load reliably for two years, a- testament to the value of a hybrid strategy. In August 2001, frequent power outages led to this investigation. It was found that fuel cell power output was crippled by a burnt fuse and failed cells within the stack.

It is recommended that the fuel cell stack be repaired or replaced to restore the 28 V needed to charge the 24 V battery. Hydrogen delivery is a significant expense for the park and there are measures to reduce hydrogen usage. It is recommended that the campground host be selected and instructed to manage the load more aggressively, perhaps by requiring high-efficiency appliances and automatic timers to ensure that appliances are not left on when not in use. Electric resistant loads such as coffee pots should be prohibited. The park may consider increasing the PV capacity, although it appears that the campground load would increase to use whatever capacity is made available. The park may always have to limit its investment in the power system by limiting the energy made available to users.

Repairing and/or expanding the existing PV/fuel cell arrangement maintains a system that is both clean and silent, and those are two important objectives of the project.

ACKNOWLEDGMENTS

This effort was supported by the National Park Service, Golden Gate National Recreation Area, and by the U.S. Department of Energy Federal Energy Management Program (FEMP). Beth Shearer is the director of FEMP and Anne Crawley manages support for renewable energy projects. Design and installation of the PV/fuel cell hybrid system was by FIRST, INC., Solar Depot, and SunPirates Inc. Instrumentation is by Mountain Energy Partners.

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