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OPERATING EXPERIENCE WITH THE NATURAL BRIDGES NATIONAL MONUMENT PHOTOVOLTAIC POWER SYSTEM* ** +

F. John Solman
Barbara L. Grossman

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

ABSTRACT

The 100-kW photovoltaic power system at Natural Bridges National Monument in southwestern Utah has been in operation since May 1980. A comparison of system simulation with actual operation has been performed, good agreement has been found, and results are presented. In addition, conservation measures and their benefits are described. Operating experience with the system is presented, including measured component performance of the arrays, batteries, inverters, and system overhead loads.

INTRODUCTION

Natural Bridges National Monument (NBNM) in southeastern Utah is the site of the 100-kW peak stand-alone photovoltaic (PV) system designed and installed by Massachusetts Institute of Technology (MIT) Lincoln Laboratory, under sponsorship of the U.S. Department of Energy and the Department of the Interior. The site was chosen because it is remote from a utility grid while retaining good public exposure. The performance of the system has been monitored extensively for ten months and comparisons have been made between model predictions and the actual system performance.

The PV power system consists of the array field plus the equipment located in the PV and generator buildings. The equipment includes a battery bank, inverters, control equipment, a data subsystem and a diesel-powered generator and battery charger (Fig. 1). The array is made up of modules procurred from three different manufacturers. It is divided into 48 subfields of about 2-kW (peak) output each. Storage for the PV system is provided by lead-acid batteries. There are two parallel strings of 112 cells in series in the battery subsystem. The diesel generator and battery charger provide backup power whenever battery discharge is excessive; they are also used to equalize the batteries every 14 to 21 days. The 50-kVA inverter dictates that the dc bus voltage be kept in the range of 210 to 280 VDC. The charge-control algorithm monitors the battery voltage and current and sheds array subfields as needed to keep the bus voltage below 280 V. Further details are given in References 1-5.

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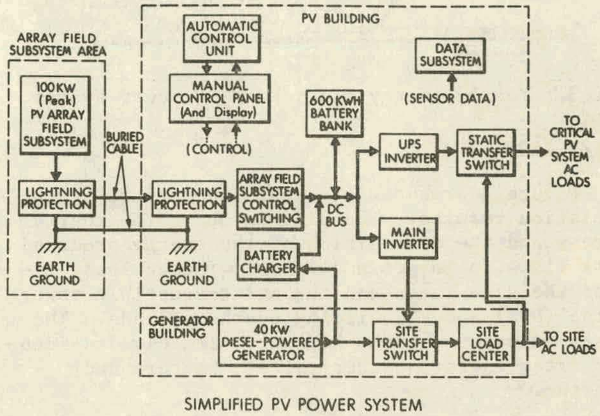

Fig. 1. Simplified PV power system block diagram.

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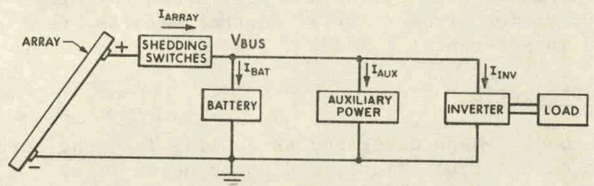

Fig. 2. System representation for computer models.

COMPUTER SIMULATION

The computer simulation models a simplified representation of the site consisting of array, battery, auxiliary power, inverter and shedding switches (Fig. 2). Insolation, load and ambient temperature are time-varying inputs into the program. Information about the system (power, current, dc bus voltage, generator usage, etc.) is determined via the computer simulation and is available in various output formats. Initial simulation work was done with SOLMET data for Albuquerque, New Mexico. Comparisons have also been run with actual site data. The models used for the array, battery (piecewise linear model), inverters (constant efficiency), and auxiliary power source (constant power with voltage limit) are given in References 1 and 4.

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DISCLAIMER

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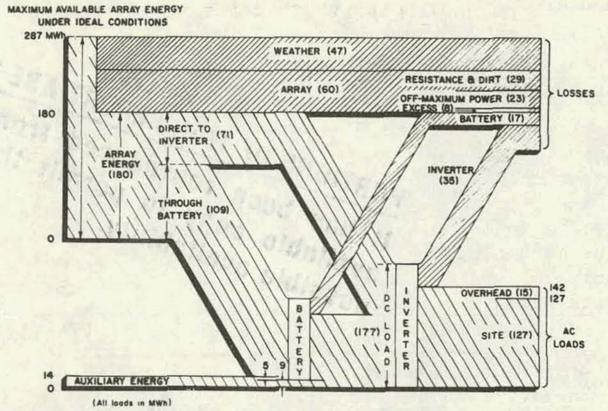

Fig. 3. Yearly energy flow, NBNM PV power system.

Energy Flow

Figure 3 presents a graphic summary of a year's simulation results. The diagram shows the energy sources and the disposition of the energy produced as it flows to losses and loads. The ac loads include the site loads and the uninterruptible power source (UPS) and PV building overhead loads. The losses associated with the system are divided into four categories: weather, array, battery and inverter.

Solar energy from the PV power system carries 89% of the ac site loads for this particular scenario of loads and system control strategy. (The goal of the system sizing and design was to carry 85-90% of load from solar.) Further details are given in References 1 and 4.

Load Categories

Loads can be described as falling into one of three categories: light, medium or heavy. The loads were categorized on a monthly basis. The loads were considered to be constant each hour. For simplicity, the load is stated at the dc input to the inverters.

Figure 4 illustrates the three load categories for the month of December. The top plot shows the fraction of the daily dc loads carried by solar versus increasing dc load. The lower plots show the power supplied to the daily dc load by the array as well as by the auxiliary power.

In the light load category, the entire load is carried exclusively by the PV system. This occurs when there is more than enough energy to carry the daytime load and to recharge the battery sufficiently each day so that the energy from the battery can carry the nighttime load.

In the heavy load category, the amount carried by solar has reached its maximum. Each additional increment of dc load means that an equal amount of additional generator power will be consumed.

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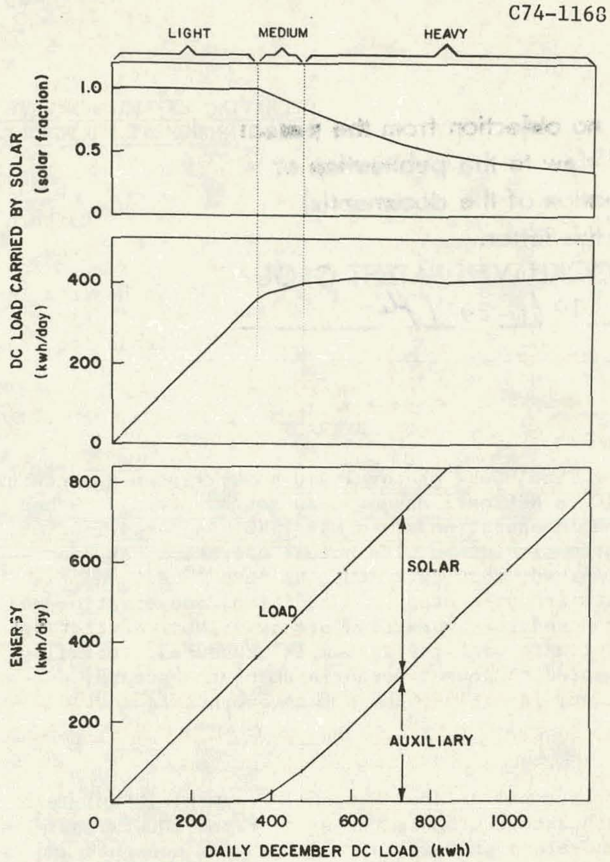

Fig. 4. Daily December dc load (kWh).

In the medium load category, there is a surplus of array energy some days and a deficit of energy on others. Even though there is enough array power on the average to meet the load, it is necessary to supply backup power whenever there are several consecutive days of poor insolation. The medium load category exists because of day-to-day variations in the weather. If every day had identical weather, then there would only be light and heavy loads.

The boundaries of the load regions vary from month to month: a daily load of 500 kWh is a "heavy" load in January whereas the same load is a "light" load in April.

Shown in Fig. 5. are the expected daily dc system loads. The loads at NBNM can be found in all three load regions.

Effects of Load

Battery State of Charge The behavior of the battery state of charge (SOC) varies, depending on whether the system is carrying a heavy, medium or light load. The behavior of the battery SOC is shown on an hourly basis for the month of December (assuming battery was fully charged at start of simulation) in Fig. 6. The top graph in Fig. 6 shows the SOC behavior when a "heavy" load is imposed on the system. There is not enough array power to carry the entire daily load, therefore there is a net discharge at the end of each day.

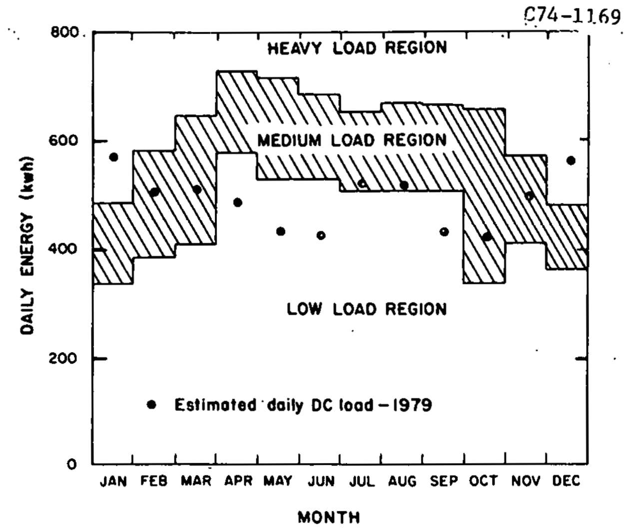

Fig. 5. Monthly load category boundaries.

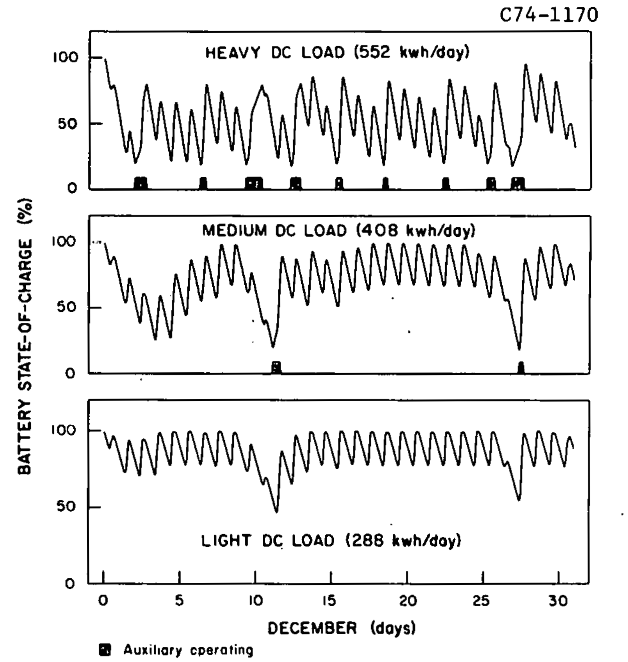

Fig. 6. Effect of load on battery state of charge.

This net daily discharge continues until the SOC reaches 20%, whereupon the system-control strategy signals the need for auxiliary power. The battery is recharged to a specified level (in this case, to a SOC of 80%) and the cycle repeats itself.

The behavior of the SOC is different when the system is carrying a "medium" load (middle graph, Fig. 6). The battery generally discharges during the nighttime but is fully charged up during the day. When there are several consecutive days of low insolation, however, there are also several days of net daily battery discharge and auxiliary power is necessary. The dips in the graph show these bad-weather sequences.

The bottom plot shows SOC versus time for a light load. The battery never discharges to the point where auxiliary power is needed.

The graphs in Fig. 6 are for the month of December; however, the battery SOC exhibits similar characteristic patterns for "heavy," "medium" and "light" loads during the other months as well.

A detailed hourly simulation is shown in Fig. 7. This shows the battery SOC, dc bus voltage and battery current for one week in February. The load is 500 kWh/day, which is a "medium" load for February. After one day of slightly bad weather (day 9), and one day of bad weather (day 10), the SOC dropped below 20% and the control algorithm signaled the generator to start up.

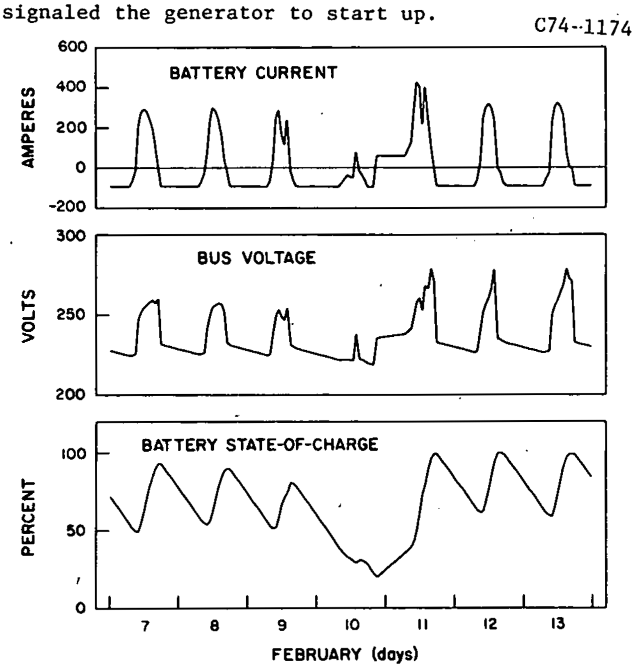

Fig. 7. Simulated hourly system data.

Load Management

System load management can be accomplished with knowledge of trends and relationships. The variation of array energy as a function of month is suggested by Fig. 5. Each year will not behave exactly as this sample year; however, a general idea is gained of what size of loads can be carried. The detailed relationships (Fig. 6) can be used for day-to-day load management. For instance, if the battery SOC is exhibiting the behavior characteristic of a heavy load, then energy conservation measures should be taken (turning off lights, deferring water pumping, etc.). But if the battery SOC is characteristic of a light load, then loads could be added judiciously.

SYSTEM PERFORMANCE

Array Performance

Array performance is monitored daily at solar noon. The current-voltage (I-V) data is recorded automatically for each individual array subfield.

Figure 8 shows a typical plot from one day's data. The data is later corrected for insolation and temperature and retained for long-term observation of array performance. (The plots shown are uncorrected; the voltage and current axis calibration must be multiplied by 1.1.)

The I-V scans have been used to uncover several module and array problems and have assisted in their rapid repair. There have been only 29 module failures out of the 4500 modules in the array field (0.6%).

The "stairstep" I-V curve of subfield #136, which has a shorted module, is clearly visible. Each module has an open-circuit voltage of 6.4 volts so the short to ground is about 20 modules from the high-voltage end of one of the two module strings.

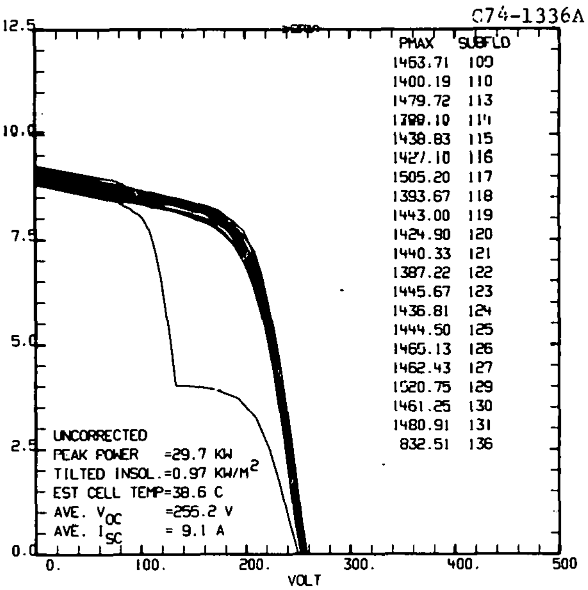

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Fig. 8. Multiple plots of I-V scans for 21 subfields using module type #2. This is an uncorrected plot. All subfields are to the same scale.

During January and February a number of arrays became inoperative following snowfalls. The problem was traced to a group of fast-blow, 15-A fuses that were accidentally used for the lightning protection fuses on the wires to the array field. The fuses were apparently blown by transient current surges of 16-17 A, which occurred when arrays were switched on and off during a period when the insolation was enhanced by snow and cloud albedo. During such a period, insolation peaks of 1.4 kW/m^2 were observed on the array area tilted pyranometer. The fuses have been replaced with a medium speed, 20-A fuse and no further problems have occurred. Because of its inherent redundancy, the array system has been quite reliable. Module failures are the topic of another paper presented at this conference by S. E. Forman (6).

Battery System

While lead-acid batteries are a fairly mature technology, their application in PV power systems leads to new design requirements and constraints.(7) These include a limited operating-voltage window dictated by voltage limits of the available inverters. This limited operating-voltage window, coupled with the relatively short daily charging time (daylight hours), led to the manufacturer recommending use of an air-lift system to prevent acid stratification. (Higher cell voltages permit the acid to be mixed by gas evolution during charge.) In addition, it is necessary to limit hydrogen gas release from the cells to minimize explosion hazard and the need to add water to the cells. While air-lift pumps, catalytic recombiners (for $H_2 + O_2$), and acid-level indicators are routinely used on batteries, this was the first system to use all three. For the combiners to operate properly, the cells must be sealed so that the evolved gas is forced to go through the catalytic element. This created some back pressure inside the cells, and combined with air blown into the cells for the air lift pump (0.5 psi), any acid spattered on the inside lid of the cells was forced out through small voids in the seal gaskets. Immediate clean-up was required because of the hazard of the cell-string voltage. Improved gaskets however, have stopped the leaks. The use of recombiners to limit water loss from charging is worthwhile since it can reduce the need to add water to the cells. For 224 cells, watering requires 5-6 manhours.

Measured Component and System Efficiencies

The measured average component and system energy efficiencies are given in Table I. The average energy efficiencies for the two inverters are lower than the values normally quoted for such units. The reason for this can be understood from the efficiency curves for the two units, Figs. 9 and 10. Both units reach maximum efficiency at full load and the

TABLE I
MEASURED AVERAGE COMPONENT AND SYSTEM ENERGY EFFICIENCIES, JULY 1980 THROUGH MARCH 1981

	Average Value (%)	Variation (%)
Battery Charger	85	±1
Main Inverter	75	±4
UPS Inverter	62	±3
Battery*	85	±5
Array+	5.4	±1.3
System‡	67	±4.5

*Battery efficiency is ratio of energy released on all discharges to the energy stored on all charges.

+Array efficiency is the ratio of the solar energy falling on the cell area to the array dc-energy output. Due to shedding, this efficiency is less than the cell efficiency and will vary seasonally and with the site load.

‡System efficiency is defined as ac-load energy delivered by the UPS and main inverters to the dc energy generated by the array and battery charger.

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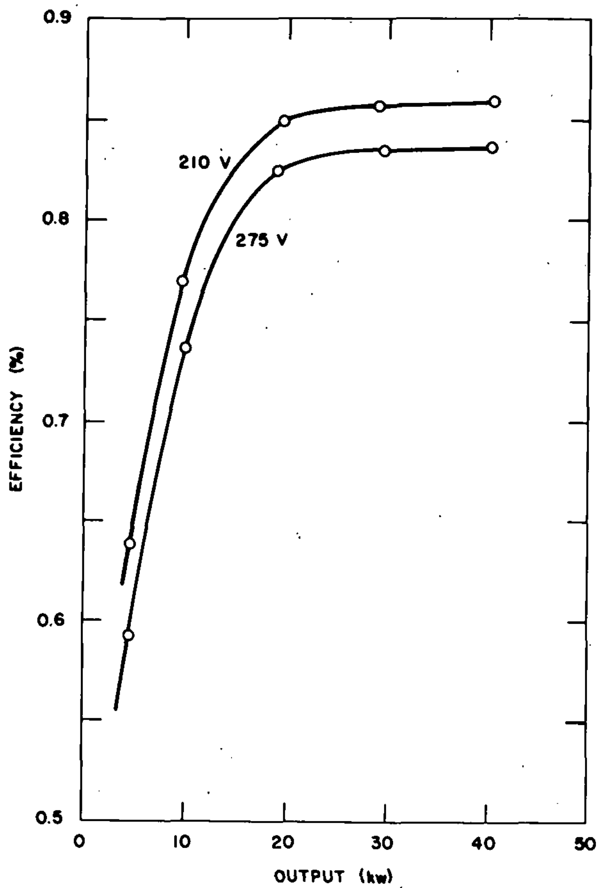

Fig. 9. Main inverter efficiency versus load.

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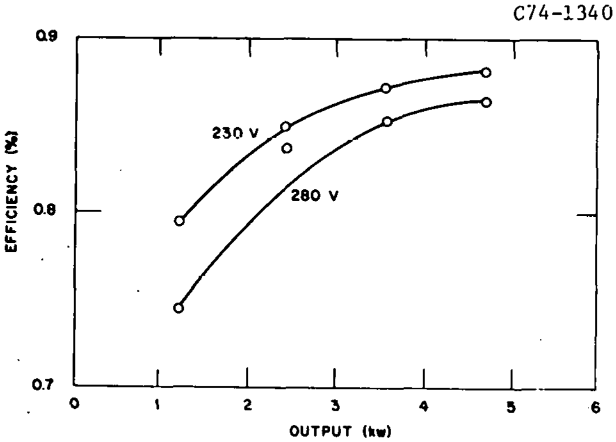

Fig. 10. UPS inverter efficiency versus load.

efficiency goes to zero at no load due to the effects of tare losses. The tare loss of the main inverter is 2.5-3.0 kW; that of the UPS inverter is 400-475 W. Both tare losses vary with input voltage and are highest at the higher voltages. Full load efficiencies of the inverters are 85% and 88% for the main and UPS inverters, respectively. The load on the main inverter varies from 8-20 kW; the UPS load is almost constant at 750 W.

Site AC-Energy Summary

For simplicity, only the site ac-energy usage is tabulated in Table II. The component and system efficiencies given in the previous section provide insight about the power handling and conversion equipment.

TABLE II
AC ENERGY SUMMARY

	1980	1981	Total
Site AC Load (kWh)	53,390	20,855	74,245
PV System*	77	98	83
PV Building*	12	11	12
UPS*	8	8	8
Diesel Generator*	33	15	28

*As percent of site ac load.

Conservation measures have been implemented at the site to reduce site load in the winter season since it would otherwise result in unnecessary diesel operation. The total site load for 1980 and 1981 when compared to the site loads in the corresponding months of 1979 is about 70% of the previous usage.

The heating and cooling of the PV building is an overhead load on the PV power system. This load averages about 12% of the site load and has been higher in the summer months due to cooling-blower energy requirements. In the winter, waste heat is used to heat the building and large fans are used only to dump excess heat outside when needed.

Operating Experience

Table III lists a summary of scheduled and unscheduled down-time for the system since last June. The inverters have been responsible for almost all unscheduled down-time. The longest outage occurred in November just before Thanksgiving. The holiday

TABLE III
OPERATING TIME SUMMARY

	1980	1981	Total
Total Months	7	3	10
Total Hours	5179	2160	7339
PV System*	80	99	85
Diesel Generator Use*	26	7	20
Battery			
Boost	0.3	1	0.4
Equal.	8	6	7
Site			
Unsched.	17	0.1	12
Sched.	1	0.8	1

*Figures are given as % of total hours in period.

delayed the manufacturer's service representative. Two subsequent main inverter failures were diagnosed over the phone and repaired by the NPS site maintenance personnel. These two repairs highlight the importance of good documentation, including anotated pictures as a tool to assist in repair of a remote system. Good communication (telephone) and on-site spare parts are also very useful in reducing the length and cost of repairs.

This system is designed for minimal operator attention and can operate automatically for long periods. However, daily checks are made to insure proper operation, to attend to the data logger and to record manually the kWhr meter data. While the diesel generator can be started automatically to provide backup power and to do the periodic battery equalizations, operator intervention has occasionally been needed in the winter months because of the cold. Operator attention averages less than one hour per day.

Almost all of the scheduled down-time of the PV system has been due to battery specific gravity readings. For safety reasons, these are done with the battery off-line and the PV system shut down. During the measurements, the site is run on the diesel generator. During the first six months of operation, measurements were taken after each battery equalization. Specific gravity readings on the 224 battery cells take about 1.5-3.0 hours, with two persons working together.

System Cost Data and Cost Projections

A cost breakdown for the system is given in Table IV. The actual costs were obtained from contracts issued by the National Park Service and Lincoln Laboratory. The costs of the system are high due to first-of-a-kind development costs, custom instrumentation, the remoteness of the site, and because of National Park Service construction and siting specifications.

TABLE IV
COST BREAKDOWN AND PROJECTIONS
(Costs in Millions, 1980 Dollars)

ITEM	FIRST SYSTEM	EXACT COPY	IMPROVED VERSION
Modules	$1.6	0.7	.07
System Design, Fab, Test	1.8	0.7	.20
Building and Site Preparation	0.45	0.4	.20
Power Components	0.20	0.2	.20
Total	$4.05	$2.0	$0.67

Cost of Energy in 1980 Dollars

Price per kWh	$1.49	$0.75	$0.25

In addition to the actual cost data for this system, an estimate of the cost to build an exact copy and a improved version at the same site are given. This exact copy would use present module prices and would be built to the original blueprints with only minor changes. The improved version would benefit from cost-reducing ideas suggested from experience with this system. It is important to note that even in the improved version, balance of system costs still dominate the cost of the system. It is believed that there are still many opportunities to reduce these costs further, so that even if module cost increased, system cost would still be competitive with diesel generated electricity in the 10-20 kW size range. The cost for electricity from diesel generators presently is 25-35¢/kWh. The fact that an improved copy is close to being competitive should be very good news.

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