

PERFORMANCE OF THE MEAD, NEBRASKA, 25 kW PHOTOVOLTAIC SOLAR ENERGY SYSTEM AND COMPARISON WITH SIMULATION[‡]

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ABSTRACT

A photovoltaic solar energy system has been providing power for irrigation and crop drying at an agricultural field station of the University of Nebraska. The system, developed and maintained jointly by MIT/Lincoln Laboratory and the University and under contract to the U. S. Department of Energy, consists of a 25 kWp PV array, a battery subsystem, an inverter, a controller, and a data collection and management system. Field data indicate that the PV array performs up to expectations if allowance is made for degradation. The array operates at an efficiency (based on cell area) of between 7 and 8%; the battery subsystem at an "in-out" efficiency of 83%, and the inverter at 87%. During the irrigation season the system delivers 70% of the energy provided by the PV array to the pump motor. Approximately 10% of the array energy is wasted when the battery is in a fully charged state and the array power exceeds the load. Performance of the system was compared with the results of a computer simulation. This comparison showed agreement to within +5% on daily energy totals for array output, inverter input, battery input and output.

FOR OVER A YEAR NOW, a 25 peak kW photovoltaic solar energy system has been providing power for irrigation and crop drying at the University of Nebraska's Agricultural Research Station in Mead, Nebraska. The system was designed and built by Massachusetts Institute of Technology's Lincoln Laboratory under Department of Energy (DOE) sponsorship and is being operated in partnership with the University. Originally conceived as a test of the application of photovoltaic solar energy to a variety of agricultural tasks, the system not only fulfills this mission but functions as a test bed for subsystem components and operational strategies as well. In this paper the system's performance in this agricultural setting is described and what has been learned about the behavior of photovoltaic devices, batteries, power conditioning equipment--about subsystem characteristics and performance in general--is discussed.

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DEFINITION OF THE SYSTEM

The system includes an array of photovoltaic cells which nominally produces a maximum output power of 25 kW at an insolation of 1 kW/m², a set of batteries which provides 90 kWh of energy storage capacity, an inverter, a controller, a power dump and a data collection and management subsystem. Utility power is available in parallel and is used: (1) for carrying the load whenever the battery depth of discharge becomes excessive, (2) for powering a battery charger during periodic equalization of the battery cells, and (3) for taking care of the overhead electrical power needs of all instrumentation, control, heating and cooling units. In addition, the system includes an uninterruptible power supply which is called into play whenever there is a loss of utility power. The block diagram of the system presented in Figure 1 defines the various electrical loads placed on the system and shows the interconnection of all subsystem elements.

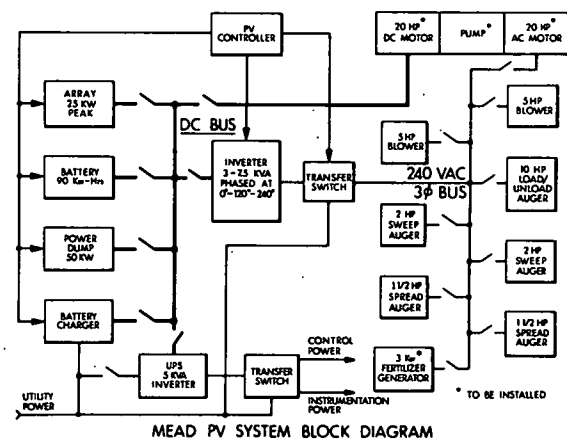


Fig. 1

The array is built up of two different types of photovoltaic modules. A Sensor Technology module is made up of 44 2-1/8-inch diameter silicon cells, connected in series, and nominally producing 10 watts maximum power at 40°C and 1 kW/m². Module short-circuit current and open-circuit voltage at these same reference conditions are 0.59 amps and 23.7 volts, respectively. Four of these modules are connected in parallel to form a series block. Nine of these blocks connected in series form a string and 42 of these strings connected in parallel provide approximately half the power at the site. This (4P x 9S x 42P) network of Sensor Technology modules would show a short-circuit current of 99 amps and an open-circuit voltage of 213 volts if the modules were all identical.

The Solarex Corporation module consists of 42 3-inch diameter cells, connected in series, and nominally producing 20 watts maximum power at 40°C and 1 kW/m². Module short-circuit current and open-circuit voltage are 1.44 amps and 23.2 volts, respectively.

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Two modules in parallel form a series block, ten of these blocks in series, a string. The full network of Solarex modules containing 35 of these strings in parallel would show a short-circuit current of 100 amps and an open-circuit voltage of 232 volts if the modules exhibited no mismatch in I-V characteristics.

The major factors which determined the electrical design of the array were: (1) power requirements of the load, (2) total daily energy requirements of the load, (3) constraints on the voltage at the DC side of the inverter, and (4) the desire to minimize power losses due to mismatch of the Solarex and Sensor Technology current-voltage characteristics. Maximum values for the instantaneous power required by the load fell in the 10 kW to 15 kW range, while it was thought that irrigation of the 80 acres of corn at the site, the heaviest load anticipated, would consume 90 kWh daily (1*). The voltage at the DC side of the inverter had to be confined to the range 100 to 150 volts. This operating range is shown in Figure 2 superimposed on a plot of an analytical model of the array I-V curve. (Details of this model are described below.) The DC bus voltage was held back from the max-power voltage so that even during peak battery charging conditions (terminal voltage up to 147 volts) a down converting maximum power tracker might be employed (1). This element, the development of which has been described in Reference 2, has not yet been added to the system. Note that holding the DC bus voltage to less than 147 volts also insures that the array power output remains relatively insensitive to changes in cell temperature.

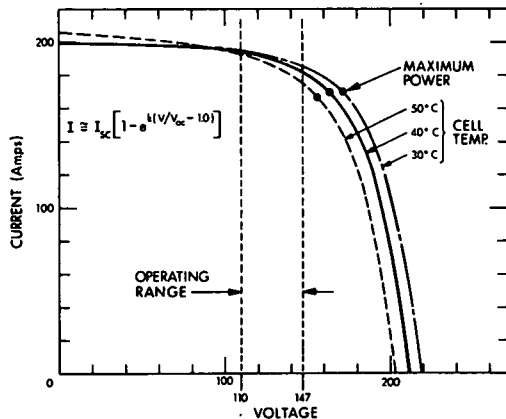


Fig. 2 Simulated I-V Characteristics - Mead PV Array

The number of battery cells placed in series is fixed primarily by the desired range of the bus voltage; the amp-hr capacity and number of parallel strings of battery cells are fixed by the amount of energy storage required. The energy storage system consists of two parallel banks of 6 volt, lead-acid C&D batteries each rated at 375 amp-hrs. There are twenty batteries connected in series in each bank, yielding a nominal terminal voltage of 120 volts and an amp-hr capacity of 750, or an energy storage capacity of nominally 90 kWh (72 kWh to the recommended 80% depth of discharge).

This capacity is sufficient, not to carry the load during day-long periods of low insolation--that was not a design goal--but rather for load-leveling purposes.

A power-conditioning subsystem includes a three-phase inverter, actually 3 separate single-phase 7.5 kVA units, produced by the Nova Electrical Company and modified by Lincoln Laboratory (3). A solid-state control unit automatically controls the power dump and

*Numbers in parentheses designate References at end of paper.

the inverter. If the bus voltage drops below a preset value, the inverter is turned off and the load placed on utility in order to insure that the battery depth of discharge does not become excessive. If the bus voltage exceeds a preset upper limit (above 147 volts), indicating that the batteries are near full charge, the power dump loads down the DC bus in incremented steps until the voltage drops below 145 volts.

SYSTEM PERFORMANCE

While the system has been used for crop drying as well as irrigation (and there are plans for several new kinds of loads this coming year), this description of system performance will be limited to discussion of performance during the past year's irrigation season.

Figure 3 shows how the array output power, the load power and the battery power vary over the course of a typical clear day. These curves have been generated from data collected at 10-minute intervals on 7 August 1978. In the early morning, before the pump motor is turned on, the few kilowatts that the array produces go to charging the battery. For approximately three hours after the load is turned on, the load exceeds array output and the batteries make up the deficiency (a 10 kW load on the batteries indicates that the batteries are discharging at a rate of approximately C/10 where C is the amp-hr capacity). By 9:30 a.m., array output is sufficient to carry the load and subsequently any excess power flows to the battery, charging up the energy storage system. At around solar noon when the array puts out 22 kW, the batteries are near full charge, the DC bus voltage has exceeded 147 volts, the power dump is brought on line, and approximately 4 kWh of energy are dissipated as heat. Eventually the power dump is taken off the bus, the array output power drops below what is required by the load, and the battery again operates in the discharge mode.

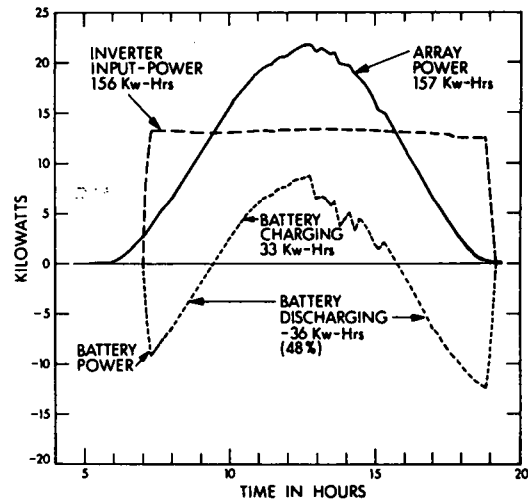


Fig. 3 Measured Performance - Mead, 7 August 1978

On this particular day, the array produced 157 kWh, the load demand was by design approximately equal to that same value (156 kWh), and the battery stored 33 kWh and discharged 36 kWh. The balance of 4 kWh was expended in the power dump. (These energy totals consistently balance to within ± 1.0 kWh.)

The load-leveling function of the battery is indicated more dramatically in the next day's data. The 8th of August was a day of broken clouds after 9 a.m. Figure 4 shows how the battery serves as a sink for excess array power and a source for a deficient inverter output.

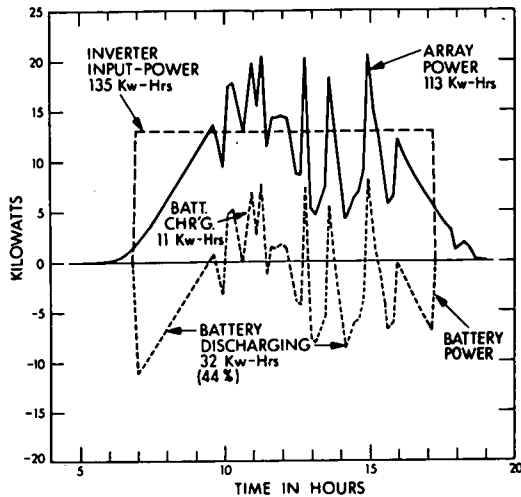


Fig. 4 Measured Performance - Mead, 8 August 1978

Data accumulated during the heart of the irrigation season from 1 August to 10 September 1978, indicates that the photovoltaic array produced all the power that was required for irrigation--the utility was never called on for this purpose. As shown in the energy profile presented as Figure 5, of the 5.22×10^3 kWh output from the array over this period, approximately 65% went directly to the inverter, 25% to the battery and 10% was dumped as excess. (The 150 kWh consumed by the uninterruptible power supply is a misleading figure: it was due to start-up transients upon installation of this unit.)

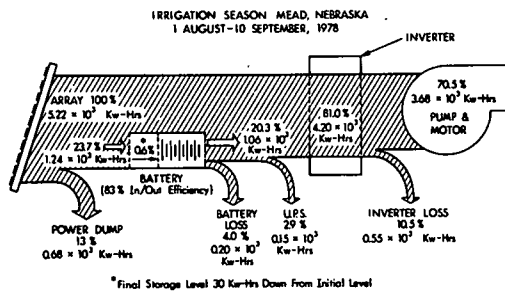


Fig. 5 System Energy Flow Profile

Estimates of subsystem efficiencies are also given in the figure. An overall inverter efficiency of 87% was obtained simply from a comparison of data collected for DC power in and AC power out. For this near constant load condition characteristic of most days during the irrigation season, the efficiency remains relatively constant over the course of a day.

Estimating the battery in-out efficiency required more effort. Since the battery state-of-charge was not continually measured over this time period, an estimate of a coulometric charging efficiency was derived from battery current flow data taken between two instants of time when the battery was assumed to be in the same state: when the bus voltage tripped the power dump into action. This gave a charging efficiency of 94%. With this, and with continuous data for the current flow in-to and out of the battery recorded from 1 August to 10 September, we estimated the change in state-of-charge over this entire period; energy stored in the battery was down by 29 kWh on 10 September compared to 1 August. Having a continuous record of battery terminal voltage, we then calculated the total energy into the battery

over this time period, E_{in} , and the total energy out, E_{out} . If we set

$$E_{stor} = +29 \text{ kWh}$$

(29 kWh of energy were drawn from storage) we defined an in-out efficiency by

$$\eta = \frac{E_{out}}{E_{in} + E_{stor}}$$

With $E_{out} = 1.06 \times 10^3$ kWh and $E_{in} = 1.24 \times 10^3$ kWh, we obtained

$$= 83.5\%$$

Note that if the estimate of change in state-of-charge or, equivalently, the estimate of E_{stor} , was in error, the estimate of η would be at most a few percent off. That is

$$\frac{E_{out}}{E_{in} + 90 \text{ kWh}} < \eta < \frac{E_{out}}{E_{in} - 90 \text{ kWh}}$$

$$79.7\% < \eta < 92\%$$

The efficiency of the photovoltaic array is not shown in Figure 5. Comparing total integrated values for incident solar flux onto the array with the total energy delivered by the array yields an efficiency based upon cell area of 7.3%.

COMPARISON WITH COMPUTER SIMULATION

In order to help evaluate the performance of the PV system, ten days of the irrigation season were simulated by a computer and the results compared with data obtained from the field. The simulation links together all the subsystems tied to the DC bus other than the uninterruptible power supply and the battery charger. (The power drawn by the former is patched in as additional load power after the fact since utility power outages cannot be foreseen. The battery charger is called on only for equalization of the battery cells and requires manual intervention into what is otherwise an automatically controlled process.)

Time histories of the insolation incident onto the array, as measured by a pyranometer set at the same inclination as the array, and of the three-phase load power drawn at the AC side of the inverter, were the inputs to the simulation. Analytical models of current-voltage characteristics of the array, battery, power dump and inverter subsystems were formulated (as described below). The computer algorithm at each instant in time, t_j , for a given load power and a given insolation, determines a value for the DC bus voltage, V_{dc} , such that Kirchoff's current law is satisfied at the DC bus mode. The non-linear current-voltage characteristics of each of the subsystems requires that an iteration scheme be employed.

Having the battery current at time, t_j , an update of the battery state-of-charge is made, applying a charging efficiency of 94% to obtain the state-of-charge at time, t_{j+1} . This process is then serially repeated.

At each step in this process, checks are made on the DC bus voltage and appropriate action taken, e.g., increment power dump on line, if V_{dc} exceeds the limits defined by the control subsystem.

An analytical model of the inverter assumed the simplest form possible:

$$V_{dc} I_{inv} = P_{load}(t_j) / \eta_{inv}$$

where P_{load} is the power demanded by the load, I_{inv} is the direct current into the inverter and η_{inv} the efficiency of the unit. More complex models are not difficult to formulate, e.g., models which make the

efficiency a function of input and/or output variables, but this simple relationship proved adequate for this study.

The power dump was modeled as a resistive load that is brought on-line when $V_{dc} = 147$ volts and increased until the DC bus voltage V_{dc} drops below 145 volts.

$$V_{dc} I_{pd}^{-1} = R$$

Figure 6 shows the voltage, current and state-of-charge characteristics of a typical C&D lead-acid battery cell. Piecewise linear fits to these curves were made in the form

$$V_{dc} = M(I_b) SOC + b(I_b)$$

where SOC is the cell state-of-charge and I_b the current into or out of the battery. Values of the coefficients m and b also depend on the number of battery cells in series and on the amp-hour capacity of the full set of batteries.

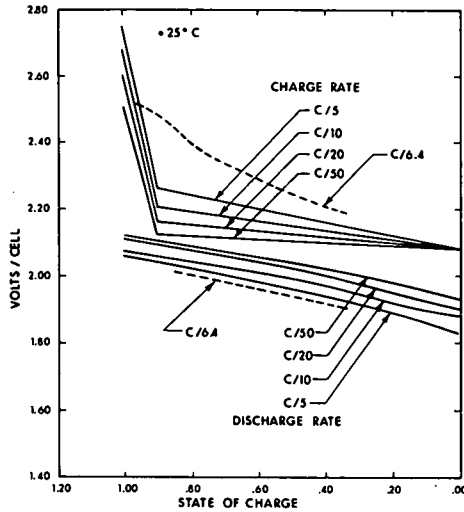


Fig. 6 Simulated Battery Characteristics

Also shown in this figure is the result of a test designed to fix independently the battery's characteristics, an experiment which proceeded as follows: an eight-hour equalization of the two parallel strings of 60 series cells was performed. The power dump was then brought onto the DC bus and set to drain the batteries at a discharge rate of C/6.5 for approximately four hours, giving the lower dotted line shown in the figure. At the end of the four hours, charging at this same rate was begun, yielding the uppermost dashed curve. (At the higher SOC levels, 0.80, the current drops off from the C/6.5 rate). The discrepancy evident on the charge side is reflected in the comparison of the results of the computer simulation with results obtained from the field and is discussed below.

The current/voltage characteristics of the photovoltaic array were synthesized from data for the Sensor Technology module and the Solarex module that has been presented in Reference 4. The I-V curve for each module was represented by

$$I = I_{sc} \left\{ 1 - e^{k(V/V_{oc} - 1)} \right\}$$

where I_{sc} and V_{oc} are the module short-circuit current and open-circuit voltage, respectively, and k is a parameter which measures the sharpness of the bend at the knee of the I-V curve and may be related to the fill-factor. I and V are defined at a reference cell temperature, T , and reference insolation level, L . To obtain the relationship between current and voltage at another temperature, T' , and light intensity level, L' , the following transformation was applied:

$$I' = I + I_{sc} \left[\frac{L'}{L} - 1 \right] + \alpha (T' - T)$$

$$V' = V - (T' - T)$$

where α and β were again estimated from the data presented in Reference 4. Values for all these parameters at a reference cell temperature of 40°C and a reference insolation level of 1 kW/m^2 are presented in Table 1.

Table 1

	Solarex	Sensor Technology
I_{sc} amps	1.44	0.589
V_{oc} volts	23.2	23.7
k	6.32	11.6
α amps/ $^\circ\text{C}$	5.8×10^{-4}	3.3×10^{-4}
β volts/ $^\circ\text{C}$	0.12	0.10

Assuming no mismatch in I-V characteristics among the Solarex modules, the I-V curve of the sub-array of 2 parallel, by 10 series, by 35 parallel modules was generated at reference temperature and insolation conditions: i.e., $I_{sc} = 100.8$ amps $V_{oc} = 232$ volts. The same process was applied to the sub-array of Sensor Technology modules yielding an I-V curve with a short-circuit current of $I_{sc} = 98.9$ amps and an open-circuit voltage, $V_{oc} = 213$ volts. The mismatch in current-voltage behavior between the Solarex sub-array and the Sensor Technology sub-array was taken into account in the generation of the full array I-V curve. This was accomplished by an addition of the two current values at common values of array voltage. Carrying this out at two different cell temperatures, 30°C and 50°C , provided estimates of α and β for the full array while a new k was calculated by requiring that the area under the I-V curve for the full array, as represented by the analytical model, be equal to the area under the curve obtained from the point by point computation of I as a function of V . This gave

$$\alpha = .040 \text{ amps}/^\circ\text{C} \quad \beta = .86 \text{ volts}/^\circ\text{C} \quad k = 8.78.$$

Figure 2 shows the resulting I-V characteristics at three different cell temperatures and at an insolation level of 1 kW/m^2 . The short-circuit current and open-circuit voltage at 40°C are

$$I_{sc} = 200 \text{ amps} \quad V_{oc} = 210.6 \text{ volts.}$$

Maximum power current and maximum power voltage were calculated to be

$$I_{mp} = 167 \text{ amps} \quad V_{mp} = 165 \text{ volts}$$

yielding a maximum power value of 27.5 kW, again at 40°C and 1 kW/m^2 .

Knowing the total cell area (286.3 m^2), the efficiency of conversion of solar insolation into electricity at 40°C is found to be 9.6%. If we back away from the maximum power voltage, back to the upper limit of the operating range of the system's bus voltage, i.e., 147 volts, the power available at 40°C and 1 kW/m^2 drops to 26.5 kW, indicating an efficiency of 9.3%, and at 50°C and 1 kW/m^2 to 25.8 kW, an efficiency of 9.0%.

These last values of cell temperature and insolation were in effect at solar noon on the 7 August 1978. (The bus voltage was also at its upper limit at that time.) The discrepancy in the model's predicted value for power output (25.8 kW) and the actual system's power output (22.0 kW) may be accounted for by mismatch losses and, more important, by soil accumulation on the front

surface of the array. A 15% drop in output power due to both of these effects is not unreasonable. In fact, measured values of performance degradation of the Mead system due to soil accumulation alone ranged from 9% to 15%. A 15% additional loss brings the array efficiency down to 7.6%, which compares well with what was observed on 7 August.

To account for reduced array output due to mismatch and soil accumulation, the impinging solar insolation was reduced by 15% in the simulation studies.

A simulation of eight days running was conducted-- 8 August through 16 August 1978--in which the state of the system was calculated at 10-minute intervals according to the method previously described. A comparison of the results of the computer simulation with field measurements for the first day of the sequence is shown in Figures 7 and 8. The excellent agreement of power input to the inverter that is shown comes as no surprise. If the load were to vary significantly over the course of a day, we would expect our assumption of a constant percentage power loss to become less appropriate. The array and battery powers also compare well. Only the bus voltage presents a significant instantaneous discrepancy, as is shown in Figure 9. Finally, Figure 9 also shows the variation in battery state-of-charge as calculated according to our previous discussion.

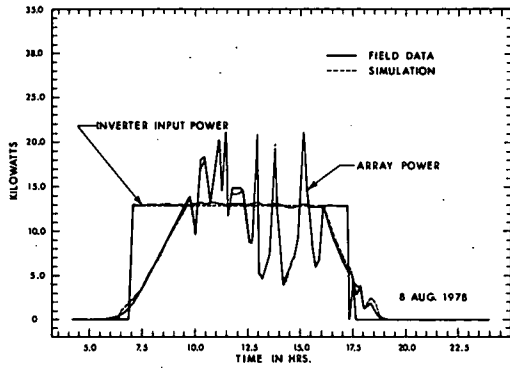


Fig. 7 Comparison of Simulation with Measured Data Array Output, Inverter Output 8 August 1978

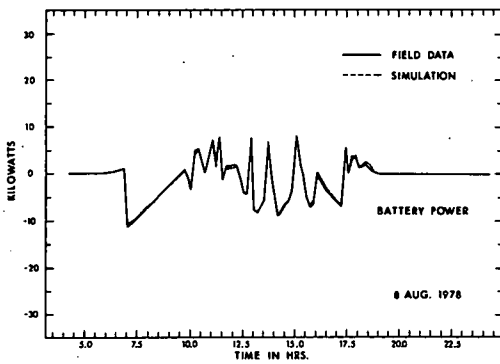


Fig. 8 Comparison of Simulation with Measured Data Battery Power 8 August 1978

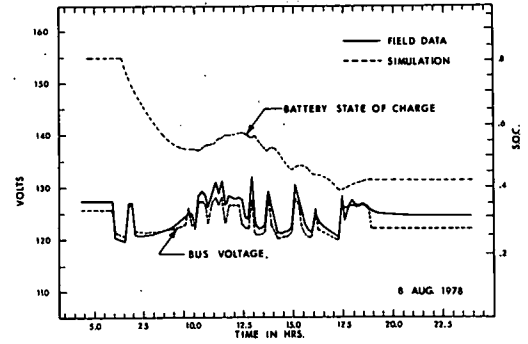


Fig. 9 Comparison of Simulation with Measured Data Bus Voltage, Battery State of Charge 8 August 1978

Results for 12 August, a clear day, are shown in Figure 10. (The load profile for this day was essentially the source as for 8 August.) Here we note that the simulation consistently underestimates the array output power and battery charge power. This discrepancy is largely accounted for by the inadequacy of our model of the battery. Figure 11 shows that the actual bus voltage is significantly higher than the value obtained from the simulation. The array in the simulation is then consistently pegged to a lower voltage than in the field and, hence, provides less power than is actually observed.

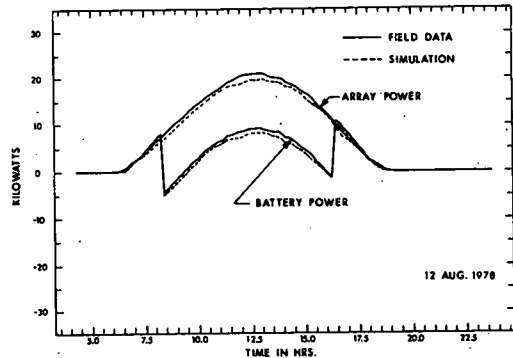


Fig. 10 Comparison of Simulation with Measured Data Array Output, Battery Power 12 August 1978

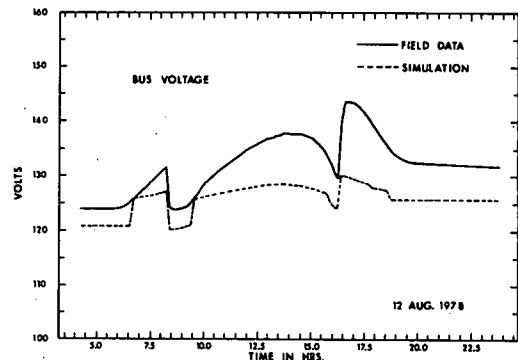


Fig. 11 Comparison of Simulation with Measured Data Bus Voltage 12 August 1978

Energy totals obtained from the simulation and from the field for this eight-day period are presented in Table 2 and again show that array output is consistently underestimated. The poor agreement between the simulation's estimate of amount of energy discharged through the power dump and what was actually expended may again be attributed to the battery model, especially the voltage-current state-of-charge characteristics on the charge side. While the simulation does have the power dump coming on-line on 13 August, this did not happen until several hours after the corresponding event occurred in the field, and not until several hours after solar noon. As a consequence of this delay, less array output energy had to be dissipated in order to keep the bus voltage below 145 volts.

4. Smokler, M. I., "User Handbook for Block II Silicon Solar Cell Modules," Jet Propulsion Laboratory Report No. 5101-36, Pasadena, California, 15 October 1977.

Table 2

	<u>Field Data</u>	<u>Simulation</u>
Array Output (kWh)	1,231	1,164
Battery Charge (kWh)	327	323
Battery Discharge (kWh)	277	295
Inverter Input (kWh)	1,160	1,134
Power Dump (kWh)	24.7	2.5

(8 August to 16 August 1978)

Finally, the battery in-out efficiency obtained from the computer simulation for the entire period 1 August to 10 September was 87%; recall that 83% was obtained from field data. This discrepancy is again explained by the differences in the battery model and the actual battery characteristics.

SUMMARY & CONCLUSIONS

We conclude from both performance data and simulation that the photovoltaic array meets the design objectives if allowance is made for degradation in output due to mismatch and soil accumulation. A 10-15% loss is not unrealistic for a silicone-encapsulated module after several months in the field. The array operates at an efficiency, based on cell area, of between 7 and 8%.

Field data indicates a battery in-out efficiency of 83% during the irrigation season. The computer simulation indicates that the performance characteristics of the battery need to be better known if the simulation is to be improved.

Plans for the future include: (1) addition of other loads including a fertilizer generator and a DC pump and evaluation of system performance, (2) addition of a battery state-of-charge meter and test of alternative control strategies, and (3) continued investigation of ways to measure performance degradation from field data.

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