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PHOTOVOLTAIC SYSTEM EVALUATION AT THE NORTHEAST RESIDENTIAL EXPERIMENT STATION, NOVEMBER 1980 — MAY 1982, FINAL REPORT

January 1983

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Prepared for
THE U.S. DEPARTMENT OF ENERGY
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ABSTRACT

Residential photovoltaic systems have been under evaluation by Massachusetts Institute of Technology Lincoln Laboratory since late 1980, as part of the U.S. Department of Energy's National Photovoltaic Program. At the MIT-operated Northeast Residential Experiment Station in Concord, Massachusetts, five residential photovoltaic systems have undergone a comprehensive testing program designed to evaluate the systems' performance and cost. Results of this activity are presented. The five systems each consist of an unoccupied structure employing a roof-mounted photovoltaic array and a utility-connected power inverter capable of sending excess PV-generated energy to the local utility system. The photovoltaic systems are designed to meet at least 50% of the total annual electrical demand of residences in the cold-climate regions of the country. Investigation included these specific issues: photovoltaic array and inverter system power rating and performance characterization, system energy production, reliability and system cost/worth.

In addition, summary load data from five houses in the vicinity of the Northeast Residential Experiment Station, and meteorological data from the station's weather station are also presented.

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1.0 INTRODUCTION

The 1978 Solar Photovoltaic Energy Research, Development and Demonstration Act (Public Law 95-590) mandated an aggressive, multiyear solar program to be administered by the U.S. Department of Energy (DOE). The objective of the resulting DOE Photovoltaic Program as described in the program plan (1) is to reduce photovoltaic system costs to a competitive level in both distributed and centralized grid-connected applications. In pursuit of this goal, the Program has directed efforts aimed at resolving the technical, institutional, legal, environmental and social issues associated with fostering the widespread adoption of photovoltaic energy systems.

In 1979, under the sponsorship of the DOE, MIT Lincoln Laboratory (MIT LL) prepared a plan (2) for residential photovoltaic system development and testing that called for the establishment of Residential Experiment Stations in the Northeast, Southwest and Southeast regions of the country. The Northeast Residential Experiment Station (NE RES) in Concord, Massachusetts, and the Southwest Residential Experiment Station (SW RES) in Las Cruces, New Mexico, began operations in 1980 and 1981, respectively. Plans are presently being made to add a Southeast Residential Experiment Station.

Each of the Residential Experiment Stations of the Solar Photovoltaic Residential Project has been designed to meet two basic objectives: residential photovoltaic system development and information dissemination to the photovoltaic community, cognizant institutions, and, ultimately, the public. In the present report, results of testing prototype residential photovoltaic systems at the NE RES are presented. A counterpart report (3) presents results of testing prototype residential photovoltaic systems at the SW RES.

1.1 The Solar Photovoltaic Residential Project

The MIT LL Solar Photovoltaic Residential Project began with the simulation of residential photovoltaic (PV) systems to gain a better understanding of their projected performance and economics. At this time other related studies were also being conducted (4,5) for Sandia Laboratories. Out of this work came the first conceptual system designs.

Five prototype residential PV systems were built at the NE RES during the 1980-1981 period. Each prototype system consists of a roof-mounted PV array, sized to meet at least 50% of the annual electrical demand of an energy-conserving house, and an enclosed structure to house the remainder of the PV system equipment, test instrumentation and work space. The prototype PV system structures are sized to accommodate the PV system/equipment only, and are not habitable. The PV arrays provide dc energy which is converted to ac energy by power-conditioning equipment, to serve all the usual loads of a residence. An additional feature common to all the prototype systems is that excess solar-generated electric energy is fed back to the local utility grid, thereby eliminating the need for on-site electrical storage. Conversely, during periods of insufficient solar generation, supplemental energy is drawn from the utility. Such a system is termed utility interactive, allowing two-way power flow between the residence with its PV system and the utility. Energy flows in each direction are separately metered. Fig. 1 shows a conceptual diagram of such a utility-interactive residential PV system.

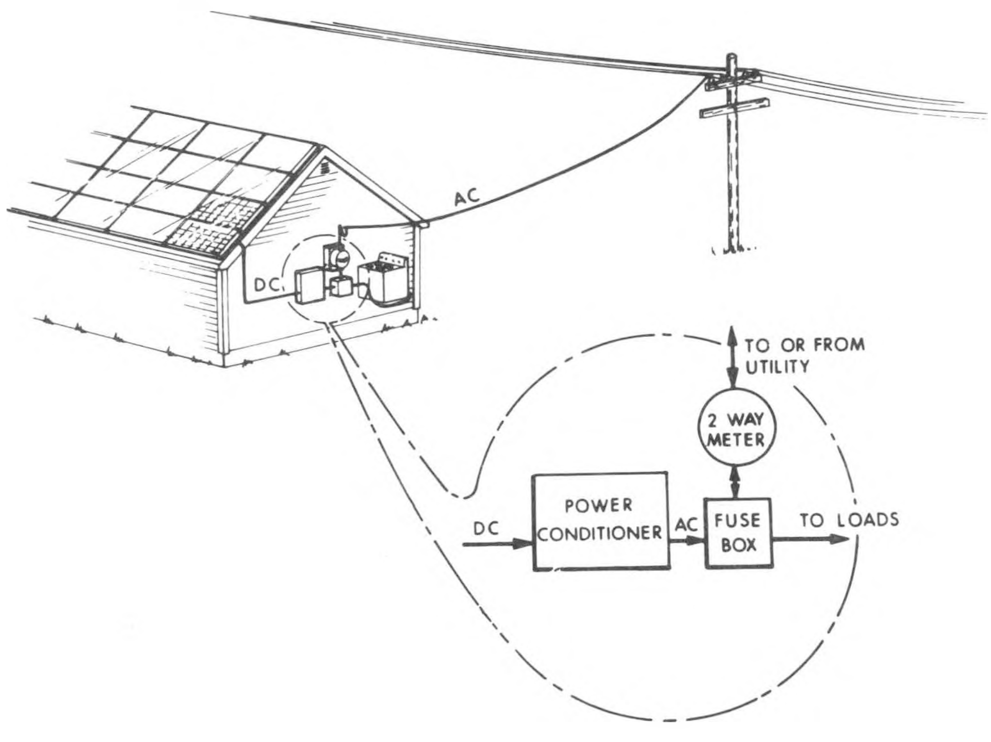

Fig. 1. Conceptual diagram of a utility-interactive residential PV system.

At the NE RES, five prototype systems are under test. To gauge quantitatively the ability of the prototype systems to meet residential load demands, five residences in the vicinity of the NE RES, representative of the occupancy and loads found in the area, were equipped with instrumentation which continually records the residences' electrical energy consumption. Telephone lines carry load information from these monitored residences to the NE RES where the data are recorded. One of the monitored houses commands a common programmable load profile for all prototype PV systems--thereby simulating an actual residential electrical load and permitting side-by-side comparison of the prototypes under essentially identical conditions.

The extensive data system at the NE RES also monitors the performance of the five prototype systems and the meteorological conditions. These data are then analyzed, reduced and published in monthly reports (6-17). Additional information on the retrieval, processing and dissemination of data collected by the residential data system is contained in Reference 18.

In addition to the routine operation of the prototype systems, special tests of limited duration were conducted. The goals of such tests were to characterize the electrical performance of the systems and their components, and to verify proper operation of the systems under both normal and abnormal operating conditions. The prototype system evaluation procedures are described in detail elsewhere (19).

1.2 The Northeast Residential Experiment Station

Figure 2 shows the NE RES which is located in Concord, Massachusetts. The site became operational with the installation of the first of five prototype systems in November 1980, and consists of the five prototype systems and space in the facility building for offices and data system equipment. Meteorological instrumentation is mounted on the facility building roof.

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Fig. 2. Aerial photograph of the Northeast Residential Experiment Station, in Concord, Massachusetts.

The NE RES is located approximately fifteen miles from Boston, Massachusetts. The latitude is 42.46°N, the longitude is 71.30°W, and the elevation is 131 feet. Some of the significant climatic parameters for the site are given in Table 1. As a test bed for evaluation of solar PV systems, the NE RES provides a location which experiences a wide range of meteorological conditions throughout the year, and the area is known for the unpredictability of its often rapidly changing weather conditions. The site has an annual rainfall of approximately 37 inches and annual snowfall of 48 inches. Record extreme temperatures for Boston (measured at Logan Airport) are -12°F and 102°F. Colder temperatures are typical at the NE RES site, which is approximately 15 miles from the coast.

TABLE 1

METEOROLOGICAL DATA
BOSTON, MASSACHUSETTS*

	Maximum Daily Temp.(°C)	Minimum Daily Temp.(°C)	Average Monthly Temp.(°C)	Heating Degree Days (Base 18.3°C)	Cooling Degree Days (Base 18.3°C)	Daily Horiz. Insolation (kWh/m^2)	Global $\overline{K}_t$ Cloudiness Index
JAN	2.16	-5.27	-1.55	616	0	1.50	0.387
FEB	3.05	-4.83	-0.88	538	0	2.24	0.417
MAR	7.00	-0.27	3.38	463	0	3.20	0.431
APR	13.50	4.88	9.22	273	0	4.18	0.439
MAY	19.50	10.05	14.77	121	11	5.11	0.463
JUN	24.77	15.16	20.00	15	65	5.73	0.491
JUL	27.44	18.38	22.94	0	144	5.51	0.485
AUG	26.27	17.38	21.83	4	112	4.69	0.462
SEP	22.33	13.72	18.05	42	33	3.97	0.479
OCT	17.33	8.61	13.00	167	0	2.80	0.455
NOV	10.94	3.72	7.33	330	0	1.59	0.365
DEC	4.05	-2.99	0.55	551	0	1.27	0.367
ANN	14.83	6.55	10.72	3122	367	4.28	0.450

*(Reference 20)

1.3 The Prototype Systems

Design and construction of the first system was managed by MIT LL. The other four prototype systems at the NE RES were supplied by industry participants in the MIT LL project and were selected through competitive procurement.

The contracts issued to the winners of the competitive procurement contained the following specific requirements/guidelines:

- Design a full-sized, single-family detached residence appropriate for the northeastern region of the country containing 1400-2000 ft^2 of living space. The residence should utilize energy conservation and passive solar features, and a PV system.
- Include a roof-mounted PV array in the PV system which is rated at between 4 and 10 kW.
- Furnish PV modules that are state-of-the-art 1979 or better, preferably of high efficiency.
- Mount the PV modules on the roof in one of three generic ways: standoff (above a standard roof), direct (replacing the shingles), or integral (replacing sheathing, felt and shingles).
- Use a power-conditioning subsystem (PCS) which converts the array dc energy to residence-compatible ac energy in parallel with the utility. The PCS must control system start-up and shut-down, and must accomplish array voltage control.
- Estimate the annual energy demands of the conceptual PV residence in the Boston area, including the heating, cooling, hot water and electric loads as well as the output of the PV system. Confirm that the gross PV system output will satisfy between 50 and 100% of the residence's annual electric demand.
- Design and construct a prototype system based upon the full-sized PV residence design; the structure should be the minimum size structure on which the full-size PV array can be mounted, and in which the remainder of the system can fit. The prototype system must duplicate as closely as possible the PV system and the roof detail of the full-size residence.

The prototype systems are each fully instrumented, and the following quantities are continuously recorded and stored on magnetic tape for subsequent analysis:

- PV array dc bus voltage
- PV array dc bus current
- PV array dc bus power
- System ac bus voltage (RMS)
- Power conditioner real ac power output
- Load real power consumption
- AC power to the utility
- AC power from the utility
- Total solar irradiance on the PV array.

1.4 The Monitored Houses

In order to characterize the electric loads that the prototype systems would have to meet, lived-in houses in communities neighboring the NE RES were chosen for monitoring. The communities considered (based on proximity to the NE RES) were Concord, Acton, Carlisle, Bedford, Lexington and Lincoln. Approximately 100 Boston Edison Company customers were sent a notice describing the Solar Photovoltaic Residential Project in which a response was requested from homeowners interested in participating in the monitoring program. Appendix A shows a sample of the letter sent to the prospective participants, and of the questionnaire to be returned by those interested in participating. From the responses, five residences were chosen for monitoring; the houses are in the communities of Concord, Lexington and Lincoln.

Obviously, the electric energy consumption for any given residence will depend critically on numerous variables: for example, the number of occupants, their energy use habits, and the mix and energy efficiency of electric appliances and equipment. In order to characterize the residential electric loads in a given geographical region accurately, it would be necessary to monitor many residences so that a credible and representative mean electric load profile could be obtained. The goal of the Residential Project is not necessarily to establish such a data base, but rather to understand the consumption of several real residences and to use that data to investigate both the effect of PV systems on a residence's electric energy consumption and the interaction between a PV residence and the utility power grid.

The quantities measured at each of the five houses include total load power, voltage, currents in each of the two 120-volt lines, and the temperature of the room in which the sensors are located.

1.5 The Meteorological Station

In order to monitor the meteorological conditions to which the prototype systems and monitored houses are exposed, instrumentation was mounted on the NE RES facility building roof to measure total horizontal irradiance, total direct normal irradiance, ultraviolet direct normal irradiance, ambient temperature, wind velocity, precipitation and ambient dew point temperature. In addition to recording data on magnetic tape, visual displays of the data are provided in the NE RES data control room.

1.6 The NE RES Data Acquisition System

All quantities at the prototypes, monitored houses and meteorological station are measured by data acquisition controllers and the information is fed (or, for the monitored houses, transmitted by telephone lines) to a data concentrator unit at the RES every five seconds. The values are accumulated and then sent every six minutes to a Hewlett Packard 9845 computer that reformats and averages the data over the six-minute interval and stores the averaged data. The six-minute data are transcribed onto a magnetic tape and also stored in core memory of a second Hewlett Packard 9845 computer. The magnetic tapes are carried from the NE RES to the Lincoln Laboratory Computer Center for processing on the Laboratory's Amdahl 470 computer. The second Hewlett Packard 9845 is used to store the six-minute data on a 24-hour revolving basis.

The magnetic tapes carry data for periods ranging from part of a day to several days. The data are brought onto the Amdahl 470 system and split and spliced into segments of 24 hours, midnight to midnight. The daily segments or "files" thus made are transcribed onto a master tape. It is anticipated that a full year of data can be accommodated on four to eight (2400 feet, 6250 bpi) tapes. Copies of all master tapes are kept for archival purposes.

The data on the master tape are used in conjunction with appropriate Fortran programs to yield all the information for daily, monthly and annual reports.

1.7 Overview of the Following Sections

The following Section 2.0 contains a description of the five prototype systems at the NE RES. Sections 3.0 to 5.0 contain findings and results of the engineering evaluation of the systems at the NE RES over the period November 1980 through May 1982. Section 6.0 contains the processed load data from the five monitored houses. Section 7.0 contains a summary of the meteorological station data. Section 8.0 projects system performance through simulation for cities in the northeastern region of the country. Section 9.0 summarizes the PV systems' cost and worth. Finally, the report concludes in Section 10.0 with a catalog of insights and lessons learned during the system test activity.

2.0 PHOTOVOLTAIC SYSTEM CHARACTERIZATION

The five prototype systems at the NE RES present a diversity of PV modules, array sizes/powers, array roof-mounting techniques, array electrical configurations, and inverters. Table 2 lists the general system features. Section 2.1 presents both mechanical (physical) and electrical design specifications, and Section 2.2 presents the performance characterization data for each system. A more complete treatment of the design and fabrication details for each prototype system is contained in the individual system suppliers' final reports (21-24). Section 2.3 details the characteristics of the five monitored houses from an electrical load viewpoint.

2.1 Prototype System Mechanical/Electrical Design Specifications

The physical characteristics of the five systems are described in the following sections.

TABLE 2

PROTOTYPE SYSTEMS: PHYSICAL FEATURES

System Supplier	PV Module Manuf.	PV Array* Area(m^2)	PV Array Peak Rated Power(kW)	Array Tilt Angle(Deg)	Array Mounting Method	Power Manuf.	Conditioner Rating(kW)
General Electric	General Electric	76.8	6.6	33.7	Direct	Abacus	6(AC)
MIT Lincoln Lab	Solarex	84.9	6.8	45.	Standoff	Windworks	8(DC)
Solarex	Solarex	68.4	5.0	40.	Standoff	Abacus	6(AC)
TriSolar Corp	Applied Solar Energy Corp.	47.2	4.8	45.	Integral	Windworks	8(DC)
Westinghouse Electric	Arco Solar	69.2	5.1	45.	Integral	Abacus	6(AC)

*Area of active modules only.

2.1.1 General Electric Prototype System

Figure 3 shows the General Electric (GE) prototype system along with a model of the conceptual full-size residence from which the prototype was derived. The system became operational in May 1981 and was officially accepted in June 1981. It uses a GE hexagonal shingle PV module and an Abacus inverter. A block diagram of the system is shown in Fig. 4.

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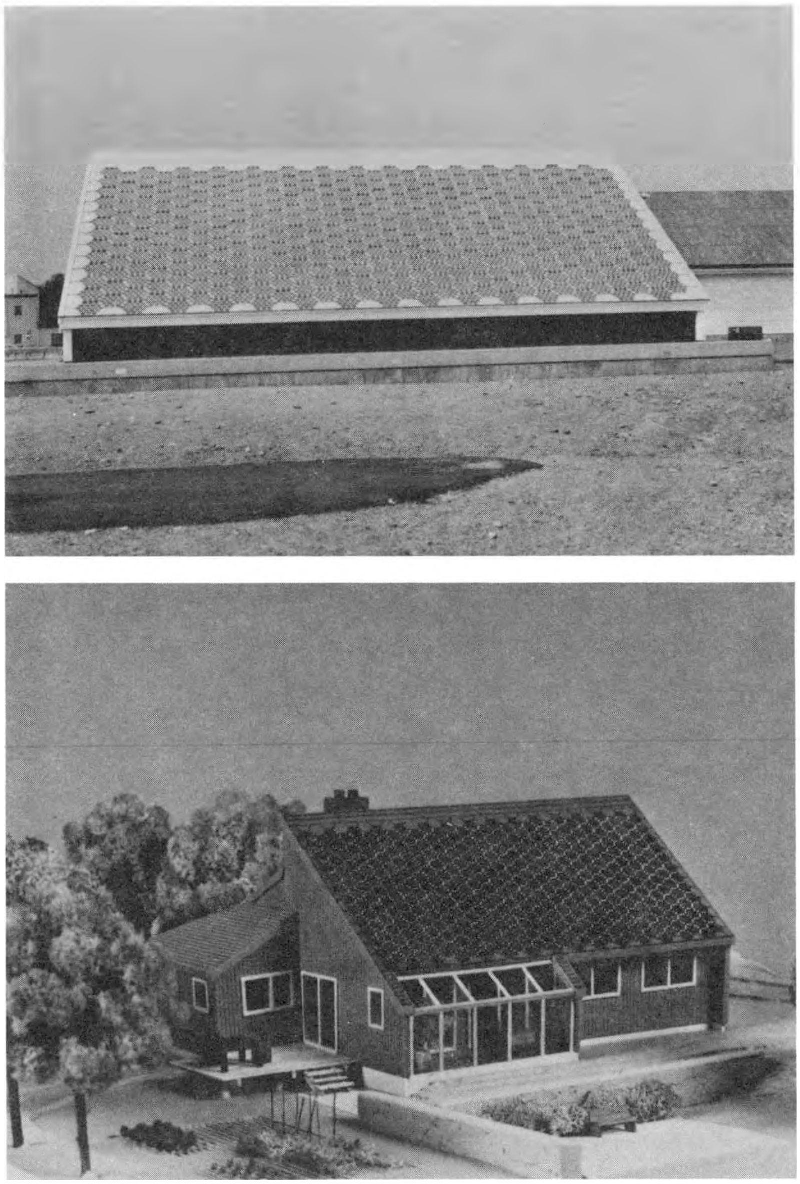

Fig. 3. The General Electric prototype system at the NE RES (top), and model of the conceptual PV residence (bottom).

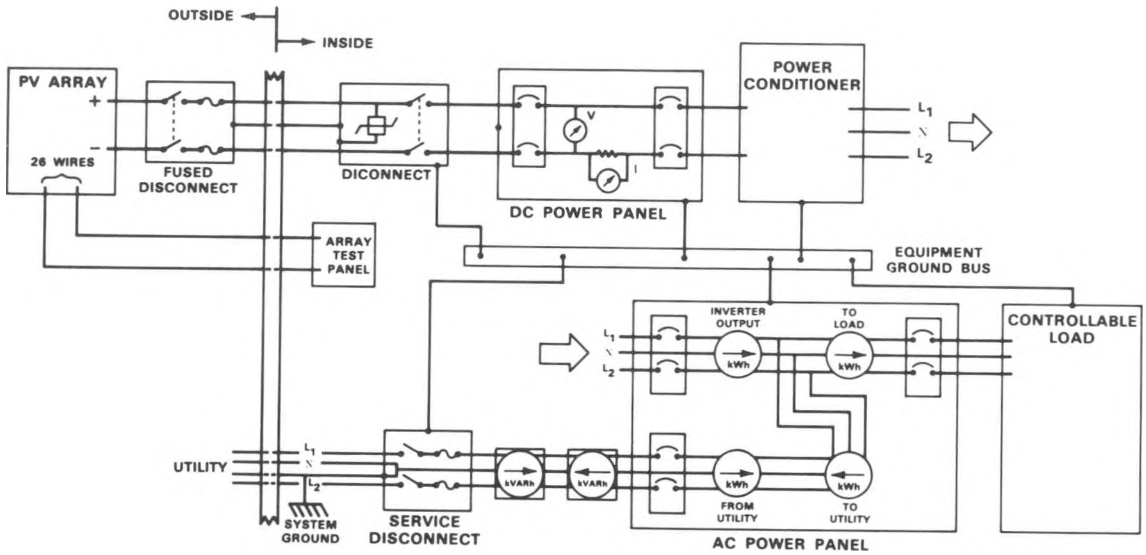

Fig. 4. General Electric PV system block diagram.

Three hundred seventy-five shingle modules are used in the GE PV array. Each module contains nineteen 100-mm-diameter solar cells. The electrical configurations of the shingle module and of the entire PV array are shown in Fig. 5. The dimensions of the smallest rectangle which encloses all the solar cells for this array is 12.47 m by 6.16 m; the gross array area is 76.8 m^2. The ratio of solar cell area to gross array area is 0.73. The shingle modules are directly mounted to the felt-covered roof sheathing in this prototype system. Figure 6 shows the array during construction.

The Abacus inverter in this prototype is shown in Fig. 7.

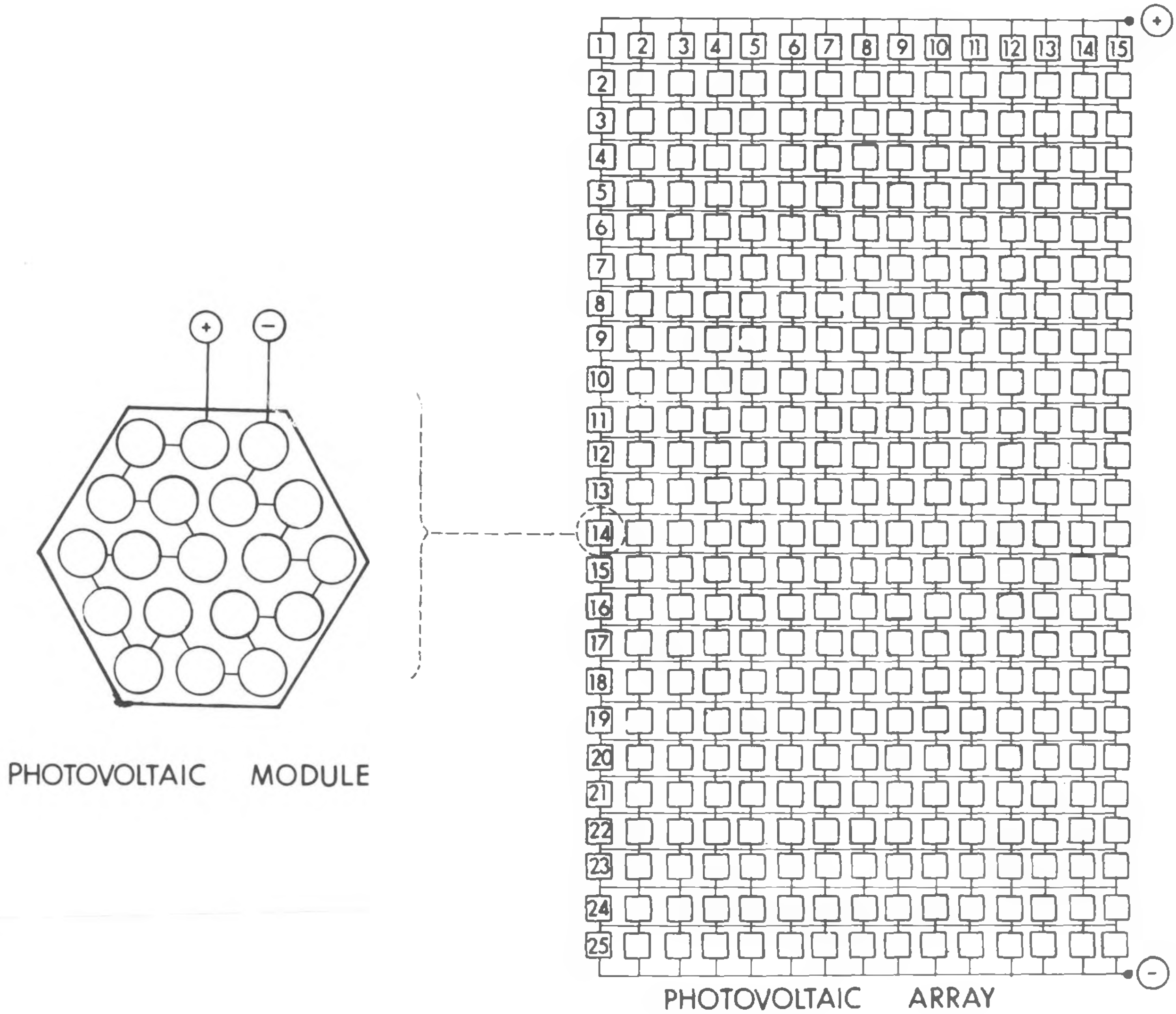

Fig. 5. Diagram of the General Electric shingle PV module and PV array on the GE prototype.

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Fig. 6. General Electric shingle PV modules being mounted on the GE prototype.

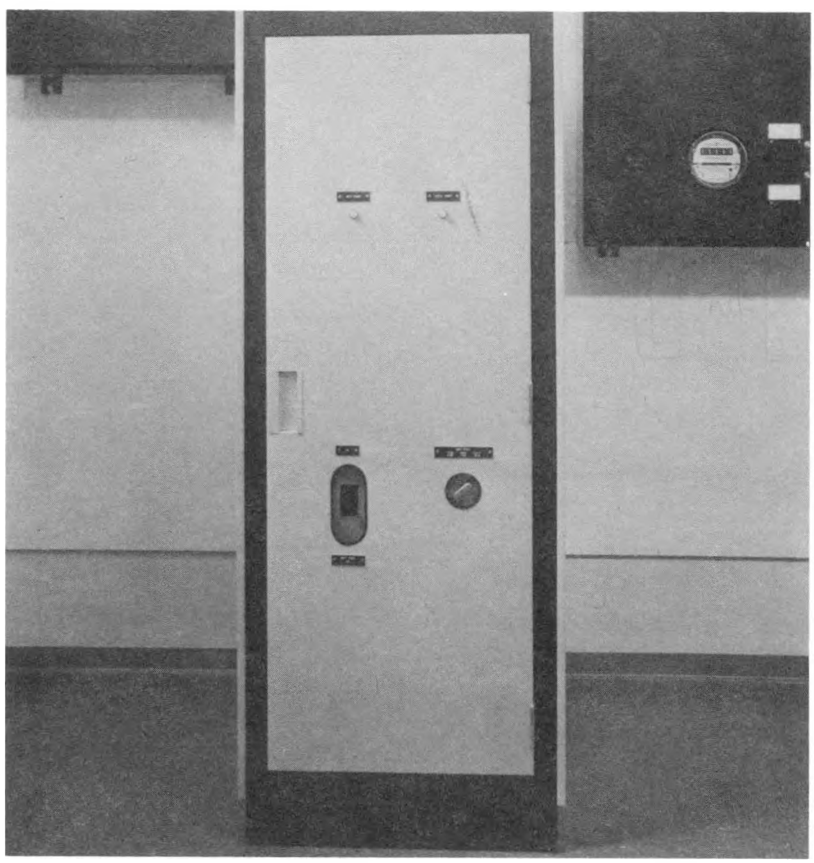

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Fig. 7. The Abacus inverter used in the General Electric PV system.

2.1.2 MIT Lincoln Laboratory Prototype System

Unlike the other four prototype systems at the NE RES, the full-size residence design upon which the MIT LL prototype system is based was actually constructed. This residence, known as the Carlisle House, is fully operational with a PV system nearly identical to that in the MIT LL prototype. The house is located in Carlisle, Massachusetts, and is now privately owned. A full report on this project is contained in Reference 25. The MIT LL prototype and a rendering of the Carlisle House are shown together in Fig. 8.

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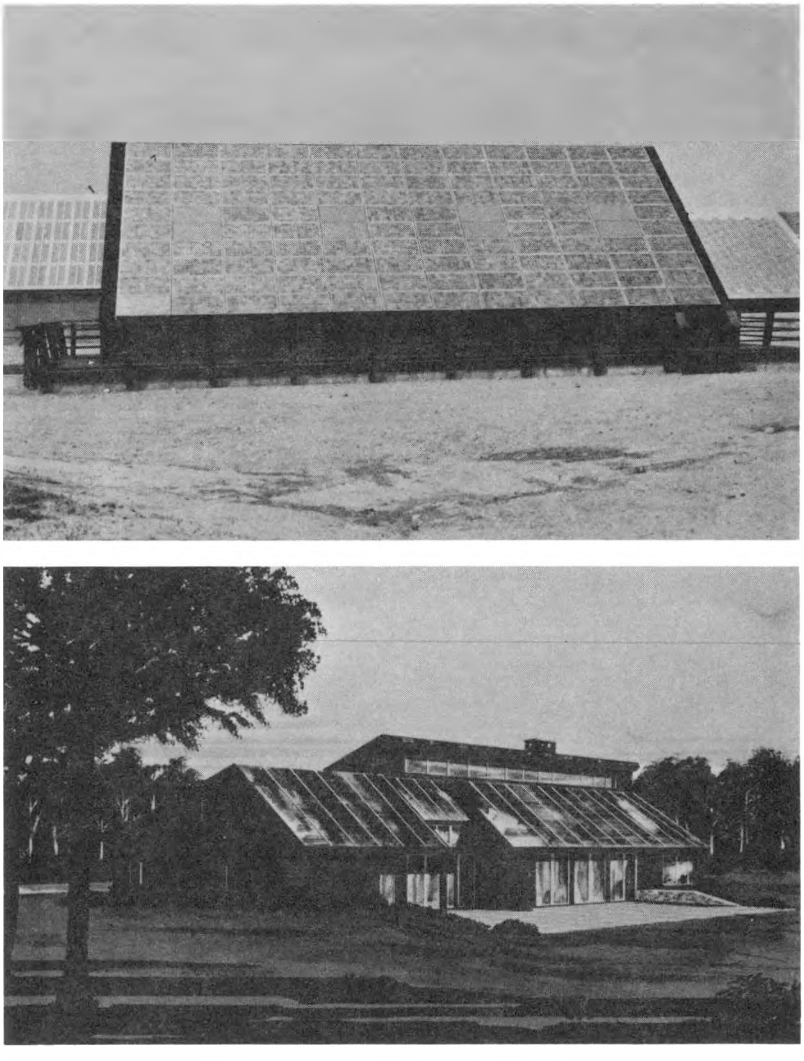

Fig. 8. The MIT LL prototype system at the NE RES (top) and rendering of the Carlisle PV house (bottom).

The MIT LL prototype was the first to become operational at the NE RES; initial system turn-on occurred in November 1980. Solarex Corporation PV modules, purchased through a competitive procurement, are used on both the prototype and Carlisle House. The power conditioner is a Gemini^R model manufactured by Windworks, Inc. A system block diagram is shown in Fig. 9.

The PV array consists of 120 Solarex modules stand-off mounted over a roof of typical construction--sheathing, paper and rolled roofing shingles.

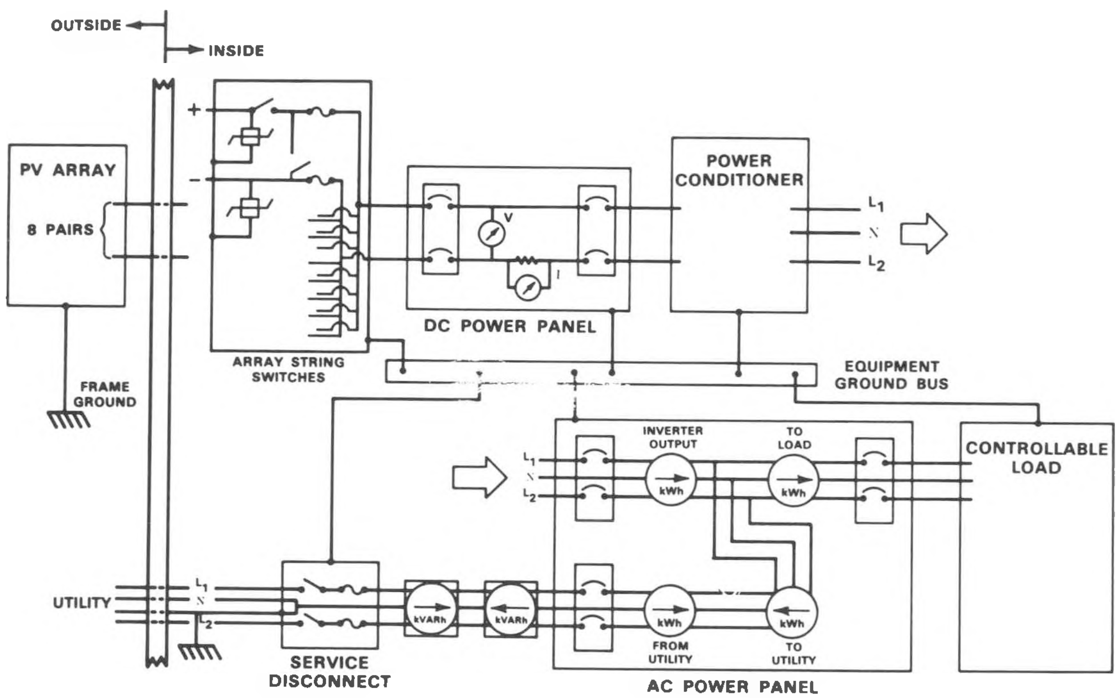

Fig. 9. MIT LL PV system block diagram.

Each module consists of 72 square polycrystalline cells, 9.4 cm x 9.4 cm. The electrical configurations of the modules and the PV array, which uses only 112 of the modules, are shown in the block diagram of Fig. 10. The PV array area, defined as the area of the smallest rectangle which encloses all the PV cells, is 14.28 m by 6.38 m, or 91.0 m^2. The net PV cell packing density, i.e., the fraction of the PV array area which is covered by the solar cells, is 0.84.

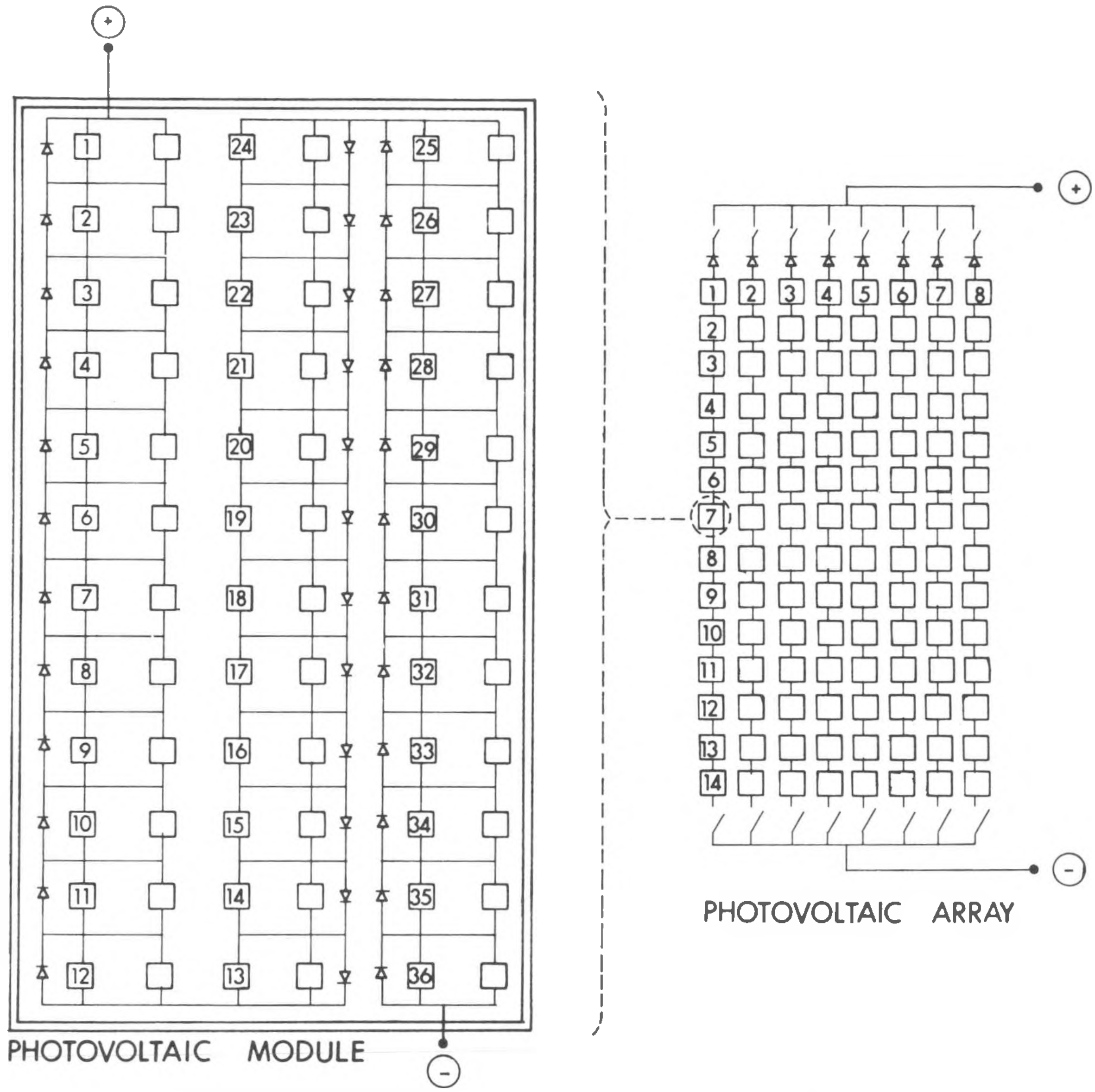

Fig. 10. Diagram of the Solarex PV module and array on the MIT LL prototype.

The stand-off mounting system used in the MIT LL prototype was designed so that the PV modules could be easily removed for inspection or replacement. Tracks are bolted to the roof running from the soffit to the ridge. Ten PV modules in each column are bolted together with wheeled brackets, and the entire assembly is rolled up the roof slope into position. Figure 11 shows modules being mounted at the Carlisle House. The Gemini inverter is shown in Fig. 12.

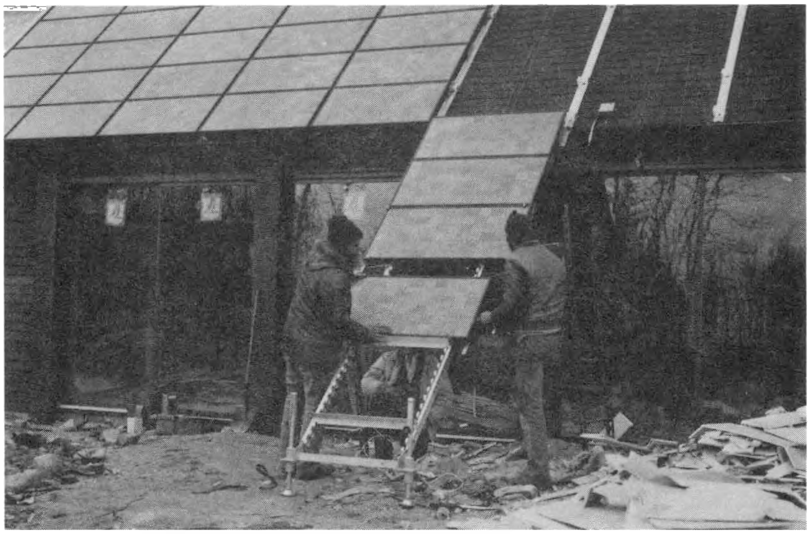

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Fig. 11. Solarex PV modules being mounted on the Carlisle house.

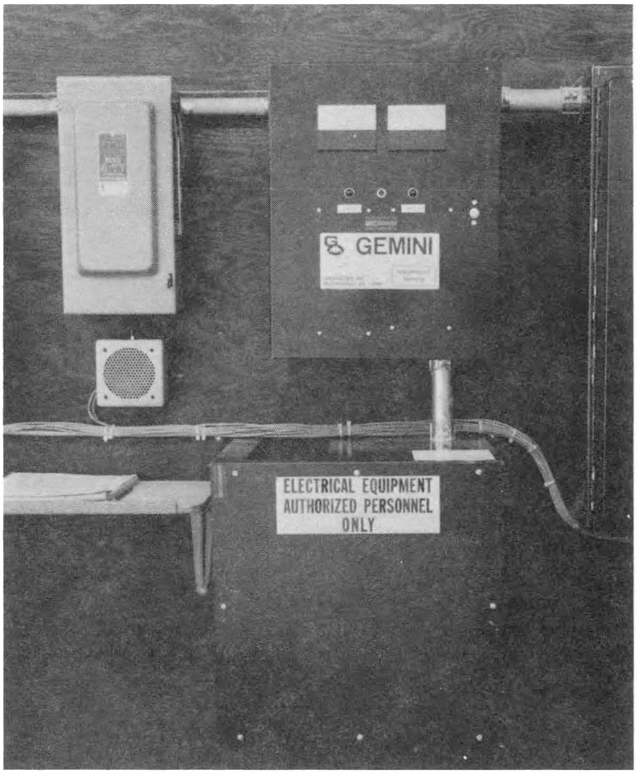

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Fig. 12. The Windworks Gemini inverter used in the MIT LL PV system.

2.1.3 Solarex Prototype System

The Solarex prototope system and corresponding conceptual PV residence are shown in Fig. 13.

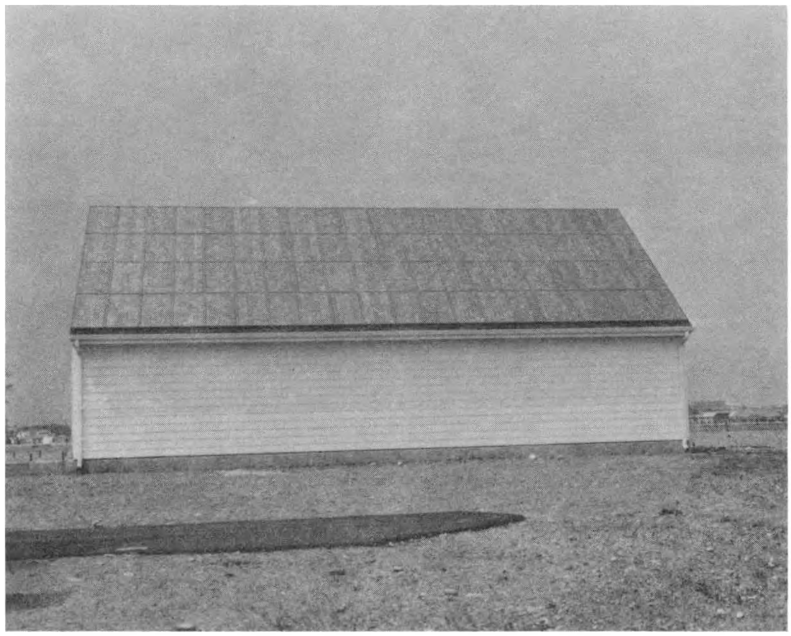

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Fig. 13. The Solarex prototype system at the NE RES (top) and rendering of the conceptual PV residence (bottom).

The system was first operated during the month of July 1981, and official acceptance was granted in February 1982. Solarex PV modules and an Abacus inverter are used in the system; a block diagram is shown in Fig. 14.

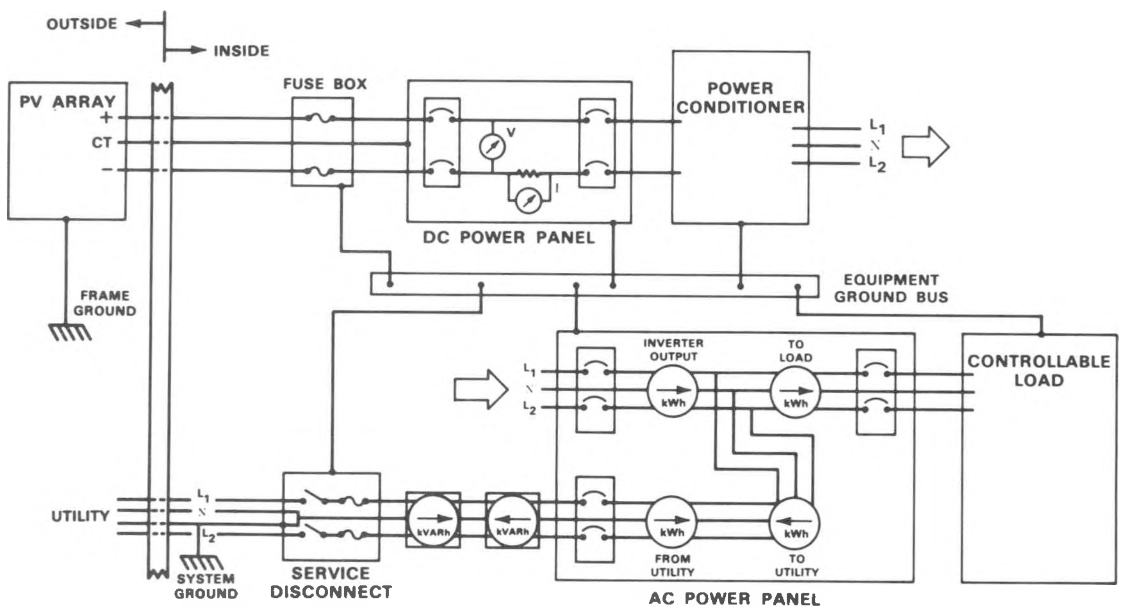

Fig. 14. Solarex PV system block diagram.

Eighty Solarex PV modules are stand-off mounted on the roof of the prototype structure; 78 modules are electrically connected in the PV array. A module contains 72 polycrystalline solar cells, each 10 cm by 10 cm. A block diagram of the module and PV array electrical configurations is shown in Fig. 15. The PV array area, as defined earlier, is 13.53 m by 5.18 m, or 70.1 m^2. The packing factor of this array is 0.82; i.e., 82% of the array area is actual PV cell area.

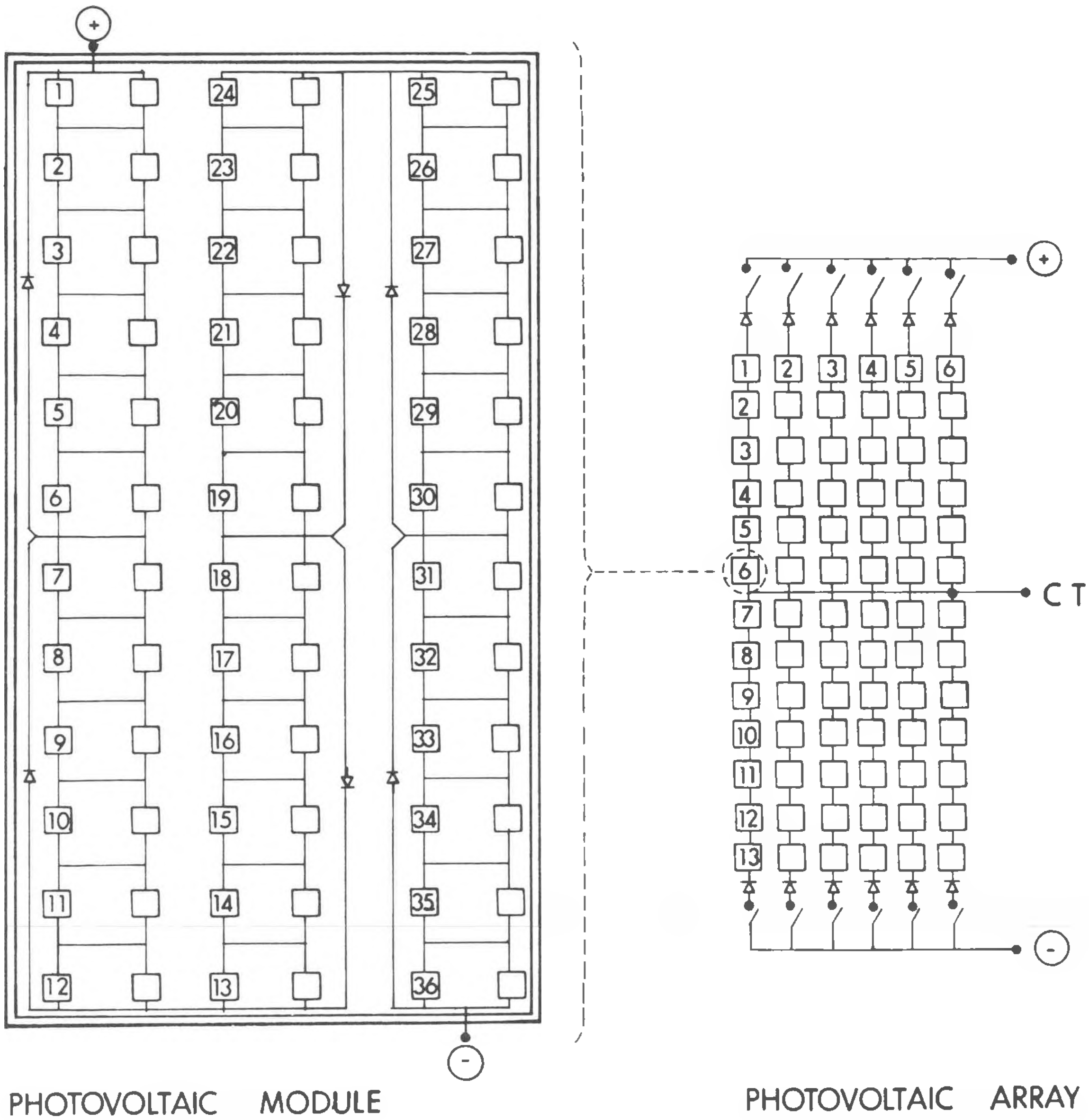

Fig. 15. Diagram of the Solarex PV module and array on the Solarex prototype.

The PV modules are mounted on Unistrut[R] channels, running both east-west and ridge-to-soffit, which are bolted to the roof. A firmly fitted cap strip secures adjacent modules to the channels. Figure 16 shows the array during construction.

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Fig. 16. Solarex PV modules being mounted on the Solarex prototype.

2.1.4 TriSolarCorp Prototype System

In December 1980, the TriSolarCorp prototype system became operational and was officially accepted. The residence and prototype are shown in Fig. 17. Applied Solar Energy Corporation (ASEC) modules and a Gemini inverter are used in the PV system. Figure 18 shows a block diagram of the system.

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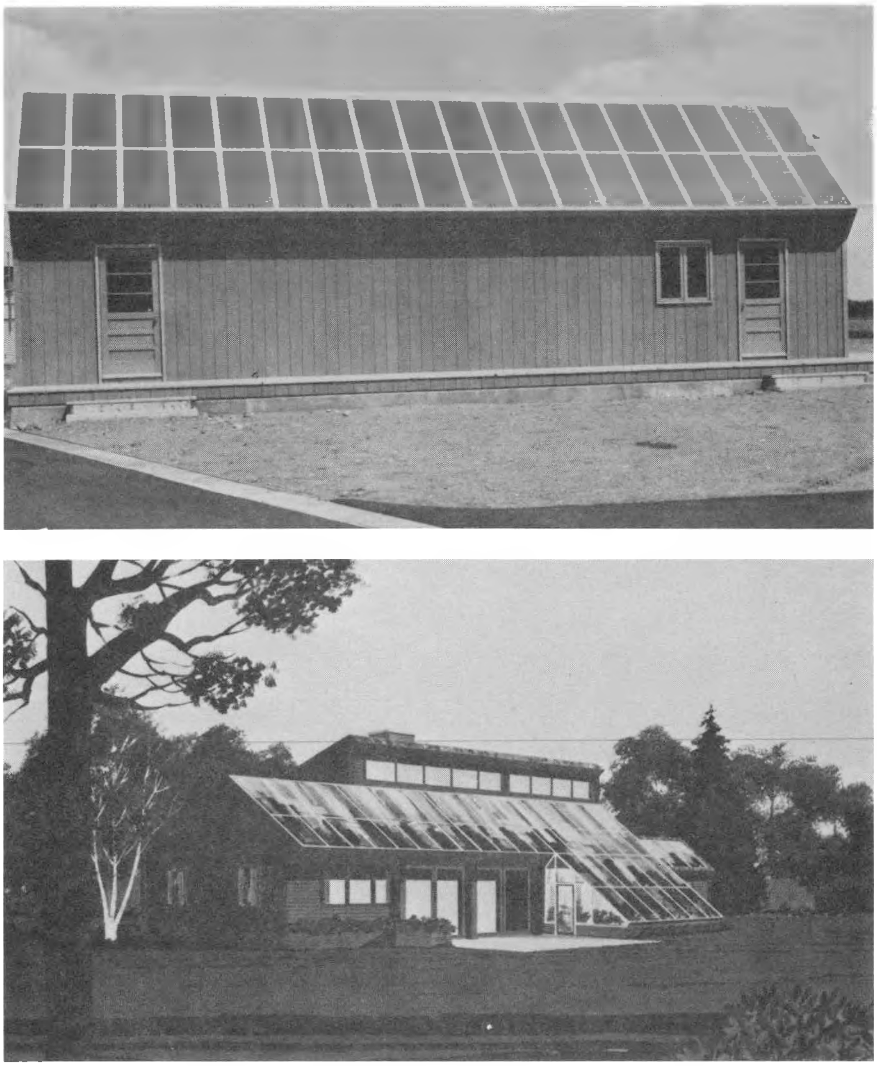

Fig. 17. The TriSolarCorp prototype system at the NE RES (top) and rendering of the conceptual PV residence (bottom).

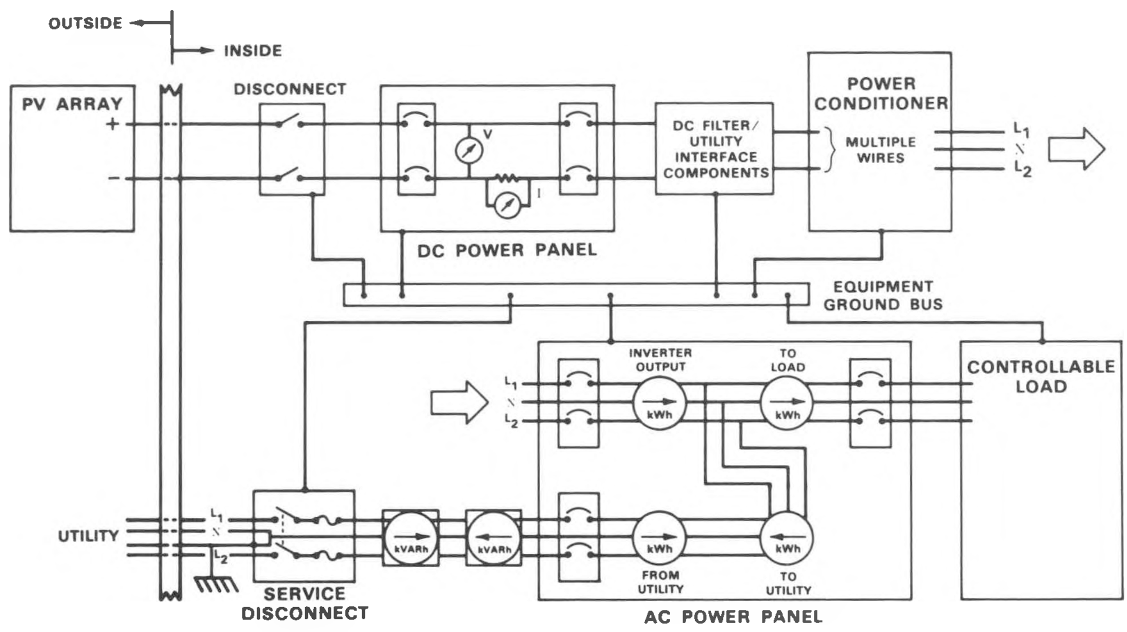

Fig. 18. TriSolarCorp PV system block diagram.

Thirty-six ASEC modules are integrally mounted on the structure's roof, replacing the plywood sheathing, felt, and shingles of a traditional roof. The ASEC modules, developed specially for this project, contain 253 square solar cells, each 6.43 cm by 6.43 cm. The electrical configurations of the module and PV array are shown in Fig. 19. The dimensions of the PV array are 14.62 m by 3.23 m, resulting in an array area of 47.2 m^2. The ratio of solar cell area to array area is 0.80.

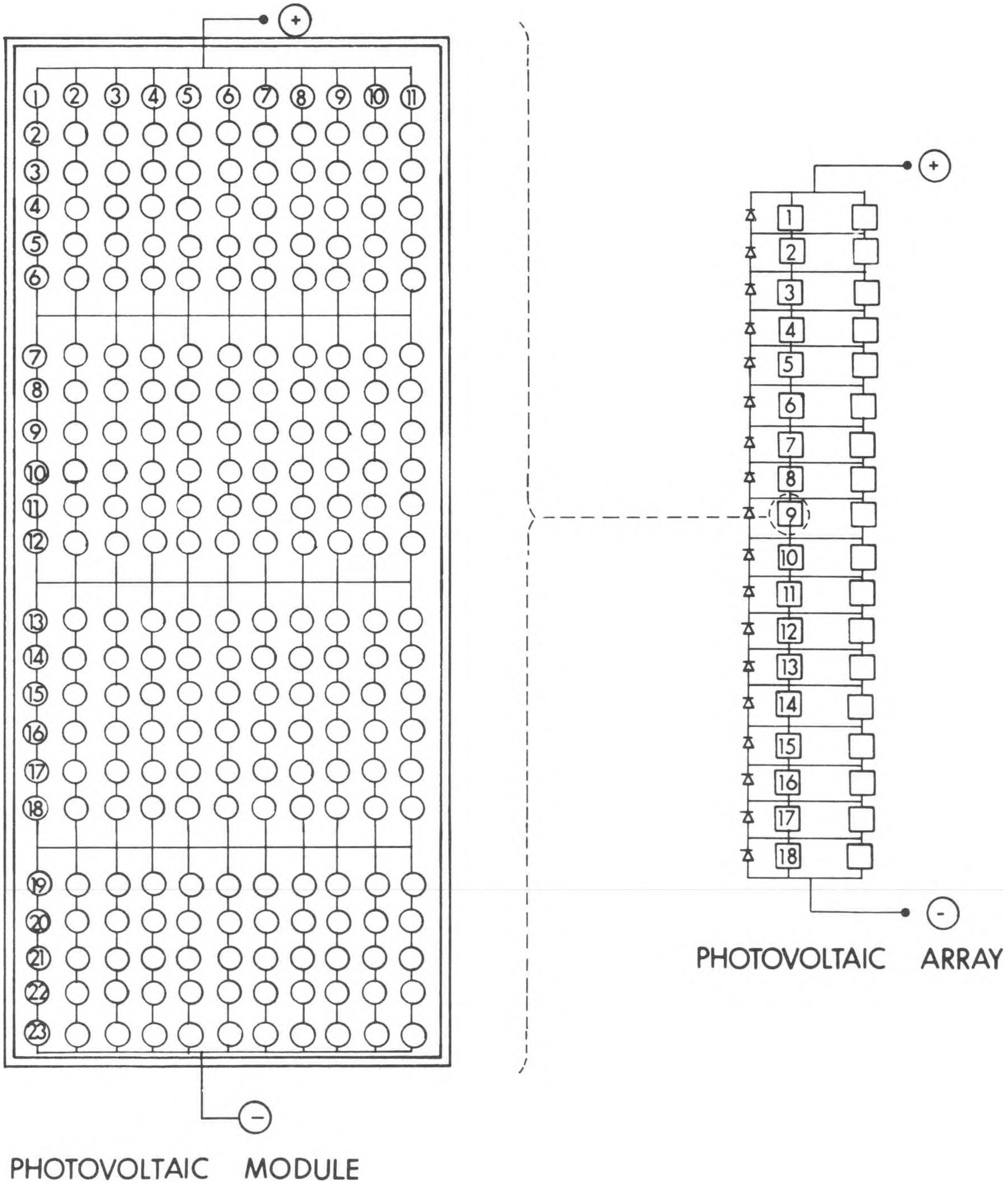

Fig. 19. Diagram of the ASEC PV module and array on the TriSolarCorp prototype.

The integrally mounted modules are shown in Fig. 20, photographed during construction of the prototype. The modules are, in effect, glazed into the roof. The attic space immediately behind the array is ventilated by a thermostatically controlled fan.

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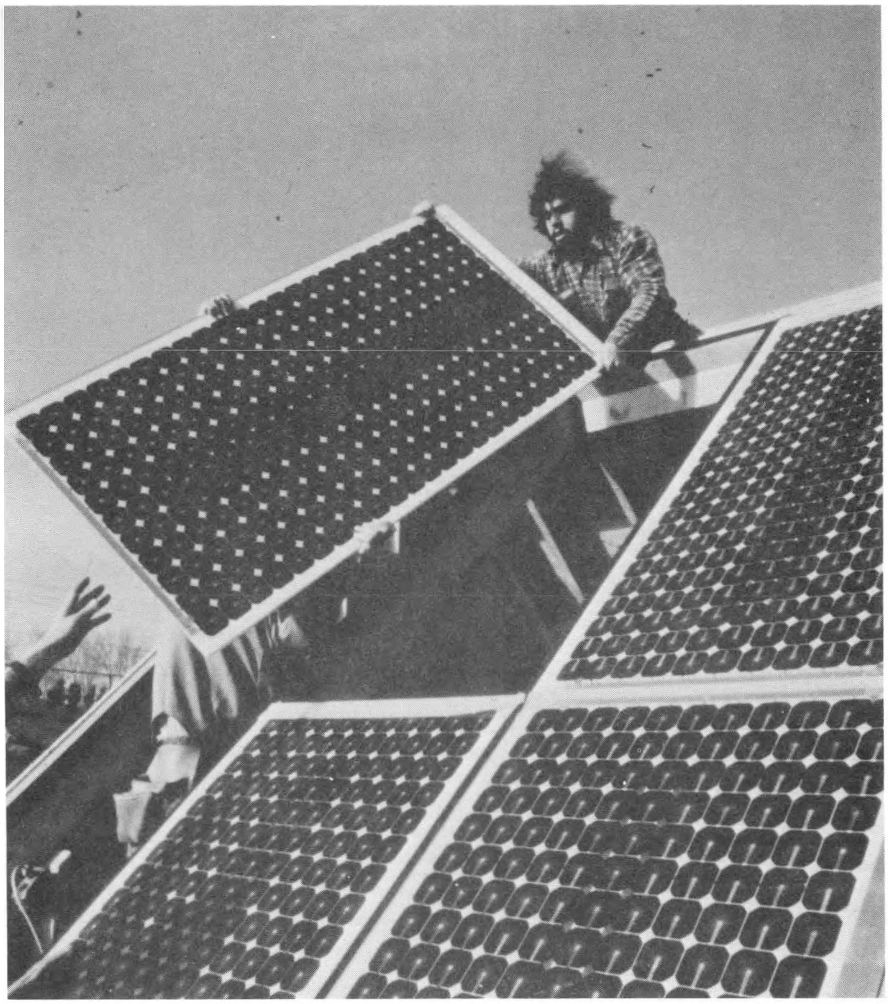

Fig. 20. ASEC PV modules being mounted on the TriSolarCorp prototype.

2.1.5 Westinghouse Prototype System

First turn-on and acceptance of the Westinghouse prototype system were accomplished in February 1981. Figure 21 shows both the prototype and the conceptual residence design. The modules used in this system were manufactured by Arco Solar; the power conditioner by Abacus Controls. A block diagram of the PV system is shown in Fig. 22.

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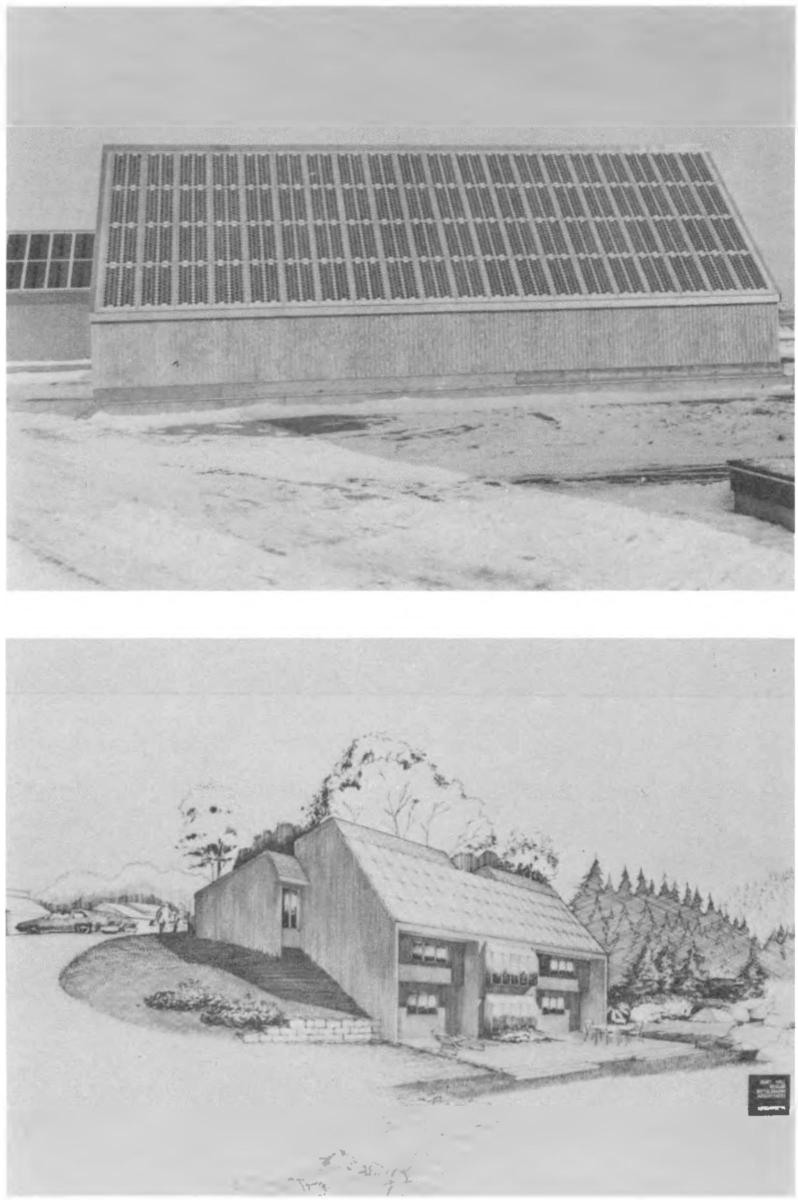

Fig. 21. The Westinghouse prototype system at the NE RES (top) and rendering of the conceptual PV residence (bottom).

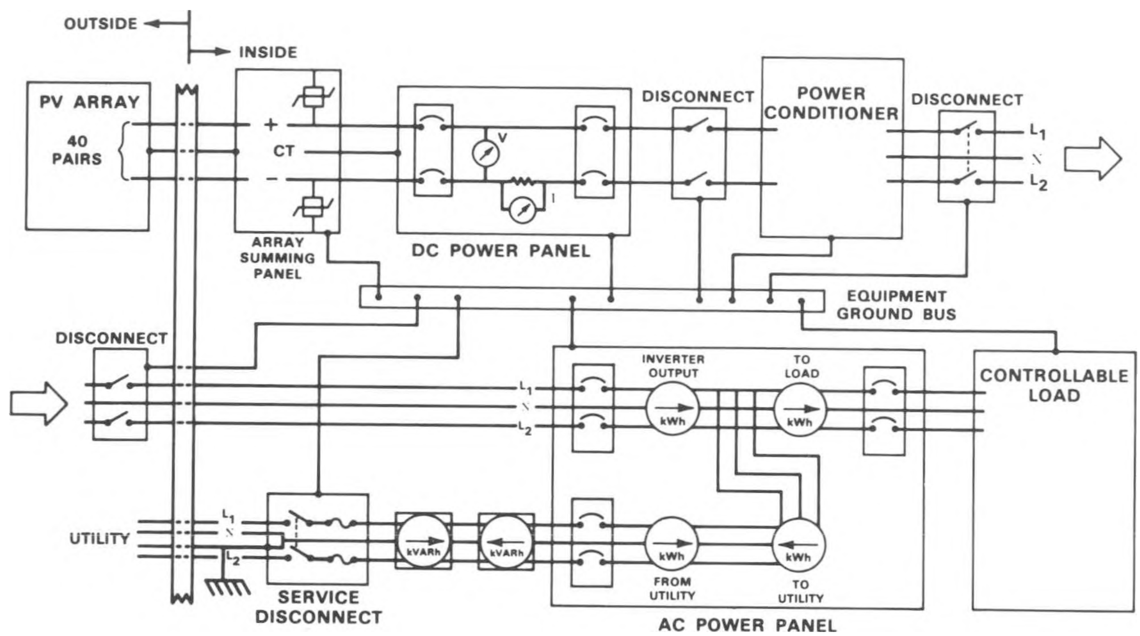

Fig. 22. Westinghouse PV system block diagram.

One hundred sixty modules are integrally roof-mounted in the Westinghouse prototype; of these, 156 are wired into the PV system. Before delivery to the site, pairs of modules were framed to form "doublets," and four doublets (eight modules) were placed in a larger frame. These eight-to-a-frame units, the building blocks of the PV array, fit between adjacent roof rafters. A one-inch air gap immediately behind the PV modules is backed by a cathedral-style ceiling.

The electrical configuration of the Arco Solar module and the PV array is shown in Figure 23.

Each module contains 35 circular solar cells, 10.4 cm in diameter. The dimensions of the array are 14.12 m by 5.03 m, for a PV array area of 71.0 m^2. The solar cells occupy 67.0% of the array area.

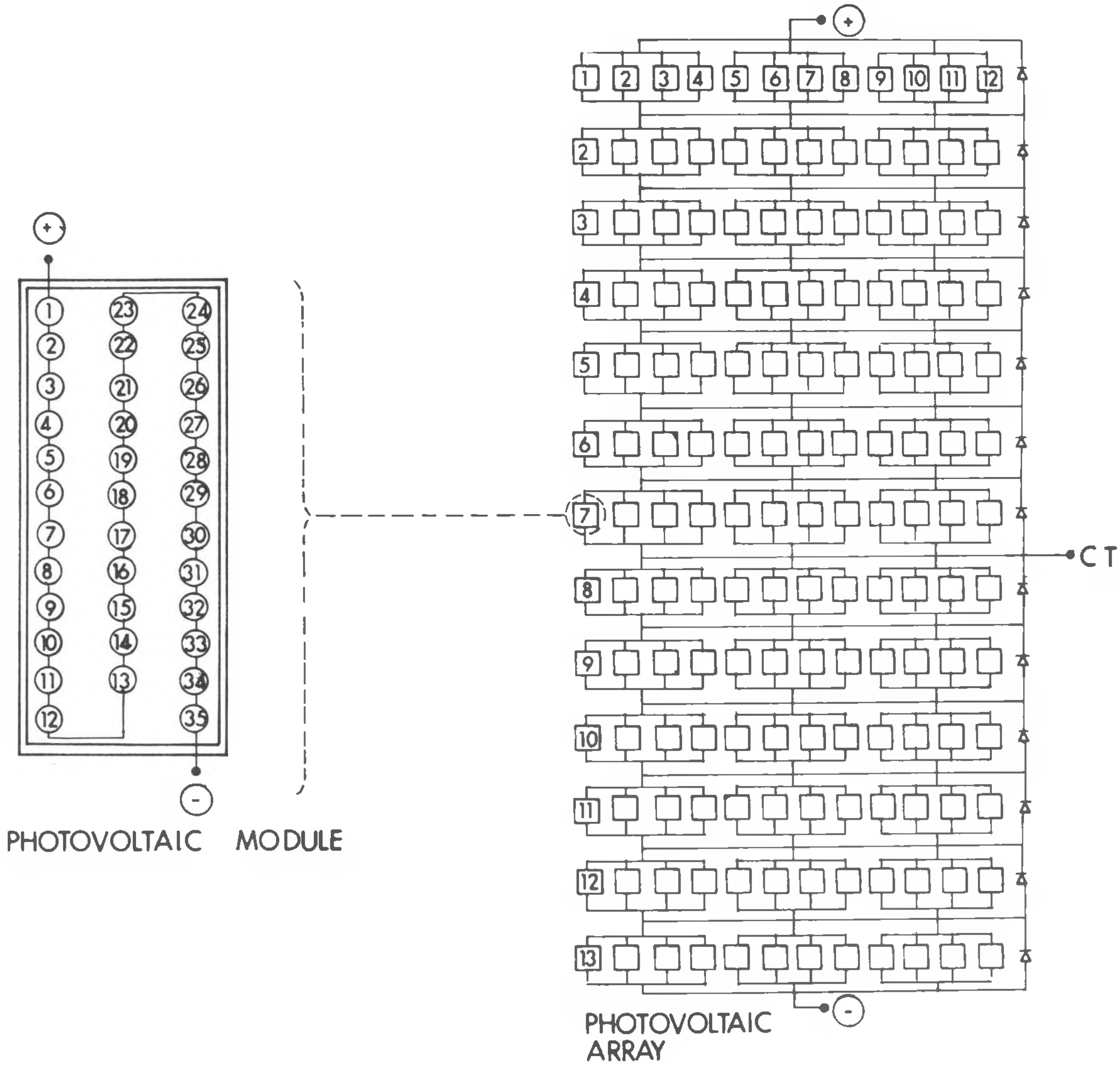

Fig. 23. Diagram of the ARCO PV module and array on the Westinghouse prototype.

2.2 Prototype System Performance Characteristics

Initial measurements were made on each of the PV systems in order to verify their operability, and also to allow for accurate determination of the system and component performance ratings.

The methods and procedures for rating PV systems remain a subject for discussion. Various codes and standards groups are, at the time of this writing, addressing the PV system rating issue in an attempt to establish standardized test and measurement procedures; the NE RES project has made significant contributions to these efforts. Appendix B of this report contains the measurement and analysis procedures underlying the performance characterization data presented below for the PV array, power conditioning system and PV system as a whole.

2.2.1 Photovoltaic Array Characterization

At the heart of the PV array characterization is the PV array current-voltage (I-V) curve. Sample curves for each of the five prototype systems are shown in Figs. 24-28. Note in the figures that the ambient temperature, average PV cell temperature and solar irradiance are recorded at the time of the I-V measurements. The MIT LL-developed I-V data measuring system used to generate these plots analyzes the raw data and prints additional pertinent parameters on each curve: open-circuit voltage, short-circuit current, maximum power, and maximum-power-point voltage and current. The I-V curve tracer and its performance are described in References 26 and 27.

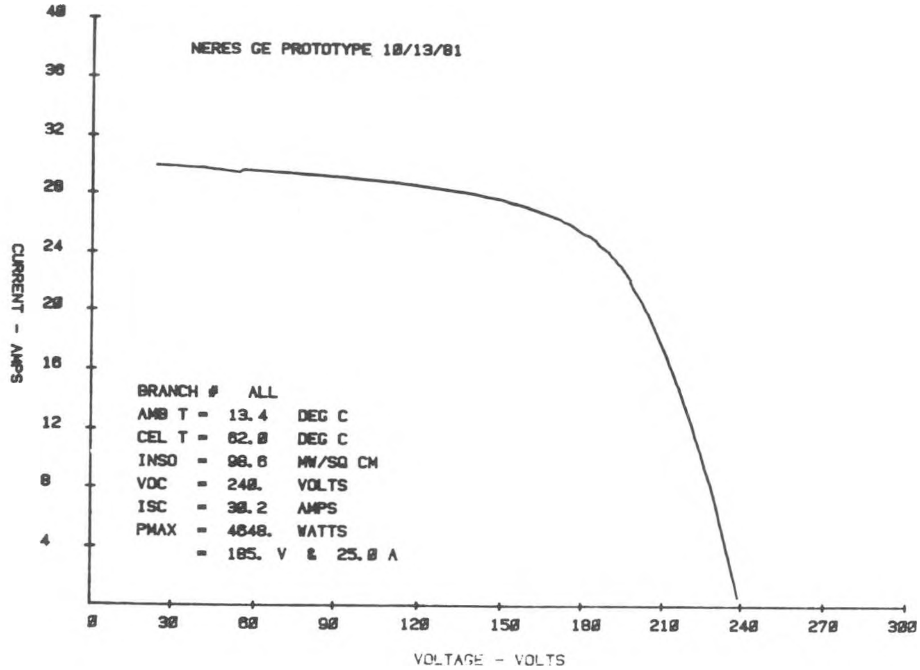

Fig. 24. I-V curve of the General Electric PV array (GE PV modules).

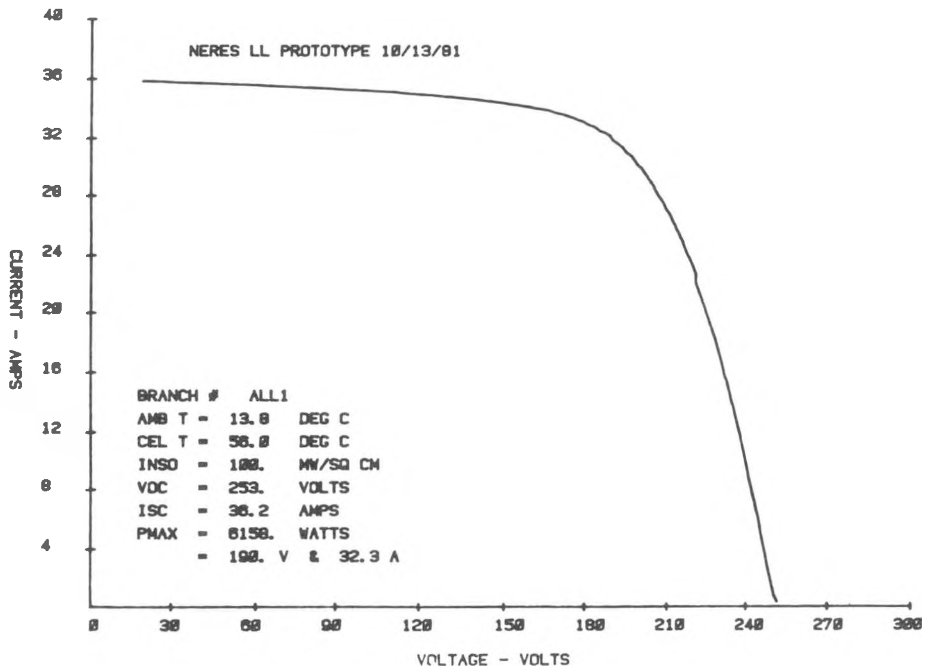

Fig. 25. I-V curve of the MIT LL PV array (Solarex PV modules).

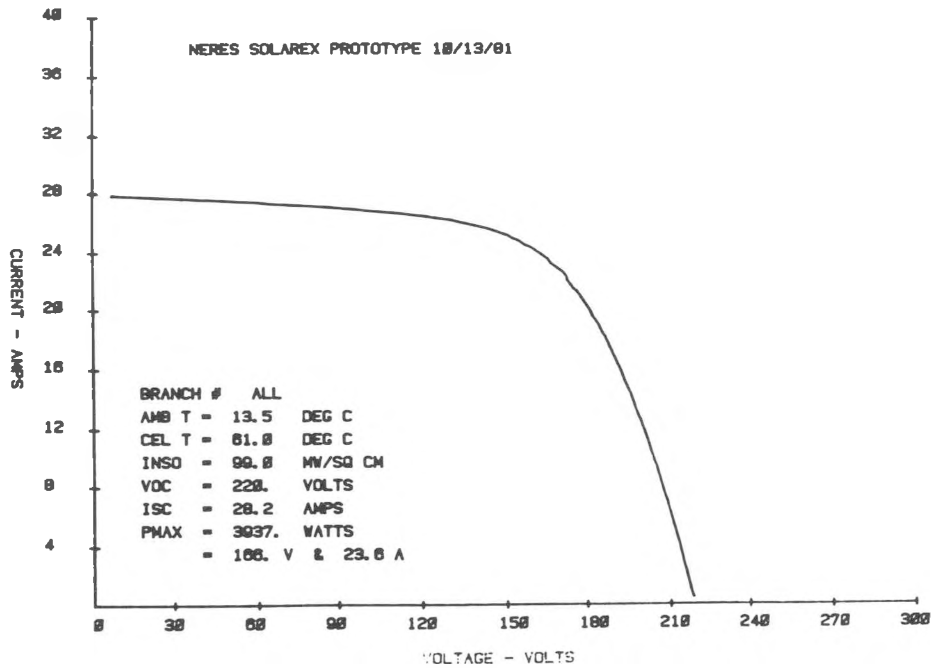

Fig. 26. I-V curve of the Solarex PV array (Solarex PV modules).

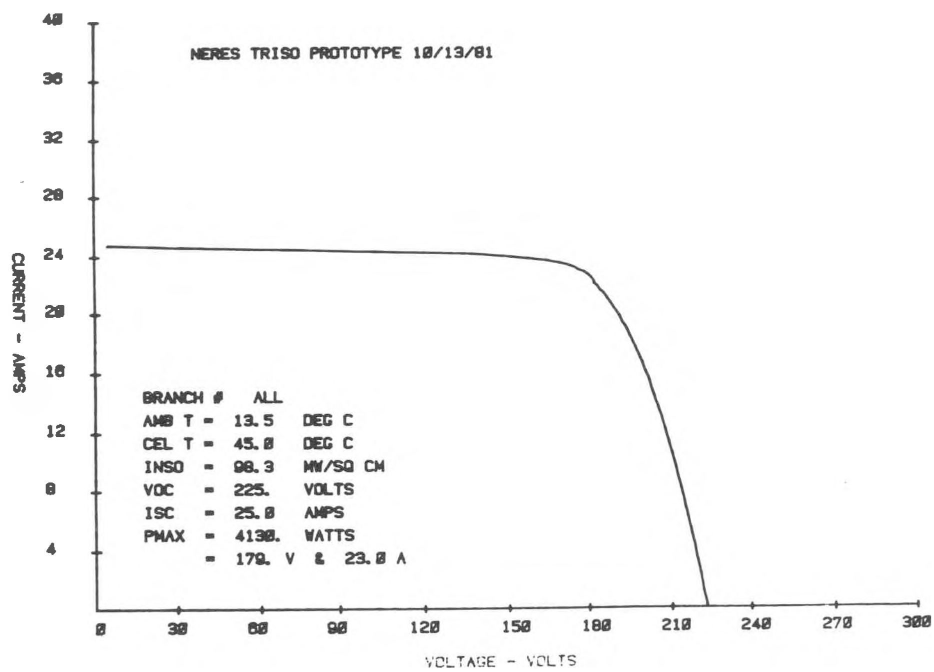

Fig. 27. I-V curve of the TriSolarCorp PV array (ASEC modules).

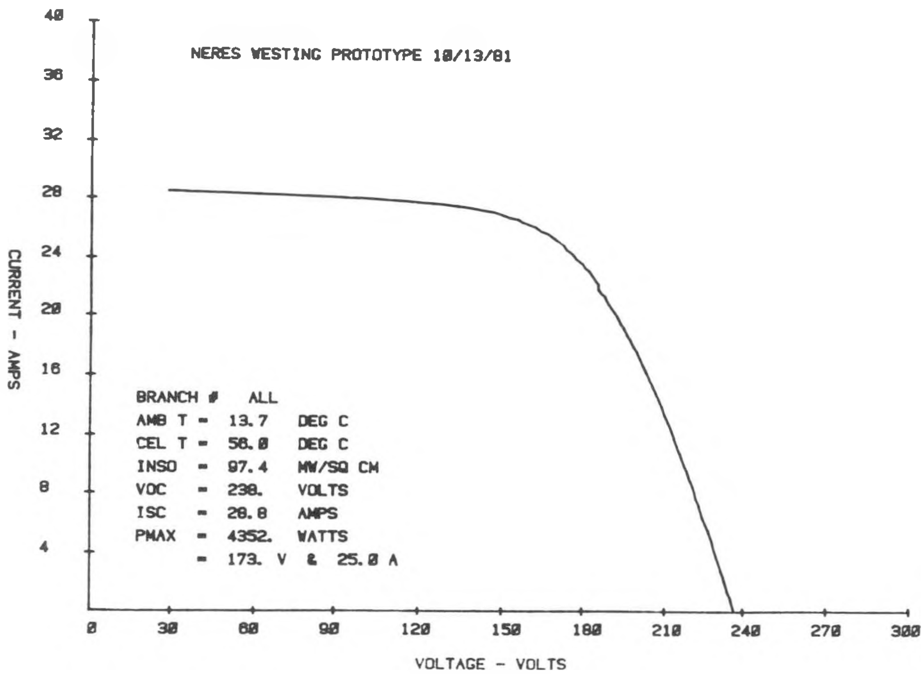

Fig. 28. I-V curve of the Westinghouse PV array (ARCO PV modules).

As described in Appendix B, additional I-V curves, measured at a variety of meteorological conditions, allow the array current and voltage temperature dependence to be determined, as well as the array series resistance. These data are array constants, which can be used to translate the reference array I-V curve to any other set of meteorological or operating conditions.

Table 3 lists the constants and reference I-V curve data for each of the five prototype systems and PV arrays. It should be noted that there are fundamental limitations to the accuracy of translating whole-array I-V curves to a new set of meteorological conditions. Among the major contributors to measurement uncertainty is the pyranometer. Pyranometers are broadband absorbers and, as such, are most appropriate for use as irradiance references in solar thermal systems. A PV device, however, has a response which is more dependent upon the spectral distribution of the irradiance; consequently, the irradiance indicated by the pyranometer may not be the effective irradiance as seen by the PV device. Ideally, a calibrated solar cell identical to the PV system under test would be used to monitor solar irradiance, but these "reference cells" are not readily available. In all cases at the NE RES, pyranometers have been used for measuring solar irradiance. Errors of up to ± 5% can be expected from any one reading of a pyranometer vis-à-vis a PV reference cell. Averaged over a large number of readings, however, this error may be reduced slightly. See Reference 28 for more on this subject.

TABLE 3
PHOTOVOLTAIC ARRAY CHARACTERISTICS

PV Array Reference I-V Data*								Constants		
Prototype System Supplier	Open Circuit Voltage (V)	Short Circuit Current (A)	Maximum Power (kW)	Max-Power Voltage (V)	Max-Power Current (A)	Solar Irradiance (kW/m^2)	PV Cell Temp. (°C)	α (A/°C)	β (V/°C)	Rs (Ω)
General Electric	267	35.5	6.2	211	29.5	1.05	42.4	.0105	1.24	1.44
MIT Lincoln Laboratory	265	35.3	6.4	205	31.2	.973	33.8	.036	1.198	1.34
Solarex	253	30.6	5.1	194	26.4	1.04	30.4	.027	1.11	1.6
TriSolar Corp	234	21.7	3.8	190	19.9	0.82	38	.0128	1.08	1.28
Westinghouse	245	28.5	4.5	178	25.5	1.01	50	.0154	1.02	1.93

*Note: All data based on measurements; systems were measured under different insolation and temperature conditions.

A second uncertainty associated with I-V curve measurements is that the optical transmissivity and absorptivity of the module surfaces and module constituents vary with time due to soiling of the surface and aging of some of the organic pottants. Thus, I-V curves measured before and after array washing will be different; similarly, I-V curve measurements made after washing but spaced over several months may also be different.

A third uncertainty associated with I-V curve measurements is determination of the average PV array operating temperature, or PV cell temperature. At the NE RES, four temperature sensors are located in each PV array, and an average temperature is computed from the four sensors. This is done in order to average out the temperature gradients which are present in the PV arrays. However, in the presence of large temperature gradients (up to 20°C variation over the array), four sensors are probably not adequate to obtain a representative average cell temperature. Figure 29 shows, as an example, the temperature indicated by each of the four sensors on the TriSolarCorp PV array for one day. Such large gradients are not common, but some uncertainty will always exist when only four temperature sensors are used.

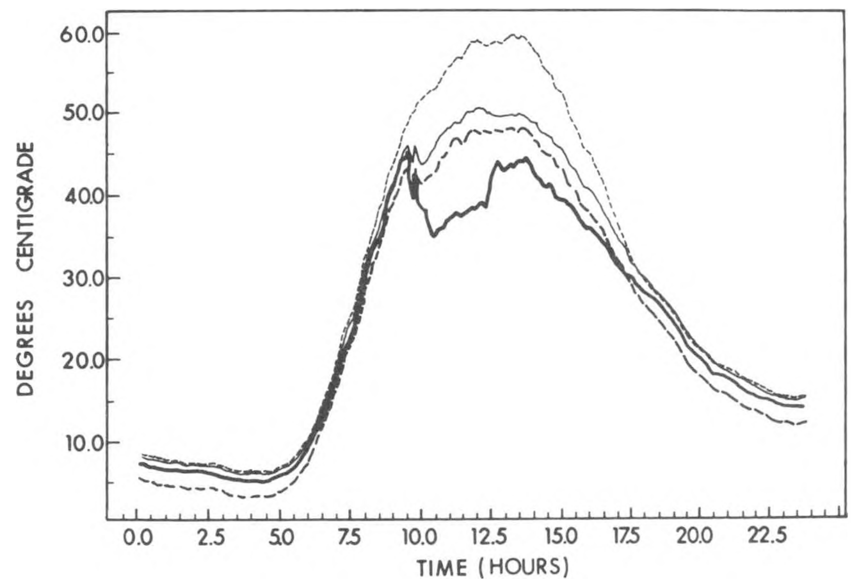

Fig. 29. Output of the four temperature sensors on the TriSolarCorp PV array for one day.

An additional area of concern is the precise positioning of the PV cell temperature measurement. Sensors mounted on the back side of the module may be indicating a temperature up to 5° or 10°C cooler than the actual PV cell temperature (see, for example, Reference 29). Sensors implanted in the module laminate, directly beneath the PV cell, are preferred. Both types of sensors are present in the NE RES prototype systems.

Such realities make PV array characterization challenging and difficult. The data reported here are as accurate as possible, given the aforementioned limitations.

Once credible I-V data have been obtained for the PV array, they may be used to translate the I-V curve to any other set of irradiance/cell temperature conditions. There are two sets of conditions which are most often used for reporting PV module or array performance: peak rating conditions and nominal rating conditions. These are defined as follows:

- Peak Rating Conditions
    1. Total irradiance on module/array surface = 1000 W/m^2
    2. Air mass 1.5 spectrum
    3. Cell temperature = 25°C
- Nominal Rating Conditions
    1. Irradiance on array surface = 1000 W/m^2
    2. Air mass 1.5 spectrum
    3. Cell temperature = NOCT

       The nominal operating cell temperature, NOCT, is defined as the average solar cell junction temperature for a module or array of modules installed in their working environment and operating under the following conditions:

        a. Irradiance on module surface = 800 W/m^2
        b. Ambient air temperature = 20°C
        c. Array electrically open circuited
        d. Wind speed = 1.0 m/s

Using these definitions, the data in Table 3, and the methods described in Appendix B, ratings have been established for each of the five prototype system PV arrays. These ratings are listed in Tables 4 and 5.

TABLE 4

PHOTOVOLTAIC ARRAY RATINGS
AT PEAK RATING CONDITIONS

Prototype System Supplier	Peak Rated Power (kW)	Max Power Voltage (V)	Max Power Current (A)	Open Circuit Voltage (V)	Short Circuit Current (A)	Peak Efficiency (%)
General Electric	6.6	224	29.5	290	33.6	8.6
MIT Lincoln Laboratory	6.8	216	31.7	275	36.0	8.0
Solarex	5.0	200	25.4	260	29.3	7.3
TriSolarCorp	4.8	202	24.0	246	26.3	10.2
Westinghouse	5.1	210	24.3	271	27.8	7.4

TABLE 5

PHOTOVOLTAIC ARRAY RATINGS
AT NOMINAL RATING CONDITIONS

Prototype System Supplier	NOCT (°C)	NOCT Rated Power (kW)	Max Power Voltage (V)	Max Power Current (A)	Open Circuit Voltage (V)	Short Circuit Current (A)	Nominal Efficiency (%)
General Electric	60.8	5.4	184	29.0	245	34.0	7.0
MIT Lincoln Laboratory	54.4	5.9	183	32.1	239	37.0	6.9
Solarex	54.3	4.3	170	25.6	227	30.0	6.3
TriSolarCorp	47.5	4.3	179	24.2	221	26.6	9.1
Westinghouse	58.3	4.3	179	24.3	237	28.3	6.2

2.2.2 Power-Conditioning Subsystem Characterization

Initial characterization of the power conditioners involved a series of measurements to determine their fundamental operating characteristics during routine operation.

Measurements were made on the power-conditioning subsystems resulting in a family of curves of power-conditioning subsystem (PCS) dc-to-ac conversion efficiency as a function of dc input power level for various dc operating voltages. A dc power supply was used to simulate the output of a PV array. The supply was connected to the power conditioner and the supply current varied from zero to the maximum rated PCS input limit. This was done at discrete fixed voltage levels in the normal operating range of the power conditioner, and at each voltage the PCS output current and voltage were measured so that the PCS efficiency could be calculated and the family of curves generated. Figures 30 and 31 show the respective Gemini and Abacus efficiency curves.*

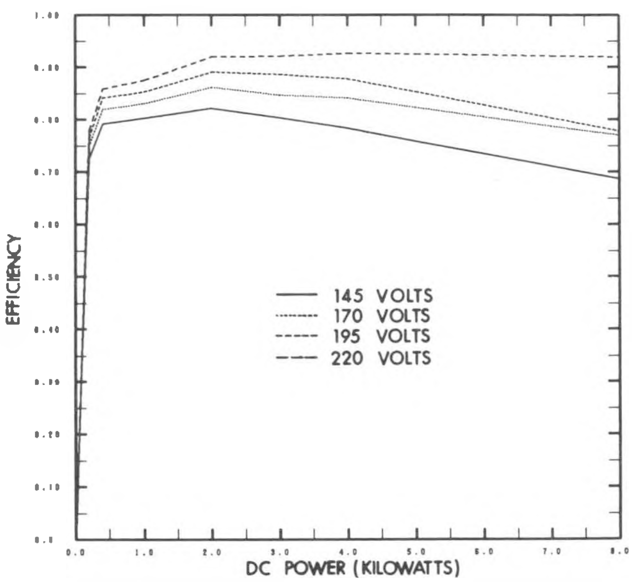

Fig. 30. Voltage and power dependence of Gemini inverter dc-ac efficiency.

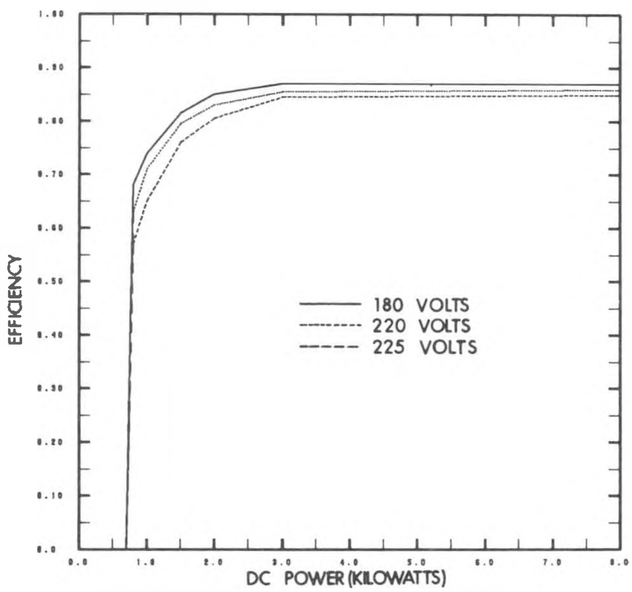

Fig. 31. Voltage and power dependence of the Abacus inverter efficiency.

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*Only the original prototype system configurations are discussed in this report. It should be noted, however, that five new power conditioners have been evaluated over short operating periods in the five prototype systems, beginning in March 1982. For a complete description of these new power conditioners and their performance, see Reference 30.

In addition to efficiency, two other quantities were measured: dc threshold power and ac standby power. The dc threshold power of a power-conditioning subsystem is defined as the dc input power level below which no ac power will be generated. This, then, is the minimum dc power output of the PV array required to operate the PCS. The PCS ac standby power is defined as the ac power from the utility consumed when no ac power is being produced by the PCS. The standby power will be consumed at night (no array power) and during periods when the PV array cannot generate sufficient dc power to overcome the PCS threshold. The ac standby power includes that for control circuitry (in the Gemini inverter, but not in the Abacus) and, if present, for the isolation transformer. Table 6 summarizes these two parameters for the five prototype systems.

TABLE 6

POWER CONDITIONING SUBSYSTEM CHARACTERISTICS

Prototype System Supplier	Power Conditioning Subsystem	PCS Rated Power(kW)	DC Threshold Power(W)	AC Standby Power(W)
General Electric	Abacus	6(AC)	750	4
MIT Lincoln Laboratory	Gemini	8(DC)	75	7
Solarex	Abacus	6(AC)	750	4
TriSolarCorp	Gemini	8(DC)	75	7
Westinghouse	Abacus	6(AC)	750	4

A further characteristic of interest is the PCS voltage control strategy, which determines at every instant the PV array operating voltage. The Gemini power conditioners, although originally designed with maximum-power-point-tracking circuitry, were modified prior to installation for quasi-constant voltage operation. The curve of Fig. 32 illustrates the Gemini's input voltage control characteristic. The "cut-off" voltages on the curve can be set anywhere in the 160- to-200-volt range.

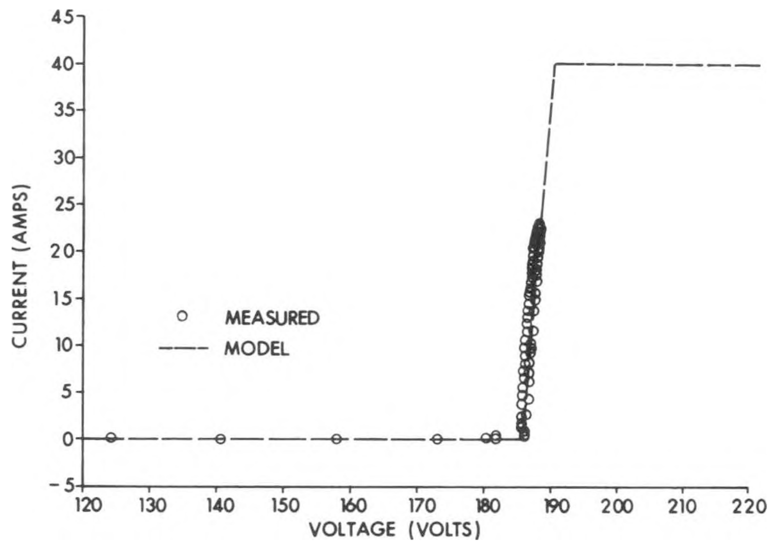

Fig. 32. The Gemini inverter operating voltage control characteristics.

The Abacus power conditioners, when first made available, contained maximum-power-tracking circuitry which would continually hunt for the PV array voltage yielding the greatest array power. The systems were operated with this circuitry until an improved "pilot cell" control was retrofit into each of the Abacus units. This control system utilizes the short-circuit current from a single solar cell (or module, in the case of the Westinghouse prototype system) separate from the PV array circuitry, to determine "wake-up" conditions. The operating voltage of the PV array is then established as a multiple of the open-circuit voltage of the pilot cell. An adjustable constant-of-proportionality may be set to maximize the array output for initial control system set-up, or for periodic adjustment.

2.2.3 Photovoltaic System Characterization

The PV system as a whole is characterized by combining the PV array and PCS characteristics reported in the previous sections. The following quantities are presented in Table 7 for the five prototype systems:

- System Peak AC Power

  The System Peak AC Power is defined as the product of the array peak dc power and the PCS efficiency at that power and voltage.

- System Peak Efficiency

  The System Peak Efficiency (sunlight-to-ac-power) is defined as the product of the array peak efficiency and the PCS efficiency at the array peak dc power point.

- System Nominal AC Power

  The System Nominal AC Power is defined as the system ac output power at 1000 W/m^2 irradiance and an array temperature equal to NOCT. It is determined from the array nominal dc power and PCS efficiency at that power and voltage.

- System Nominal Efficiency

  The System Nominal Efficiency is defined as the product of the array efficiency at nominal rating conditions and the PCS efficiency at the array nominal dc power point.

TABLE 7

PHOTOVOLTAIC SYSTEM RATINGS

Prototype System Supplier	System Peak AC Power (kW)	System Peak Efficiency (%)	System Nominal AC Power (kW)	System Nominal Efficiency (%)
General Electric	5.6	7.3	4.7	6.1
MIT Lincoln Laboratory	6.3	7.4	4.8	5.7
Solarex	4.3	6.3	3.7	5.5
TriSolarCorp	4.2	8.8	3.7	7.7
Westinghouse	4.4	6.3	3.7	5.4

2.3 Monitored House Characteristics

As part of the NE RES activity, the electrical loads of five houses have been monitored. These houses are geographically close to the NE RES site and are scattered in the Massachusetts communities of Concord, Lexington and Lincoln. Table 8 lists the features of the monitored houses, which are occupied by families of four or five, each with one or two working adults. All have oil-fired heating systems and oil-fired or electric-resistance hot water systems.

TABLE 8

MONITORED HOUSES FEATURES

	MH2	MH3	MH4	MH5	MH6
Occupants	5	5	4	5	4
Working Adults (Daytime Hours)	2	2	1	2	1
Heating System	Oil	Oil and Electric (2 rooms)	Oil	Oil	Oil
Domestic Hot Water System	Electric	Electric	Oil	Electric	Oil
Cooking	Electric	Electric	Electric	Electric	Electric
Clothes Drying	Electric	Electric	Electric	Electric	Electric
Air Conditioning	None	None	Window	None	Window

3.0 SYSTEM AND COMPONENT SAFETY/PERFORMANCE ASSESSMENTS

Since the initiation of the Solar Photovoltaic Residential Project in 1979, efforts have been made to involve code- and standards-writing organizations, such as the National Fire Protection Association (NFPA) and the Institute of Electrical and Electronics Engineers (IEEE), in the PV activities. At present the IEEE has established a Standards Coordinating Committee on Photovoltaics which is working on numerous draft standards for PV systems and components. The NFPA is even further along; since the summer of 1982, the draft National Electrical Code (NEC) Article 690 on Solar Photovoltaic Systems has been available for public review. It is anticipated that the article will be included in the 1984 NEC Handbook.

In addition to the codes and standards efforts, Underwriters Laboratories, Inc. (UL) has been an active participant in the US DOE Photovoltaic Program. Under MIT Lincoln Laboratory contract, UL has produced the "Draft Standard for Power Conditioning Units for Use in Residential Photovoltaic Power Systems" (31), and is prepared to evaluate inverters for UL listing. Under Jet Propulsion Laboratory (JPL) contract, a similar UL standard for PV modules has also been prepared (32).

All of these efforts has been assisted in varying degrees by the Residential Photovoltaic Project.

None of these safety or standards efforts were under way at the time of the initiation of the NE RES activity. However, the PV modules used in the NE RES prototypes have been subjected to the JPL environmental test sequence. Additionally, preliminary assessments of the five systems vis-à-vis the proposed NEC requirements have been made. A summary of the findings is presented below.

3.1 Module Environmental Tests

A sequence of environmental tests (33) has been used by JPL as part of their Flat-Plate Solar Array Project. A manufacturer will typically submit up to ten PV modules for testing, some of which are used as "control" samples for comparison with those undergoing the various tests. The tests are intended to identify module-design weaknesses resulting from accelerated environmental stresses.

Each of the NE RES prototype system suppliers submitted modules, identical to those now in use in the corresponding systems, to this environmental test sequence. Since only a limited number of modules were made available, an abbreviated version of the testing was conducted. It is important to note that no attempt was made to judge the modules' performance in terms of success or failure. The results reported in Table 9 are those observed, and are presented without subjective conclusion.

TABLE 9
MODULE ENVIRONMENTAL TESTING RESULTS*

Prototype System Supplier	General Electric	MIT Lincoln Lab	Solarex	TriSolarCorp	Westinghouse
Module Mfg.	General Electric Block IVA	Solarex	Solarex	ASEC 60-3056	Arco Solar 16-2300
Failure					
Cracked Cell(s)	---	---	Ha	Hu	NOT TESTED
Electrical Degradation	TC, Hu	Hu	---	Hu	
Edge Delamination	---	TC, Hu	---	---	
Center Delamination	---	Hu	---	---	
Blisters/Back Delamination	---	Hu	TC	Hu	
High-Voltage Breakdown	---	---	---	---	
Other	TC[1]	TC[2]	TC[2]	TC[3]	

1. Dummy (edge fill-out) shingles show scrim/rubber dissimilar shrinkage and delamination. Amber discoloration around cells, interconnect discoloration.
2. Air bubbles at edge of laminate, some cells touching after test.
3. Junction boxes warped, bonding broken.

TC=temperature cycling
Hu=humidity test
Ha=hail test

In the chart, these abbreviations indicate the test during which a module exhibits the degradation or fault indicated.

*Tests performed by the Jet Propulsion Laboratory.

3.2 Preliminary System Safety Audit

An audit of the five prototype systems at the NE RES was conducted to assess their compliance with the Massachusetts Building Code and the National Electrical Code, including the proposed PV section. The general findings given below, applicable to all systems, are followed by specific comments on each of the systems.

- All disconnect switches should be labeled as per NEC Section 110-22.
- The PV-power-source ratings must be provided at an accessible location near the disconnecting means, as per proposed NEC Section 690-52.
- Any circuits over 150 volts to ground shall not be accessible to other than qualified persons as per proposed NEC Section 690-7. Note that accessible wiring is defined as wiring which can be exposed by removal of a wireway cover (snap or screw-mounted) using a screwdriver, without damaging any equipment or the structure.
- Overcurrent protection is required on the PV-power-source circuits unless such circuits are rated for the short-circuit current of the PV array.

3.2.1 General Electric

- Covers are needed for unfinished outlet boxes. (Subsequently corrected.)
- Module interconnect wiring, flat conducting cable, is not presently code-approved.

3.2.2 MIT Lincoln Laboratory

- Wiring used to interconnect modules is not presently code-approved.
- The dc system is floating (ungrounded), which is not in compliance with the proposed NEC Section 690-41.

3.2.3 Solarex

- Frame ground rod must be bonded to the system ground conductor.
- Use of XHHW conductors for module interconnection is not presently code-approved.
- The location of module junction boxes at the roof ridge (accessible from inside the structure) introduces hazards that could be avoided. At present a ladder is required for access to the junction boxes, and the attic door (in the attic floor) must be covered. (String wiring has since been brought to a more accessible panel.)

- The original one-half-inch plywood attic flooring did not meet the Massachusetts Building Code. (This condition has since been corrected.)
- If work is to be performed regularly in the attic space, a guard rail must be placed around the floor opening.

3.2.4 TriSolarCorp

- The dc system is floating (ungrounded), which is not in compliance with the proposed NEC Section 690-41.
- Metal batten strips on PV array are not grounded; grounding is required.
- Conductors of parallel No. 10 AWG wire are used. The NEC only allows paralleling of conductors sized No. 1/0 and larger.

3.2.5 Westinghouse

- Array wiring cables stapled to the ceiling are not code-approved.
- The high-voltage array-combiner panel is readily accessible.

Most of the above-cited safety issues are being addressed, to bring the site in compliance with the NEC. At present, code-approved photovoltaic-specific wiring methods are being identified in ongoing work at the Underwriter's Laboratories. Consequently, no action regarding array wiring modifications of the prototype systems will be undertaken until such code-approved methods are identified. To insure the safety of all site personnel and visitors at the NE RES, the prototype systems are kept locked at all times and visitors are not admitted to a prototype without a NE RES employee-escort.

4.0 SYSTEM PERFORMANCE DURING ROUTINE OPERATION

During routine, "run-of-the-weather" operation, the five prototype systems are providing power to a time-varying resistive load which is controlled to replicate the electrical energy usage of one of the five monitored houses. In this mode of operation, data are being collected to present a summary of the gross system energy production and the interaction between the PV system, the residence-like electric load, and the utility. The bulk of the systems' operating time is spent in this mode. At other times, special tests have been conducted, or extreme conditions have been imposed on the systems to evaluate system survivability.

The sections below summarize the PV system performance.

4.1 PV System Energy Production Summary

Monthly reports are generated (see, e.g., References 6-17) which summarize the performance of the prototype systems, the monitored houses and the NE RES weather station. The data are presented in two forms: a single-page Monthly Summary table which gives totals for the month, and the multipage Brief Monthly Report which gives a 24-hour, average-day-of-the-month, tabular summary for all the pertinent quantities. Appendix C contains all the Monthly Summaries available up to publication of this report. The month-by-month energy production for the prototypes is summarized here in Figs. 33-37, over the period April 1981 through March 1982.

Note that only two of the systems have operated for a full twelve-consecutive-month period: MIT LL and TriSolarCorp. The others have less accrued operating time which makes energy production comparisons among the systems difficult. The highest average per day PV system energy production occurs during a different month for each system. The MIT LL system has its highest output in May, while TriSolarCorp produces its peak energy in April, but also has consistently high output through August. This may be explained in general terms as follows. During parts of the month of April 1981, there were several disconnected strings in the MIT LL PV array, reducing the system energy production; full power was present all during May. As the average ambient temperature steadily increases through June, July and August,

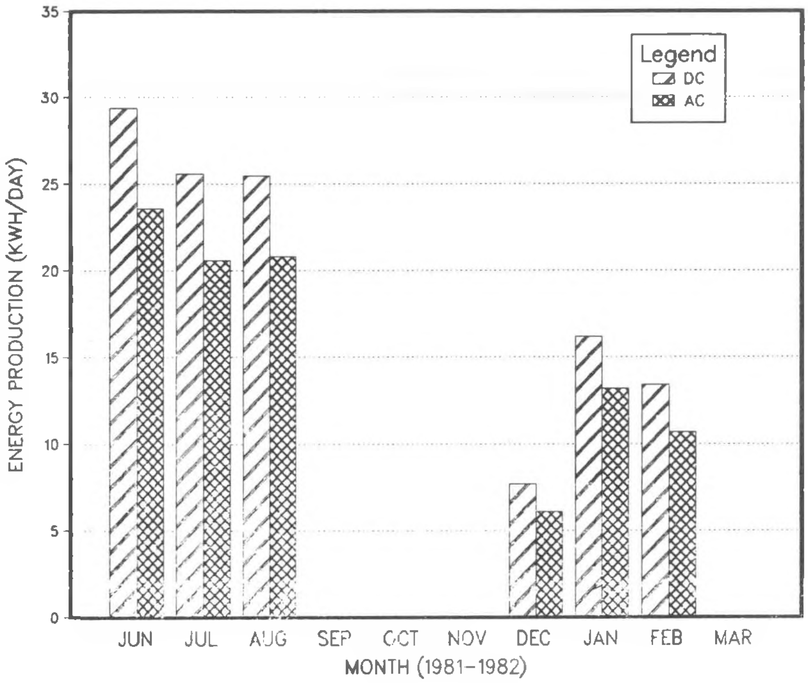

Fig. 33. General Electric prototype system energy production summary.

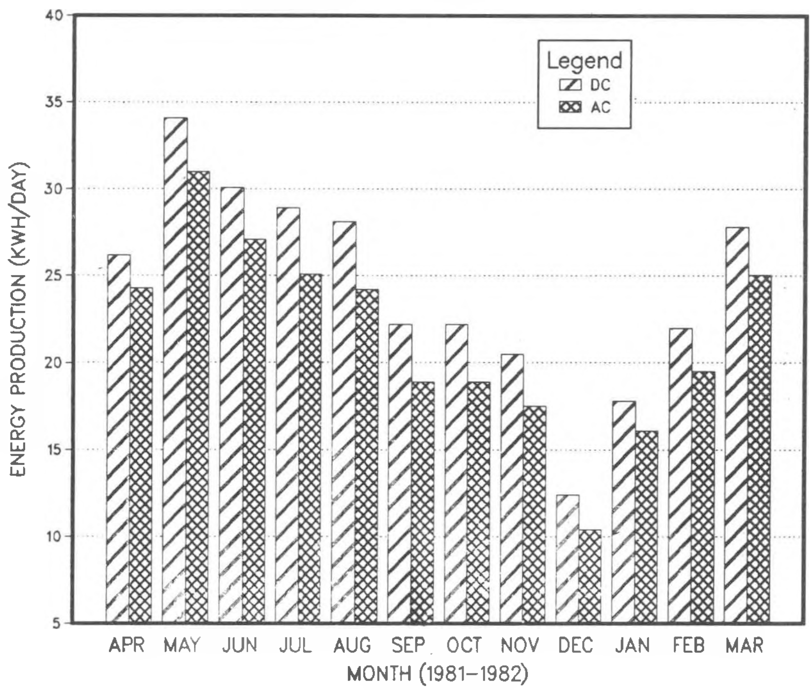

Fig. 34. MIT LL prototype system energy production summary.

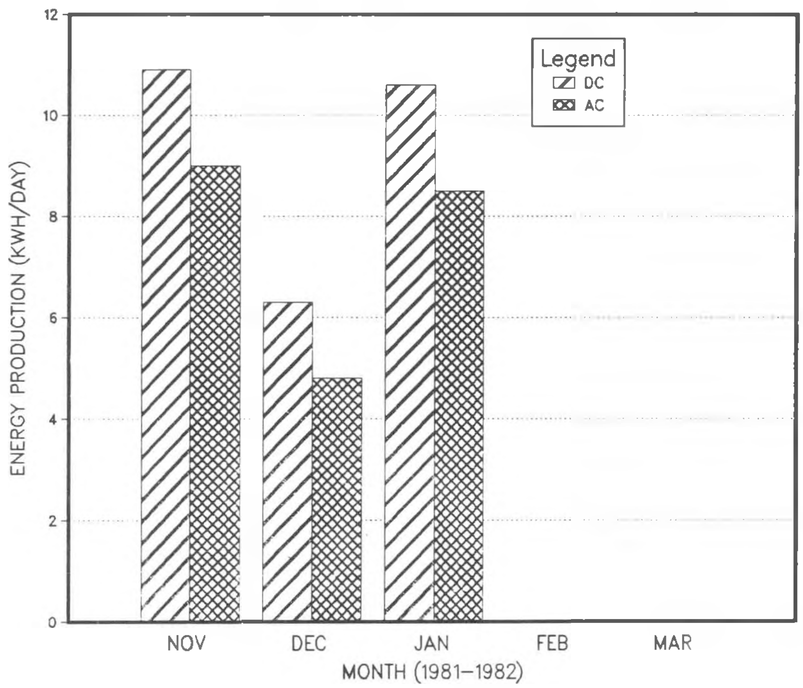

Fig. 35. Solarex prototype system energy production summary.

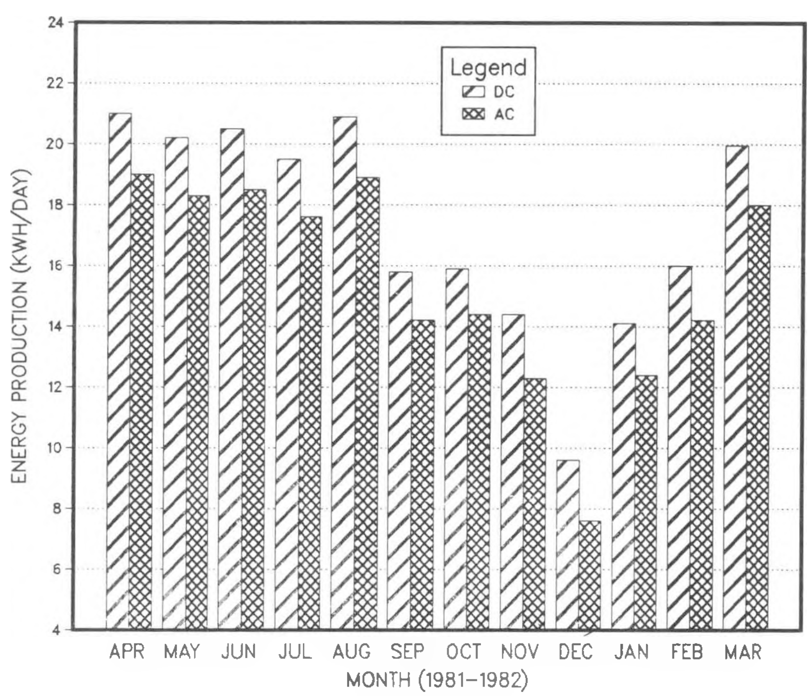

Fig. 36. TriSolarCorp prototype system energy production summary.

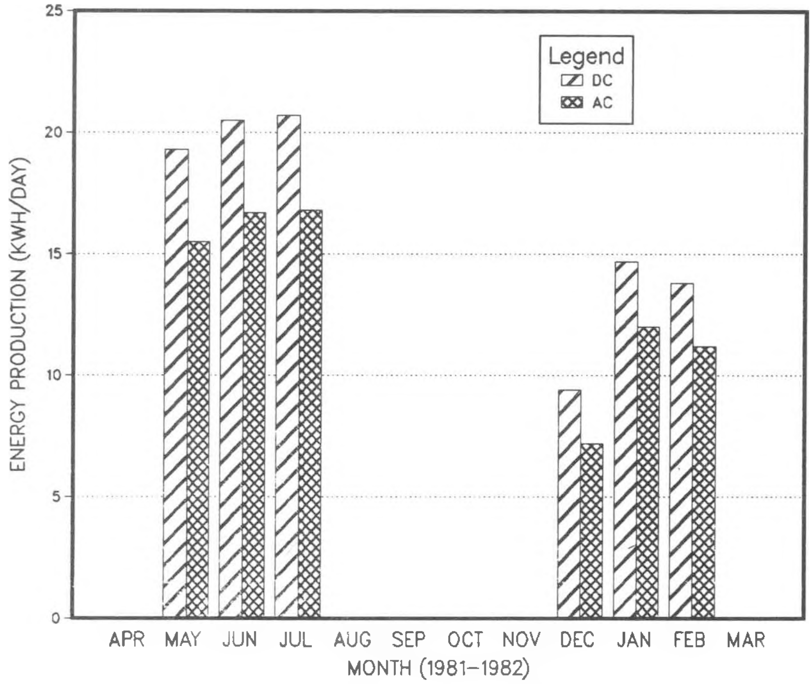

Fig. 37. Westinghouse prototype system energy production summary.

the MIT LL array operates at higher temperatures, reducing efficiency and average output. The TriSolarCorp prototype, however, utilizes a thermostatically controlled fan to help maintain low PV operating temperatures which tends to stabilize the array efficiency and output over those summer months.

Figure 38 shows the monthly average daily maximum PV operating temperatures for the MIT LL and TriSolarCorp arrays, and Figure 39 compares the daily insolation on the arrays. As the figures show, the MIT LL array tends to operate hotter, while the two arrays receive very similar amounts of insolation.

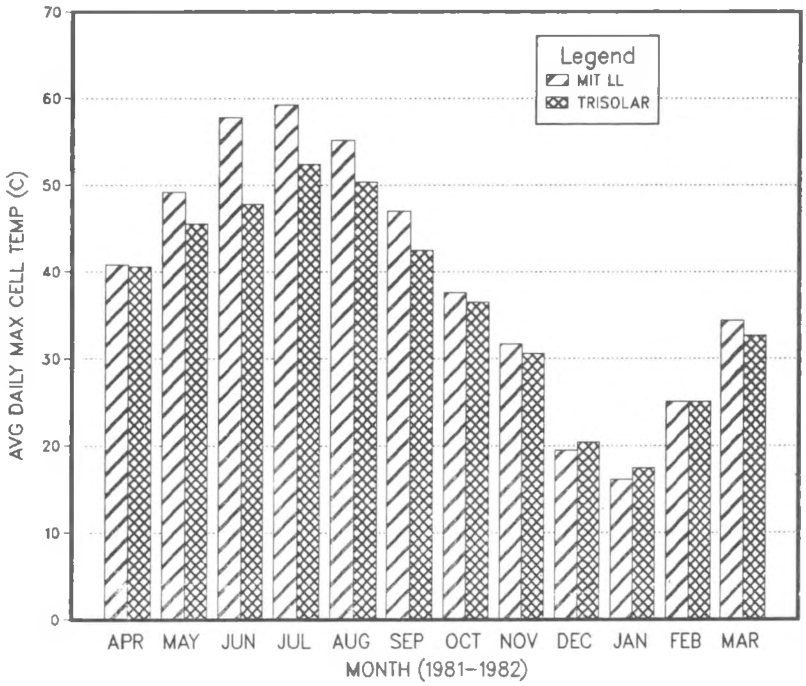

Fig. 38. Comparison of MIT LL and TriSolarCorp maximum PV array operating temperatures.

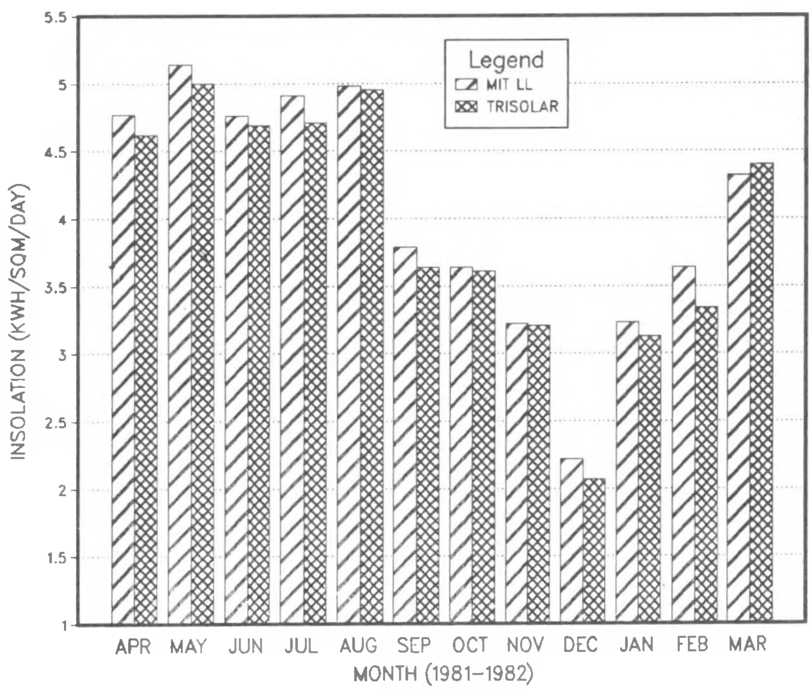

Fig. 39. Comparison of total insolation on MIT LL and TriSolarCorp PV arrays.

4.2 Direct PV Energy Utilization

When a PV system is providing power to a residential load, both the source and load are time-varying. Most residential loads are independent of the PV system output (or, equivalently, the solar irradiance), and there may even be an inverse relationship between heating and lighting loads and the solar source. As a consequence, there is a continual mismatch between the PV system output and the load, which results in PV energy being sent to the utility at times when PV output exceeds the load, and utility energy being "imported" at times when the load exceeds the PV system output. Figure 40 shows the output of Monitored House 4 for one day; the output of the Tri-SolarCorp PV system is also shown for that day to illustrate the typical PV load mismatch. The timing of the peak solar output vis-à-vis the typical residential demand profile as seen by the utility is useful for evaluating the potential impact of large numbers of residential PV systems on utility power generation.

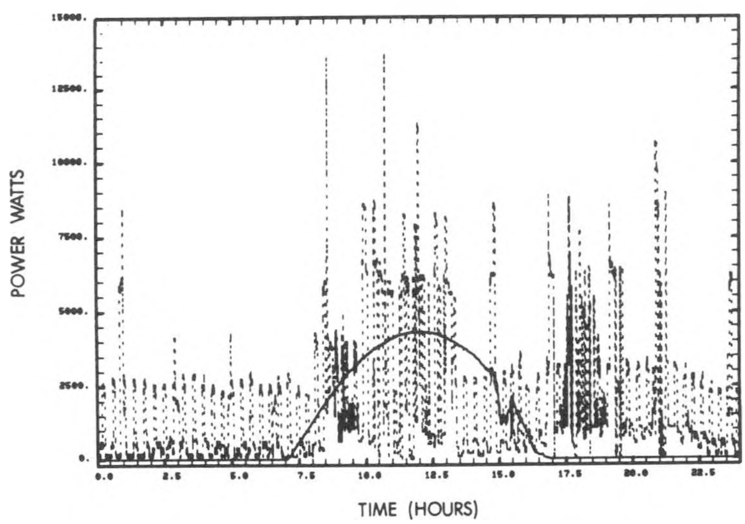

Fig. 40. Plot of Monitored House 4 load (dashed line), and TriSolarCorp PV system output (solid line) for one day.

For a homeowner there is a more immediate concern; namely, economics. The magnitude of the PV system energy production (on a daily, monthly or annual basis), the fraction of that energy which goes directly to the load, and the prevailing utility buy-back rate and policy are critical to the worth of a PV system to a homeowner. Only if the utility is trading PV-generated kWhs exactly one-for-one with utility-generated kWhs does the PV energy direct-utilization fraction become insignificant. In this case a knowledge of the net monthly energy exchange, either to the utility or from the utility, is adequate for determining a homeowner's monthly utility bill.

In all other cases, where the utility buy-back rate (defined as the ratio of the price paid by the utility for a PV-generated kWh to the price paid by the homeowner for a utility-generated kWh) is not equal to 1.0, the homeowner's monthly utility bill depends upon the gross exchanges of energy between the PV system-equipped residence and the utility.

A recent study (34) showed that computation of total energy to the utility and total energy from the utility in one-hour-time-step computer simulations of PV systems may be in error by as much as 50%. The error is reduced as the time step is shortened. Work continues on gathering more five-second PV system/residence-utility energy exchange data to understand further the errors in calculating energy flows based on performance averaged over discrete time intervals. Ultimately a correction formula will be determined whereby computer simulations may be made more accurate.

Figures 41-45 show the hypothetical energy exchange for the TriSolarCorp PV system as if it were supplying energy to each of the five monitored houses. From the figures it can be seen that the percent of PV energy directly utilized by the monitored houses is low, ranging from 20-50%. Not unexpectedly, the highest direct-utilization fractions occur in the winter months when the load is highest and PV system output is lowest.

Refer to Section 9.0 of this report for projections of the homeowner economics given this hypothetical energy exchange data.

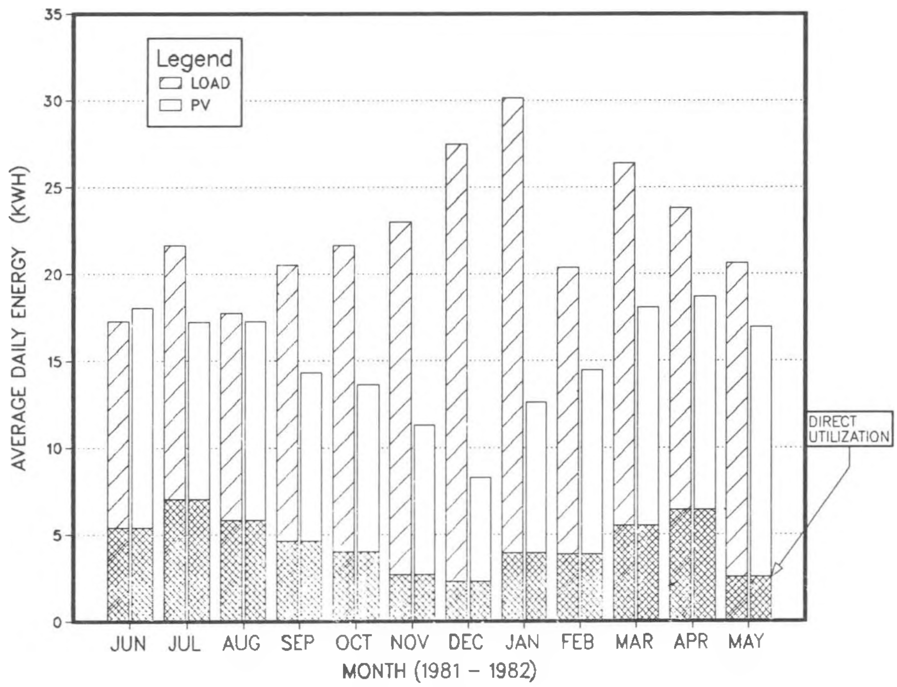

Fig. 41. Hypothetical PV residence-utility energy exchange: Monitored House 2 with TriSolarCorp PV system.

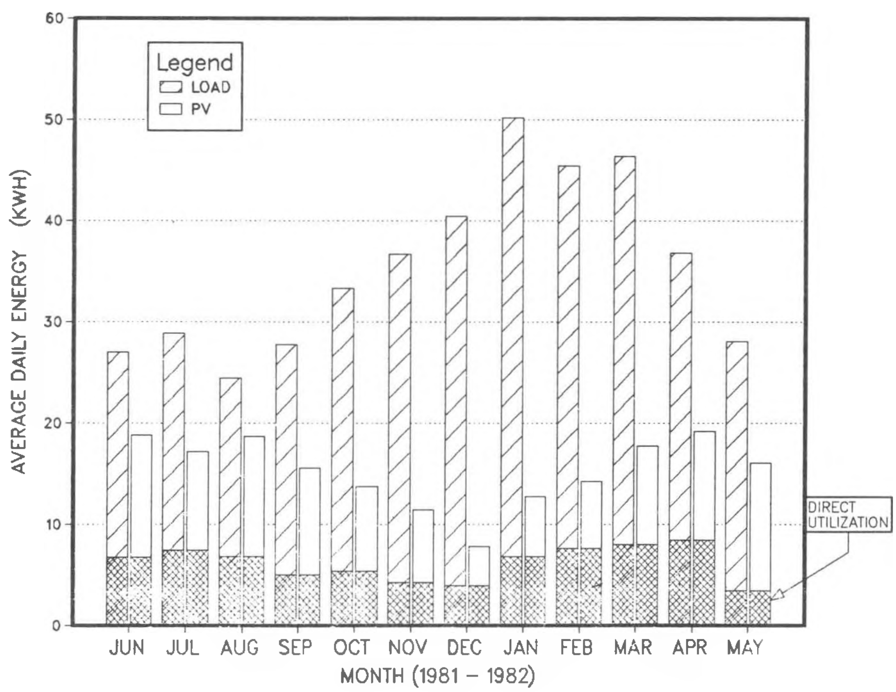

Fig. 42. Hypothetical PV residence-utility energy exchange: Monitored House 3 with TriSolarCorp PV system.

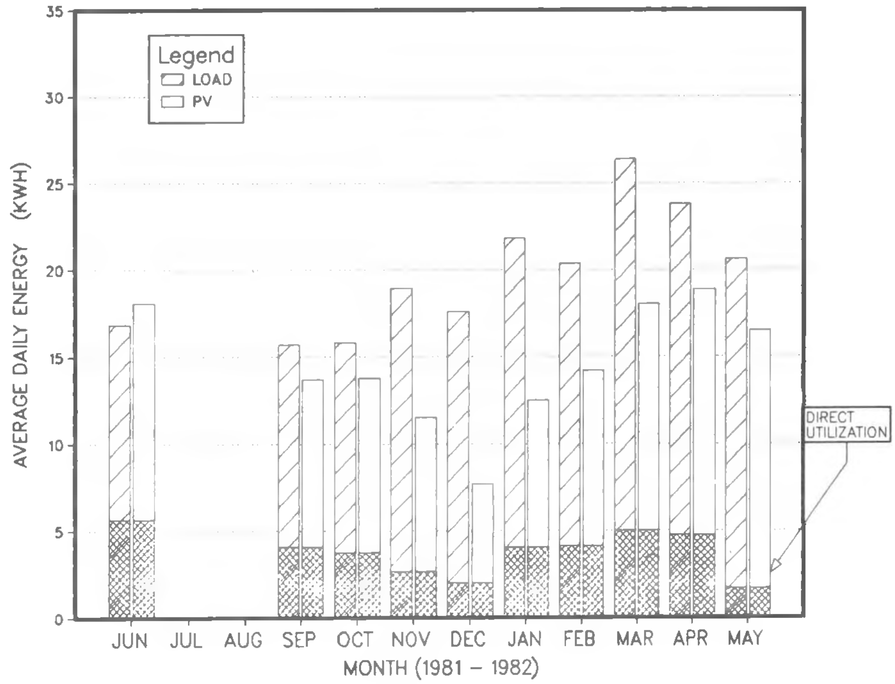

Fig. 43. Hypothetical PV residence-utility energy exchange Monitored House 4 with TriSolarCorp PV system.

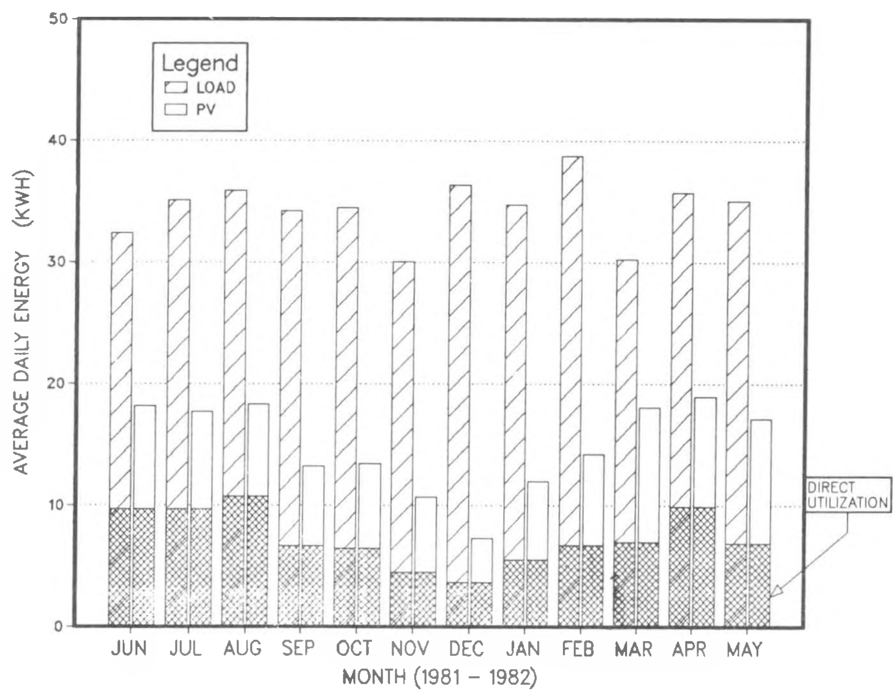

Fig. 44. Hypothetical PV residence-utility energy exchange: Monitored House 5 with TriSolarCorp PV system.

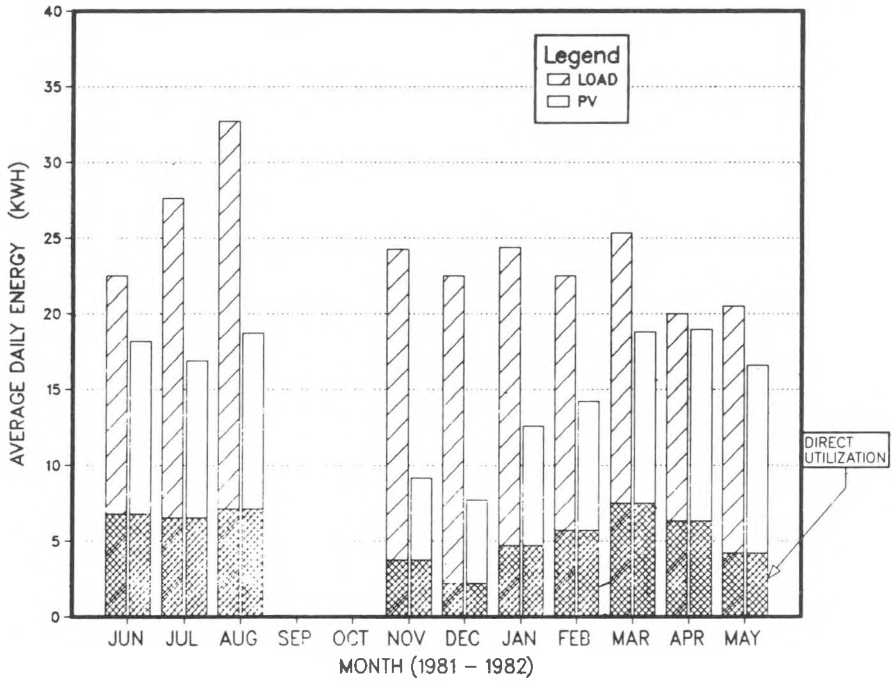

Fig. 45. Hypothetical PV residence-utility energy exchange: Monitored House 6 with TriSolarCorp PV system.

4.3 System Performance Extrema

Records of performance extrema were kept during the prototype system evaluation period. A summary of these phenomena is given in Table 10.

As noted in the previous section, the General Electric, Solarex and Westinghouse prototypes have not operated durıng all months and therefore may not show extrema values for some quantities as high as would be expected based on comparison with the other systems.

TABLE 10
SYSTEM PERFORMANCE EXTREMA

	General Electric*	MIT Lincoln Laboratory	Solarex*	TriSolarCorp	Westinghouse*
PV ARRAY					
Peak Rated Power(kW)	6.6	6.8	5.0	4.8	5.1
Days Power Exceeded Rated Power	2	69	12	43	21
Total Days of Operation	139	422	60	475	133
Peak Measured Power(kW)	6.9	9.0	6.3	6.0	6.4
Irradiance(kW/m^2)	1.05	1.20	1.30	1.26	1.26
Cell Temperature(°C)	17.5	23.8	36.9	30.0	21.7
Date	1/17/82	3/2/82	4/18/82	2/18/82	2/18/82
Peak Irradiance(kW/m^2)	1.37	1.26	1.30	1.29	1.26
Date	4/18/82	4/18/82	4/18 + 3/20/82	4/18/82	2/18/82
NOCT(°C)	60.8	54.4	54.3	47.5	58.3
Max. Meas. Cell Temp(°C)	80.0**	80.0**	68.1	59.4	65.8
Irradiance(kW/m^2)	1.28	1.18	1.30	0.89	0.91
Ambient Temp.(°C)	29.5	32.5	9.6	27.7	27.6
Date	7/6/81	7/7/81	3/20/81	7/31/81	7/31/81
Max. Energy Output(kWh/day)	37.2	49.5	32.4	30.5	29.4
Insolation(kWh/m^2-day)	7.2	7.0	7.4	6.9	6.5
Date	6/13/81	4/14/82	4/14/82	5/13/81	7/10/81
Avg. Monthly Output(kWh/day)	29.4	30.5	21.7	20.2	20.7
POWER CONDITIONER					
Peak Measured Power(kW)	5.7	8.3	5.3	5.6	5.4
Date	1/17/82	3/2/82	4/18/82	2/18/82	2/18/82
Max. Energy Output(kWh/day)	30.2	45.0	27.6	27.8	24.6
Date	6/13/81	4/14/82	4/14/82	5/13/81	7/10/81

*System not operative all months.
**Maximum sensor reading possible. Actual value may have been higher.

The array peak rated power (array maximum power at 1000 W/m^2 irradiance and a cell temperature of 25°C) is shown as the first entry in Table 10. Following this is the number of days when the measured array power exceeded this peak rated power. As can be seen from the table, the two systems that operated for twelve full months, MIT LL and TriSolarCorp, achieved higher-than-rated power many times: 69 for MIT LL and 43 for TriSolarCorp. The occurrences of higher-than-rated array power happen only between late September and mid-April. They are a regular and frequent condition in all the included months except December. For example, the MIT LL array exceeded rated array power on each of 13 days in February 1982, 15 days in March 1982, and 11 of the first 18 days of April 1982. The TriSolarCorp prototype exhibits a similar pattern: 10 days in February, 13 days in March, 8 days in April. There are several further observations that can be made:

- A greater number of higher-than-rated array power incidences occur between the winter solstice and the vernal equinox, than between the autumnal equinox and the winter solstice (i.e., there are more occurrences on the "spring side" than the "autumn side" of the solstice). This is due to lower prevailing ambient, and therefore PV cell, temperatures in those spring-side months, and a greater percentage of clear-sky, high-irradiance days.
- Conversely, higher-than-rated array powers have never been measured during the summer months, principally due to the high ambient and cell operating temperatures.
- Despite the lack of operating data for a complete 12-month period, it appears that the direct-mount PV array will register many fewer higher-than-rated array power days than the other systems. This is not unexpected, since the direct-mount array typically operates hotter than either the standoff or integral arrays.

It is also of interest to note the magnitude of the highest recorded array power for each system. For the MIT LL array the peak measured power is 9.0 kW, which is 32.4% more than the peak rated power. The other systems have recorded peaks approximately 25% greater than their ratings, except for the General Electric prototype which was not operating during the prime, peak-power-producing months. The ratio of the peak measured, or "expected," power to the peak-rated power is of interest to those designing PV systems as it affects component sizing, circuit fusing, and array-voltage/current-control strategy. From the results cited above, it seems likely that a 25-30% increase over the peak rated power can be expected in this region of the country.

Of similar interest is the peak irradiance on the array surface. The highest recorded tilted irradiance was 1370 W/m^2, measured in April on the General Electric (33.7° tilt from horizontal) array. Irradiance of this magnitude occurs only when there is significant enhancement due to diffuse irradiance from reflective clouds, in addition to unattenuated direct irradiance.

4.4 Unscheduled System Downtime

Photovoltaic system reliability is a factor not always considered in simulations or projections of future PV system viability, yet it is one of the fundamental factors involved in determining system cost and performance. There are several ways that reliability can be defined for the prototype systems at the NE RES:

- The number of instances of system failure (defined as the occurrence of unplanned circumstances resulting in a PV system power output less than 70% of the normally expected output and requiring operator intervention for correction) subtracted from the total number of days in the evaluation period, then divided by the total number of days in the evaluation period. If, for example, a system failed on a Monday and was fixed the following Friday, a single system failure event is considered to have occurred, not five (one for each day the system was down).
- The total number of days the PV system is in the failed mode (i.e., the total elapsed time between each failure and the corresponding repair/return-to-service) subtracted from the total days in the evaluation and divided by the total number of days in the evaluation period. This has the advantage of adding "realism" to the reliability data. That is, if a system failed on a Monday and was restored on the following Friday, then the full five-day down period is charged to the system reliability. On the other hand, such tabulations may unjustifiably penalize a system for something as easily corrected as a blown fuse which might have gone uncorrected over a holiday weekend. Some modes of failure (associated with the power-conditioning system), however, did result in systems remaining inoperative for weeks, even months, while a solution to the problem was being sought. It seems inappropriate to consider such protracted downtime as just a single-failure event.

Of the two reliability definitions, the first would yield the most optimistic result, as if a mature PV industry infrastructure were extant, and any system failures could be attended to and repaired on a same-day basis. The second definition would result in the most pessimistic system reliability statistic, charging the system for time consumed by engineering redesign of what proved to be developmental components which had failed, and service response time. Clearly these two approaches will bracket the reliability one could reasonably expect from these specific systems.

Reliability data are summarized in Table 11. All data are for the period beginning with official system acceptance, which is not necessarily coincident with the first system turn-on, through March 1982. A set of tests was performed on each of the five prototypes as they were completed and ready for operation. The acceptance tests were designed to demonstrate that the systems were fully operational and complete; and acceptance was withheld until the systems passed these tests.

Note that the total number of system failure events varies from 1 to 7, but the resulting total downtime is as much as 267 days. For comparison, the number of utility outages at the NE RES is also reported. Clearly the systems fall into one of two categories: short duration or long-duration failure periods. The failures have been almost exclusively associated with the power conditioners. The Abacus inverters all experienced problems which resulted in system failure, or were of such a nature as to warrant preemptive manual system shutdown while resolution to the problem was sought. Consequently, lengthy periods of system downtime were accumulated while redesign efforts were under way. In the case of the Solarex prototype system, the Abacus inverter failure kept the system inoperative for the full 58 days following its acceptance, resulting in 0% reliability based on event duration as shown in Table 11. The Gemini inverter problems were both fewer and less severe. As a result, the problems typically were diagnosed and solved within hours (e.g., replacing a fuse in the TriSolarCorp Gemini) or, at most, days (replacing a current shunt in the MIT LL Gemini inverter). It is notable that the PV arrays did not cause any system failures. This is no doubt due to the inherent modularity in this subsystem, which reduces the impact of module failure, as well as the high reliability of individual solar cell modules.

TABLE 11
PV SYSTEMS RELIABILITY DATA

	General Electric	MIT Lincoln Laboratory	Solarex	TriSolarCorp	Westinghouse
Date of First System Turn-On	5/6/81	11/24/80	7/9/81	12/10/80	2/5/81
Date of System Acceptance	5/22/81	11/24/80	2/1/82	12/10/80	3/1/81
Days Since Acceptance (As of 3/31/82)	313	438**	58	476	395
System Failure Events (Number of Events)					
PV Array*	0	0	0	0	0
Power Conditioner/ Control	6	1	1	0	6
Protection/Safety	0	0	0	1	0
TOTAL	6	1	1	1	6
Total Downtime(days)	174	16	58	<1	267
Utility Outages	3	3	3	3	3
Reliability(%) Based on:					
No. of Events	97.8	99.8	98.3	99.8	98.5
Event Duration	44.4	96.3	0	99.4	32.4

*Note: Snow cover events are not included here. **Data through 2/5/82, when new inverter installed.

Figure 46 shows a timeline of the operating periods for each of the five systems.

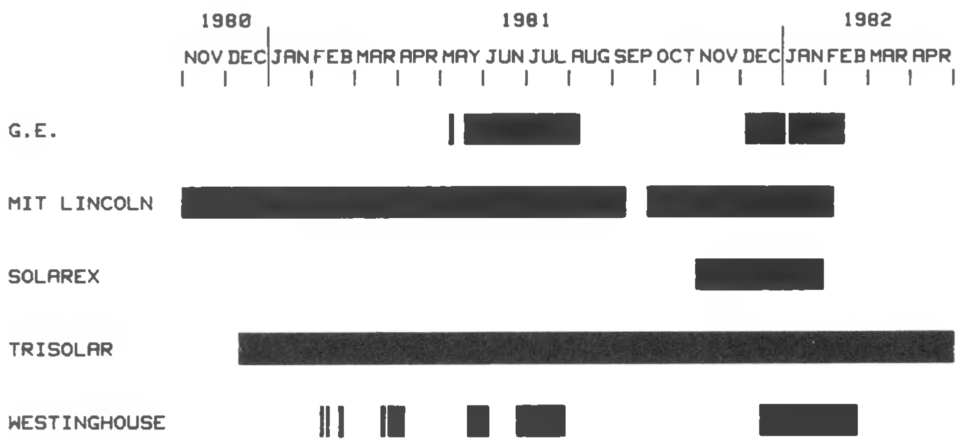

Fig. 46. Prototype systems' operating history time line.

4.5 Module Failures

The array I-V characteristic was measured and plotted for each of the systems approximately once a month; the I-V curves were analyzed to determine whether the array was at full power. Most single-module failures are detected by this method. If a failure was suspected after looking at the whole-array I-V curve, additional I-V curves were made for array substrings in order to localize the failure. At this point, the methods for finding the specific failed module vary, depending upon array wiring configuration and the accessibility of module interconnection wiring.

Thus far at the NE RES, only the General Electric prototype system has suffered module failures. Checkout of the GE PV array at system turn-on in May 1981 showed an array I-V curve fill factor (the array maximum power divided by the product of the open-circuit voltage and short-circuit current) of 0.68. At the beginning of August 1981, however, the fill factor had fallen to 0.62, indicating problems in the array. Further measurements of the array substrings showed ten modules (out of the 375 in the array) which appeared to be open-circuited. These ten modules were removed and replaced with new modules. Of these ten, eight were found to be open-circuited but the other two were functional. The eight failures were diagnosed as cell interconnect wiring "lifting off" the back metallization of the cells, a condition probably exacerbated by the high summer temperatures. One of the two functioning modules which had been removed from the array had appeared as a failure because of a non-crimped, module-to-module interconnection. No problems were found with the second module or array wiring. Subsequent to the replacement of these ten modules, the PV array was re-measured and four possible additional open-circuited modules were found. Based upon the problems which surfaced with these modules at the NE RES, materials changes were made to improve the adhesion of the cell-to-cell interconnect wiring prior to deployment of the shingle modules at the Southwest Residential Experiment Station in Las Cruces, New Mexico.

Two ARCO modules in the Westinghouse prototype and one of the ASEC modules in the TriSolarCorp prototype were found with shattered glass superstrates. At least two of these three appear to have suffered from acts of vandalism. The third shattered module, one of the two ARCO modules, was possibly attributable to stresses induced by thermal expansion/contraction of the aluminum frames, although no definitive explanation has yet been determined.

4.6 Module Leakage Current

Leakage current is measured by open-circuiting and floating the PV array, then connecting an ammeter from either the positive or negative array terminal to the frame or frame ground. Any current measured in this way is being "leaked" from the cell circuit to the conductive framing material/ground. Clearly, excessive current is both an undesirable and unsafe condition. Leakage current greater than 10 microamps per module has been judged unacceptable.

At the NE RES, periodic measurements of array leakage current were made to quantify and track the changes in leakage current with varying ambient (primarily humidity) conditions.

Higher-than-acceptable leakage current was measured at two of the prototype systems:

- Seven of the 120 Solarex modules were removed from the MIT LL prototype after leakage currents as high as 700 microamps were measured for a series string of 14 modules. These modules were returned to Solarex for further evaluation. In all cases the problem was identified as reduced electrical insulation between the main cell-circuit bus bar and the module frame due to materials delamination at the module edges which allowed moisture to penetrate. The modules were dried out, resealed and returned to service, and no further problems have occurred.
- Routine leakage current measurements of the Solarex array in the Solarex prototype indicated a string of modules with very high leakage current. Further investigation revealed that the problem lay not with the PV modules but with module interconnect wiring. The wiring insulation had been penetrated where a set of wires was inadvertently crimped between array-framing channels. This resulted in a near dead short from the power wiring to the frames. The wiring was repaired in the field and the system restored to normal operation with no further leakage problems.

Leakage current of approximately 500 microamps has been measured for the full array in the Westinghouse prototype; however, measurements made at other times have been as low as 40 microamps, with all triple-quads (twelve modules in parallel) measuring below 3 microamps. No modules will be removed from the array unless a persistent high level of current leakage is observed, which has not been the case to date.

Measurement of both the TriSolarCorp and General Electric PV arrays consistently shows low leakage current because there are no grounded frames around the modules. Any leakage current measured is probably occurring at junction boxes or conduit runs, but has been negligible to date (less than 1 microamp per module).

4.7 Prototype System Roof Weatherseal and Structural Integrity

One fundamental mechanical requirement of the roof-mounted PV arrays is that they maintain the integrity of the roof weatherseal over the life of the system. Periodic inspections of each system were made, typically after rain and snow storms, to determine whether any leaks had developed.

On two occasions several inches of snow accumulated in the attic space of the Solarex prototype. It was determined that the snow had blown in through a 1.5-inch gap between the north-facing roof slope and a cap strip which laps over the roof ridge to ventilate the attic space. Despite the presence of a mesh screen in this gap, snow infiltrated the structure though rain has not been a problem. This particular situation is not attributable to the PV array, but rather to the roof ridge vent detailing. Prior to the onset of the 1982-83 winter, this will be modified.

In none of the other prototypes was there any event of rain or snow leaking into the structure.

An additional area of concern in regard to a roof-mounted PV array is the possible effects the array may have on the structure through heating, mechanical stress, loading or other mechanisms. Periodic inspections of the systems were made in order to identify any abnormal structural conditions which, if left unattended, could create a safety hazard. At the time of this report no incidences of such structural damage were extant.

4.8 Array Maintenance

During the system test period, three areas of routine system maintenance were investigated: module failure detection, module removal/replacement, and array washing.

As described earlier, the procedure for finding a module failure begins with I-V curve measurement of the whole array, then of the array substrings (as access allows), until a problem has been isolated to a specific group of modules.

In all but the TriSolarCorp system, the array wiring allows electrical access only to groups of modules connected either in series or in parallel, and not to individual modules. Access to all modules in the TriSolarCorp array is possible in the attic space.

Open-circuiting is the most common failure mode found in PV modules; approximately 90% of all the failed modules found in systems fielded by MIT LL have been open-circuit failures. To pinpoint an open-circuited module in a series string of modules requires gaining access to the electrical terminals of each module. In some cases this can be done in-situ (e.g., the TriSolarCorp array); in other arrays, the suspect modules must be removed from the roof frames for access (e.g., the MIT LL and Solarex arrays). Locating an open-circuit failure in a group of parallel-connected modules is accomplished in a different manner. By monitoring the short-circuit current of the parallel-connected modules and successively shadowing each of the suspect modules, a failure can be located, since shadowing the failed module will not change the short-circuit current of the group.

Such a procedure was followed during the failure search of the General Electric PV array. The I-V curve measurements of the whole array and each of 25 substrings were made in about an hour. Successive shadowing of each of the 15 modules in the suspicious substrings required approximately thirty minutes per substring. The total time required for a crew of three people to locate the 10 open-circuited modules was approximately three and a half hours.

The second maintenance task investigated was the time, manpower and equipment required to remove and replace a module or modules from the roof-mounted arrays.

On 28 October 1981, two representatives of General Electric removed ten modules from the direct-mount PV array. The two men each climbed a stand-off type ladder to position themselves alongside the module to be removed. The silicone caulking around the module was scraped away, and the module was removed from the mounting nails with a special hand-held tool. (When the module is slid out from its position, the electrical conductors are cut.) The electrical connectors of a new module were spliced onto the old leads, the module was inserted in position, and the edges were re-caulked. The total time required by two workers to remove and replace one module was one hour.

On 19 October 1981, four representatives of Westinghouse replaced one of the shattered modules in their integrally mounted PV array. Prior to their arrival, two carpenters had removed the sheet rock and foam board insulation in the ceiling immediately behind the defective module. The module was electrically disconnected from inside the prototype and was physically removed by workmen who climbed the roof on a ladder and lifted the module doublet (two modules framed together) with suction cups. The new module doublet was then put in place. Upon completion of the module replacement and rewiring, the carpenters replaced the ceiling materials. The total time required by two workmen to replace one module, including carpentry, physical removal and electrical wiring, was approximately eight hours.

In May 1981, a shattered ASEC module in the TriSolarCorp integral-mount PV array was replaced. Working inside the prototype's attic space, the maintenance crew first electrically disconnected the damaged module then, using staging platforms to work on the roof, loosened the aluminum cap strips, cut the silicone glazing compound, and removed the module. The total time expended by a crew of two workmen for module removal and replacement was approximately three hours.

The MIT LL stand-off mounted PV array was designed specially to simplify module removal and replacement. The ten modules in each vertical column are secured together in "daisy chain" fashion by wheeled brackets which roll on tracks or rails bolted to the roof. At the head of each column along the roof ridge, there is a small pulley secured to the roof; one end of the cable looping through the pulley attaches to the top module and the other end is brought to the bottom of the column. A crank-pulley and rail extension is hooked to the bottom edge of the array column, stop blocks are removed and the column of modules can be lowered from the roof for removal and inspection. Such a procedure requires approximately two hours for a crew of two to remove and replace a column of ten modules.

No data are available yet for module removal/replacement on the Solarex prototype.

The final task of system maintenance investigated at the NE RES was routine washing of the PV arrays. A local window-cleaning company was contracted to wash each of the five arrays, using standard equipment and detergents. Three workmen performed the job using cold water, a commercial detergent and sheepskin-covered applicators on the ends of long poles. The total washing time for all but the General Electric prototype was approximately 3.5 man-hours per array. Due to the overlapping of the shingle modules, the GE array was more difficult to wash; the three workmen spent approximately 2.5 hours, or 7.5 man-hours on this array.

It should be noted that the roof-mounted PV arrays are accessible from the ground by using either poles of a manageable length or step ladders. If any of these arrays were on the roof of a two-story residence, accessibility would be much more difficult and the washing time and cost would increase accordingly.

4.9 Array Voltage Control

The voltage at which a PV array operates is critical in determining the amount of power that it will produce. The controls which determine the PV array voltage at every instant reside in the power conditioner. Three modes of voltage control have been used in the prototype systems at the NE RES: maximum-power-point tracking, voltage proportional pilot-cell operation, and a variable voltage-range method employed by the Gemini inverters. The goal of any voltage-control strategy is to maximize the power produced by the PV array while still maintaining overall control-system reliability and durability.

The Abacus inverters initially contained circuitry which would hunt for the array voltage maximizing array power. During December 1981, however, these units were all modified to use a pilot-cell control strategy. In this mode of operation, the open-circuit voltage of a single roof-mounted solar cell, separate from those in the PV array, is monitored and the array voltage is maintained at a multiple of the cell voltage. In the case of the Westinghouse array, a full module is used for pilot control, instead of a single cell. The constant of proportionality between the pilot-cell voltage and the array voltage may be adjusted at the time of first use and then seasonally thereafter to maintain the optimum ratio.

The Gemini inverters use yet a third approach to array voltage control. Figure 33 (Section 2.2.2) shows a plot of the Gemini input voltage-current characteristic. The operating voltage of the array is found at the intersection of the array I-V curve with the Gemini I-V control curve.

A detailed discussion and comparison of various control strategies, including the three described above, is contained in Reference 35.

A brief comparison of three strategies based on computer simulation of system performance is given in Section 7.0. Voltage-control-related phenomena witnessed at the NE RES are discussed below.

4.9.1 Maximum-Power-Point Tracking

The Abacus maximum-power-point-tracking circuitry when hunting for the maximum-power voltage would typically overshoot and undershoot the true maximum-power point, resulting in operation off this voltage most of the time. In addition, the rate at which voltage steps were taken was not optimal to track a maximum-power voltage which was changing rapidly with irradiance. Figure 47 shows the measured operating voltage of the Westinghouse PV array/ Abacus inverter over the course of a clear-sky day. Also shown is the predicted maximum-power voltage. Note that the array was rarely operated at its maximum power point; as a result, the measured energy production that day was ~6% less than the maximum energy available. Due to the inadequacies of the maximum-power-point-tracking circuitry, all Abacus inverters were modified to use the pilot-cell control.

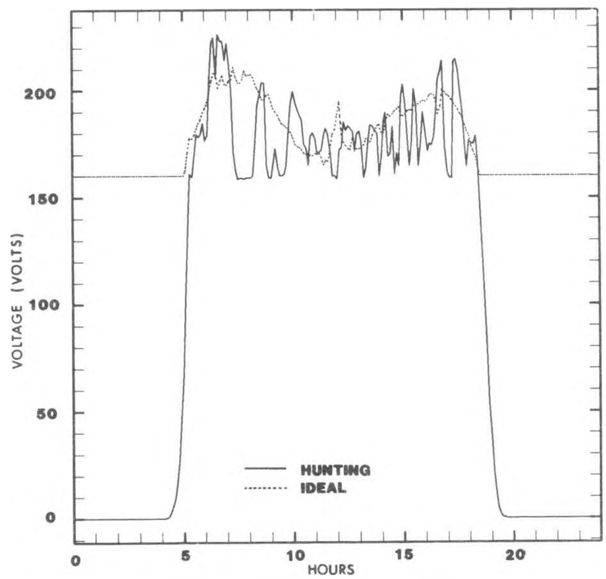

Fig. 47. Measured and predicted optimum array operating voltage for the Westinghouse PV array with maximum-power tracking.

4.9.2 Pilot-Cell Voltage Control

The pilot-cell voltage control strategy, described earlier, was implemented in all the Abacus inverters in December 1981, and has been more successful than its predecessor, the maximum-power tracker. Figure 48 shows, for a clear day, the measured voltage for the Westinghouse array, along with the predicted maximum-power voltage. The two voltage curves are much closer than those previously shown for the maximum-power-tracking control. The discrepancy at sunrise is due to the fact that the simulation "wakes up" instantly, but the inverter requires at least 750 watts of available dc power before start-up is attempted. Figure 49 compares the measured and predicted Westinghouse array power for this same day. The predicted maximum dc energy production for the day is 18.6 kWh, and the actual measured value was 18.2 kWh, a difference of less than 3%.

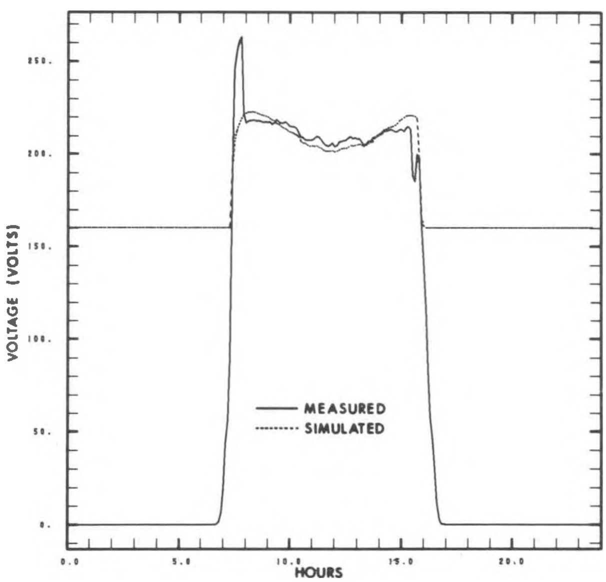

Fig. 48. Measured and predicted optimum array operating voltage for the Westinghouse array with pilot-cell control.

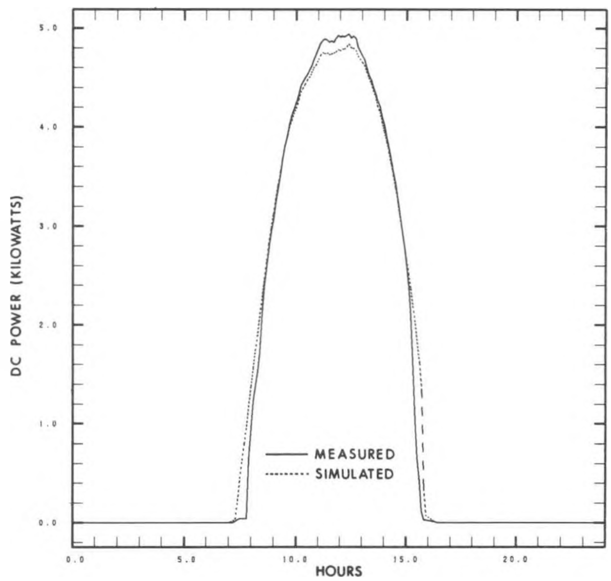

Fig. 49. Measured and predicted Westinghouse array power for one day with pilot-cell voltage control.

The pilot cell has proven able to approximate an ideal maximum-power-point tracker quite well. For a discussion of problems with this approach discovered during periods of snow cover, see Section 4.10.

4.10 PV System Insolation Utilization

The Abacus and Gemini power conditioners in the prototype systems have differing requirements for determining when to wake up and shut down. Ideally, a power conditioner would be able to utilize each day all available dc power from the PV array from the first moment of measureable sunlight to the last. In reality the inverters have dc voltage, current or power cut-offs, or thresholds below which no dc-to-ac power conversion takes place. In section 2.2.2, these threshold values were described. Clearly, the higher the dc power threshold the shorter the operating hours and the lower the daily energy production.

Due to the relatively large dc threshold of the Abacus inverters--approximately 750 watts--these units have failed to operate on many low irradiance days when the Gemini inverters were operating. Additionally, system start-up on clear days is delayed until the necessary power is available, and nighttime shut-off occurs earlier for the Abacus-equipped systems than for the Gemini-equipped systems.

One index of the systems' ability to use the available insolation is the insolation utilization efficiency. This quantity is defined as the ratio of the insolation on the array surface while the system is operating to the total insolation. This efficiency may be calculated over a period of one or more days.

Figure 50 shows the insolation utilization efficiency for the five systems during the month of January 1982. Note that periods of snowcover throughout the month will tend to lower the utilization efficiencies, but should affect all systems approximately equally. As can be seen, the Abacus-equipped systems have a significantly lower utilization efficiency than the Gemini-equipped systems. On the clearest, cloudless days the utilization efficiency of the Gemini systems is typically 99.9%, and the Abacus systems 99.0%. When days with low sunlight are averaged in with the clear days, however, the difference in the two inverters becomes pronounced.

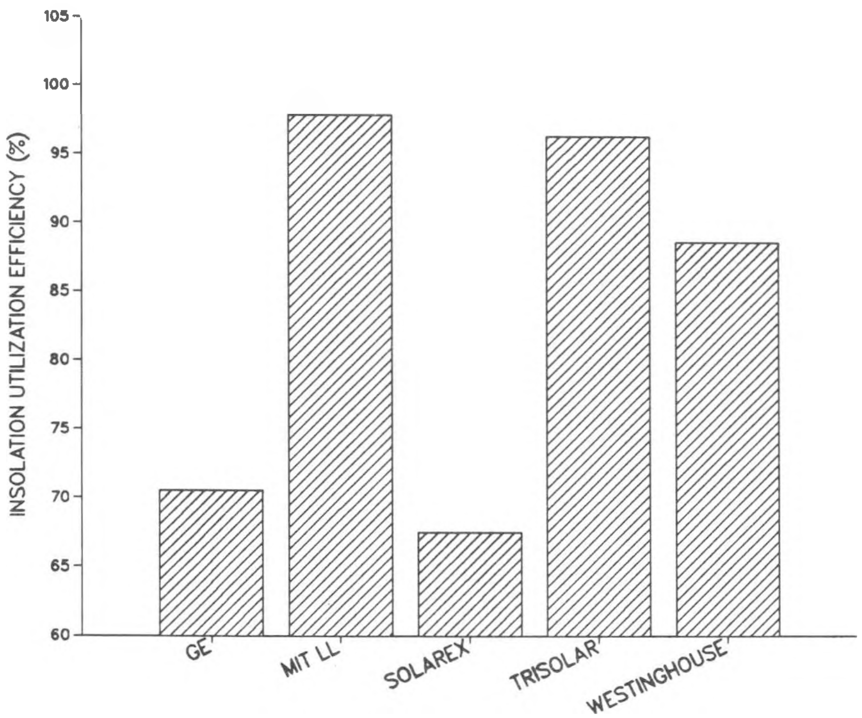

Fig. 50. Insolation utilization efficiency for prototype systems in January.

4.11 Snow Experiences

Of the two regional Residential Experiment Stations, only the NE RES routinely experiences snow; during the winter of 1981-1982 a total of 62 inches of snow fell at the NE RES during 20 storms. The heaviest snowfall occurred on 6 December 1981 and totalled 17 inches. In addition, 14 inches of snow fell during a late season storm on 6 April 1982.

The opportunities to observe the effect of snowfall on the performance of the PV systems were many this past winter. It was observed that the five snow-covered PV arrays shed snow at different rates and that the mechanisms involved are complexly interrelated--for example, array tilt angle, surface geometry, heat loss through the prototype's roof, wind speed and direction, ambient temperature, moisture content of the snow, solar irradiance intensity.

The major concern in snow-cover periods is the amount of PV energy that is "lost" due to partial or total obscuration of the array. Since the MIT LL array was observed to be among the last arrays in each storm to shed snow cover completely, it was studied over a three-day period in January 1982 to quantify the PV system energy lost in a worst-case situation.

On 23 January 1982, there was a moderate (4-inch) snowfall over the course of the day, which completely covered all the PV arrays. The following day was cloudy and very cold, with no snow; no systems were operating. On 25 January 1982, however, the sky was clear all day, the snow began to slide off the arrays, and the PV systems were operating at least part of the time. Figure 51 shows a plot of the predicted PV system output power for the MIT LL prototype and the actual measured output over the course of this day. As the figure shows, the actual output was approximately 10% of the predicted, no-snow output. The difference between the two is significant and is attributable exclusively to the blanket of snow covering most of the array. Note that snow is being shed from the array over the course of the day, consequently the peak measured system power output occurs approximately two hours after solar noon.

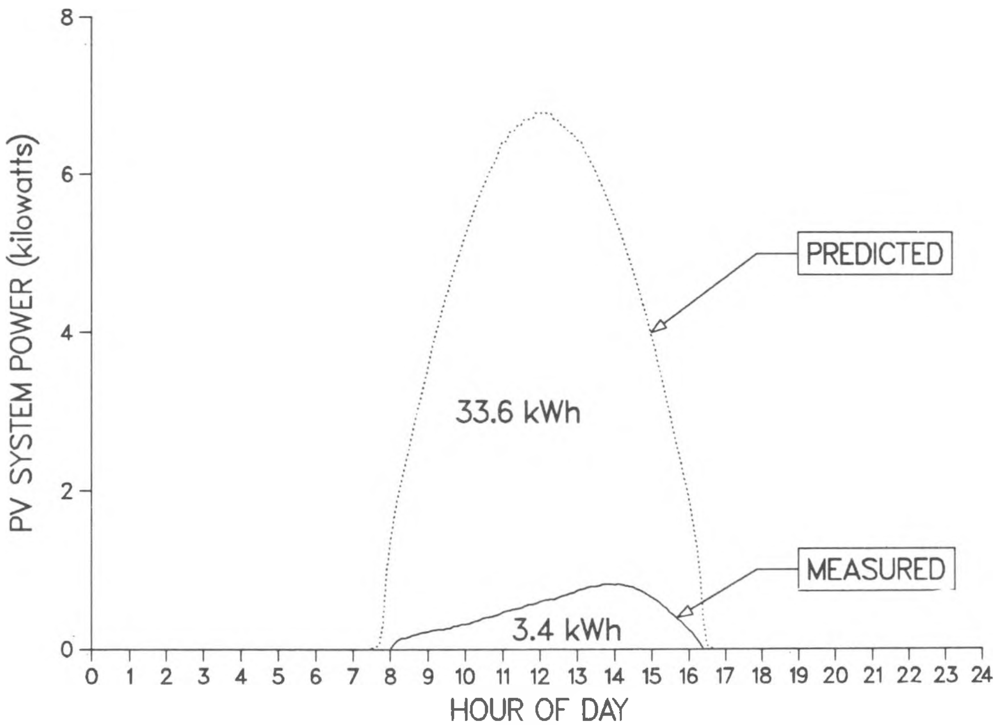

Fig. 51. Plot showing predicted and measured MIT LL array power for one day of partial snow cover (25 January 1982).

Figure 52 is a similar plot for 26 January 1982, which was also a cold, clear-sky day. Note that progressively more array area is becoming cleared of the snow. Total measured system output was approximately 30% of the predicted clear-array output. On the following day, 27 January 1982, the array was completely cleared of snow by noontime, and output for the remainder of the day was as predicted.

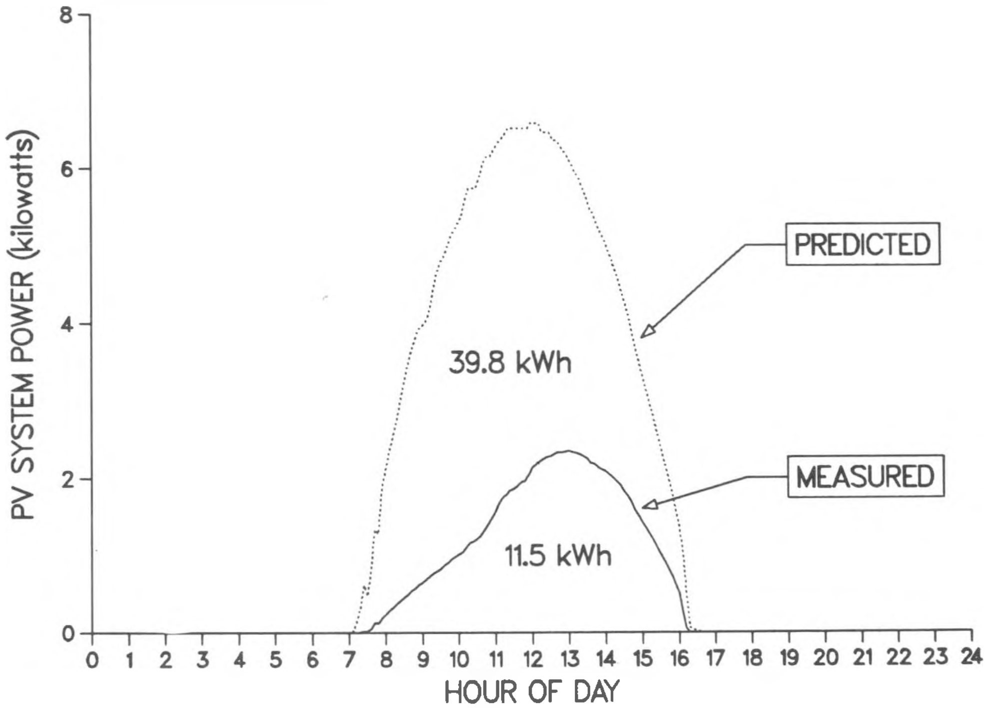

Fig. 52. Plot showing predicted and measured MIT LL array power for one day of partial snow covering (26 January 1982).

At the time of the late-January snow storm, the prototypes using the Abacus inverters were all operating with a pilot-cell-to-control-system start-up, array voltage control and system shutdown. In essence, the Abacus-equipped systems monitor the output of a single roof-mounted solar cell to judge the conditions for system control. In the case of the General Electric prototype system, the pilot cell is located along the west edge of the PV array, and is among the last sections of the array to be uncovered. Consequently, the system does not attempt to turn on until the pilot cell is uncovered and indicating adequate turn-on sunlight conditions, which has been observed to be as many as two days after a substantial portion of the PV array has been cleared of snow. However, if the pilot cell were to be uncovered while a large fraction of the array remained snow covered, attempts at system start-up would repeatedly fail due to the lack of available array power. In either case, control of the system via a pilot cell is difficult and nonoptimal.

5.0 SYSTEM PERFORMANCE DURING EXTREME OPERATION

In addition to routine system operation and tests of routine system functions, a series of extreme-condition tests were planned for the prototype systems. Such tests, described in Reference 19, include short-circuiting of the PV array, dousing a hot array with cold water, shadowing portions of the array to induce hot-spots, and imposing extreme ac and dc voltages on the power conditioner. The array shadowing has been completed at this writing.

For this test, rubber masks were cut to the size of the individual solar cells in each of the five arrays. During the period 17 July 1981 through 5 August 1981, five cells in each array were covered with the masks, and system operation continued as normal. Prior to placement of the masks, and again immediately after the masks were in place, I-V curves of the arrays were generated.

At the end of the three-week period, additional I-V curves were measured both before and after removal of the masks. In the TriSolarCorp, Westinghouse and MIT LL arrays, no change in the array performance, as measured before and after the test period, was observed. On the General Electric array, however, significant degradation of the array fill factor was noticed. It was at this time that the ten failed modules in the array were located, as described in Section 4.4. None of the ten failed modules had been part of the shadowing experiment; each of the previously shadowed modules was fully functional. In light of this discovery, it was decided that the module failures occurred during the period of the shadow test, but not as a direct result of it.

6.0 MONITORED HOUSE LOAD DATA

As noted in Section 1.0, the primary quantities measured every five seconds at each of the five monitored houses are the electrical load power, the line voltage and the currents. The power consumption values and the voltage and current readings are processed to yield 6-minute averages. These variables furnish a complete portrait of the residential electrical loads, from the standpoint of PV system design.

Figure 40 (Section 4.2) shows a sample daily load power profile for Monitored House 4 (MH4); the day shown is 23 November 1981. Also shown on the plot is the power output of the TriSolarCorp prototype PV system for comparison. Not unexpectedly, the load profile exhibits large peaks in the morning, around noon, and in the evening (probably associated with cooking). At other times the on-off duty cycle of a refrigerator may be seen. Clearly, for a detailed accounting of the underlying constituent appliances of this load, a daily log of appliance usage by the occupants is needed. Such information is not available, however, and the precise contributors to the load can only be surmised.

At the time of this writing a project is under way to analyze and characterize individual appliance loads in an attempt to identify the constituents of a residential composite load from 5-second load power data.

Among the features of interest in this load profile is the fraction of the total daily load which occurs during the hours of PV system power generation, i.e., sunhours. For the load profile in Figure 40, the total load is 17.8 kWh, and only 4.8 kWh (approximately 27%) of this occurred during sunhours. The daily sunhours load fraction depends upon many factors and is observed to vary markedly from weekday to weekend day, and from season to season.

Figures 53 through 57 show the average daily load of the monitored houses, along with the fraction of the load occurring during sunhours. Note that the sunhours load fraction is largest in the summer, when the daylight hours are longest and the loads are typically smallest.

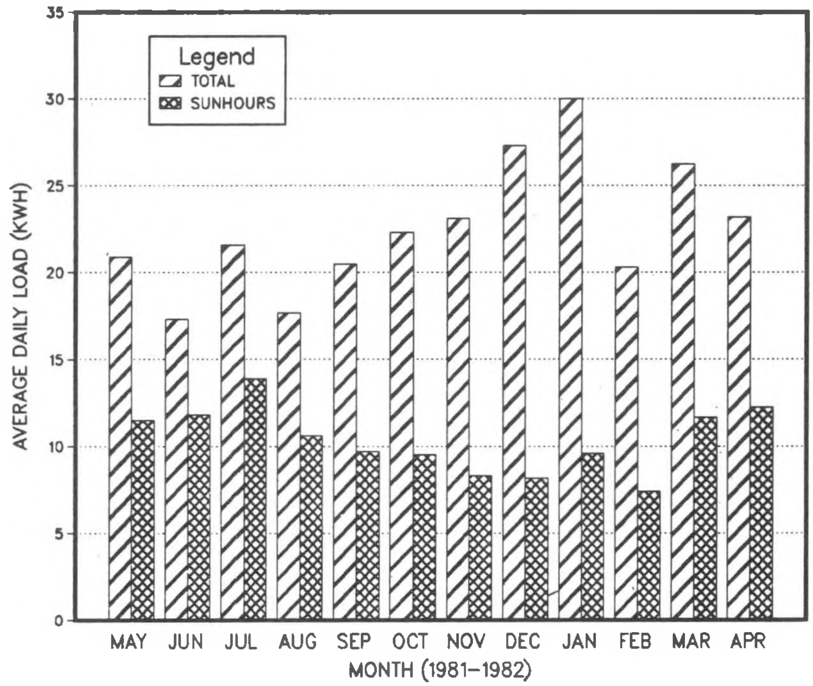

Fig. 53. Monitored House 2 electrical load summary.

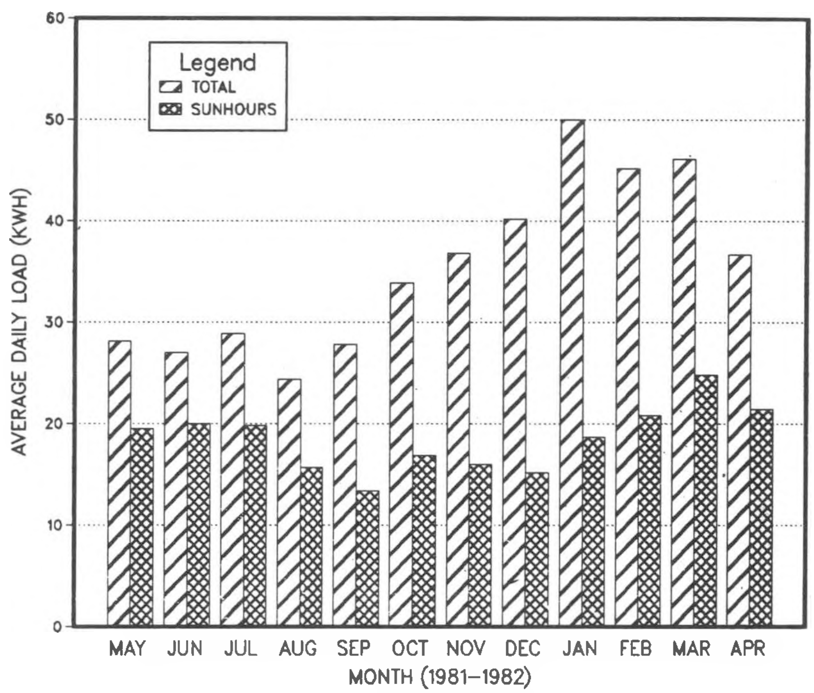

Fig. 54. Monitored House 3 electrical load summary.

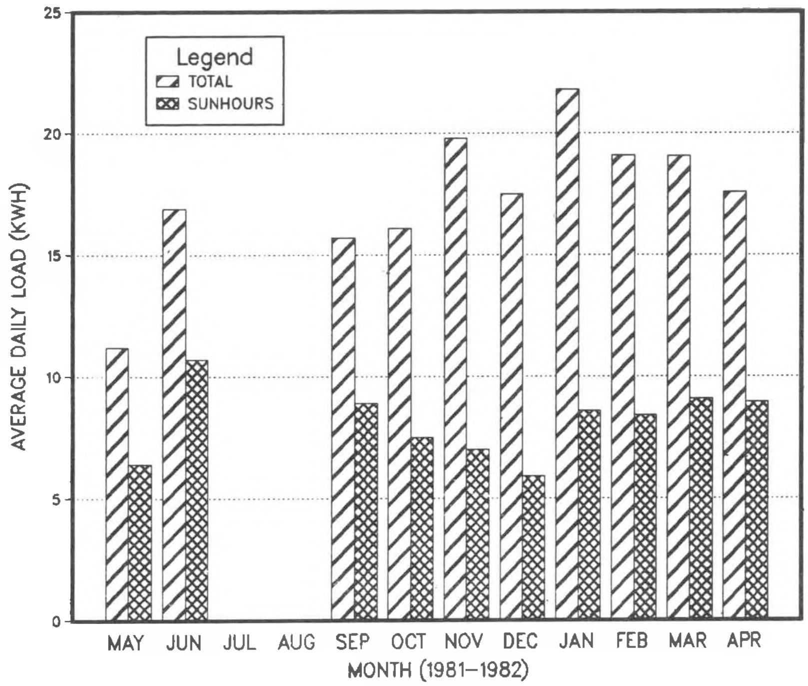

Fig. 55. Monitored House 4 electrical load summary.

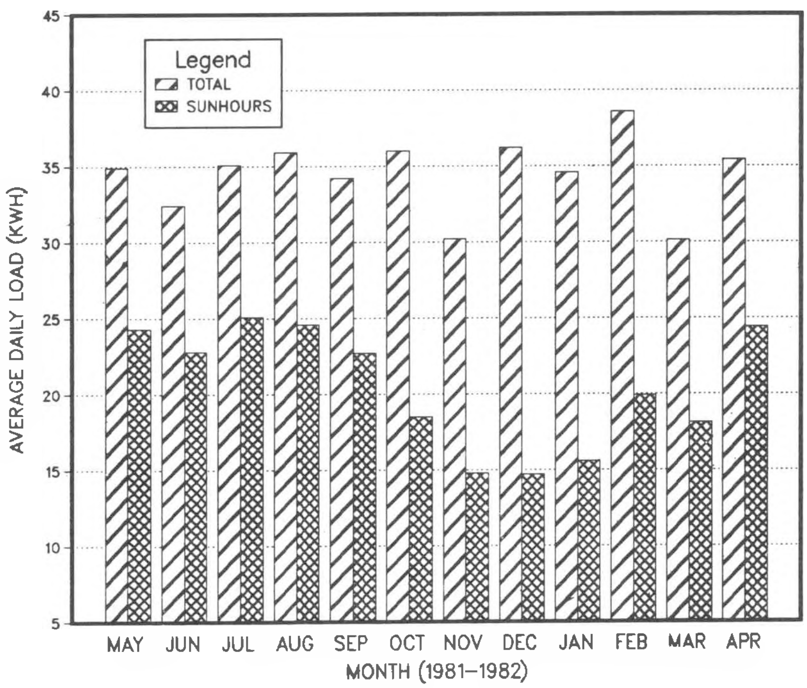

Fig. 56. Monitored House 5 electrical load summary.

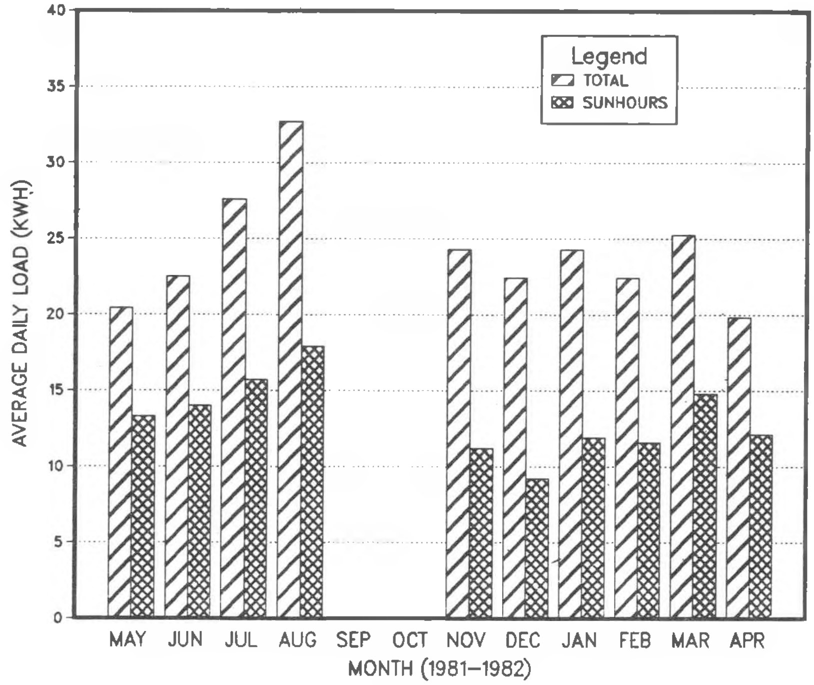

Fig. 57. Monitored House 6 electrical load summary.

As discussed in the introduction to this report, it is not possible to obtain data which are truly representative of an average residence, since there are only five houses being monitored as part of the NE RES project. Instead, data for the actual residences are presented to show several examples of measured loads which are of value in understanding the electrical interaction of a PV system and a house.

Monitored House 2 (MH2), whose average daily loads are typically neither the highest nor the lowest among the five monitored houses, has been selected for summarizing additional residential load data.

Figures 58 and 59 show 24-hour average weekday and weekend day load profiles for MH2 based upon data collected for the period May 1981 through April 1982. The average weekday energy consumption was 22.3 kWh and weekend consumption 25.2 kWh.

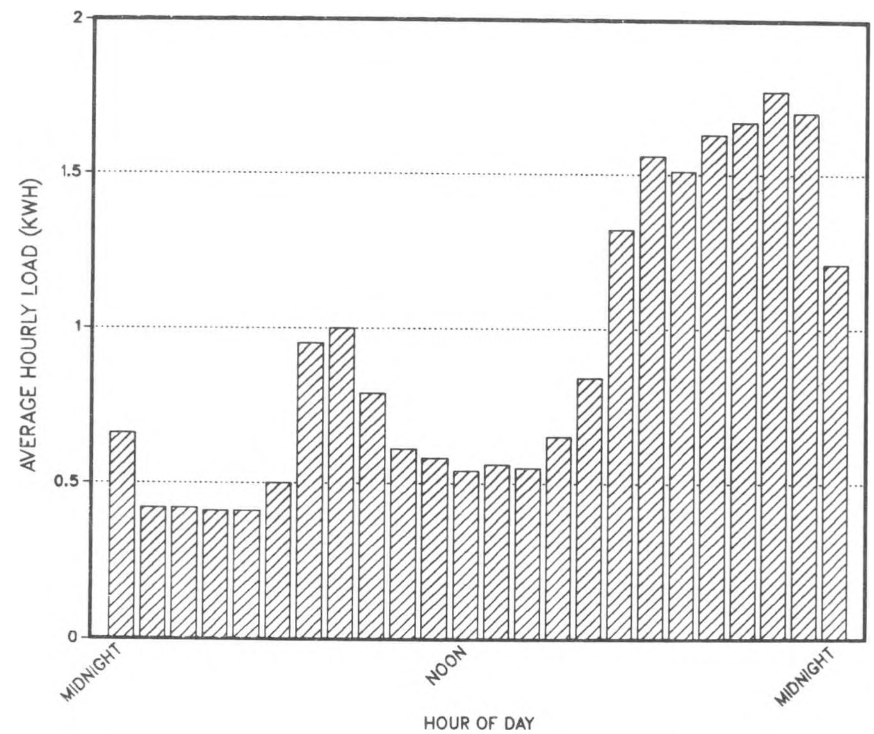

Fig. 58. Monitored House 2 average weekday load profile.

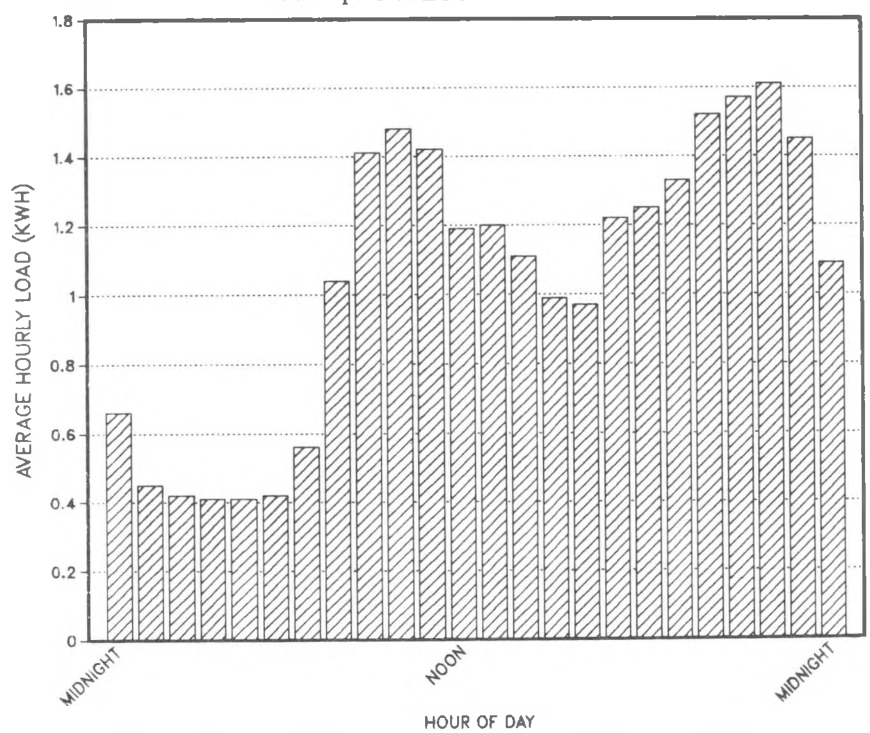

Fig. 59. Monitored House 2 average weekend day load profile.

7.0 METEOROLOGICAL STATION DATA SUMMARY

The meteorological station at the NE RES measures the following quantities every five seconds: total horizontal irradiance, total direct normal irradiance, ultraviolet direct normal irradiance, ambient temperature, wind velocity, precipitation and ambient dew-point temperature. These quantities (excluding precipitation) are processed to result in 6-minute average values. These data are presented below, and summarize the weather conditions to which the NE RES and prototype systems were exposed.

Figure 61 shows the average daily total horizontal insolation for each month, May 1981 through April 1982. For comparison, long-term average values for Boston (Logan Airport) are also shown (20). Similarly, Figs. 62, 63 and 64 show the average ambient temperature, the maximum and minimum ambient temperatures, and wind speed for the NE RES site (36). The monthly total precipitation is shown in Fig. 65.

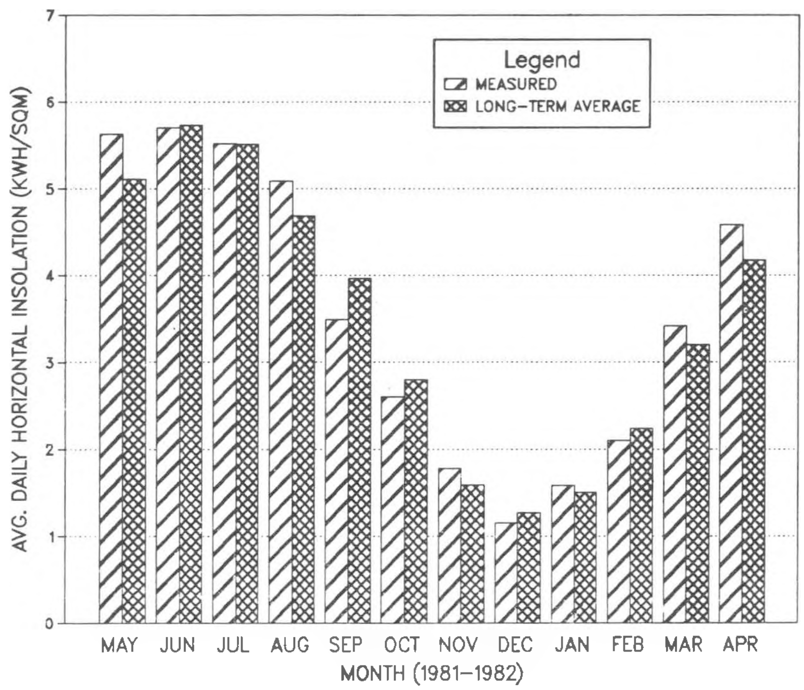

Fig. 61. Average daily horizontal insolation at the NE RES, and long-term average insolation for Boston.

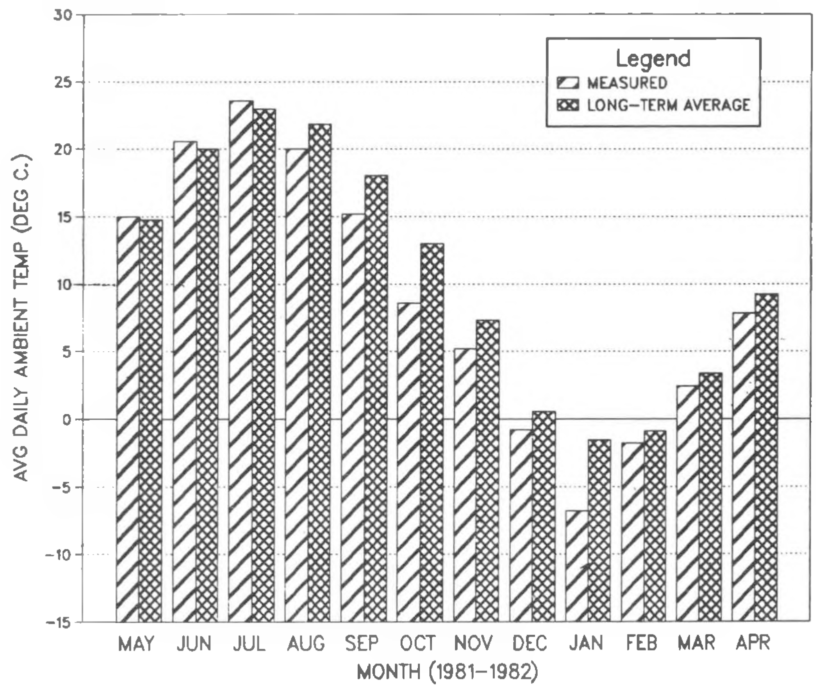

Fig. 62. Average daily ambient temperature at the NE RES, and long-term average for Boston.

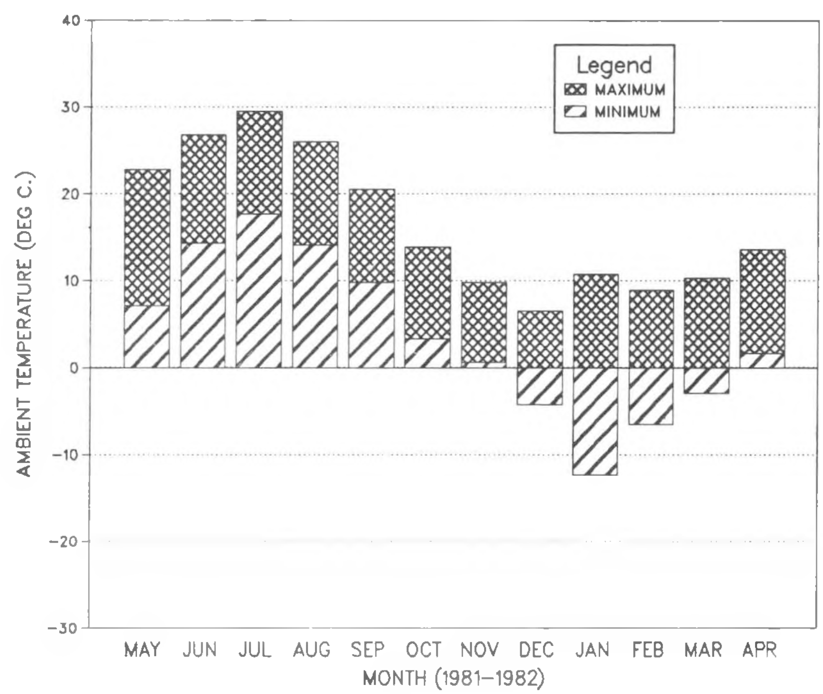

Fig. 63. Average daily maximum and minimum ambient temperatures at the NE RES.

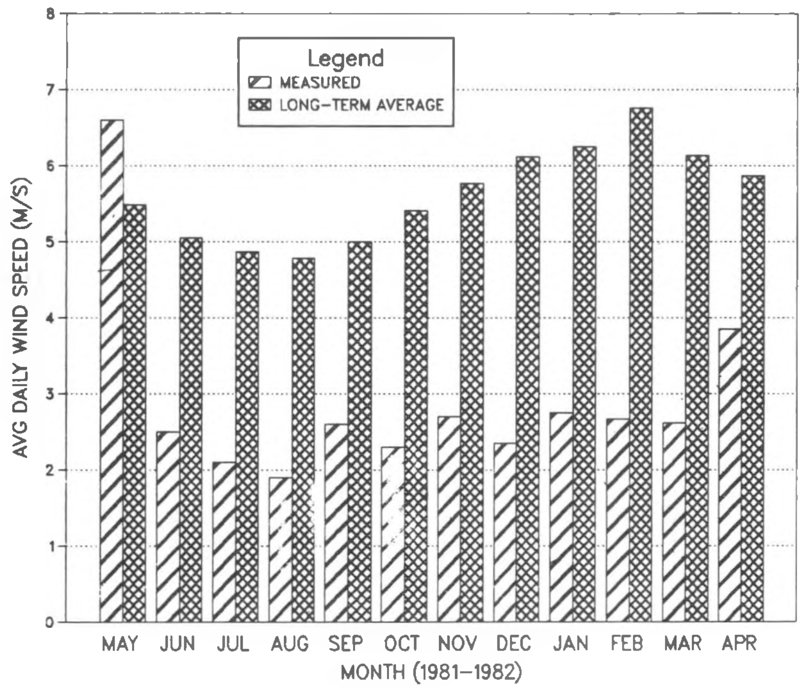

Fig. 64. Average daily wind speed at the NE RES, and long-term average windspeed for Boston.

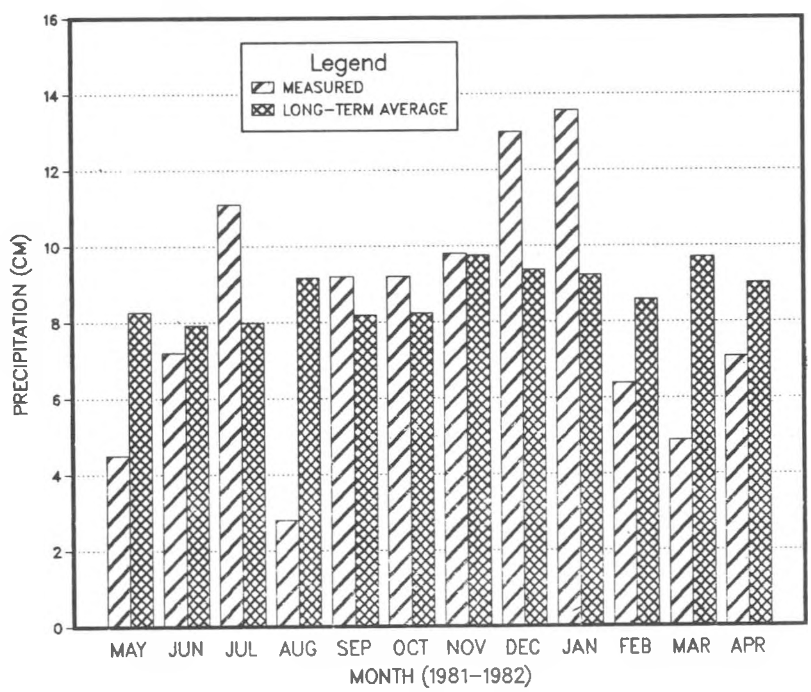

Fig. 65. Total monthly precipitation at NE RES, and long-term average precipitation for Boston.

8.0 PERFORMANCE PROJECTIONS--SIMULATIONS

The five prototype systems at the NE RES have been analytically modeled, and the models verified against the measured system performance. With these models, computer-based performances for the prototype systems may be simulated using any available meteorological data--for example, the measured and recorded data at the NE RES, or the often used SOLMET TMY data.

The utility of simulations is that given a stream of appropriate weather data as the driving function, an accurate estimation of the performance of any of the prototypes can be calculated. Since a full year's worth of measured system performance data is not available for all five prototypes, simulation provides a means for predicting performance for a typical or average year so that comparisons among systems can be made. Additionally, the simulation can be used to judge the effect of varying the system parameters--e.g., array tilt angle, array area, and voltage control strategy--on the system performance.

The following section describes the simulation methodology, and the remaining sections present simulation results.

8.1 General Framework for Simulation

The general framework for the simulation of PV prototype energy systems that has been developed at MIT LL utilizes TRNSYS, a computer simulation program package developed at the Solar Energy Laboratory of the University of Wisconsin.

For simulation purposes, each PV system is divided into four major functional components, which are individually described with computer models:

1. A simple, time-dependent, thermal model of an array. This computes cell temperature, given irradiance, ambient temperature and wind speed.
2. A model of an array's dc-current-voltage characteristics as a function of irradiance and cell temperature.
3. Models of the electrical characteristics of the dc-voltage control at the interface between the power conditioner and PV array.
4. Models of power conditioner ac output, given the dc input.

A TRNSYS-compatible subroutine has been written for each of these components. Each of the component models and the entire TRNSYS simulation have been well calibrated and verified against measured thermal and electrical performance of the prototype systems at the NE RES. References 37 and 38 provide a thorough discussion of the thermal and electrical modeling of the PV systems.

The simulation requires complete specification of the parameters identifying a specific system, in addition to weather data (ambient temperature, wind speed, and irradiance), which drives the simulation and determines the system performance.

The thermal model, which calculates PV cell operating temperature, assumes that the equilibrium cell temperature varies linearly with irradiance. As Reference 38 describes in detail, the slope of the cell temperature-versus-irradiance curve is a function of wind speed and decreases as the wind speed increases. A particular value is calculated by an exponential interpolation between three known points. These points were determined by measurements made on the prototype PV arrays. The temperature calculated in this way is the "steady-state cell temperature," the temperature that the array would reach in thermal equilibrium. Based on an exponential model of temperature change, a simple formula is used to determine the dynamic cell temperature as a function of the calculated steady-state temperature and a previous value of the dynamic cell temperature. The electrical properties of the array are modeled by a subroutine which requires as inputs cell temperature, tilt irradiance, and array operating voltage, and provides as outputs the corresponding array current and power. The basis for this routine is the TRW model (39) of a PV array current-voltage characteristic at a specified irradiance and temperature. The JPL model (40) is used for translating the I-V curve to other irradiances and cell temperatures.

The voltage at which an array operates is determined by the power conditioner to which it is connected. The Abacus inverters, as originally configured, utilized a maximum-power-point-tracking circuitry which would hunt for the array voltage that maximizes array power. In all the Abacus units this was changed, however, to a pilot-cell control strategy whereby the array operating voltage is maintained at a value directly proportional to the open-circuit voltage of a single pilot cell. The Gemini inverter approximates the maximum power voltage by imposing a simple linear I-V relationship upon the array. When prototype systems incorporating a Gemini inverter are simulated, the array operating voltage is determined by a voltage-control subroutine (see Section 4 for details of the voltage control). When prototype systems involving an Abacus inverter are simulated, an ideal maximum-power-point tracker is assumed. This is not indicative of the actual Abacus operating characteristics, as discussed in Section 4.8.

The output of the inverter is determined as a function of array voltage and power. Characteristic curves of inverter efficiency versus array power for a range of dc voltages were determined by measurement, as shown in Section 2.2.2.

8.2 Simulated Prototype System Annual Energy Production

Figures 66 through 70 compare the annual dc and ac energy production for the five prototype systems assuming operation in four cities: Boston, New York, Caribou (Maine), and Washington, D.C. In all cases SOLMET TMY meteorological data were used. The systems perform best in Washington, D.C., which receives the highest annual insolation of the four sites. It should be noted that no system outages or performance degradation effects, such as soiling or module failures, were included in the one-year simulations. The results, therefore, are slightly optimistic (representative of mature, high-reliability products), but are nonetheless valid for comparison.

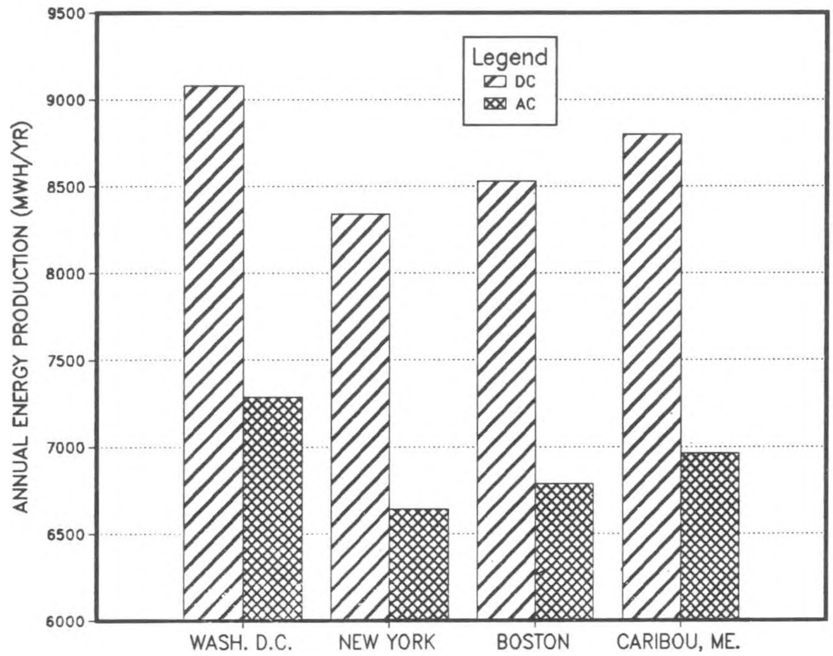

Fig. 66. Simulation results: General Electric prototype system energy production in four cities.

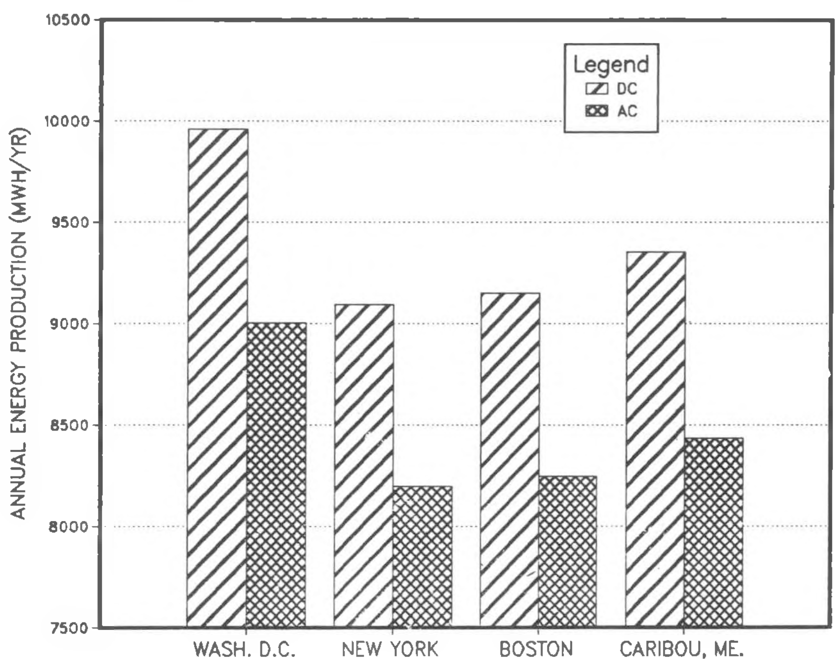

Fig. 67. Simulation results: MIT LL prototype system energy production in four cities.

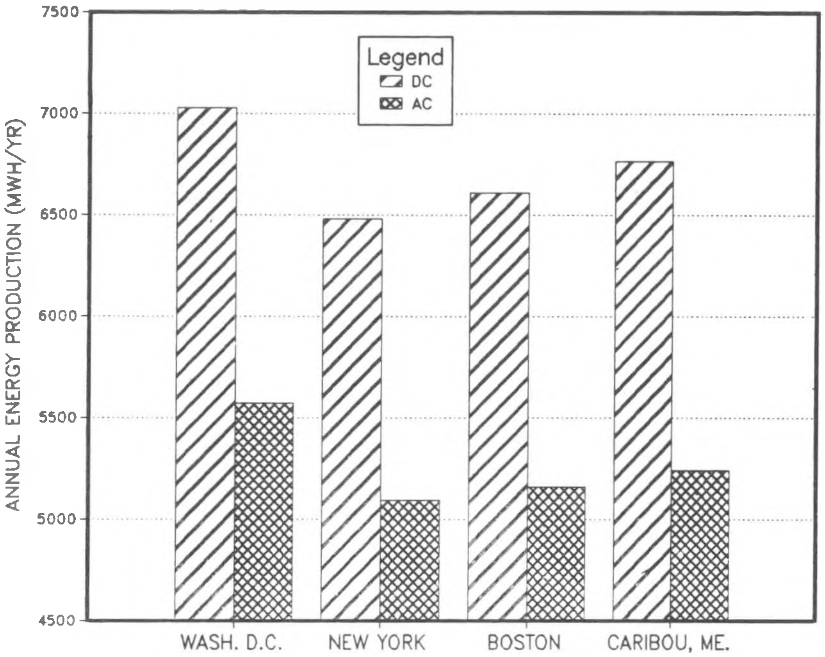

Fig. 68. Simulation results: Solarex prototype system energy production in four cities.

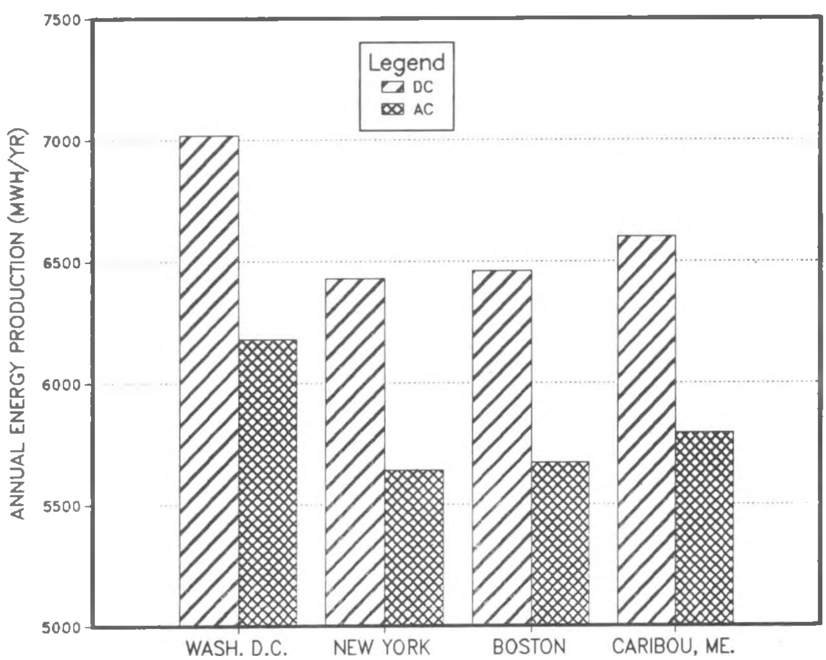

Fig. 69. Simulation results: TriSolarCorp prototype system energy production in four cities.

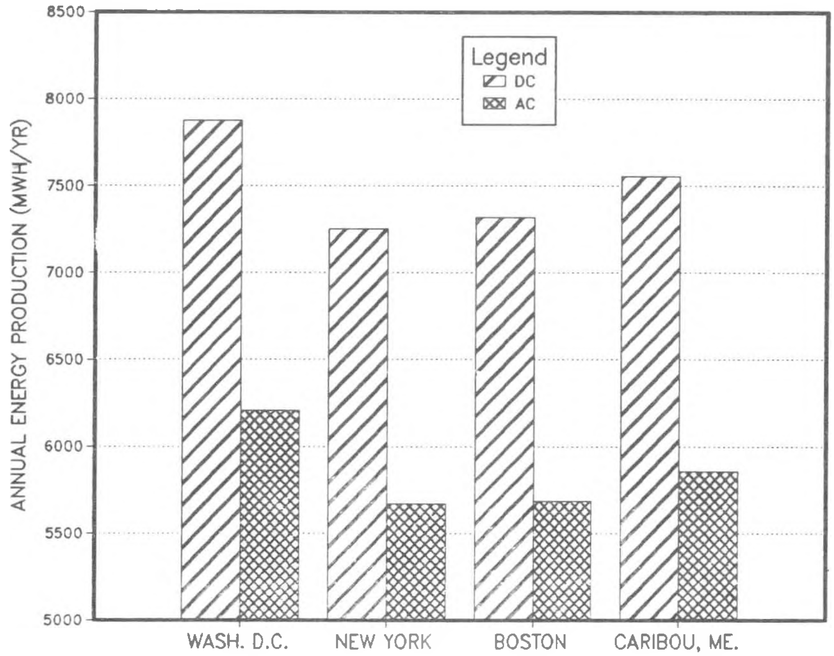

Fig. 70. Simulation results: Westinghouse prototype system energy production in four cities.

8.3 Sensitivity Study: Array-Mounting Method

The actual array operating temperature for any of the prototype systems is difficult to predict accurately using a strictly theoretical approach. The greatest success in predicting array operating temperature was achieved by analyzing performance data for each of the systems and utilizing the empirical relationship between the cell temperature rise constant and wind speed. This constant is strongly dependent upon both the array-mounting method and the thermal properties of the modules themselves. In order to perform a sensitivity study on array-mounting methods, that is, to predict the effect on performance of mounting a given array in several different ways, requires either empirical data for one product which has actually been mounted in these different ways or utilization of an analytical approach. Since the former is not available, the latter was employed to generate the results presented here.

The TriSolarCorp prototype system was chosen for study. A one-year simulation was performed using SOLMET TMY data for Boston, and the TriSolar-Corp system assuming three different array-mounting approaches: integral mount with an attic fan (as the system actually operates), direct mount, and standoff mount. The operating temperature of the array in each of the three mounting configurations was calculated from the theoretical models; the TriSolarCorp array I-V curve was modeled by the TRW equations (39), and models of the actual Gemini voltage control and efficiency were used. Figure 71 shows the resultant annual dc and ac energy production predicted by the simulation.

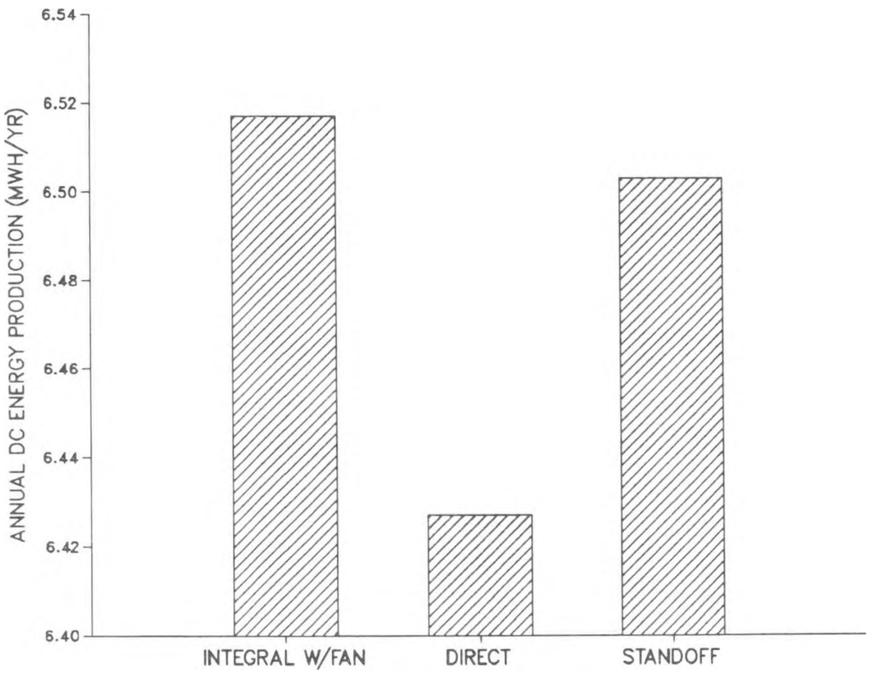

Fig. 71. Simulated TriSolarCorp PV system output for three array-mounting methods.

Note that although the integral-mount PV array results in the greatest system output, it is obtained at the expense of powering an attic fan. The annual parasitic energy demand of such a fan may well eliminate any gains in PV system output due to the lower operating temperatures. The difference in annual energy production between the direct and the integral mounts is only 90 kWh (dc), or 1.3% of the total output. However, PV cell operating temperature is known to be a critical factor which influences performance degradation mechanisms, and ultimately determines PV cell lifetime. For this reason, as well as to improve cell efficiency, low-temperature operation is preferred.

Future study will be directed toward validation of these analytical predictions through additional experimentation at the NE RES.

8.4 Sensitivity Study: Array Tilt Angle

Again using the TriSolarCorp prototype system, a sensitivity study of array tilt angle was conducted by computer simulation. The PV array was assumed to be facing due south; the tilt angle was varied from 0° (horizontal) to 90° (vertical).

Figure 72 shows a plot of the simulated annual PV system output as a function of array tilt angle for the Boston location using TMY meteorological data. Though the actual prototype has a tilt angle of 45°, the figure shows that a tilt angle of approximately 30° yields the highest energy production. However, the total annual tilted insolation and annual system energy production vary less than 3% for tilt angles between 20 to 50°.

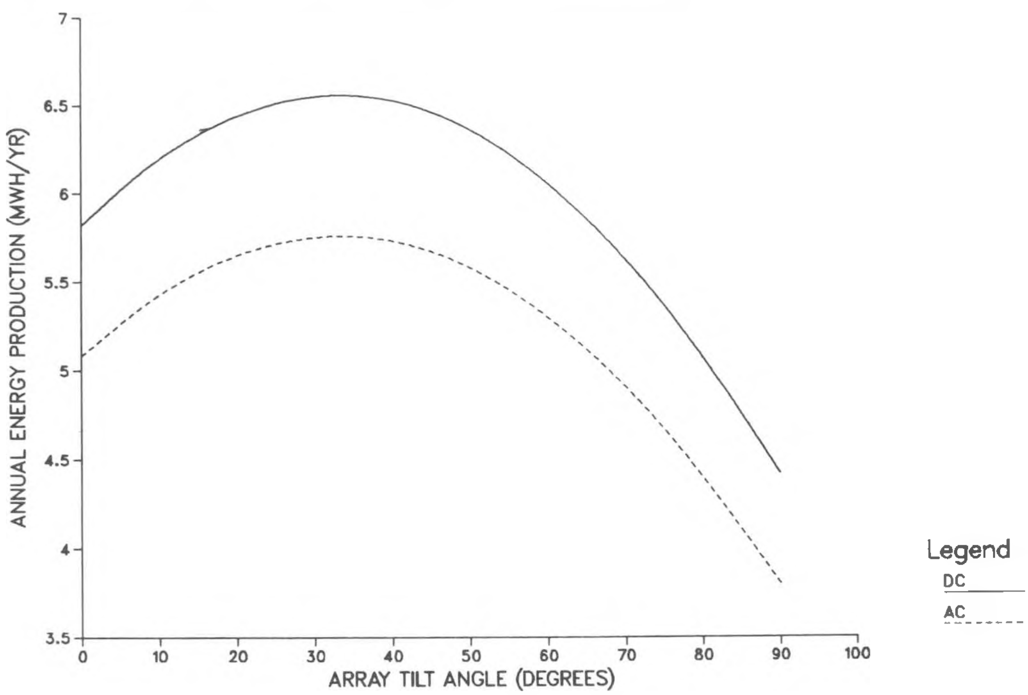

Fig. 72. Simulated TriSolarCorp PV system output as a function of array tilt angle.

8.5 Sensitivity Study: Array-Voltage Control

Three array-voltage control strategies have been investigated, and their effect on the annual energy output of the TriSolarCorp prototype predicted. As before, the Boston TMY weather data were used, and the system is assumed to be using the Gemini inverter in all cases. The three voltage control strategies studied are: ideal (no losses) maximum-power-point tracking, fixed-voltage operation, and the fixed-voltage-range strategy employed by the Gemini and described in Section 4.8.

Figure 73 shows the simulated annual system dc and ac energy production for each of these control options. As expected, ideal maximum-power-point tracking results in the highest energy output. Also note that fixed operation at any voltage between 186 to 203 volts will result in higher annual system energy output than the present Gemini control strategy.

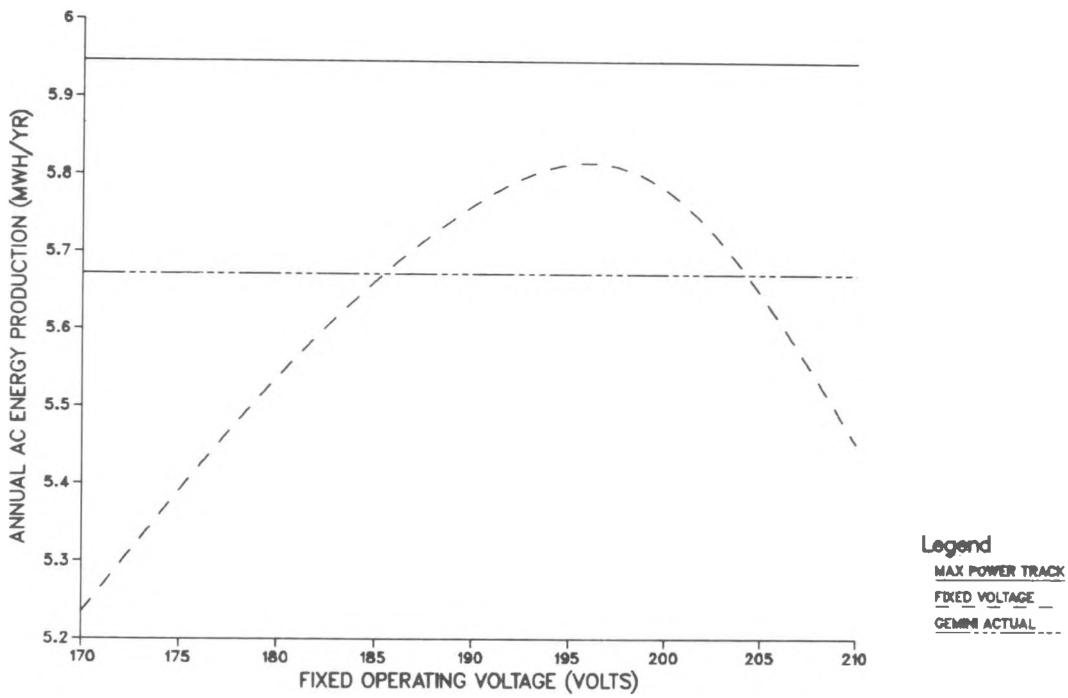

Fig. 73. Simulated TriSolarCorp PV system output as a function of fixed operating voltage. Maximum power tracking and actual Gemini control system outputs are also shown.

The difference in annual energy output between ideal maximum-power-point tracking and operating at the best fixed voltage is less than 2%.

Reference 35 provides an expanded discussion of voltage control strategies and their impact on system energy production.

9.0 PROTOTYPE RESIDENTIAL PV SYSTEMS COST/WORTH

The following sections present a summary of the prototype systems as-built costs and case-study projections of their worth.

9.1 Prototype Systems Cost Summary

Each of the prototype system suppliers was given a cost-reporting form on which to record the expenses incurred in system construction. The costs associated with the construction of the residential PV systems were divided into four categories covering all materials and labor for installation and wiring of the PV array and power-conditioning unit.

Tables 13-17 present the cost data for the five NE RES prototype systems. In all cases a standard labor rate of $15/hr. was assumed. Additionally, for those PV arrays which displace some or all of the standard roof materials--plywood sheathing, tar paper or roofing felt, and shingles--a materials and installation credit was given, as follows:

plywood sheathing---0.66 $/ft^2
roofing felt--------0.17 $/ft^2
asphalt shingles----0.92 $/ft^2.

TABLE 13
GENERAL ELECTRIC PROTOTYPE SYSTEM COST SUMMARY

Photovoltaic Array Data:

Peak Rated Power(kWp) 6.6

Mounting Method Direct

Total Area(m^2) 76.8

Active Modules Area(m^2) 76.8

	Unit Data	Total Cost	Normalized Cost($/watt)
Photovoltaic Array Cost ($)	$136275	$136275	$20.65
Array Installation Cost:			
Materials ($)	$ 857	$ 857	$ 0.13
Labor(man-hours)	57 Mh	$ 855	$ 0.13
Roofing Credit ($)	$ 727	($ 727)	($ 0.11)
Array Wiring Cost:			
Materials ($)	$ 848	$ 848	$ 0.13
Labor(man-hours)	37 Mh	$ 555	$ 0.08
Power Conditioner Cost ($)	$ 12090	$ 12090	$ 1.83
PC Installation/Wiring Cost:			
Materials ($)	$ 445	$ 445	$ 0.07
Labor(man-hours)	26 Mh	$ 390	$ 0.06
	TOTAL	$151588	$22.97/Wp

TABLE 14
MIT LINCOLN LABORATORY PROTOTYPE SYSTEM COST SUMMARY

Photovoltaic Array Data:

Peak Rated Power(kWp) 6.8

Mounting Method Standoff

Total Area(m^2) 91.0

Active Modules Area(m^2) 84.9

	Unit Data	Total Cost	Normalized Cost($/watt)
Photovoltaic Array Cost ($)	$84000	$84000	$12.35
Array Installation Cost:			
Materials ($)	$ 4937	$ 4937	$ 0.73
Labor(man-hours)	150 Mh	$ 2250	$ 0.33
Roofing Credit ($)	--	--	--
Array Wiring Cost:			
Materials ($)	$ 532	$ 532	$ 0.08
Labor(man-hours)	144 Mh	$ 2160	$ 0.32
Power Conditioner Cost ($)	$ 3180	$ 3180	$ 0.47
PC Installation/Wiring Cost:			
Materials ($)	$ 12	$ 12	~ 0
Labor(man-hours)	6 Mh	$ 90	$ 0.01
	TOTAL	$97161	$14.29/Wp

TABLE 15
SOLAREX PROTOTYPE SYSTEM COST SUMMARY

Photovoltaic Array Data:

Peak Rated Power(kWp) 5.0

Mounting Method Standoff

Total Area(m^2) 71.0

Active Modules Area(m^2) 68.4

	Unit Data	Total Cost	Normalized Cost($/watt)
Photovoltaic Array Cost ($)	$73260	$73260	$14.65
Array Installation Cost:			
Materials ($)	$ 1413	$ 1413	$ 0.28
Labor(man-hours)	301 Mh	$ 4515	$ 0.90
Roofing Credit ($)	--	--	--
Array Wiring Cost:			
Materials ($)	$ 1034	$ 1034	$ 0.21
Labor(man-hours)	24 Mh	$ 360	$ 0.07
Power Conditioner Cost ($)	$12800	$12800	$ 2.56
PC Installation/Wiring Cost:			
Materials ($)	$ 27	$ 27	$ 0.01
Labor(man-hours)	3 Mh	$ 45	$ 0.01
	TOTAL	$93454	$18.69/Wp

TABLE 16
TRISOLARCORP PROTOTYPE SYSTEM COST SUMMARY

Photovoltaic Array Data:

Peak Rated Power(kWp) 4.8

Mounting Method Integral

Total Area(m^2) 47.2

Active Modules Area(m^2) 47.2

	Unit Data	Total Cost	Normalized Cost($/watt)
Photovoltaic Array Cost ($)	$155646	$155646	$32.43
Array Installation Cost:			
Materials ($)	$ 748	$ 748	$ 0.16
Labor(man-hours)	92 Mh	$ 1380	$ 0.29
Roofing Credit ($)	$ 901	($ 901)	($ 0.19)
Array Wiring Cost:			
Materials ($)	$ 371	$ 371	$ 0.08
Labor(man-hours)	80 Mh	$ 1200	$ 0.25
Power Conditioner Cost ($)	$ 3522	$ 3522	$ 0.73
PC Installation/Wiring Cost:			
Materials ($)	$ 50	$ 50	$ 0.01
Labor(man-hours)	40 Mh	$ 600	$ 0.13
	TOTAL	$162616	$33.88/Wp

TABLE 17
WESTINGHOUSE ELECTRIC PROTOTYPE SYSTEM COST SUMMARY

Photovoltaic Array Data:

Peak Rated Power(kWp) 5.1

Mounting Method Integral

Total Area(m^2) 71.0

Active Modules Area(m^2) 69.2

	Unit Data	Total Cost	Normalized Cost($/watt)
Photovoltaic Array Cost ($)	$57720	$57720	$12.03
Array Installation Cost:			
Materials ($)	$ 7985	$ 7985	$ 1.66
Labor(man-hours)	230 Mh	$ 3450	$ 0.72
Roofing Credit ($)	$ 1411	($ 1411)	($ 0.29)
Array Wiring Cost:			
Materials ($)	$ 819	$ 819	$ 0.17
Labor(man-hours)	174 Mh	$ 2610	$ 0.54
Power Conditioner Cost ($)	$16000	$16000	$ 3.33
PC Installation/Wiring Cost:			
Materials ($)	$ 36	$ 36	$ 0.01
Labor(man-hours)	1 Mh	$ 15	~0
	TOTAL	$90046	$17.66/Wp

In the tables, the costs are shown normalized by the peak rated array power, a standard format for reporting PV system costs. The total system costs ranged from \$14.29 to \$33.88 per peak watt. Note that design-related expenses are not included in these tables. In all cases, the PV array dominates the total system cost, accounting for 68% (Westinghouse) to 96% (TriSolarCorp) of the total. Of the five systems, the lowest balance-of-system (BOS) cost, which includes all cost items except the PV array purchase, was for the TriSolarCorp prototype (\$1.45/Wp). The other systems, in order of increasing BOS' cost, are: MIT LL (\$1.94/Wp), General Electric (\$2.32/Wp), Solarex (\$4.04/Wp) and Westinghouse Electric (\$5.63/Wp).

The second largest constituent of the system cost is the power conditioner purchase; the Abacus inverter contributes between \$1.83/Wp (General Electric) and \$3.33/Wp (Westinghouse) to the total; the Gemini inverter contributes less than \$1.00/Wp (\$0.73/Wp, TriSolarCorp and \$0.47/Wp, MIT LL).

If both major system cost contributors (the PV array and the power conditioner) are excluded, and a revised BOS' cost figured, the lowest BOS' cost system is TriSolarCorp (\$0.73/Wp). The other systems are ranked as follows: General Electric (\$0.94/Wp); MIT LL (\$1.47/Wp); Solarex (\$1.48/Wp); and Westinghouse (\$2.30/Wp). The BOS' figures are useful for determining the core of the system cost, which is not likely to be significantly reduced by improvements in technology or increased manufacturing volume. The General Electric and TriSolarCorp prototypes have low BOS' costs, primarily because there is little or no metal framing required to mount their arrays, and installation proceeded smoothly and efficiently with a well-prepared crew. Systems requiring extensive array-mounting material--for example, standoff support rails or multimodule frames--result in the highest BOS' costs (Westinghouse, \$2.30/Wp; Solarex, \$1.48/Wp; MIT LL, \$1.47/Wp).

9.2 Prototype Systems Worth Analysis

In the following sections, two indicators of the prototype residential PV systems worth are presented. The first is a comparison of the past year's monthly utility bills for each of the monitored home owners with the monthly bills assuming they had been served by a PV system over the same period.

The second economic worth indicator discussed is the life-cycle cost of delivered energy to the monitored houses assuming the presence of a PV system.

9.2.1 Monthly Utility Bills

The monthly utility bills for the five monitored houses over the period May 1981 to April 1982 have been calculated for the hypothetical situation where the TriSolarCorp PV system was assumed to be located on each of the houses.

The actual rates for residential customers of the Boston Edison Company, the utility serving the monitored houses, were used. Table 18 explains the rate structures present during this period. For energy sold back to the utility, the Massachusetts Department of Public Utilities has established a one-for-one buyback rate. On a monthly basis, however, no credit will be given for any net energy sold back to the utility. Under these rates a homeowner's bill can never be less than the zero-kWh usage amount.

TABLE 18

METHOD OF CALCULATION OF TOTAL MONTHLY BOSTON EDISON UTILITY BILL

TOTAL MONTHLY BILL

Total Monthly Bill = Base Rate Charges + Summer Surcharge + Fuel Charges + Conservation Service Charge

BASE RATES

- Compute monthly base rate charges according to rates listed below.

Monthly kWh Usage	Rate
0-15 kWh	$2.48
next 35 kWh	7.12 ¢/kWh
next 50 kWh	5.47 ¢/kWh
next 50 kWh	4.46 ¢/kWh
next 150 kWh	4.08 ¢/kWh
next 84 kWh	3.71 ¢/kWh
next 616 kWh	4.96 ¢/kWh
all kWh over 1000	1.92 ¢/kWh

SUMMER SURCHARGE

- During months July - October inclusive add 1.92 ¢/kWh to all monthly usage above 350 kWh.

FUEL CHARGES

- Compute fuel charges for total monthly kWh usage according to monthly rates listed below:

Month	Fuel Charge
MAY 1981	5.1927 ¢/kWh
JUN 1981	5.1927 ¢/kWh
JUL 1981	3.7656 ¢/kWh
AUG 1981	4.5673 ¢/kWh
SEP 1981	4.5673 ¢/kWh
OCT 1981	4.5673 ¢/kWh
NOV 1981	4.6984 ¢/kWh
DEC 1981	4.6984 ¢/kWh
JAN 1982	5.0391 ¢/kWh
FEB 1982	5.7327 ¢/kWh
MAR 1982	5.7327 ¢/kWh
APR 1982	5.7327 ¢/kWh

CONSERVATION SERVICE CHARGE

- A conservation service charge of $0.19 is included in each monthly bill, to help offset the cost of energy audits.

Figures 74-78 show the monitored house monthly bills calculated both with and without the presence of the PV system. In several instances the net monthly energy exchange was from the PV residence to the utility, resulting in the lowest monthly bill possible ($2.67). Table 19 summarizes the annual energy and cash flows for the five monitored houses. The average annual utility bill was reduced by approximately $550, which represents approximately 40-60% of the total bill without the PV system.

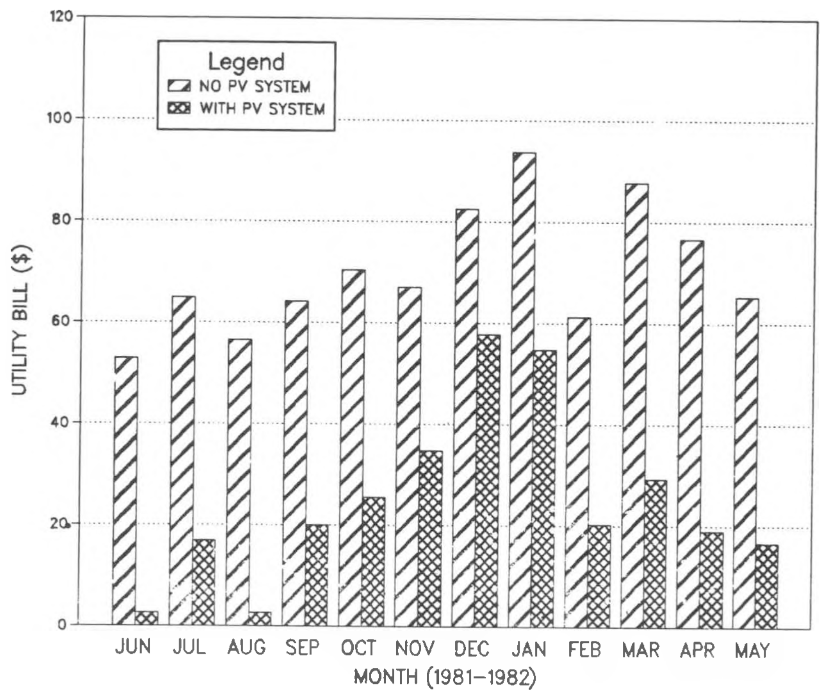

Fig. 74. Hypothetical utility bill: Monitored House 2 with TriSolarCorp PV system.

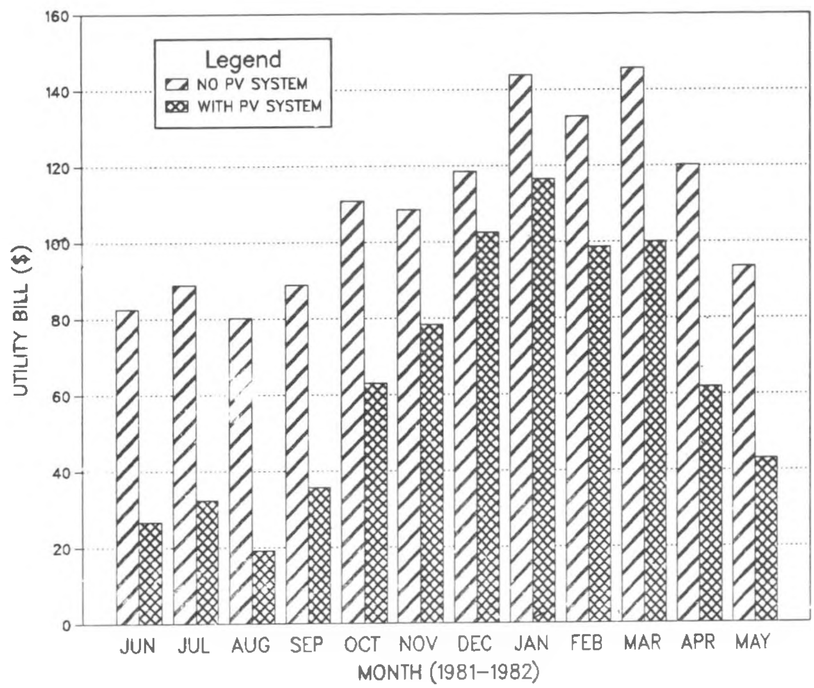

Fig. 75. Hypothetical utility bill: Monitored House 3 with TriSolarCorp PV system.

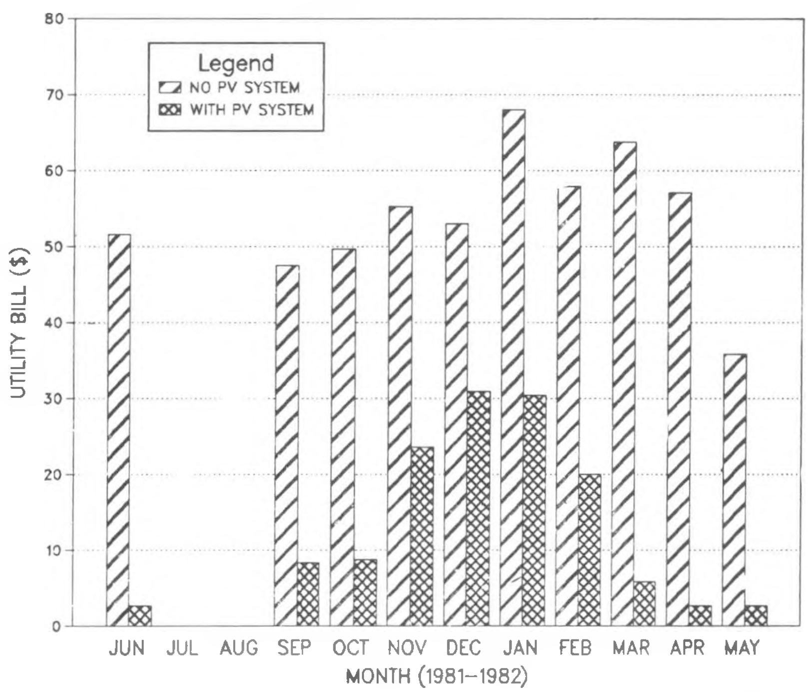

Fig. 76. Hypothetical utility bill: Monitored House 4 with TriSolarCorp PV system.

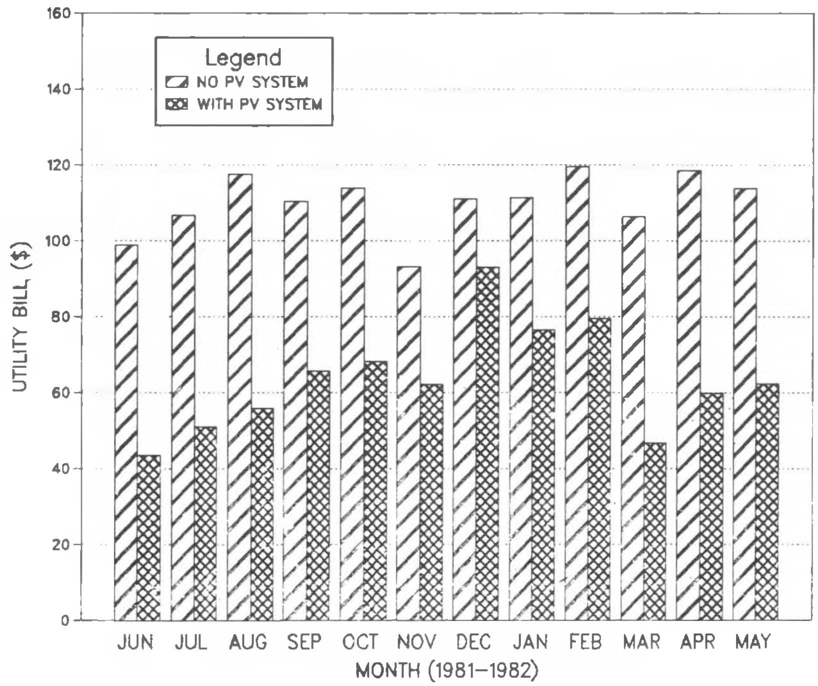

Fig. 77. Hypothetical utility bill: Monitored House 5 with TriSolarCorp PV system.

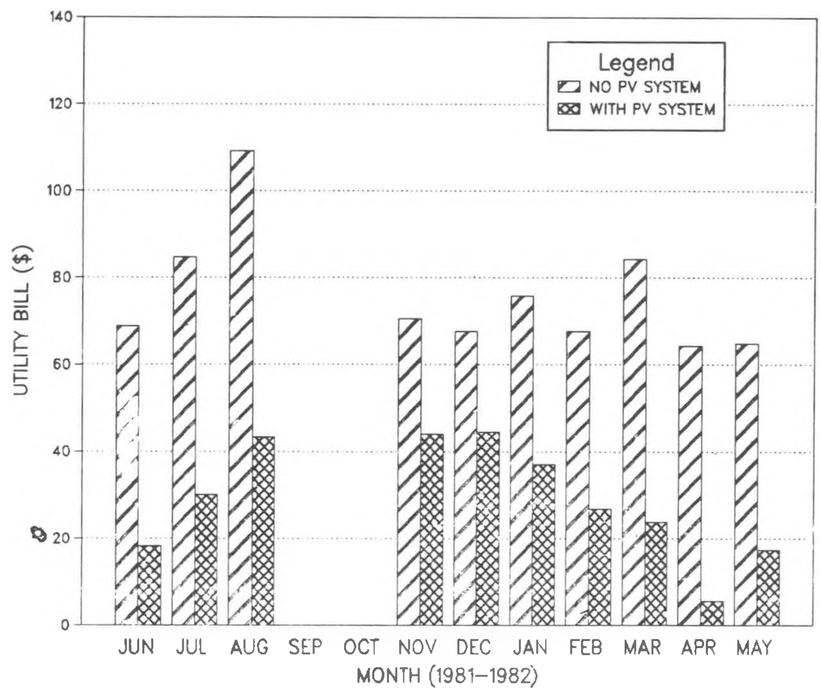

Fig. 78. Hypothetical utility bill: Monitored House 6 with TriSolarCorp PV system.

TABLE 19

HYPOTHETICAL MONITORED HOUSE UTILITY BILLS:
WITH AND WITHOUT 4.8 kWp PV SYSTEM

MONITORED HOUSE	WITHOUT PV SYSTEM		WITH PV SYSTEM				
	Total Load (kWh)	Annual Bill ($)	Energy to Utility (kWh)	Energy From Utility (kWh)	Net Total Energy Exchange (kWh)	Annual Bill ($)	Annual Savings ($)
MH2	8243.	843.19	3873.	6598.	2725.	299.96	543.23
MH3	12914.	1314.05	3328.	10677.	7349.	777.90	536.15
MH4*	5265.	539.63	3250.	4131.	881.	135.95	403.68
MH5	12548.	1320.96	2798.	9898.	7100.	764.76	556.20
MH6*	7373.	757.90	2947.	5712.	2765.	290.71	467.19

*Totals for 10 months of data only.

Lifecycle energy costs for the hypothetical PV-system-equipped monitored houses are presented in the following sections.

9.2.2 Lifecycle Energy Cost

The lifecycle energy cost expresses the levelized price of electricity, in ¢/kWh, delivered by a PV system over its lifetime. This quantity was calculated for each of the monitored houses, assuming they were equipped with the TriSolarCorp 4.8-kWp PV system. The methodology used to compute the lifecycle energy cost is taken from Appendix D of Reference 1. Tables 20 and 21 present the basic equations and baseline assumptions involved, and the hypothetical annual energy exchange for the five monitored houses is summarized in Table 22.

TABLE 20

PV SYSTEM LIFECYCLE ENERGY COST ANALYSIS BASIC EQUATIONS

Basic Equations

$$E_p = \left(\frac{FCR}{U \cdot S \cdot F}\right) C_t + \left(\frac{1}{U \cdot S}\right) OM$$

$$U = (1 - L_d) \left[1 - SB_f \ (1 - SB_r)\right]$$

$$FCR = b_1 + b_2 + CRF$$

$$CRF = k / \left[1 - (1 + k)^{-N}\right]$$

$$F = CRF \left(\frac{1 + g}{k - g}\right) \left[1 - \left(\frac{1 + g}{1 + k}\right)^{N}\right]$$

$$k = i_d \ (1 - T_m)$$

Definitions

E_p = Lifecycle PV system energy price (\$/kWh).

CRF = Capital recovery factor; a factor which converts a net present value sum to a series of payments in fixed dollars over a given period.

FCR = Fixed charge rate; a factor which converts an initial capital investment into a corresponding annual expense equivalent.

U = Utilization coefficient; the fraction of the PV system output which is effectively provided to the load.

F = A factor to convert a levelized energy price to a real energy price in constant dollars.

k = After-tax discount rate; the homeowner discount rate modified by the homeowner marginal tax bracket to yield the effective after-tax investment opportunity cost.

TABLE 21

PV SYSTEM LIFECYCLE ENERGY COST ANALYSIS ASSUMPTIONS

VARIABLE	DEFINITION	BASELINE VALUE
b_1	Property tax rate	0
b_2	Insurance rate	0.003
t_m	Homeowner's marginal tax bracket	0.35
g	General inflation rate	0.06
i_d	Homeowner's nominal discount rate	0.065
N	PV system lifetime	30 years
L_d	Rate of degradation of PV system output	0.08%/yr.
SB_f	Fraction of PV system output sold to utility	see Table 22
SB_r	Rate at which utility "buys" PV system output	1
S	Annual PV system output	see Table 22
C_t	Cost of PV system	160000.
OM	Annual operation and maintenance expense	$100.

TABLE 22

HYPOTHETICAL MH-UTILITY ENERGY EXCHANGE DATA

Monitored House	PV System Energy Production, S (kWh/yr)	Energy Sold to Utility (kWh/yr)	Sell-back Fraction, SBF
MH2	5519	3873	0.70
MH3	5565	3328	0.60
MH4*	5260	3900	0.74
MH5	5448	2798	0.51
MH6*	5529	3536	0.64

*Annual totals estimated by extrapolation of data for 10 months.

It is not the intent of this discussion to present the definitive PV system energy price calculations/projections, but rather to present the methodology by which levelized PV energy prices may be determined, to evaluate several hypothetical PV energy prices by making all the required assumptions, and to gain insight into the sensitivity of this calculation to several of the key variables.

The PV systems were assumed to have a 30-year lifetime. The energy provided in the first year was identical to the actual system performance during the (May 1981 to April 1982) 12-month period. Degradation of system output of 0.08%/year for all remaining years was assumed.

Figure 79 shows the levelized price of energy delivered by the 4.8-kW PV system for each of the monitored houses, using the baseline economic assumptions. The energy price is clearly very high using the actual price of this developmental PV system. Figure 80 shows the levelized energy price for MH2 with the 4.8-kWp PV system as a function of the system's purchase price. A family of curves is presented in the figure for a range of sell-back rates.

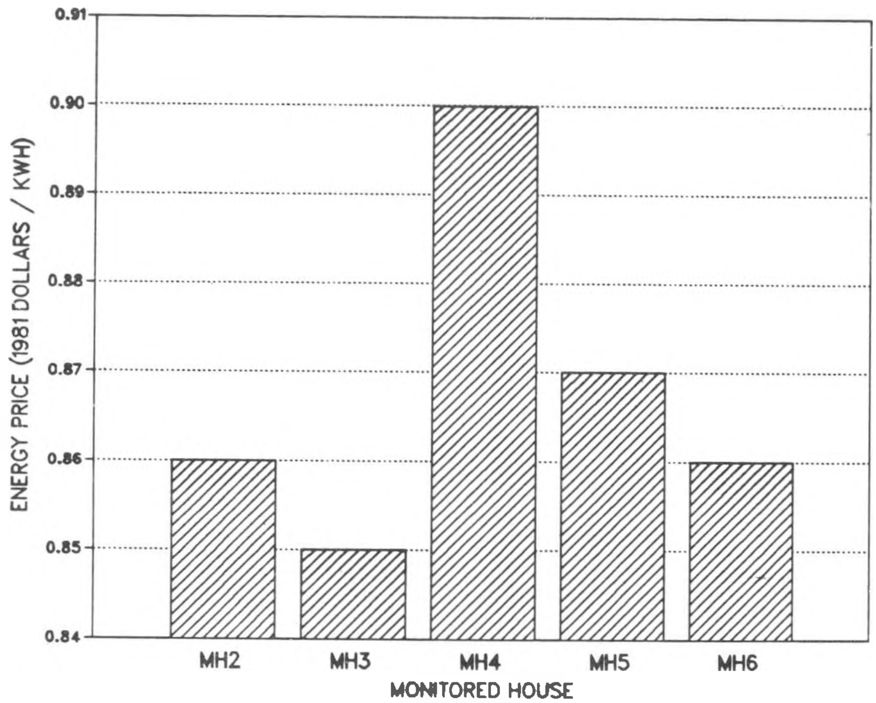

Fig. 79. PV system worth analysis: hypothetical levelized energy price resulting from placing the TriSolarCorp PV system on each monitored house.

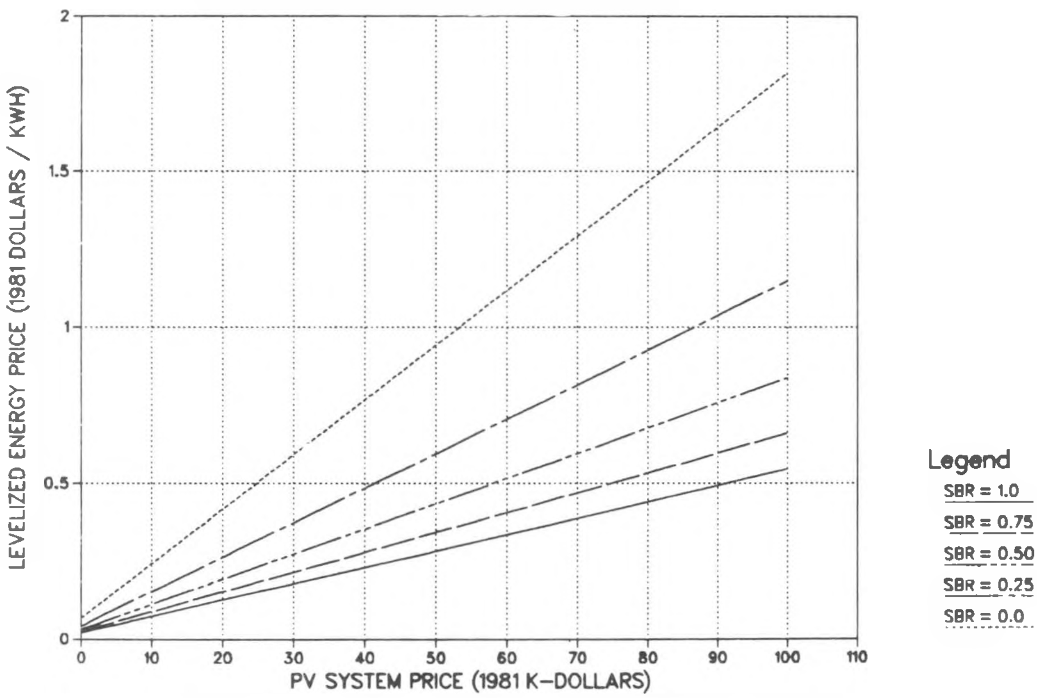

Fig. 80. PV system worth sensitivity: system cost and sell-back rate.

The lowest energy price is realized for the highest sell-back rate, as expected. Given a sell-back rate of 1.0 and a system price of $10,500, the U.S. DOE price goal for a 4.8-kWp system, the levelized PV energy price is $0.075/kWh--less than the present average Boston Edison rate. Of the five PV systems, the MIT LL prototype is the lowest cost (on a $/Wp basis) at $14.29/Wp. A 4.8-kWp PV system at that rate would cost approximately $70,000, which results in a levelized energy price of $0.39/kWh, approximately four times as costly as the present utility rate. However, the appropriate number with which to compare the PV system levelized energy price is not the present utility energy price but the average or levelized price of utility energy over the same 30-year period. To do so requires making assumptions about energy price inflation over this period. This has not been done, since it is believed that a credible set of assumptions regarding long-term future utility energy prices cannot be determined.

Figure 81 shows the sensitivity of the levelized PV energy price to system cost and system lifetime. From the figure it is clear that system lifetime must be at least twenty years to achieve a competitively low, delivered energy price.

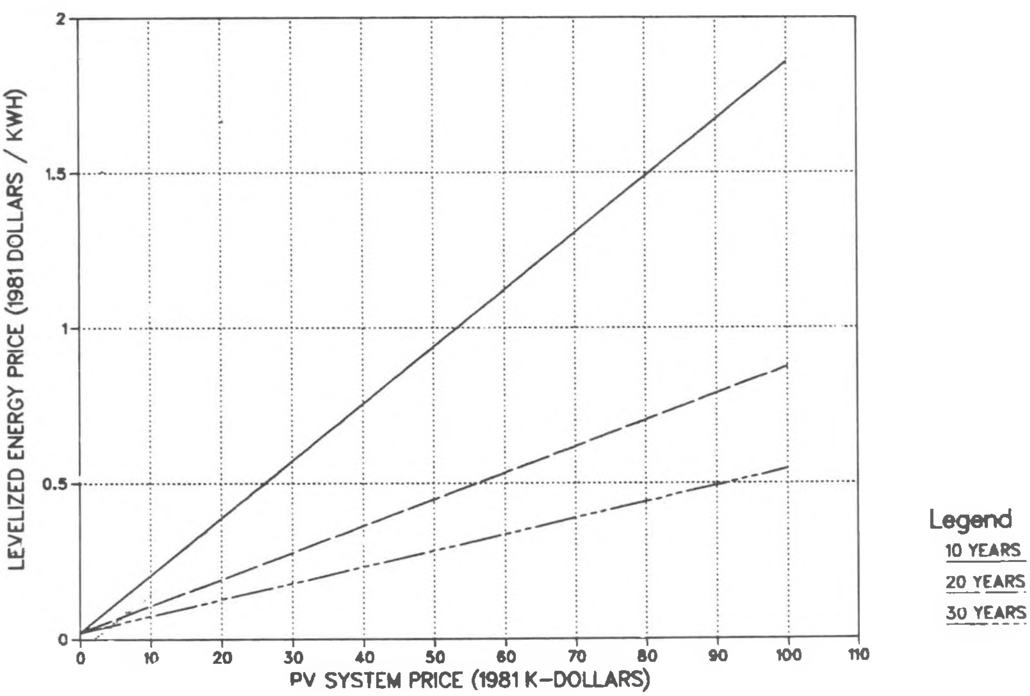

Fig. 81. PV system worth sensitivity: system cost and system lifetime.

10.0 RESIDENTIAL PV SYSTEM EVALUATION--LESSONS LEARNED

Over the past one and a half years of residential PV systems testing and evaluation, numerous insights have been gained into how the systems work, how they fail, and how often they do either. The five systems have been evaluated from engineering performance, safety and cost standpoints, and it is the intent of this entire report to present lessons learned from this activity.

What follows is a summary of some of the significant lessons learned at the NE RES. It provides a record of past experiences as well as directs attention to any system design weaknesses or areas where further study and experiment are required.

- The photovoltaic arrays are more reliable than the power conditioners to which they were originally connected. Further, most module failures are benign; that is, a system will continue to operate with a failed module.
- Some of the second-generation power conditioners, which were developed largely due to the deficiencies of those units originally operating in the prototype systems, appear to offer improved reliability and performance.
- The Abacus maximum-power-point tracker performed very poorly in actually following the PV array maximum power point. The pilot-cell control which replaced the maximum-power-point tracker is a superior array-controlling circuit.
- Ideal maximum-power-point tracking yields only marginal increases in annual PV energy production over fixed-voltage operation, as discussed in Reference 35, at the expense of additional circuitry and complexity.
- Array I-V curves are a fundamental measurement which must be made to characterize a PV array and also to diagnose a module failure condition. At present only laboratory-built devices are readily available to make I-V curve measurements.
- Determining the rating of a PV array is difficult and challenging given the variation in cell temperature across an array, the difficulty in measuring an accurate cell temperature, the uncertainty associated with using a pyranometer insolation reference, and the soiling of the array top surface.
- Array power degradation due to accumulation of natural airborne soilants over a one-year period is impossible to determine from I-V curve data, due to the measurement uncertainties mentioned above.

- The time required to locate a failed module in an array is highly dependent upon the array wiring configuration and the level of wiring accessibility. Arrays with a small number of modules and electrical access to each module (e.g., TriSolarCorp) are easier to diagnose than an array with a large number of modules and limited electrical access (e.g., General Electric).

- Maximum array power was measured in the months of February or March, and maximum energy production was measured in April or May. The maximum array power was as high as 1.3 times the peak rated power.

- Tilt insolation as high as 1.37 kW/m^2 has been measured at the NE RES and can be expected in other sites as well. Higher values have been measured (approaching 1.5 kW/m^2) at other MIT LL field sites.

- Array washing was accomplished easily by a professional window washer using standard equipment and procedures.

- Snow on the PV arrays is a common wintertime occurrence. Snow shedding occurs at unpredictable rates and in unpredictable patterns. Worst-case snow cover events resulted in reduced system output for two and a half days.

- Pilot-cell array control is vulnerable to occlusion of the pilot cell by snow. During array snow cover conditions, the pilot-cell-controlled systems often operated erratically or not at all, depending upon the relative cell/array snow cover.

- Snow infiltration into an attic space beneath a PV array did occur, but was a result of architectural design inadequacies, and not the fault of the PV array.

- One safety-related event was recorded at the NE RES during installation of the Solarex array. One workman was installing the Unistrut[R] frames on the roof which eventually would hold the Solarex modules. The frames were hoisted up to a staging platform and the pieces installed one at a time in a rectangular grid pattern. While on the staging, the workman was testing the uniformity of the frame rectangles by holding a module-sized sheet of glass up to each frame. The glass slipped, the workman tried to recover it, and both fell to the ground. The glass was broken and the workman bruised and shaken. The lesson learned here is simple--never work alone, and do not risk personal safety in order to save falling equipment.

- PV array operating temperatures vary widely among the five systems/mounting schemes. Among the future areas of investigation at the NE RES is the modification of array installations to enhance passive cooling.

- Minimizing materials reduces array installation costs dramatically. This is likely to be a necessary system feature to ensure future economic viability. Investigation of cheaper retrofit mounting methods should be pursued.
- Present PV system costs are dominated by the PV array price. This item has the greatest leverage over system economics.

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APPENDIX A

A REQUEST TO AN ELECTRIC ENERGY CONSUMER

As part of the national program to develop renewable energy sources, the U.S. Department of Energy is sponsoring a project aimed at the widespread use of solar electric power systems in houses during the late 1980s. These systems, known technically as photovoltaic systems, use solar cells to convert the sun's energy into direct current (dc) electricity, which, after being converted to alternating current (ac), can be used in the house exactly the same as the power supplied by the electric utility company. Massachusetts Institute of Technology Lincoln Laboratory is directing The Solar Photovoltaic Residential Project and plans to test experimental solar electric systems during the next few years.

In order to test these experimental systems in a realistic manner, we want to learn how electricity is used in typical houses in this area. We will monitor energy usage in several residences and hope you might be willing to participate. We would install some meters to monitor the electricity use, water flow and temperatures in your house and would provide a telephone line to send the information to our laboratory. This equipment would not interfere in any way with any use of your house.

If you are interested in participating, please fill out the enclosed form and mail it to us in the postage-paid envelope. At the end of the experiment, we will give you information about your use of energy and you will have participated in a program of national importance.

Name____Telephone________________

Address____

____Zip____________

My house is a

- ___ Single family detached residence
- ___ Apartment or condominium
- ___ Mobile home

Number of people usually living in the house

- ___ 1 or 2
- ___ 3 or 4
- ___ 5 or more

Adults working daytime hours (part or full time)

- ___ none
- ___ 1
- ___ 2 or more

House heating

- ___ Oil
- ___ Gas
- ___ Electric-baseboard
- ___ Electric-heat pump
- ___ Wood
- ___ Solar

Domestic hot water

- ___ Oil
- ___ Gas
- ___ Electric
- ___ Solar

Kitchen Cooking

- ___ Gas
- ___ Electric

Clothes Dryer

- ___ Gas
- ___ Electric

Air Conditioning

- ___ Central
- ___ Window

APPENDIX B

TERRESTRIAL PHOTOVOLTAIC SYSTEM POWER TEST PROCEDURE AND POWER PERFORMANCE RATING

1.0 SCOPE AND PURPOSE

This document provides a standard test procedure for measuring the electrical performance characteristics of installed, flat-plate residential and intermediate-size photovoltaic systems. The measurements described are divided into two sections: PV array measurement and power conditioning subsystem measurement. Electrical storage subsystems are not addressed here. Measurement results are used to determine both the system power output at peak and nominal rating conditions, according to procedures contained herein.

2.0 DEFINITIONS

- NOCT

The nominal operating cell temperature, NOCT, is defined as the average solar cell junction temperature for a module or array of modules installed in their working environment and operating under the following conditions:

1. Irradiance on module surface = 800 W/m^2
2. Ambient Air Temperature = 20°C
3. Electrically Open Circuited
4. Wind Speed = 1. m/s

- Peak Rating Conditions

Peak Rating Conditions are defined as:

1. Irradiance on module/array surface = 100 W/m^2
2. Air Mass 1.5 spectrum
3. Cell temperature = 25°C

- Nominal Rating Conditions

The Nominal Rating Conditions are defined as:

1. Irradiance on array surface = 1000 W/m^2
2. Air Mass 1.5 spectrum
3. Cell temperature = NOCT

2.1 Glossary of Terms

C_I	Current temperature coefficient
C_V	Voltage temperature coefficient
A	Constant in I-V curve model equation
B	Constant in I-V curve model equation
I	Current
I_{mp}	Max power current
I_{mpp}	Peak rated max power current
I_{sc}	Short-circuit current
I_{scp}	Peak-rated short-circuit current
k	Array temperature rise coefficient
L	Insolation
NOCT	Nominal operating cell temperature
P_{mpn}	Array NOCT rated maximum power
P_{mpp}	Array peak rated maximum power
P_{sn}	System NOCT rated maximum power
P_{sp}	System peak rated maximum power
R_s	Series resistance
T_a	Ambient temperature
T_c	Cell operating temperature
V	Voltage
V_{mp}	Max power voltage
V_{mpp}	Peak-rated max-power voltage
V_{oc}	Open-circuit voltage
η_{pscn}	Power conditioning subsystem efficiency at P_{mpn}
η_{pcsp}	Power conditioning subsystem efficiency at P_{mpp}

3.0 METHODOLOGY

This document applies to all utility interactive residential-sized PV systems.

3.1 Introduction

The method described here begins with measurement of the photovoltaic array current and voltage in order to characterize the shape of the current-voltage curve, determine the dependence of the array operating temperature on insolation, and determine the current and voltage temperature coefficients. Analytical expressions are used to describe the I-V curve, and translate it with both cell operating temperature and insolation. An additional linear relationship between cell operating temperature rise over ambient and insolation is used to predict array operating temperature under any set of conditions.

3.2 Fundamental Equations

The following equations are used to model an I-V curve, predict array operating temperature and translate the I-V curve with insolation and array operating temperature.

I-V Curve Model[1]

$$I(V) = I_{sc} \left[1 - A \left\{ \exp \left(V / B \, V_{oc} \right) - 1 \right\} \right] \quad (1)$$

$$A = \left[1 - I_{mp} / I_{sc} \right] \left[\exp \left(- V_{mp} / B \, V_{oc} \right) \right] \quad (2)$$

$$B = \left[V_{mp} / V_{oc} - 1 \right] / \left[\ln \left(1 - I_{mp} / I_{sc} \right) \right] \quad (3)$$

I-V Curve Translation Equations

(Note: Subscripts 1 and 2 refer to sets of insolation and cell temperature conditions from which and to which the I-V data is translated.)

$$I_2 = I_1 + I_{sc1} (L_2/L_1 - 1) + C_I (L_2/L_1) (T_{c2} - T_{c1}) \quad (4)$$

$$V_2 = V_1 + C_v (T_{c2} - T_{c1}) - R_s(I_{sc2} - I_{sc1}) \quad (5)$$

PV Cell Operating Temperature

$$T_c = T_a + kL \quad (6)$$

3.2 Array Measurements

At least five complete photovoltaic array current-voltage curves should be measured under clear-sky conditions at the dc wiring access point nearest the power conditioning subsystem. When measurement of the entire array is not possible, due to its size for example, I-V curves should be made on the subarray segments. These may be treated individually in order to determine their current, voltage and power ratings as described in Section 3.4 Ratings for the complete array then may be determined by combining the ratings of each subarray according to the following rules:

- For subarrays in parallel, add currents at constant voltage.
- For subarrays in series, add voltages at constant current.

At the time of measurement the irradiance on the array surface should be measured using a reference cell appropriate for use with the solar cells under test. The reference cell must be mounted in the same plane as the array and must not have a significantly different field of view. If a pyranometer is used instead of a standard cell, errors as much as 10% may be incurred.

The array operating temperature should be measured, preferably by module-implanted temperature sensor(s) or by temperature sensor(s) applied to the rear side of the solar cells. Rear-side measurements however, may lead to errors of up to 10°C. In some systems, the PV cell operating temperatures have been found to vary as much as 20°C from one position to another in the array. Consequently, cell temperature must be measured in four or more distributed positions in the array and an average temperature calculated. The ambient air temperature should also be measured at the time of each I-V curve measurement.

Ideally, the air mass at the time of measurement should be 1.5, however, errors of only a few percent may be incurred with an air mass in the range of 1 to 2 (Ref. 2). Air mass may be estimated from the following empirical formula (Ref. 3):

$$AM(\gamma) = \left[\sin\gamma + 0.15(\gamma + 3.885)^{-1.253}\right]^{-1} \quad (7)$$

where γ = solar altitude at the time of measurement.

At the time of these I-V curve measurements the irradiance on the array surface must be greater than 750 W/m^2, as indicated by the standard cell reference. Appendix Fig. B-1 shows a sample format for summarizing the minimum required I-V curve measurement data.

Four constants are determined from this data for use in equations (1) through (6).

3.3.1 Series Resistance, R_s

The array series resistance can be determined by examining any of the array I-V curves. R_s is equal to the negative of the reciprocal of the I-V curve slope near the open-circuit voltage. Typical values of R_s are on the order of 1.5 ohms for residential-size photovoltaic arrays. A typical photovoltaic array I-V curve and R_s calculation are shown in Fig. B-2.

3.3.2 Voltage Temperature Coefficient, C_v

Choose the two I-V curves which are at the highest and lowest average cell operating temperatures. From equation (5) and this data, C_v may be evaluated as follows:

$$C_v = V_{oc2} - V_{oc1} + R_s(I_{sc2} - I_{sc1}) / (T_{c2} - T_{c1}) \quad (8)$$

SAMPLE I-V DATA SUMMARY

Site Address ______________________

____

____

____

Date ______________________

Measurement #				
Time				
Ambient Temperature				
PV Cell Temp 1				
PV Cell Temp 2				
PV Cell Temp 3				
PV Cell Temp 4				
Avg. PV Cell Temp				
Insolation				
Open-Circuit Voltage				
Max-Power Voltage				
Max-Power Current				
Short-Circuit Current				

Fig. B-1

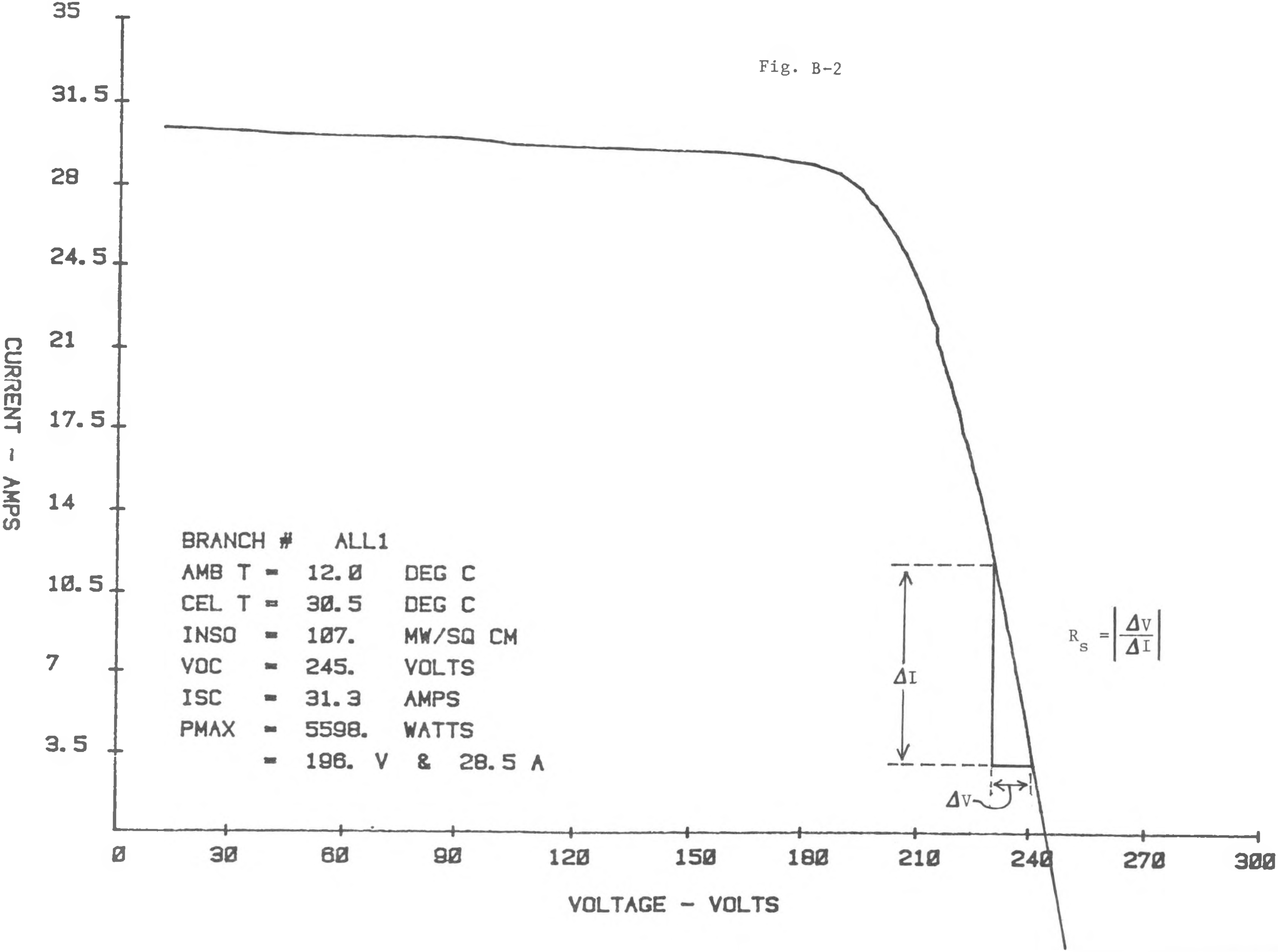
CURRENT - AMPS
35
31.5
28
24.5
21
17.5
14
10.5
7
3.5
VOLTAGE - VOLTS
0
30
60
90
120
150
180
210
240
270
300
BRANCH # ALL1
AMB T = 12.0 DEG C
CEL T = 30.5 DEG C
INSO = 107. MW/SQ CM
VOC = 245. VOLTS
ISC = 31.3 AMPS
PMAX = 5598. WATTS
= 196. V & 28.5 A
ΔI
ΔV
$R_s = \left|\frac{\Delta V}{\Delta I}\right|$

Fig. B-2

This equation is evaluated using the open-circuit voltages, short-circuit currents, and cell operating temperatures from the two I-V curves, and also the series resistance determined as in section 3.1.1.

3.3.3 Current Temperature Coefficient, C_I

To a very good approximation, the array short-circuit current at one set of conditions will translate to the short-circuit current at any other set of conditions. Using this fact, the array current temperature coefficient may be evaluated from (4) as follows:

$$C_I = \left[I_{sc2} \, (L_1/L_2) - I_{sc1} \right] / (T_{c2} - T_{c1}) \tag{9}$$

To evaluate (8), two I-V curves should be chosen which were measured at approximately the same insolation level, but at differing cell operating temperatures. Since C_I is a function of the insolation level, using I-V curves at similar insolation (ideally identical) eliminates the ambiguity of deciding on the insolation level at which C_I has been evaluated.

3.3.4 PV Cell Temperature Rise Coefficient, k

The difference between the average PV cell operating temperature and the ambient air temperature is approximately a linear function of the insolation on the array. Consequently it is possible to determine the constant, k, which describes this temperature rise insolation dependence. The wind speed over the surface of the array also influences the array operating temperature. Measurements should be taken during average wind conditions, and a sufficient number of measurements should be made to average out any abnormal wind conditions. For each measured array I-V curve a "k" should be determined as follows:

$$k_i = \frac{T_{ci} - T_{ai}}{L_i} \tag{10}$$

The average of these values should be calculated to determine the PV cell Temperature Rise Coefficient, k.

$$k = \frac{1}{n} \sum_{i=1}^{n} k_i$$

3.4 Array Current, Voltage and Power Ratings

Using the constants obtained above, the photovoltaic-array maximum-power current and voltage, open-circuit voltage, and short-circuit current can be determined at both peak and nominal rating conditions.

3.4.1 Array Peak Rated Current, Voltage and Power

Peak rating conditions are defined as:

- irradiance on array surface = 1000 W/m^2
- air mass 1.5 spectrum
- PV cell operating temperature = 25°C

Choose any one of the I-V curves to represent the initial (subscript 1) conditions from which extrapolations will be done. The array peak-rated short-circuit current is then given by (4).

$$I_{scp} = I_{sc1} (1000./L_1) + C_I (1000./L_1) (25. - T_{c1}) \qquad (11)$$

The array peak-rated open-circuit voltage is given by (5),

$$V_{ocp} = V_{oc1} + C_v (25. - T_{c1}) - R_s (I_{scp} - I_{sc1}) \qquad (12)$$

The array peak-rated maximum-power point can be approximated very closely by assuming that the maximum-power point at one set of conditions will translate to the maximum-power point at any other set of conditions.

Making this assumption then,

$$V_{mpp} = V_{mp1} + C_v (25.- T_{c1}) - R_s (I_{scp} - I_{sc1}) \qquad (13)$$

$$I_{mpp} = I_{mp1} + I_{sc1} (1000./L_1 - 1) + C_I(1000./L_1) (25. - T_{c1}) \quad (14)$$

and,

$$P_{mpp} = V_{mpp} \times I_{mpp} \quad (15)$$

For greater precision in determining the maximum-power point at the peak-rating conditions, many points around the maximum-power point of the reference curve must be translated and the new maximum found among these. If actual measured data points around the maximum power point are available, these should be used.

If not all the data points of the measured I-V curve are available, the following iterative procedure may be followed to find the array maximum-power point under peak-rated conditions (or any insolation and PV cell operating temperature other than the measured conditions):

- Model the array I-V curve using the measured I-V data and equations (1) through (3).
- Calculate the short-circuit current and the open-circuit voltage at the peak-rated conditions from equations (10) and (11).
- Pick an initial guess for the maximum-power voltage at the peak-rated conditions equal to 75% of the open-circuit voltage at peak-rating conditions.
- Determine the voltage at the measured conditions which corresponds to this initial guess for the maximum-power voltage using equation (5).
- Calculate the current corresponding to this measured-conditions voltage, using equation (1).
- Calculate the current at peak-rating conditions which corresponds to this measured-conditions current, using equation (4).
- Calculate the power at peak-rating conditions for the voltage and current determined above.

- Increase (or decrease) the maximum-power-point voltage guess, calculate the corresponding current and power. Compare this power with the previous value and update the maximum-power-point voltage guess and repeat until the maximum-power point has been determined to the desired accuracy.

3.4.2 Determination of Array NOCT

The nominal operating cell temperature is a reference temperature indicative of typical or nominal array operating temperatures. NOCT may be determined from equation (6) using the constant k from section 3.3.4. From (6),

$$NOCT = 20. + k(800.) \qquad (16)$$

3.4.2 Array NOCT Rated Current, Voltage and Power

Array ratings at a PV cell temperature equal to NOCT and insolation equal to 1000 W/m^2 may be determined from the procedure outlined in section 3.4.1; everywhere replacing the peak rating cell temperature of 25°C with the NOCT determined above.

3.5 <u>Power Conditioning Subsystem Measurements</u>

Measurements of dc power input and ac power output for the power conditioning subsystem must be made in order to characterize the PCS efficiency as a function of power level. Measurements must be made under normal system operating conditions, during periods when the insolation is greater than 500 W/m^2.

3.5.1 PCS Efficiency

From the data above the efficiency of the PCS at both the array peak rated power and array NOCT rated power may be determined. The greater the number and range of PCS efficiency data available, the less uncertainty there will be in extrapolation or interpolation to determine these peak and NOCT PCS efficiencies.

3.6 System Peak Rated and NOCT Rated Maximum Power

The system peak-rated ac maximum-power output is defined as the product of the array peak-rated power and the PCS efficiency at that dc power level.

$$P_{sp} = P_{mpp} \times \eta_{pcsp} \tag{17}$$

Likewise the system NOCT rated maximum power is the product of the array NOCT rated power and the corresponding PCS efficiency.

$$P_{sn} = P_{mpn} \times \eta_{pcsn} \tag{18}$$

APPENDIX C

NERES MONTHLY SUMMARY
JUNE 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	26.8	******	24.8
Average minimum ambient air temperature....................(deg. C)	14.3	******	15.2
Average ambient air temperature............................(deg. C)	20.6	******	20.0
Average degree days heating/cooling...............(deg. C days/day)	0.0	******	0.5
Total precipitation...(cm)	7.2	******	8.1
Average wind speed...(m/s)	2.5	******	5.0
Average total horizontal insolation.................(kWh/m**2/day)	5.7	******	5.7

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used.......................(kWh/day)	17.3	27.0	16.9	32.4	22.5
Average electric energy in use during sunhours...........(kWh/day)	11.8	20.0*	10.7	22.8	14.0

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy.....................................(kWh/day)	30.1	20.5	29.4	20.5	******	29.2*
Average PV DC energy/rated power.....................(kWh/day/kWp)	4.6	3.9	4.3	4.3	******	4.0*
Array peak power..(kW)	6.7	4.6	6.3	4.4	******	6.2
Average array peak power......................................(kW)	5.6	3.9	5.1	3.6	******	N/A
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	4.76	4.64	5.82	4.69	******	4.47*
Average total tilt insolation: PV system on..........(kWh/m**2/day)	4.72	4.28	5.49	4.68	******	4.45
Peak insolation..(kW/m**2)	1.04	1.00	1.14	1.03	******	1.00
Average peak insolation..................................(kW/m**2)	0.88	0.82	0.94	0.85	******	0.83
PV array efficiency..(%)	7.4	6.4	6.5	9.4	******	6.7
Average maximum panel temperature..........................(deg. C)	57.8	49.6	62.7	47.8	******	57.2
Average minimum panel temperature..........................(deg. C)	12.8	7.6	10.1	14.3	******	8.9

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output.............................(kWh/day)	27.1	16.7	23.6	18.5	******	26.3
Average PCU AC peak power output..............................(kW)	5.2	3.3	4.3	3.3	******	5.6
PCU peak power output...(kW)	6.2	3.9	5.3	4.1	******	7.0
PCU efficiency...(%)	90.0	81.5	80.5	90.3	******	90.1*

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load.....................................(kWh/day)	19.9	0.0	14.6	0.3	******	18.8
Average energy supplied to utility feed..................(kWh/day)	19.9	16.7	14.0	18.0	******	17.6
Average energy supplied by utility feed..................(kWh/day)	13.7	0.0	7.8	0.4	******	10.2
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION....................	25	12	7	27	0	19

*Estimated
The load data source for the imposed load was changed from MH3 to MH4 on 6/12.
NOTES: MITLL had between 5 and 8 of 8 strings on line. One string had current leakage problems.
GE came on line 6/9.
TRISC was on line full month.
SOLRX was not on line.
CARLE was on line full month.

NERES MONTHLY SUMMARY
JULY 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	29.5	******	27.4
Average minimum ambient air temperature....................(deg. C)	17.7	******	18.4
Average ambient air temperature............................(deg. C)	23.6	******	22.9
Average degree days heating/cooling...............(deg. C days/day)	0.2	******	0.0
Total precipitation...(cm)	11.1	******	7.0
Average wind speed...(m/s)	2.1	******	4.9
Average total horizontal insolation.................(kWh/m**2/day)	5.52	******	5.52

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used........................(kWh/day)	21.6	28.9	******	35.1	27.6
Average electric energy in use during sunhours............(kWh/day)	13.9	19.8	******	25.1	15.7

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy......................................(kWh/day)	28.9	20.7	25.6	19.5	******	21.8
Average PV DC energy/rated power.....................(kWh/day/kWp)	4.1	4.0	3.8	4.1	******	2.8
Array peak power..(kW)	7.3	4.9	6.5	4.4	******	6.8
Average array peak power......................................(kW)	5.8	3.9	4.9	3.5	******	4.6
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	4.91	4.75	5.34	4.71	******	3.87
Average total tilt insolation: PV system on..........(kWh/m**2/day)	4.69	4.18	5.06	4.69	******	3.83
Peak insolation...(kW/m**2)	1.18	1.04	1.30	1.05	******	.93
Average peak insolation.................................(kW/m**2)	0.94	0.89	0.96	0.88	******	0.75
PV array efficiency..(%)	7.3	6.0	6.8	8.8	******	5.5
Average maximum panel temperature..........................(deg. C)	59.3	56.9	66.2	52.4	******	57.1
Average minimum panel temperature..........................(deg. C)	14.3	15.3	15.1	17.8	******	18.6

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output..............................(kWh/day)	25.1	16.8	20.6	17.6	******	19.8
Average PCU AC peak power output..............................(kW)	5.2	3.3	4.1	3.2	******	4.3
PCU peak power output...(kW)	6.1	4.2	6.0	4.1	******	6.4
PCU efficiency...(%)	86.9	81.2	80.4	90.2	******	90.8

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load......................................(kWh/day)	5.0	0.2	2.4	2.5	******	9.8
Average energy supplied to utility feed...................(kWh/day)	24.0	16.8	20.1	17.2	******	13.8
Average energy supplied by utility feed...................(kWh/day)	4.8	0.3	1.9	2.1	******	4.1
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION.....................	18	19	26	20	0	12

NOTES: MITLL went down July 17 for 1 day due to failure of inverter protection diode. One of 8 strings off 6/26-7/2.
WEST was shut off July 20 due to inverter malfunction.
GE was down 2 hours when inverter was found off on July 16.
TRISC was on line full month.
SOLRX is off line.
CARLE was off line for 1 week (July 10-18) due to IDAC modifications.
Shadowing tests run on prototypes from July 15 through end of month.
MH5 providing load since June 30. Imposed loads shut off July 3 through July 31 due to hot weather.

NERES MONTHLY SUMMARY
AUGUST 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	26.0	30.4	26.3
Average minimum ambient air temperature....................(deg. C)	14.1	15.2	17.4
Average ambient air temperature............................(deg. C)	20.0	22.8	21.8
Average degree days heating/cooling..............(deg. C days/day)	-0.5	0.0	-0.1
Total precipitation...(cm)	2.8	******	8.8
Average wind speed...(m/s)	1.9	******	4.8
Average total horizontal insolation..................(kWh/m**2/day)	5.09	******	4.69

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used.........................(kWh/day)	17.7	24.4	******	35.9	32.7
Average electric energy in use during sunhours............(kWh/day)	10.6	15.7	******	24.6	17.9

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy......................................(kWh/day)	28.1	******	25.5	20.9	******	24.2
Average PV DC energy/rated power......................(kWh/day/kWp)	4.0	******	3.8	4.4	******	3.1
Array peak power...(kW)	6.6	******	5.7	4.4	******	7.3
Average array peak power.......................................(kW)	5.2	******	4.4	3.6	******	5.4
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	4.98	******	5.57	4.95	******	4.57
Average total tilt insolation: PV system on..........(kWh/m**2/day)	4.85	******	5.35	4.94	******	3.71
Peak insolation..(kW/m**2)	1.06	******	1.16	1.05	******	1.17
Average peak insolation..................................(kW/m**2)	0.90	******	0.91	0.89	******	0.87
PV array efficiency...(%)	6.8	******	6.5	9.0	******	6.2
Average maximum panel temperature..........................(deg. C)	55.2	******	70.7	50.4	******	60.6
Average minimum panel temperature..........................(deg. C)	10.2	******	16.2	14.6	******	12.7

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output..............................(kWh/day)	24.2	******	20.8	18.9	******	22.1
Average PCU AC peak power output...............................(kW)	4.5	******	3.8	3.3	******	5.0
PCU peak power output..(kW)	5.9	******	4.8	4.0	******	6.9
PCU efficiency..(%)	86.1	******	81.6	90.4	******	91.3

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load......................................(kWh/day)	28.5	******	0.6	24.7	******	19.7
Average energy supplied to utility feed...................(kWh/day)	15.1	******	20.3	11.3	******	16.0
Average energy supplied by utility feed...................(kWh/day)	19.6	******	0.2	17.4	******	13.8
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION.....................	27	0	5	28	0	19

NOTES: Shadowing tests run on prototypes from July 15 until August 4.
Imposed loads have been off (July 3 - Aug. 10) due to hot weather. MH5 providing load.
Utility power failures of 4 and 3 hours (Aug. 13 & 14) at NERES.
MITLL had one of eight strings taken off line on Aug. 11 due to high leakage current.
WEST has been taken off line since July 20 due to inverter malfunction.
GE inverter shut-off Aug. 6 pending repair.
TRISC on line full month.
SOLRX is off line.
CARLE off line 8/5-8/6, 8/10-8/14, 8/28-8/31 due to IDAC repairs.

NERES MONTHLY SUMMARY
SEPTEMBER 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	20.5	22.4	22.3
Average minimum ambient air temperature....................(deg. C)	9.8	10.9	13.7
Average ambient air temperature............................(deg. C)	15.2	16.6	18.0
Average degree days heating/cooling...............(deg. C days/day)	-3.4	-2.8	-1.4
Total precipitation...(cm)	9.2	******	8.0
Average wind speed...(m/s)	2.6	******	5.0
Average total horizontal insolation.................(kWh/m**2/day)	3.49	******	3.97

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used.........................(kWh/day)	20.5	27.8	15.7	34.2	******
Average electric energy in use during sunhours............(kWh/day)	3.7	13.4	8.9	22.7	******

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy......................................(kWh/day	22.2	******	******	15.8	******	22.3
Average PV DC energy/rated power.....................(kWh/day/kWp)	3.2	******	******	3.3	******	2.9
Array peak power..(kW)	7.4	******	******	4.7	******	7.9
Average array peak power......................................(kW)	5.4	******	******	3.5	******	5.6
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	3.79	3.74	4.60	3.64	******	3.39
Average total tilt insolation: PV system on..........(kWh/m**2/day)	3.79	******	******	3.63	******	3.37
Peak insolation..(kW/m**2)	1.10	1.07	1.12	1.09	******	1.07
Average peak insolation..................................(kW/m**2)	0.84	0.82	0.98	0.82	******	0.79
PV array efficiency..(%)	7.0	******	******	9.3	******	6.7
Average maximum panel temperature..........................(deg. C)	47.0	48.1	62.5	42.5	******	49.6
Average minimum panel temperature..........................(deg. C)	6.4	6.6	7.5	9.8	******	9.1

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output..............................(kWh/day)	18.9	******	******	14.2	******	20.5
Average PCU AC peak power output..............................(kW)	4.9	******	******	3.2	******	5.2
PCU peak power output...(kW)	6.5	******	******	4.3	******	7.5
PCU efficiency...(%)	85.1	******	******	89.9	******	91.9

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load......................................(kWh/day)	32.3	******	******	34.0	******	16.6
Average energy supplied to utility feed...................(kWh/day)	11.0	******	******	6.9	******	15.8
Average energy supplied by utility feed...................(kWh/day)	24.9	******	******	27.4	******	11.7
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION....................	11	0	0	26	0	23

NOTES: Imposed load provided by MH5.
MITLL inverter off 9/9-9/25 for repairs. All 8 strings on line 9/25.
WEST inverter off since 7/20 pending repair.
GE inverter off since 8/6 pending repair. Data system off line 9/17-9/24.
TRISC PV system down 9/13-9/14 due to arcing/grounding in one line of utility feed.
SOLRX inverter has been off pending repair. Data system brought on line 9/17.
CARLE inverter down 9/9-9/10. Blown fuse replaced.
MH2 on line full month (occasional brief interruptions); MH3 back on line 9/21; MH4 brought on line 9/2;
MH5 on line full month; MH6 off line full month due to phone line problems.

NERES MONTHLY SUMMARY
OCTOBER 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	13.9	14.3	17.3
Average minimum ambient air temperature....................(deg. C)	3.3	3.9	8.6
Average ambient air temperature............................(deg. C)	8.6	9.1	13.0
Average degree days heating/cooling...............(deg. C days/day)	-9.6	-9.4	-5.4
Total precipitation...(cm)	9.2	******	7.7
Average wind speed..(m/s)	2.3	******	5.4
Average total horizontal insolation.................(kWh/m**2/day)	2.6	******	2.8

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used..........................(kWh/day)	22.3	33.9	16.1	36.0	******
Average electric energy in use during sunhours............(kWh/day)	9.5	16.9	7.5	18.5	******
Number of complete days of monitored house data....................	23	25	26	11	******

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy...(kWh/day)	22.3	******	******	16.6	******	24.0
Average PV DC energy/rated power.....................(kWh/day/kWp)	3.2	******	******	3.5	******	3.1
Array peak power...(kW)	7.7	******	******	5.2	******	8.0
Average array peak power...(kW)	4.8	******	******	3.3	******	4.9
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	3.66	3.74	3.64	3.77	******	3.55
Average total tilt insolation: PV system on..........(kWh/m**2/day)	3.46	******	******	3.76	******	3.51
Peak insolation...(kW/m**2)	1.19	1.16	1.19	1.14	******	1.10
Average peak insolation...(kW/m**2)	0.77	0.76	0.74	0.75	******	0.70
PV array efficiency..(%)	7.0	******	******	9.3	******	6.3
Average maximum panel temperature..........................(deg. C)	37.6	40.7	46.8	36.5	******	40.7
Average minimum panel temperature..........................(deg. C)	-0.4	-0.8	0.0	2.4	******	2.1

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output................................(kWh/day)	18.7	******	******	14.6	******	22.0
Average PCU AC peak power output................................(kW)	4.2	******	******	3.0	******	4.6
PCU peak power output...(kW)	6.8	******	******	4.8	******	7.6
PCU efficiency..(%)	83.9	******	******	88.0	******	91.7

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load..(kWh/day)	16.1	******	******	16.8	******	25.4
Average energy supplied to utility feed...................(kWh/day)	15.4	******	******	10.6	******	18.7
Average energy supplied by utility feed...................(kWh/day)	12.4	******	******	13.1	******	23.8
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION.....................	23	0	0	26	0	21

NOTES: Imposed load changed from MH5 to MH4 on 10/1.
MITLL had 1 of 8 strings taken off line on 10/20.
WEST inverter off since 7/20 pending repair.
GE inverter off since 8/6 pending repair.
TRISC on line full month.
SOLRX PV system brought on line 10/29.
CARLE data system off line 10/4-10/9 and 10/12-10/13 due to IDAC failures.

NERES MONTHLY SUMMARY
NOVEMBER 1981

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average maximum ambient air temperature....................(deg. C)	9.8	9.0	10.9
Average minimum ambient air temperature....................(deg. C)	0.6	0.6	3.7
Average ambient air temperature..........................(deg. C)	5.2	4.8	7.3
Average degree days heating/cooling...............(deg. C days/day)	13.2	14.0	11.0
Total precipitation...(cm)	9.8	******	11.5
Average wind speed..(m/s)	2.7	******	5.8
Average total horizontal insolation.................(kWh/m**2/day)	1.78	******	1.59

MONITORED HOUSE (MH) INFORMATION	MH2	MH3	MH4	MH5	MH6
Average total electric energy used........................(kWh/day)	23.1	36.8	19.8	30.2	24.3
Average electric energy in use during sunhours............(kWh/day)	8.3	16.0	7.0	14.8	11.2
Number of complete days of monitored house data....................	19	24	24	12	13

PROTOTYPE AND ISEE PHOTOVOLTAIC ARRAY INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PV DC energy......................................(kWh/day)	20.5	******	******	14.4	10.9	22.2
Average PV DC energy/rated power.....................(kWh/day/kWp)	2.9	******	******	3.0	2.1	2.8
Array peak power...(kW)	8.5	******	******	5.7	6.0	7.6
Average array peak power.....................................(kW)	4.6	******	******	3.3	3.0	5.6
Average total tilt insolation: during sunhours.......(kWh/m**2/day)	3.22	2.99	3.11	3.21	2.96	3.14
Average total tilt insolation: PV system on..........(kWh/m**2/day)	3.20	******	******	3.20	2.71	3.26
Peak insolation..(kW/m**2)	1.24	1.21	1.16	1.20	1.19	1.01
Average peak insolation................................(kW/m**2)	0.71	0.68	0.69	0.72	0.70	0.70
PV array efficiency...(%)	7.2	******	******	10.0	5.3	6.5
Average maximum panel temperature.........................(deg. C)	31.7	32.9	39.4	32.4	30.6	36.3
Average minimum panel temperature.........................(deg. C)	-3.1	-3.7	-3.1	-0.6	-2.1	-1.5

PROTOTYPE AND ISEE POWER CONDITIONING UNIT (PCU) INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average PCU AC energy output..............................(kWh/day)	17.5	******	******	12.3	9.0	20.4
Average PCU AC peak power output.............................(kW)	4.2	******	******	3.0	2.6	5.2
PCU peak power output..(kW)	7.4	******	******	5.2	5.1	7.2
PCU efficiency..(%)	85.4	******	******	85.5	82.3	91.7

PROTOTYPE AND ISEE AC ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average imposed load......................................(kWh/day)	30.3	******	******	30.4	29.0	54.3
Average energy supplied to utility feed...................(kWh/day)	13.4	******	******	8.6	6.2	16.3
Average energy supplied by utility feed...................(kWh/day)	26.4	******	******	26.6	27.0	52.1
NUMBER OF COMPLETE DAYS OF PV SYSTEM OPERATION.....................	25	0	0	24	21	12

NOTES: Imposed load source changed from MH4 to MH3 on 11/4.
MITLL had 1 of 8 strings off line until 11/24.
WEST inverter off since 7/20 pending repair.
GE inverter off since 8/6 pending repair.
CARLE had 1 of 9 strings taken off line on 11/23.
MH6 back on line 11/12.

NERES MONTHLY SUMMARY
DECEMBER 1981

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	2.33	2.20	4.05
Average daily minimum ambient air temperature..............(deg. C)	-4.23	-4.22	-2.99
Average ambient air temperature............................(deg. C)	-0.81	-1.27	0.55
Total degree days heating/cooling.....................(deg. C days)	593./ 0.	608./ 0.	551./ 0.
Total precipitation..(cm)	13.06	******	10.77
Average wind speed...(m/s)	2.35	******	6.21
Average daily horizontal insolation.................(kWh/m**2/day)	1.15	******	1.27

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	27.32	40.22	17.53	36.21	22.41
Average daily electric energy used during sunhours........(kWh/day)	8.15	15.23	5.85	14.74	9.19
Monitored house data hours/hours in month......................(%)	99.32	99.48	99.41	98.38	99.41

PHOTOVOLTAIC (PV) SYSTEM INFORMATION PV ARRAY AND POWER CONDITIONING UNIT (PCU)	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily array dc energy output.....................(kWh/day)	12.39	9.36	7.69	9.59	6.26	7.40
Average daily array dc energy output/rated array power(kWh/day/kWp)	1.77	1.80	1.13	2.00	1.20	0.95
Peak array power for month......................................(kW)	7.62	5.05	5.35	5.25	4.76	5.97
Average daily array peak power..................................(kW)	3.58	2.78	2.34	2.64	2.07	1.45
Average daily total tilt insolation.................(kWh/m**2/day)	2.22	2.08	2.14	2.07	2.00	2.24
Average daily insolation during system on-hours......(kWh/m**2/day)	2.34	3.35	2.61	2.15	3.04	1.94
Insolation utilization efficiency...............................(%)	92.23	45.70	44.09	93.02	66.08	29.98
Peak insolation for month..................................(kW/m**2)	1.15	1.08	1.06	1.10	1.08	0.97
Average daily peak insolation.................... .....(kW/m**2)	0.58	0.56	0.54	0.55	0.55	0.54
Array efficiency..(%)	7.04	7.57	7.14	10.25	6.03	5.30
Average daily maximum array temperature...................(deg. C)	19.51	20.28	22.87	20.42	18.65	21.74
Average daily minimum array temperature...................(deg. C)	-7.63	-8.00	-7.02	-5.06	-5.85	-6.09
Average daily PCU ac energy output.......................(kWh/day)	10.39	7.17	6.12	7.56	4.84	6.47
Peak PCU power for month..(kW)	6.27	4.23	4.51	4.79	4.08	5.57
Average daily PCU peak power....................................(kW)	3.08	2.34	2.01	2.38	1.72	1.74
PCU efficiency..(%)	83.86	76.63	79.61	78.82	77.26	87.43
Array and PCU data hours during sunhours..............(hours/month)	254.51	146.68	186.14	267.26	246.99	136.51
Sunhours..(hours/month)	277.06	277.06	277.06	277.06	277.06	277.06
System reliability..(%)	100.00	54.90	69.50	100.00	100.00	46.80

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX.	CARLE
Average daily PCU ac energy output.......................(kWh/day)	10.39	******	6.12	7.56	4.84	6.47
Average daily energy from utility........................(kWh/day)	31.92	******	31.40	27.97	30.19	111.02
Average daily energy to utility..........................(kWh/day)	7.19	******	3.66	4.98	2.62	4.29
Average daily energy to load.............................(kWh/day)	34.68	******	33.48	30.63	31.78	111.37
System-utility data hours/hours in month.......................(%)	94.79	******	67.58	98.59	90.52	50.80

NOTES: Imposed load for prototypes provided by MH3. All prototype PV arrays washed 12/3.

MITLL PDAC offline 12/2 - 12/3, modifications for IV curve-tracer.

WEST inverter back online 12/14; no system-utility energy flow data, load readings in error, transducer under repair.

GE inverter back online 12/4, off 12/5-12/6, 12/12-12/13, 12/31; 12/10 inverter over-voltage trip level adjusted to correct wake-up problems; array partially shaded by MITLL proto for last 1/2 hr. of sunlight on 12/19-12/21, 12/28-12/30.

TRISC programmable load off 12/25-12/28, blower motor failed/repaired.

SOLRX 6 of 78 modules offline 12/4-12/31 due to high leakage current; progr. load off 12/23-12/28, sticking relay.

CARLE failing contactor caused inverter shut-downs thru-out the month; 1 of 9 strings off-line due to high leakage current; back-up resistance domestic hot water and space heating not included in load.

NERES MONTHLY SUMMARY
JANUARY 1982

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature...... ......(deg. C)	-1.67	-2.46	2.16
Average daily minimum ambient air temperature..............(deg. C)	-12.32	-12.03	-5.27
Average ambient air temperature...........................(deg. C)	-6.82	-7.34	-1.55
Total degree days heating/cooling....................(deg. C days)	780./ 0.	796./ 0.	616./ 0.
Total precipitation...(cm)	13.56	******	9.37
Average wind speed...(m/s)	2.75	******	6.35
Average daily horizontal insolation.................(kWh/m**2/day)	1.58	******	1.50

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	30.01	49.97	21.77	34.63	24.31
Average daily electric energy used during sunhours........(kWh/day)	9.63	18.73	8.56	15.61	11.90
Monitored house data hours/hours in month......................(%)	94.28	94.29	94.01	83.27	94.28

PHOTOVOLTAIC (PV) SYSTEM INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
PV ARRAY AND POWER CONDITIONING UNIT (PCU)						
Average daily array dc energy output.....................(kWh/day)	17.77	14.65	16.23	14.07	10.60	19.29
Average daily array dc energy output/rated array power(kWh/day/kWp)	2.61	2.87	2.42	2.94	2.12	2.54
Peak array power for month.................. ....(kW)	7.68	6.25	6.88	5.12	5.07	7.89
Average daily array peak power..............................(kW)	4.44	3.76	4.11	3.28	2.72	4.29
Average daily total tilt insolation.................(kWh/m**2/day)	3.23	3.05	3.09	3.13	2.97	3.05
Average daily insolation during system on-hours......(kWh/m**2/day)	3.31	4.03	4.14	3.18	4.01	3.74
Insolation utilization efficiency............................(%)	97.81	88.57	70.51	96.32	67.49	34.65
Peak insolation for month...........................(kW/m**2)	1.15	1.09	1.05	1.09	1.11	1.14
Average daily peak insolation.......................(kW/m**2)	0.74	0.69	0.69	0.70	0.68	0.64
Array efficiency...(%)	6.57	7.68	7.45	9.73	6.22	5.85
Average daily maximum array temperature..................(deg. C)	16.09	16.73	20.77	17.44	16.78	20.94
Average daily minimum array temperature..................(deg. C)	-15.37	-16.00	-15.23	-12.82	-13.66	-14.30
Average daily PCU ac energy output.......................(kWh/day)	16.11	12.02	13.17	12.36	8.50	17.88
Peak PCU power for month....................................(kW)	7.22	5.20	5.68	4.81	4.27	7.51
Average daily PCU peak power................................(kW)	4.17	3.15	3.44	3.05	2.26	4.04
PCU efficiency...(%)	90.65	82.07	81.15	87.84	80.14	92.68
Array and PCU data hours during sunhours..............(hours/month)	262.00	255.86	207.41	262.98	216.08	85.63
Sunhours............ ....(hours/month)	287.53	287.53	287.53	287.53	287.53	287.53
System reliability.................... ....(%)	100.00	100.00	79.50	100.00	93.00	37.40

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output.......................(kWh/day)	16.11	12.02	13.17	12.36	8.50	17.88
Average daily energy from utility........................(kWh/day)	40.35	17.62	43.52	38.81	36.38	107.89
Average daily energy to utility..........................(kWh/day)	9.29	9.89	7.05	6.36	4.91	8.42
Average daily energy to load.............................(kWh/day)	46.67	19.52	49.22	44.76	39.31	115.49
System-utility data hours/hours in month.......................(%)	93.54	92.72	72.19	93.74	77.96	30.77

NOTES: Imposed load provided by MH3. Data system down 1/24-1/25 (27 hrs), 1/26-1/27 (14 hrs) due to failing DCU. Frequent snowfalls thru month: 1/8 (dusting), 1/9 (1"), 1/11 (dusting), 1/13 (6"), 1/14 (3"), 1/20 (1"), 1/23 (4").

MITLL PDAC off briefly for repairs on 1/22. Array snow covered 1/23-1/27.

WEST PDAC off 5 hrs due to program. load repairs on 1/11. Also, load off 1/1-1/8, 1/13-1/19, 1/20-1/22 for repairs.

GE inverter off 1/1-1/4, 1/9-1/10; refused to wake up on 1/29, power sensor adjusted, normal operation since.

SOLRX 6 of 78 modules offline; inverter failed to wake up on 1/11, OV trip adjusted, normal operation since; PV system shut down 1/26-1/29 for array wiring work; inverter failed utility loss-of-power test on 1/29, shut off thru end of month pending repairs; programmable load off 1/6-1/8, 1/14-1/19, 1/30-1/31 for repairs.

CARLE 1 of 9 strings offline; inverter off 1/1-1/20 due to contactor repair; average of 57.58 kwh/day used for back-up resistance DHW and space heating not included in load; IDAC offline 3.5 hrs on 1/29 due to phone-line problem.

NERES MONTHLY SUMMARY
FEBRUARY 1982

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	2.35	1.49	3.05
Average daily minimum ambient air temperature..............(deg. C)	-6.49	-6.79	-4.83
Average ambient air temperature............................(deg. C)	-1.78	-2.96	-0.88
Total degree days heating/cooling..................(deg. C days)	563./ 0.	426./ 0.	538./ 0.
Total precipitation...(cm)	6.39	******	8.89
Average wind speed...(m/s)	2.67	******	6.26
Average daily horizontal insolation..................(kWh/m**2/day)	2.10	******	2.24

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	20.25	45.19	19.10	38.61	22.44
Average daily electric energy used during sunhours........(kWh/day)	7.44	20.76	8.36	19.85	11.60
Monitored house data hours/hours in month.....................(%)	96.16	99.72	99.66	99.72	99.72

PHOTOVOLTAIC (PV) SYSTEM INFORMATION PV ARRAY AND POWER CONDITIONING UNIT (PCU)	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily array dc energy output.....................(kWh/day)	22.01	13.76	13.39	15.97	******	23.51
Average daily array dc energy output/rated array power(kWh/day/kWp)	3.24	2.70	2.03	3.34	******	3.09
Peak array power for month......................................(kW)	8.04	6.43	6.70	5.97	******	7.89
Average daily array peak power..................................(kW)	5.43	3.93	4.15	3.75	******	5.30
Average daily total tilt insolation.................(kWh/m**2/day)	3.64	3.29	3.37	3.34	3.27	3.58
Average daily insolation during system on-hours......(kWh/m**2/day)	3.45	3.59	3.58	3.38	******	3.79
Insolation utilization efficiency..............................(%)	81.34	52.28	27.71	99.75	******	93.06
Peak insolation for month...........................(kW/m**2)	1.25	1.26	1.23	1.26	1.26	1.09
Average daily peak insolation.......................(kW/m**2)	0.80	0.79	0.78	0.80	0.79	0.74
Array efficiency...(%)	7.58	7.80	7.29	10.09	******	6.84
Average daily maximum array temperature...................(deg. C)	25.14	24.42	29.79	25.13	28.21	27.82
Average daily minimum array temperature...................(deg. C)	-10.16	-10.54	-9.90	-5.57	-8.05	-8.71
Average daily PCU ac energy output.......................(kWh/day)	19.49	11.16	10.73	14.22	******	21.72
Peak PCU power for month..(kW)	7.33	5.37	5.59	5.64	******	7.42
Average daily PCU peak power....................................(kW)	4.96	3.30	3.47	3.52	******	4.97
PCU efficiency...(%)	88.56	81.05	80.12	89.03	******	92.38
Array and PCU data hours during sunhours.............(hours/month)	203.83	191.34	111.23	286.36	******	171.84
Sunhours...(hours/month)	289.03	289.03	289.03	289.03	289.03	289.03
System reliability...(%)	91.91	67.80	37.90	100.00	0.00	96.88

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output.......................(kWh/day)	19.49	11.16	10.73	14.22	******	21.72
Average daily energy from utility........................(kWh/day)	34.41	36.37	39.67	32.33	******	96.94
Average daily energy to utility..........................(kWh/day)	11.81	6.26	7.25	7.78	******	12.23
Average daily energy to load.............................(kWh/day)	41.68	41.07	44.17	38.80	******	104.67
System-utility data hours/hours in month......................(%)	71.60	68.73	40.61	99.75	******	57.79

NOTES: Imposed load provided by MH3. Light snowfalls on 2/9 (3") and 2/19 (2").
MITLL Acheval inverter installed and running on 2/5 (Gemini inverter running 2/1-2/5, data not included here); offline 2/7-2/8 due to inverter DC contactor failure; offline 2/8-2/10 due to inverter malfunction; load off 2/23, 2/25.
WEST offline 2/20 thru end of month due to inverter malfunction.
GE inverter wake-up problems 2/4 and 2/5, manually started; offline 2/12 thru end of month due to inverter malfunction.
SOLRX offline since 1/29 due to inverter malfunction.
CARLE all 9 strings online as of 2/2; offline 2/1-2/2 due to inverter DC fuse tripping; no data 2/2-2/8, 2/10, 2/12-2/17 due to IDAC repairs and modifications; special heat load experiment, heat pump off 2/19-2/24; average of 13.2 kwh/day used for back-up resistance domestic hot water and space heating not included in load.

NERES MONTHLY SUMMARY
MARCH 1982

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	7.37	8.26	7.00
Average daily minimum ambient air temperature..............(deg. C)	-2.93	-3.26	-0.27
Average ambient air temperature..........................(deg. C)	2.46	2.36	3.38
Total degree days heating/cooling....................(deg. C days)	492./ 0.	495./ 0.	463./ 0.
Total precipitation..(cm)	4.88	******	10.16
Average wind speed..(m/s)	2.62	******	6.21
Average daily horizontal insolation.................(kWh/m**2/day)	3.42	******	3.20

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	26.24	46.11	19.05	30.11	25.24
Average daily electric energy used during sunhours........(kWh/day)	11.67	24.82	9.10	18.11	14.79
Monitored house data hours/hours in month......................(%)	99.77	77.46	99.60	98.51	60.70

PHOTOVOLTAIC (PV) SYSTEM INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
PV ARRAY AND POWER CONDITIONING UNIT (PCU)						
Average daily array dc energy output.....................(kWh/day)	27.84	******	******	19.95	******	27.45
Average daily array dc energy output/rated array power(kWh/day/kWp)	4.09	******	******	4.17	******	3.61
Peak array power for month....................................(kW)	8.99	******	******	5.95	******	7.86
Average daily array peak power................................(kW)	6.32	******	******	4.16	******	5.60
Average daily total tilt insolation.................(kWh/m**2/day)	4.32	4.39	4.48	4.40	4.27	4.28
Average daily insolation during system on-hours......(kWh/m**2/day)	4.38	******	******	4.41	******	4.22
Insolation utilization efficiency..............................(%)	95.76	******	******	99.46	******	90.52
Peak insolation for month...............................(kW/m**2)	1.20	1.26	1.29	1.27	1.27	1.15
Average daily peak insolation...........................(kW/m**2)	0.88	0.90	0.90	0.91	0.88	0.80
Array efficiency...(%)	7.88	******	******	9.61	******	6.80
Average daily maximum array temperature...................(deg. C)	34.41	35.35	42.77	32.68	38.82	36.78
Average daily minimum array temperature...................(deg. C)	-6.63	-7.32	-6.36	-4.40	-4.64	-5.54
Average daily PCU ac energy output.......................(kWh/day)	25.04	******	******	17.99	******	25.20
Peak PCU power for month......................................(kW)	8.28	******	******	5.63	******	7.38
Average daily PCU peak power..................................(kW)	5.83	******	******	3.90	******	5.23
PCU efficiency...(%)	89.94	******	******	90.18	******	91.82
Array and PCU data hours during sunhours.............(hours/month)	283.29	******	******	352.50	******	341.22
Sunhours...(hours/month)	362.80	362.80	362.80	362.80	362.80	362.80
System reliability...(%)	100.00	0.00	0.00	100.00	0.00	96.10

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output.......................(kWh/day)	25.04	******	******	17.99	******	25.20
Average daily energy from utility........................(kWh/day)	28.78	******	******	28.09	******	80.61
Average daily energy to utility..........................(kWh/day)	17.01	******	******	10.86	******	14.49
Average daily energy to load.............................(kWh/day)	36.39	******	******	35.20	******	89.61
System-utility data hours/hours in month.......................(%)	79.51	******	******	98.74	******	95.62

NOTES: Imposed load changed from MH3 to MH5 on 3/19 thru 3/24. Light snowfall (1 inch or less) on 3/4, 3/9, 3/17, 3/19.
MITLL, WEST, TRISC, and Weather Station data system DACs offline 3/12 from 9:00 until mid-afternoon.
MITLL PV system off 3/10-3/17 for diagnostic equipment testing.
WEST inverter off since 2/20 pending repair.
GE inverter off since 2/12 pending repair.
SOLRX inverter off since 1/29 pending repair.
CARLE inverter off 3/14-3/15 due to DC fuse tripping; average of 6.08 kwh/day used for back-up resistance domestic hot water and space heating not included in load.

NERES MONTHLY SUMMARY
APRIL 1982

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	13.61	15.45	13.50
Average daily minimum ambient air temperature..............(deg. C)	1.68	1.28	4.88
Average ambient air temperature............................(deg. C)	7.84	8.14	9.22
Total degree days heating/cooling.....................(deg. C days)	315./ 0.	306./ 0.	273./ 0.
Total precipitation...(cm)	7.09	******	8.86
Average wind speed...(m/s)	3.85	******	5.95
Average daily horizontal insolation.................(kWh/m**2/day)	4.59	******	4.18

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	23.19	36.70	17.57	35.43	19.82
Average daily electric energy used during sunhours........(kWh/day)	12.25	21.45	8.96	24.43	12.11
Monitored house data hours/hours in month......................(%)	89.92	82.08	95.91	95.13	95.52

PHOTOVOLTAIC (PV) SYSTEM INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
PV ARRAY AND POWER CONDITIONING UNIT (PCU)						
Average daily array dc energy output.....................(kWh/day)	30.50	8.86	******	20.85	21.69	33.45
Average daily array dc energy output/rated array power(kWh/day/kWp)	4.49	4.03	******	4.36	4.34	4.40
Peak array power for month....................................(kW)	8.73	2.27	******	5.79	6.31	8.23
Average daily array peak power................................(kW)	6.39	1.77	******	4.10	4.86	6.44
Average daily total tilt insolation.................(kWh/m**2/day)	4.65	4.75	5.20	4.75	4.79	4.61
Average daily insolation during system on-hours......(kWh/m**2/day)	4.63	4.71	******	4.71	5.19	4.83
Insolation utilization efficiency..............................(%)	96.56	92.40	******	98.79	61.93	98.42
Peak insolation for month................................(kW/m**2)	1.26	1.23	1.37	1.29	1.30	1.11
Average daily peak insolation............................(kW/m**2)	0.91	0.91	0.98	0.92	0.95	0.84
Array efficiency...(%)	7.85	7.10	******	9.48	6.67	6.99
Average daily maximum array temperature...................(deg. C)	36.61	35.68	46.75	35.16	39.01	40.24
Average daily minimum array temperature...................(deg. C)	-1.98	-2.84	-1.59	-0.07	0.49	-0.74
Average daily PCU ac energy output.......................(kWh/day)	26.86	7.78	******	18.81	18.10	29.40
Peak PCU power for month......................................(kW)	8.02	2.05	******	5.43	5.29	7.53
Average daily PCU peak power..................................(kW)	5.88	1.60	******	3.84	4.13	5.86
PCU efficiency...(%)	88.06	87.86	******	90.25	83.45	87.91
Array and PCU data hours during sunhours.............(hours/month)	269.84	331.16	******	334.56	234.51	257.41
Sunhours...(hours/month)	395.27	395.27	395.27	395.27	395.27	395.27
System reliability...(%)	100.00	98.80	0.00	100.00	64.70	100.00

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output.......................(kWh/day)	26.86	7.78	******	18.81	18.10	28.83
Average daily energy from utility........................(kWh/day)	26.31	15.51	******	22.49	21.30	55.87
Average daily energy to utility..........................(kWh/day)	18.65	5.52	******	13.03	13.88	16.20
Average daily energy to load.............................(kWh/day)	34.47	17.90	******	28.26	24.90	67.81
System-utility data hours/hours in month.......................(%)	69.58	86.00	******	85.64	59.44	63.75

NOTES: Imposed load data source changed from MH3 to MH5 on 4/16 until 4/21. Blizzard 4/6-4/7, 14" snowfall.
Data system down 4/19-4/20 (26 hours), 4/9, 4/20, 4/23 (1 hour or less each day), 4/28 (4 hours).

MITLL PV system off for special tests of new Gemini inverter 4/23-4/30; no array DC and utility power readings 4/22-4/23.

WEST Sunsine inverter installed and running on 4/1; PV system off for inverter repair 4/2: PDAC off 4/17-4/19; load off 4/1-4/12.

GE inverter offline since 2/12; start-up attempt on 4/8, inverter malfunction.

TRISC PV system off for special tests with new Gemini inverter 4/12-4/15; load off 4/15-4/20.

SOLRX inverter back on 4/8; PV system off 4/27 thru end of month due to inverter malfunction; PDAC off 4/29-4/30; load off 4/8-4/12, shut off 4/20 thru end of month pending repair.

CARLE Acheval inverter installed and running on 4/9 (Gemini inverter running 4/1-4/9, PV system data not included here); no utility power readings 4/30; average of 4.24 kWh/day used for back-up resistance domestic hot water and space heating not included in load.

NERES MONTHLY SUMMARY
MAY 1982

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	20.22	26.81	19.50
Average daily minimum ambient air temperature..............(deg. C)	8.49	7.92	10.05
Average ambient air temperature............................(deg. C)	14.28	16.28	14.77
Total degree days heating/cooling...................(deg. C days)	128./ 0.	20./ 0.	121./ 14.
Total precipitation...(cm)	6.60	******	8.81
Average wind speed...(m/s)	2.41	******	5.45
Average daily horizontal insolation..................(kWh/m**2/day)	4.94	******	5.11

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used......................(kWh/day)	15.36	31.42	13.83	36.36	19.18
Average daily electric energy used during sunhours........(kWh/day)	8.84	22.29	8.58	25.61	13.32
Monitored house data hours/hours in month........................(%)	87.32	98.95	70.85	98.79	92.89

PHOTOVOLTAIC (PV) SYSTEM INFORMATION PV ARRAY AND POWER CONDITIONING UNIT (PCU)	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily array dc energy output....................(kWh/day)	30.15	10.26	******	19.80	17.24	37.05
Average daily array dc energy output/rated array power(kWh/day/kWp)	4.43	4.66	******	4.14	3.45	4.87
Peak array power for month......................................(kW)	8.63	2.29	******	5.62	6.11	7.66
Average daily array peak power..................................(kW)	6.49	1.97	******	4.01	4.34	6.96
Average daily total tilt insolation.................(kWh/m**2/day)	4.77	4.61	5.13	4.53	4.65	5.47
Average daily insolation during system on-hours......(kWh/m**2/day)	4.58	5.20	******	4.47	4.29	5.42
Insolation utilization efficiency................................(%)	99.69	97.70	******	99.67	94.15	99.01
Peak insolation for month.............................(kW/m**2)	1.28	1.27	1.39	1.27	1.35	1.05
Average daily peak insolation.........................(kW/m**2)	0.98	0.94	1.01	0.93	0.98	0.98
Array efficiency...(%)	7.74	7.10	******	9.37	6.11	6.90
Average daily maximum array temperature..................(deg. C)	52.50	48.48	61.17	47.04	55.99	59.55
Average daily minimum array temperature..................(deg. C)	5.64	5.05	6.41	8.76	7.89	5.30
Average daily PCU ac energy output......................(kWh/day)	26.57	8.92	******	17.75	14.93	32.40
Peak PCU power for month..(kW)	7.95	2.06	******	5.26	5.54	6.89
Average daily PCU peak power....................................(kW)	5.91	1.77	******	3.75	3.94	6.29
PCU efficiency...(%)	88.11	86.95	******	89.64	86.59	87.46
Array and PCU data hours during sunhours..............(hours/month)	388.96	255.16	******	407.67	273.54	122.02
Sunhours..(hours/month)	447.15	447.15	447.15	447.15	447.15	447.15
System reliability..... ....(%)	100.00	100.00	0.00	100.00	100.00	100.00

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output......................(kWh/day)	26.57	8.92	******	17.75	14.93	31.15
Average daily energy from utility.......................(kWh/day)	20.13	20.69	******	25.91	0.46	30.16
Average daily energy to utility.........................(kWh/day)	20.46	4.85	******	11.65	14.90	20.73
Average daily energy to load............................(kWh/day)	26.13	24.79	******	31.98	0.00	40.01
System-utility data hours/hours in month.........................(%)	89.12	58.69	******	91.61	61.55	19.50

NOTES: Imposed load data source provided by MH3. Scattered data outages on 5/13 (2 hours data lost between 10:00-15:00).
MITLL PDAC offline 5/28 16:46-18:00, 5/29 9:03 thru end of month; PV system shut down 5/18 8:44-12:56 for inverter transfer switch installation; load off 5/1-5/3.
WEST Sunsine 4 kW inverter installed on 5/19 and running thru end of month (PV system data not included here).
GE inverter on/off for testing 5/19-5/26.
TRISC PDAC offline 5/7 23:50 thru 5/10 8:01.
SOLRX DECC inverter installed 5/11; PV system shut down 5/18 8:44 to 5/19 9:10 for inverter transfer switch installation; load off pending repairs.
CARLE no data 5/9 thru end of month, IDAC needs repair; PV system running entire month; no utility power readings 5/1-5/3; average of 1.77 kWh/day used for back-up resistance domestic hot water and space heating not included in load.
Weather Station WDAC offline 5/26 10:00-15:03.

NERES MONTHLY SUMMARY

QUANTITY	UNITS	DEFINITION
METEOROLOGICAL INFORMATION		
Average daily maximum ambient air temperature	(deg. C)	Average of highest 6-minute-avg readings for each day
Average daily minimum ambient air temperature	(deg. C)	Average of lowest 6-minute-avg readings for each day
Average ambient air temperature	(deg. C)	Average of all readings for month
Total degree days heating/cooling	(deg. C days)	Heating base 18.3 deg. C, cooling base 23.9 deg. C
Total precipitation	(cm)	Expressed in equivalent centimeters of water
Average wind speed	(m/s)	Average of all readings for month
Average daily horizontal insolation	(kWh/m**2/day)	Sum of average-hour values for month
MONITORED HOUSE INFORMATION		
Average daily electric energy used	(kWh/day)	Sum of average-hour values for month
Average daily electric energy used during sunhours	(kWh/day)	Sum of average-hour values for month
Monitored House data hours/hours in month	(%)	Per cent monitored house data coverage for month
PHOTOVOLTAIC (PV) SYSTEM INFORMATION		
PV ARRAY AND POWER CONDITIONING UNIT (PCU)		
Average daily array dc energy output	(kWh/day)	Sum of average-hour values for month
Average daily array dc energy output/rated array power	(kWh/day/kWp)	Sum of avg.-hour values for month/rated array peak power
Peak array power for month	(kW)	Highest of all 6-minute-peak readings for month
Average daily array peak power	(kW)	Avg. of highest 6-minute-peak readings for each day*
Average daily total tilt insolation	(kWh/m**2/day)	Sum of average-hour values for month
Average daily insolation during system on-hours	(kWh/m**2/day)	Sum of average-hour values for month
Insolation utilization efficiency	(%)	Total monthly insolation during system on-hours/ total monthly total tilt insolation
Peak insolation for month	(kW/m**2)	Highest of all 6-minute-peak readings for month
Average daily peak insolation	(kW/m**2)	Avg. of highest 6-minute-peak readings for each day*
Array efficiency	(%)	Average daily array dc energy output/(average daily insolation during system on-hours x array area)
Average daily maximum array temperature	(deg. C)	Avg. of highest 6-minute-avg readings for each day*
Average daily minimum array temperature	(deg. C)	Average of lowest 6-minute-avg readings for each day
Average daily PCU ac energy output	(kWh/day)	Sum of average-hour values for month
Peak PCU power for month	(kW)	Highest of all 6-minute-peak readings for month
Average daily PCU peak power	(kW)	Avg. of highest 6-minute-peak readings for each day*
PCU efficiency	(%)	Average daily PCU ac energy output/average daily array dc energy output
Array and PCU data hours during sunhours	(hours/month)	Hrs of data upon which energy outputs + effc's. are based
Sunhours	(hours/month)	Algorithmically computed daylight hours
System reliability	(%)	Total hours of PV system operational availability during sunhours/total sunhours in month
PV SYSTEM-UTILITY ENERGY FLOW		
Average daily PCU ac energy output	(kWh/day)	Sum of average-hour values for month
Average daily energy from utility	(kWh/day)	Sum of average-hour values for month
Average daily energy to utility	(kWh/day)	Sum of average-hour values for month
Average daily energy to load	(kWh/day)	Sum of average-hour values for month
System-utility data hours/hours in month	(%)	Hrs of data upon which sys-util calc's are based/hrs in mth

*Day is omitted from average if 1 consecutive hour of data is missing or invalid from 10 a.m. to 2 p.m.

NERES MONTHLY SUMMARY
JUNE 1982

Site Location	NERES	CARLE
Latitude:	42.46	42.53
Longitude:	71.30	71.36
Elevation:	40.5m	91.4m

METEOROLOGICAL INFORMATION	NERES	CARLE	BOSTON NORMALS
Average daily maximum ambient air temperature..............(deg. C)	21.66	21.20	24.77
Average daily minimum ambient air temperature..............(deg. C)	12.27	8.24	15.16
Average ambient air temperature............................(deg. C)	16.86	13.90	20.00
Total degree days heating/cooling....................(deg. C days)	66./ 0.	125./ 0.	15./ 74.
Total precipitation..(cm)	29.08	******	8.10
Average wind speed..(m/s)	2.74	******	5.05
Average daily horizontal insolation.................(kWh/m**2/day)	4.68	******	5.73

MONITORED HOUSE INFORMATION	MH2	MH3	MH4	MH5	MH6
Average daily electric energy used.......................(kWh/day)	15.55	29.98	15.14	43.79	18.56
Average daily electric energy used during sunhours........(kWh/day)	10.09	21.54	9.60	31.29	12.84
Monitored house data hours/hours in month......................(%)	19.17	97.96	97.86	97.38	97.68

PHOTOVOLTAIC (PV) SYSTEM INFORMATION	MITLL	WEST	GE	TRISC	SOLRX	CARLE
PV ARRAY AND POWER CONDITIONING UNIT (PCU)						
Average daily array dc energy output.....................(kWh/day)	25.44	15.52	******	17.74	16.13	25.73
Average daily array dc energy output/rated array power(kWh/day/kWp)	3.74	3.53	******	3.71	3.23	3.39
Peak array power for month....................................(kW)	8.04	4.49	******	5.41	6.10	7.53
Average daily array peak power................................(kW)	5.37	3.23	******	3.58	3.41	5.04
Average daily total tilt insolation.................(kWh/m**2/day)	4.12	4.03	4.53	3.95	4.03	3.88
Average daily insolation during system on-hours......(kWh/m**2/day)	4.04	3.99	******	3.94	4.08	3.88
Insolation utilization efficiency..............................(%)	98.22	97.03	******	98.97	96.10	98.88
Peak insolation for month...............................(kW/m**2)	1.24	1.22	1.34	1.21	1.29	0.98
Average daily peak insolation...........................(kW/m**2)	0.84	0.82	0.91	0.82	0.85	0.70
Array efficiency...(%)	7.44	7.11	******	9.57	6.27	6.73
Average daily maximum array temperature...................(deg. C)	45.67	43.21	55.91	42.00	49.78	******
Average daily minimum array temperature...................(deg. C)	9.94	8.90	10.40	13.03	11.77	******
Average daily PCU ac energy output.......................(kWh/day)	21.85	13.62	******	15.70	13.88	22.51
Peak PCU power for month......................................(kW)	7.22	4.07	******	5.07	5.51	6.81
Average daily PCU peak power..................................(kW)	4.80	2.92	******	3.34	3.08	4.55
PCU efficiency...(%)	85.90	87.71	******	88.49	86.07	87.51
Array and PCU data hours during sunhours.............(hours/month)	341.79	434.84	******	439.30	227.61	397.14
Sunhours...(hours/month)	451.79	451.79	451.79	451.79	451.79	451.79
System reliability...(%)	100.00	100.00	0.00	100.00	100.00	100.00

PV SYSTEM-UTILITY ENERGY FLOW	MITLL	WEST	GE	TRISC	SOLRX	CARLE
Average daily PCU ac energy output.......................(kWh/day)	21.83	13.62	******	15.70	13.88	******
Average daily energy from utility........................(kWh/day)	21.87	14.09	******	24.46	0.53	******
Average daily energy to utility..........................(kWh/day)	15.28	9.70	******	9.59	13.83	******
Average daily energy to load.............................(kWh/day)	28.49	18.07	******	30.62	0.0	******
System-utility data hours/hours in month.......................(%)	75.97	97.41	******	97.96	50.80	******

NOTES: Imposed load data source provided by MH3.
MITLL Acheval inverter disconnected 6/24; output-filtered Gemini running 6/24-6/30 (PV system data not included here).
GE Abacus inverter on/off for testing 6/17-6/18.
SOLRX DECC inverter disconnected 6/16; Abacus inverter running 6/17-6/30 (PV system data not included here).
CARLE no data 6/1-6/3 pending IDAC and sensor repairs; no utility power and array temperature readings 6/3-6/30.
MH2 RDAC offline 6/5 thru end of month pending repair.

APPENDIX REFERENCES

A1. Jet Propulsion Laboratory, "Solar Cell Array Design Handbook, Volume 1," National Aeronautics and Space Administration, October 1976.

A2. Bird, R. E., and Hulstrom, R. L., "Atmospheric Effects on Solar Cell Calibration and Evaluation," Solar Energy Research Institute, Golden, Colorado, December 1981.

A3. Kasten, Fritz, "A New Table and Approximation Formula for the Relative Optical Air Mass," Technical Report 136, U.S. Army Materiel Command, Cold Regions Research & Engineering Laboratory, Hanover, New Hampshire, November 1964.