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1995 PVUSA Progress Report

March 1996

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PVUSA Project Team

for

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EXECUTIVE SUMMARY

Photovoltaics for Utility Scale Applications (PVUSA) is a national public-private partnership that is assessing and demonstrating the viability of utility-scale (US) photovoltaic (PV) electric generation systems and recent developments in PV module technology. This report updates the project's progress, reviews the status and performance of the various PV installations during 1995, summarizes key accomplishments and conclusions, and serves as the final report under Pacific Gas and Electric Company's project management.

Objectives

The PVUSA project has five objectives. These objectives are designed to narrow the gap between a large utility industry that is unfamiliar with PV and a small PV industry that is aware of a potentially large utility market but unfamiliar with how to meet its requirements. The objectives are:

1. Evaluate the performance, reliability, and cost of promising PV modules and balance-of-system (BOS) components side by side at a single location
2. Assess PV system operation and maintenance (O&M) in a utility setting
3. Compare PV technologies in diverse geographic areas
4. Offer U.S. utilities hands-on experience in designing, procuring, and operating PV systems
5. Document and disseminate knowledge gained from the project

PVUSA participants include the U.S. Department of Energy, the California Energy Commission (CEC), the Electric Power Research Institute (EPRI), Pacific Gas and Electric Company (PG&E), and 10 utilities and other energy-related agencies. Since inception in 1986, PG&E has led the PVUSA Project Team, which manages daily activities and performs technology transfer.

Project Scope

PVUSA consists of two types of demonstrations: (1) emerging module technologies (EMTs), which are state-of-the-art PV technologies in 20-kW (nominal) arrays; and (2) US systems, which represent more mature PV technologies in turnkey systems ranging from 200 to 500 kW (nominal). Several PVUSA participants have hosted the installation

of EMT arrays or US systems at their utility sites. PVUSA's primary test site in Davis, California, is the location of eight EMT arrays and three US systems.

PVUSA is fielding EMT arrays primarily to encourage commercialization of promising PV module technologies. Lessons learned by manufacturers will be important input for PV technology development decisions. EMTs also provide information on various components making up the array (e.g., junction boxes, inter-array wiring). This information is of interest regardless of the future commercialization of the full array.

US systems are vendor-optimized turnkey PV systems representing mature module technologies that have the potential to produce low-cost energy and also meet the O&M, power quality, reliability, and lifetime requirements necessary for utility applications. US systems are expected to capture much of the economies of scale of larger systems and provide realistic evidence of satisfactory system protection requirements, installation requirements and costs, performance, and O&M costs. These systems incorporate innovative BOS designs and expose the PV industry to commercial procurement and construction practices.

The project, begun in 1986, has undertaken three EMT procurements (EMT-1, EMT-2, and EMT-3) and two US system procurements (US-1 and US-2). Tables ES-1, ES-2, and ES-3 list PVUSA EMT, US, and host utility system suppliers, completion dates, PV technologies employed, and system sizes. All completion dates in this report are as of December 1995.

Accomplishments

Significant contributions were made toward meeting each of the project's five objectives. The achievements are summarized below. Details of project accomplishments in past years are provided in *1989-1994 PVUSA Progress Reports*, topical reports, journal articles, and conference papers.

Evaluating Performance, Reliability, and Cost of PV Modules and BOS Components

PVUSA has continued to fulfill its primary objective of evaluating a wide range of promising PV module and BOS technologies in a utility setting. Measures of evaluation have included electrical energy production, efficiency, capacity factor, performance index, and BOS experience.

In 1995, the electrical energy production of PVUSA's 19 systems equaled 2.3 million kWh, about one-third of the cumulative generation from 1989 through 1995. This quantity was almost exactly the same amount generated in 1994 and would be enough to satisfy the electricity requirements of about 375 homes, based on an average

Table ES-1
PVUSA Davis EMT Systems

Completion Date	Supplier	Module Technology	dc System Efficiency ^a (%)	dc Power ^a (kW)
	EMT-1			
1/89	Siemens Solar (ARCO)	Microgridded single-crystal silicon	11.1	18.7
6/89	Sovonics	Tandem-junction amorphous silicon	3.5	17.3
12/89	Utility Power Group	Tandem-junction amorphous silicon	3.3	15.7
10/90	Solarex	Bifacial polycrystalline silicon	8.6	15.7
3/91	ENTECH	22x linear concentrator, crystalline silicon	11.3	16.5
	EMT-2			
11/94	AstroPower	Thin-film polycrystalline silicon on ceramic	5.9	17.1
	EMT-3			
12/95	Solar Cells	Cadmium telluride	6.3	12.0
12/95	Amonix	260x point-focus concentrator, crystalline silicon	tdb	19.0 ^b

^a Calculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For concentrators, a direct normal irradiance of 850 W/m² is used. For EMT arrays, dc efficiency is reported since the emphasis is on comparing module performance.

^b Based on supplier's estimate. A rating will be calculated during the spring of 1996.

Table ES-2
PVUSA Davis and Kerman US Systems

Completion Date	Supplier	Technology	ac System Efficiency ^a (%)	ac Power ^a (kW)
	US-1 Davis			
9/92	Advanced PV Systems	Amorphous silicon, fixed tilt, APS PCU	4.2	479
6/93	Integrated Power Corp.	Ribbon silicon (MSEC EFG), one-axis active-tracking, KWI PCU	8.0	196
5/94	Siemens Solar	Single-crystal silicon, one-axis passive-tracking, Bluepoint PCU	7.9 ^b	67 ^b
	US-2 Kerman			
6/93	Siemens Solar	Single-crystal silicon, one-axis passive-tracking, Omnion PCU	9.8	498

^a Calculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For US systems, ac efficiency is reported since the emphasis is on system performance. Power conditioning unit (PCU) efficiencies of 90 to 95 percent account for almost all of the difference between ac and dc efficiencies.

^b Based on 50% of the installed array; one of the two PCUs is not operational.

Table ES-3
PVUSA Host Utility Systems

Completion Date	Host Utility Sponsor	Supplier	Technology	System Efficiency ^a (%)	Power ^a (kW)
10/89	Maui Electric (Kihei, HI)	Sovonics	Tandem-junction amorphous silicon, fixed tilt, DECC PCU	3.7 dc	18.5 dc
7/92	City of Austin (Austin, TX)	IPC	Ribbon silicon (MSEC EFG), one-axis active-tracking, Omnion PCU	8.4 ac	17.9 ac
7/93	NREL (NYPA) (Maspeth, NY)	IPC	Tandem-junction amorphous silicon (USSC), fixed tilt, Omnion PCU	3.1 ac	12.9 ac
8/93	NYSERDA (Farmingdale, NY)	IPC	Ribbon silicon (MSEC EFG), one-axis active-tracking, Omnion PCU	8.4 ^b ac	17.9 ^b ac
4/94	SMUD (Sacramento, CA)	UPG	Single-crystal silicon (SSI), one-axis active-tracking, Omnion PCU	10.1 ac	207 ac
11/94	CSW (Fort Davis, TX)	UPG	Single-crystal silicon (SSI), one-axis active-tracking, Omnion PCU	9.6 ac	98 ac
9/95	CSW (Fort Davis, TX)	ENTECH	21x linear concentrator, crystalline silicon, Omnion PCU	11.0 ac	83 ac
12/96	DOD (Yuma, AZ)	UPG	Single-crystal silicon (SSI), fixed tilt, Kenetech PCU	tbd	375 ^c ac
6/96	PSCo (Aurora, CO)	New World Power	Single-crystal silicon (AstroPower), one-axis active-tracking, Omnion PCU	tbd	22 ^c ac

^a Calculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For concentrators, a direct normal irradiance of 850 W/m² is used. Generally, EMTs are rated on array dc output and USs are rated on ac output (determined by contract).

^b Estimated rating based on same-size system at Austin, Texas. A final rating will be calculated upon system acceptance by NYSERDA.

^c Based on supplier's estimate (system yet to be rated).

residential customer load of about 500 kWh/month. 1995 was also a landmark year, with the project surpassing the 5 million kWh mark in March. Its generation reached a cumulative total of 7.1 million kWh at the end of the year.

System efficiencies ranged from about 3 percent for systems consisting of amorphous silicon modules to about 7-10 percent for those using single-crystal silicon. Only 4 of the

18 systems rated by PVUSA met or exceeded suppliers' efficiency estimates. Efficiencies of fielded arrays and systems appear to be degrading slightly (average 2 percent, relative) each year.

Annual capacity factors ranged from 7 to 21 percent, although monthly capacity factors for several systems exceeded 30 percent during the summer. Peak period capacity factors for several systems in PG&E's service territory were in the 50-66 percent range.

System reliability was evaluated with a measure called the performance index (PI). The PI, which was developed and implemented by PVUSA in 1994 and approved in 1995 to replace the previously reported availability statistic, is a dimensionless ratio of actual to expected generation. The PI is a very quick and useful indicator of the general health of the PV system over any given time period. For 1995, the PI ranged from 38 to 97 percent for the 16 systems with available performance data. Eight systems operated with a PI of 80 percent or higher. Low 1995 performance indices are primarily attributable to extensive PCU downtime. Consistently low annual performance indices (e.g., 31 percent in 1994) for IPC US-1 due to PCU downtimes resulted in the procurement in 1995 of a replacement PCU from Kenetech WindPower, Inc. This procurement demonstrated a substantial price reduction from previous procurement rounds (less than 50¢/W compared to over \$1/W). Start-up was smooth and the PCU has operated reliably, except for two warranty repairs.

BOS experience showed that the modules that are panelized and prewired at the factory reduce field labor and provide an overall cost benefit. The project also proved that savings can be realized if module and/or panel supports are integrated into the array structure.

Assessing PV System O&M in a Utility Setting

PVUSA has developed and maintained an O&M database to standardize data collection, minimize data omissions, and calculate O&M costs for the Davis and Kerman installations. Improvements to the database in 1993 enhanced the ability to input standardized events and execute specific maintenance queries.

In 1995, the Kerman installation—as an unstaffed PV plant that is remotely monitored and operated—once again provided the most credible PVUSA data on mature system O&M cost. From June 1993 through 1995, the Kerman plant's cumulative O&M cost was 1.5¢/kWh.

O&M experience has indicated that, in general, module reliability is very good. In 1995, the overall failure rate at Davis and Kerman was about 8 per 10,000 modules (0.08 percent), which is less than in prior years. The high module reliability demonstrates the value of requiring module qualification tests. The majority of failures were related to

BOS components. Wiring and connection failures, tracking system misoperation, and PCU problems required the most O&M effort.

Comparing PV Technologies in Diverse Geographic Areas

PVUSA host utility systems are distributed from New York to Hawaii. Comparing the performance of PVUSA's systems has verified that geographic-dependent performance variations are not solely the result of differences in the quantity of solar radiation. The recent installation of two same-design systems by UPG at Sacramento, CA and Fort Davis, Texas will allow direct comparison of performance in different climatic regimes. Two lightning strikes damaged some equipment at the Texas site in 1995, showing the need for improved design for such environments. Differing soil conditions at these two sites showed that support structure designs must be tailored to local soils. Installation of two Sovonics systems, one in Hawaii and one in Davis, has allowed the direct comparison of seasonal efficiencies, annual generation, and maintenance requirements in the different climates. Similar comparisons have been made between the two IPC/MSEC systems, installed in Austin, Texas and Farmingdale, New York, which are smaller versions of the IPC system at Davis.

Comparing the performance of systems at different sites has also verified and encouraged PV technology improvements. For example, the SSI US-2 system at Kerman has shown better tracking accuracy than its predecessor at Davis; this improvement has been attributed to the use of a different refrigerant and larger connecting tubes. Based on their experiences at PVUSA Davis, ENTECH and Amonix have also modified their tracking system designs, which have or will be applied at other sites. When the innovative, PVUSA-fielded MSEC module disk and screw-on cable connector were found to be inadequate, the supplier responded quickly with a redesign and retrofit. Between the Davis and Maui installations, Sovonics redesigned their module to include a dimpled Tefzel front surface, reducing delamination problems at Maui compared to Davis.

Offering U.S. Utilities Experience in Designing, Procuring, and Operating PV Systems

To date, PVUSA has achieved extensive experience procuring, siting, installing, operating, maintaining, and characterizing utility-grade PV plants. The cooperative nature of the project, in turn, has created opportunities to share this experience and discuss issues among members. By generating the communication between utilities and the PV industry necessary for successful commercialization, PVUSA has narrowed the gap in understanding and expectation between utilities and industry. Through its communication efforts, the project has provided key information to utilities on technology status and manufacturer/integrator capabilities, and provided the PV industry with results on performance, durability, and quality control. Accomplishments

have included the development of engineering standard practices, design criteria, and procurement specifications for utility PV systems, and contracting experience.

Achievements in 1995 included procurement and installation of two EMT arrays and a replacement PCU at Davis and one US system at a host utility site. These additions increased PVUSA's total rated capacity to over 1,800 kW, with two more systems totaling about 400 kW planned or under construction. Systems are being operated or being installed in California by PG&E, the Sacramento Municipal Utility District (SMUD), and the U.S. Department of Defense (DOD); in Hawaii by Maui Electric; in Texas by the City of Austin and by Central and South West Services (CSW); and in New York by the New York State Energy Research and Development Agency (NYSERDA) and the New York Power Authority (NYPA).

PVUSA conducts workshops at Davis to provide U.S. utilities an opportunity for hands-on experience that can be directly applied to PV systems in their service territories. In 1995, PVUSA conducted two workshops, both held at the Davis site. The first, on BOS issues, was held in January to discuss the importance of properly designed systems and share the experience of the various BOS designs employed in the PVUSA systems. The second workshop focused on power conversion, data collection, and rating of systems. Previous workshop topics have included procurement, construction, system design, safety, and preventive and failure-related maintenance.

Documenting and Disseminating Knowledge Gained from the Project

The project has continued the technology transfer activities necessary for commercial dialog and technical information exchange between the PV industry and utility users. Along with a monthly update newsletter, PVUSA has generated 17 topical reports, a model technical specification, 5 workshop notebooks, and 33 papers/articles. Project staff have conducted hundreds of tours for groups ranging from grade school students to state governors. In addition, by participating on PV standards development committees, PVUSA has contributed a utility perspective to PV standards. Initially, PVUSA contributed to the development of the flat-plate module qualification test, recently approved as an IEEE Recommended Practice. More recently, the PVUSA field wet resistance test, a method to indicate electrical safety and corrosion susceptibility, and other field acceptance testing procedures are being used as the foundation for another IEEE Recommended Practice.

In 1995, technology transfer activities included hosting two workshops, publishing six topical reports and a journal article, and issuing a model technical specification. The project team also attended two workshops and three conferences, at which they presented papers. In addition, project members made presentations and participated in a number of meetings held in this country and abroad. PVUSA hosted 82 tours of the Davis site, for a total of 392 visitors.

Project Transition and Future Direction

In response to competitive pressures and expected regulatory changes affecting the electric utility industry, PG&E decided to relinquish PVUSA management responsibilities. In mid-1995, the Steering Committee (SC) selected CEC and SMUD as the new PVUSA project managers in 1996. Transition activities began immediately after the SC decision, and are scheduled for completion by early 1996.

As reported in the *1994 PVUSA Progress Report*, the Steering Committee has endorsed some general new directions for PVUSA. These directions are based on the reconnaissance work performed by UNISUN. The PVUSA program will continue to educate utilities and other users on PV technology to allow planning, purchasing, and operating systems with a greater level of confidence and success. The areas of focus endorsed by the Steering Committee include

1. Continue as a user-driven, rather than supplier-driven, program.
2. Use the Davis site, as a well-equipped testing facility, for continued long-term performance evaluation of modules and systems, and for testing—and possibly qualifying—components, either cooperatively or on a fee-for-service basis with manufacturers.
3. Emphasize nearer-term interests, including smaller system configurations and short-term component testing.
4. Continue technology transfer through reports, assistance, and workshops, and increase linkages to other regional and national programs in order to provide synergy and avoid possible duplication of efforts.

These general directions will be revisited and formalized, and specific strategies for implementation developed, once the CEC and SMUD officially assume management.

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1

INTRODUCTION

This section discusses PVUSA's background and scope, project sites, schedule, participants and funding, project transition, and report format.

Background and Scope

Two key elements are required for the acceptance and widespread use of PV by utilities, independent power producers, or third parties. These elements are (1) the knowledge and understanding of the technology, and (2) the availability of field-proven components and designs. PVUSA is a national public-private partnership that is assessing and demonstrating the viability of grid-connected PV electric generating systems. Through field installation and testing, PVUSA is providing its members, and the industry as a whole, vital module and system performance information to build confidence in predicting the performance, reliability, and lifetime economics of PV and to improve product designs. One of a cadre of programs in the U.S., PVUSA is helping to ready technology and markets to increase the use of renewable and sustainable energy supplies.

PVUSA offers utilities the hands-on experience needed to evaluate and use maturing PV technology, provides manufacturers with a test bed for their products, and encourages technology improvement and cost reductions in PV modules and balance-of-system (BOS) components. The project also establishes the communication channels between utilities, government laboratories, and the PV industry that will be necessary for successful development and commercialization of utility PV systems. The specific objectives of PVUSA are:

- Evaluate the performance, reliability, and cost of promising PV modules and BOS components side by side at a single location
- Assess PV system operation and maintenance (O&M) in a utility setting
- Compare PV technologies in diverse geographic areas
- Offer U.S. utilities hands-on experience in designing, procuring, and operating PV systems
- Document and disseminate knowledge gained from the project

The project consists of emerging module technology (EMT) arrays and utility-scale (US) systems. EMTs are state-of-the-art PV module technologies that have not been

extensively field tested. The 20-kW size of the EMT arrays was selected to demonstrate the ability of suppliers to manufacture modules on a production basis rather than a research basis, and allow a statistically credible evaluation, while minimizing the risks associated with a new technology.

PVUSA has fielded EMT arrays primarily to encourage promising PV module technologies to move out of the laboratory and into pilot production. During this evolution, EMT manufacturers can determine whether the manufacturing process merits further development or scaling up. The lessons learned by manufacturers are important input for PV technology commercialization decisions. EMTs also enable PVUSA to establish baseline information regarding the various components of an array (e.g., junction boxes and inter-array wiring). This information is of interest regardless of the future commercialization of the specific module. In addition, EMTs have afforded PVUSA an opportunity to create and establish procedures for performing and tracking O&M costs for PV systems, which have then been used as a basis for developing corresponding procedures for US systems. There have been three procurements of EMTs, designated EMT-1, EMT-2, and EMT-3.

US systems are vendor-optimized turnkey PV systems that use mature module technologies and have the potential to produce low-cost energy and also meet O&M, power quality, reliability, and lifetime requirements necessary for utility applications. Those systems selected for demonstration are nominally 200 kW or larger. They are expected to capture much of the economies of scale of larger systems and provide realistic evidence of meeting acceptable criteria for system protection, installation, system costs, system performance, O&M costs, and grid interaction. They incorporate innovative BOS designs that are expected to lead to cost-effective approaches for utility applications, and provide both the project participants and the PV industry with exposure in commercial procurement and construction practices. There have been two procurements of US systems, designated US-1 and US-2.

The system procured through US-2 has been strategically sited within PG&E's distribution system to provide empirical data on the impact of PV on the local grid, near the town of Kerman, California. In this grid-interactive configuration, the PV system operates in parallel with the utility's 12.47-kV service, supporting a distressed feeder and transformer bank in the Kerman substation. Efforts at the Kerman installation focus on evaluating the costs and benefits of distributed PV generation that is strategically located in an electric transmission and distribution (T&D) system, and furnishing information on the operational and power quality aspects of an unattended PV plant on a high-impedance distribution line.

Project Sites

Most of the EMT arrays and US systems are at PVUSA's main demonstration site in Davis, California, shown in Figure 1-1. The Kerman grid-support system shown in

Figure 1-2 is near the town of Kerman, 15 miles west of Fresno, California. Tables 1-1 and 1-2 list the PVUSA EMT and US systems installed at the Davis and Kerman sites.

In addition, several utilities are hosting PVUSA systems in their service territories. PVUSA also cooperatively monitors other PV systems of utility interest. Host utilities are:

- Maui Electric/State of Hawaii
- City of Austin, Texas
- New York Power Authority (NYPA)
- New York State Energy and Research Development Authority (NYSERDA)
- Sacramento Municipal Utility District (SMUD)
- Central and South West Services, Incorporated (CSW)
- U.S. Department of Defense (DOD)
- Public Service Company of Colorado (PSCo)

Table 1-3 lists the host utility system suppliers, completion dates, PV technologies employed, and system efficiencies and sizes. As a PVUSA host utility, Virginia Electric Power Company (VEPCO) also installed a 20-kW nominal system in 1993, but in 1995 elected to decommission the system and discontinue PVUSA membership.

PVUSA's major PV component and system suppliers include:

- Advanced Photovoltaic Systems (APS) – modules and turnkey systems
- Amonix, Inc. – concentrator array
- AstroPower – modules
- Bluepoint Associates – power conditioning units (PCUs)
- Delta Electronic Control Corporation/Helionetics (DECC) – PCUs
- ENTECH – integrated trackers/concentrator modules
- Integrated Power Corporation (IPC) – turnkey systems
- Kenetech WindPower, Inc. (KWI) – PCUs
- Mobil Solar Energy Corporation (MSEC) – modules
- New World Power Corporation (NWP) – turnkey system
- Omnion Engineering, Inc. – PCUs

Figure 1-1
PVUSA Main Demonstration Site at Davis, California

Figure 1-2
PVUSA Kerman Site

Table 1-1
PVUSA Davis EMT Systems

Completion Date	Supplier	Module Technology	dc System Efficiency ^a (%)	dc Power ^a (kW)
EMT-1				
1/89	Siemens Solar (ARCO)	Microgridded single-crystal silicon	11.1	18.7
6/89	Sovonics	Tandem-junction amorphous silicon	3.5	17.3
12/89	Utility Power Group	Tandem-junction amorphous silicon	3.3	15.7
10/90	Solarex	Bifacial polycrystalline silicon	8.6	15.7
3/91	ENTECH	22x linear concentrator, crystalline silicon	11.3	16.5
EMT-2				
11/94	AstroPower	Thin-film polycrystalline silicon on ceramic	5.9	17.1
EMT-3				
12/95	Solar Cells	Cadmium telluride	6.3	12.0
12/95	Amonix	260x point-focus concentrator, crystalline silicon	tbd	19.0 ^b

^aCalculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For concentrators, a direct normal irradiance of 850 W/m² is used. For EMT arrays, dc efficiency is reported since the emphasis is on comparing module performance.

^bBased on supplier's estimate. A rating will be calculated during the spring of 1996.

Table 1-2
PVUSA Davis and Kerman US Systems

Completion Date	Supplier	Technology	ac System Efficiency ^a (%)	ac Power ^a (kW)
US-1 Davis				
9/92	Advanced PV Systems	Amorphous silicon, fixed tilt, APS PCU	4.2	479
6/93	Integrated Power Corp.	Ribbon silicon (MSEC EFG), one-axis active-tracking, KWI PCU	8.0	196
5/94	Siemens Solar	Single-crystal silicon, one-axis passive-tracking, Bluepoint PCU	7.9 ^b	67 ^b
US-2 Kerman				
6/93	Siemens Solar	Single-crystal silicon, one-axis passive-tracking, Omnion PCU	9.8	498

^aCalculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For US systems, ac efficiency is reported since the emphasis is on system performance. Power conditioning unit (PCU) efficiencies of 90 to 95 percent account for almost all of the difference between ac and dc efficiencies.

^bBased on 50% of the installed array; one of the two PCUs is not operational.

Table 1-3
PVUSA Host Utility Systems

Completion Date	Host Utility Sponsor	Supplier	Technology	System Efficiency ^a (%)	Power ^a (kW)
10/89	Maui Electric (Kihei, HI)	Sovonics	Tandem-junction amorphous silicon, fixed tilt, DECC PCU	3.7 dc	18.5 dc
7/92	City of Austin (Austin, TX)	IPC	Ribbon silicon (MSEC EFG), one-axis active-tracking, Omnion PCU	8.4 ac	17.9 ac
7/93	NREL (NYPA) (Maspeth, NY)	IPC	Tandem-junction amorphous silicon (USSC), fixed tilt, Omnion PCU	3.1 ac	12.9 ac
8/93	NYSERDA (Farmingdale, NY)	IPC	Ribbon silicon (MSEC EFG), one-axis active-tracking, Omnion PCU	8.4 ^b ac	17.9 ^b ac
4/94	SMUD (Sacramento, CA)	UPG	Single-crystal silicon (SSI), one-axis active-tracking, Omnion PCU	10.1 ac	207 ac
11/94	CSW (Fort Davis, TX)	UPG	Single-crystal silicon (SSI), one-axis active-tracking, Omnion PCU	9.6 ac	98 ac
9/95	CSW (Fort Davis, TX)	ENTECH	21x linear concentrator, crystalline silicon, Omnion PCU	11.0 ac	83 ac
12/96	DOD (Yuma, AZ)	UPG	Single-crystal silicon (SSI), fixed tilt, Kenetech PCU	tbd	375 ^c ac
6/96	PSCo (Aurora, CO)	New World Power	Single-crystal silicon (AstroPower), one-axis active-tracking, Omnion PCU	tbd	22 ^c ac

^aCalculated at the time of initial acceptance and based on PVUSA Test Conditions (PTC) and total module area. PTC are defined as 1,000 W/m² plane-of-array irradiance, 20°C ambient temperature, and 1 m/s wind speed. For concentrators, a direct normal irradiance of 850 W/m² is used. Generally, EMTs are rated on array dc output and USs are rated on ac output (determined by contract).

^bEstimated rating based on same-size system at Austin, Texas. A final rating will be calculated upon system acceptance by NYSERDA.

^cBased on supplier's estimate (system yet to be rated).

- Siemens Solar Industries (SSI) – modules and turnkey systems
- Solar Cells, Inc. (SCI) – modules
- Solarex – modules
- Sovonics – modules
- United Solar Systems Corporation (USSC) – modules
- Utility Power Group (UPG) – modules and turnkey systems

Schedule

Figure 1-3 shows the overall schedule for project activities, except for those of host utilities. Additional activities for 1996 will be identified after the project transitions to new management.

Figure 1-3
PVUSA Overall Schedule

EMTs

At Davis, EMT-1 consists of five 20-kW (nominal) arrays, as listed in Table 1-1. The EMT-1 arrays were completed by early 1991. Except for AstroPower, all EMT-2 and EMT-3 contracts were terminated or suspended in 1993, primarily because of unacceptable delays in supplier schedules. The AstroPower EMT-2 array was completed in late 1994. Reconsideration of the suspended EMT-2 and EMT-3 contracts resulted in PVUSA issuing requests in 1994 for updated proposals to Amonix, Golden Photon, and Solar Cells. The Steering Committee in March 1995 directed PVUSA to procure Amonix and Solar Cells EMT-3 arrays. The target completion date was September 1 for both arrays. Both suppliers requested extensions. Solar Cells was completed on September 29 while Amonix completed construction on October 12, a significant improvement over previous EMT procurements. PVUSA offered to contract with Golden Photon to complete module qualification by September 1995. However, Golden Photon was not able to make the schedule. All EMT arrays are installed with PVUSA-supplied BOS components, including 25-kW Delta Electronic Control Corporation (DECC) Helionetics inverters.

US Systems

US-1 at Davis consists of a 479-kW fixed-tilt amorphous silicon system, a 196-kW active-tracking crystalline silicon system, and a 67-kW (50 percent of the installed array) passive-tracking crystalline silicon system. US-2 at Kerman consists of a 498-kW passive-tracking crystalline silicon system. Two US-1 systems at Davis and the US-2 system at Kerman were completed by mid 1993. The third US-1 system was accepted by PVUSA in 1994 with one of two PCUs operational. The 498-kW Kerman system was the object of extensive testing, data collection, and analysis for grid-support benefits validation, which was completed in late 1994. A new PCU was procured and installed in 1995 on one of the US-1 systems to replace a troublesome, obsolete unit. This procurement, showcasing a new technology, took only 16 weeks from award to acceptance.

Technology Transfer

PVUSA has regularly reported on array performance and selected topics of interest through quarterly and annual reports, papers, and presentations. However, the project has recognized a need to provide in-depth documentation of its experience in key areas. Efforts in 1995 focused on completing several topical reports based on the experience gained over many years. Two workshops associated with these reports were also conducted. From project inception through 1995, PVUSA has generated 17 topical reports (6 in 1995), a model technical specification (in 1995), 5 workshop notebooks (2 in 1995), and 33 papers/articles (6 in 1995).

Participants and Funding

PVUSA is a national cooperative research and development project. Participants are listed below.

Government Agencies/Research Institutes

- Department of Energy (DOE)
 - Jet Propulsion Laboratory (JPL)
 - National Renewable Energy Laboratory (NREL)
 - Sandia National Laboratories (SNL)
- Department of Defense (DOD) Tri-Service PV Review Panel
- Electric Power Research Institute (EPRI)
- California Energy Commission (CEC)

Utilities/Other Agencies

- Pacific Gas and Electric Company (PG&E)
- Central and South West Services, Incorporated (CSW)
- City of Austin, Texas
- New York State Energy Research and Development Authority (NYSERDA)
- Niagara Mohawk Power Corporation
- Public Service Company of Colorado (PSCo)
- Sacramento Municipal Utility District (SMUD)
- Salt River Project (SRP)
- San Diego Gas and Electric (SDG&E)
- State of Hawaii/Maui Electric

Participation by additional utilities and research organizations is encouraged. For more information, please contact the PVUSA project office, (916) 753-0725.

PVUSA's management structure consists of three groups: the Steering Committee (SC), which coordinates overall project direction and approves the project's scope, schedule, and budget; the Technical Review Committee (TRC), which assesses and reviews technical aspects of the project; and the Project Team, managed by PG&E, which conducts daily activities and facilitates technology transfer. The Project Team consists of PG&E and its two principal subcontractors, Bechtel Construction Company and Endecon Engineering.

Total project commitments for the core program under PG&E's management are over \$34 million (including indirect costs and overhead), including partial funding for 1996. This figure does not include the labor and hardware costs incurred by host utilities in the installation of their systems. Funding committed by PVUSA sponsors is shown in Table 1-4.

Table 1-4
Funds Committed Through 1995 by PVUSA Sponsors
(Includes Partial Funding for 1996)

Organization	Amount (\$ millions)	Percent
Pacific Gas and Electric Company	13.2	38
U.S. Department of Energy	16.3	47
Electric Power Research Institute	3.5	10
California Energy Commission	1.3	4
Other Utilities	0.3	1
Total	34.6	100

Project Transition

To better prepare for a more competitive electric utility environment, PG&E decided in 1994 to decrease funding for research and development of generation technologies. Consequently PG&E decided to relinquish management of the PVUSA project at the end of 1995. PVUSA responded with significant efforts to ensure a smooth transition of project management to a new project manager. After conducting an industry/utility/government survey and developing a business plan in 1994 and identifying potential new management, the SC gave tentative approval in March 1995 of a joint CEC/SMUD management team. In June 1995, the SC reaffirmed the decision, wherein CEC will assume ownership of the PVUSA assets, while SMUD will have primary responsibility for daily management operations. Although the transition was scheduled for January 1, 1996, unexpected delays in finalizing agreements between various parties and securing/training personnel for the new team have caused the transfer date to be postponed until second quarter, 1996. Efforts to transfer to the new project team the contracts, records, and knowledge gained by the PG&E-led team will be completed in early 1996. This is the final report under PG&E's project management.

Report Format

This report describes PVUSA activities during 1995 and covers the following:

Section 1 discusses the background and scope, project sites, schedule, participants and funding, and project transition.

Section 2 summarizes engineering, procurement, and construction activities for the year.

Section 3 reviews the performance of the 19 PVUSA systems in operation during 1995. It summarizes overall performance and reports on energy production, efficiency, and other indicators. In addition, this section notes key BOS experience.

Section 4 describes major maintenance activities during 1995 at the Davis, Kerman, and project participants' sites, and presents estimates of maintenance costs at the Davis and Kerman sites.

Section 5 evaluates the 1995 grid-support performance of the Kerman PV plant.

Section 6 briefly describes PVUSA's data acquisition systems for the Davis and Kerman sites.

Section 7 summarizes special tests, specifically current-voltage curve tests, power quality tests, soiling studies, ground resistance tests, and APS soil anchor corrosion tests.

Section 8 lists 1995 safety-related activities.

Section 9 discusses activities to transition PVUSA over to new management.

Section 10 describes technology transfer activities.

Section 11 presents the key findings and conclusions.

Appendix A contains weather data.

Appendix B contains detailed monthly weather and performance summaries.

Appendix C presents detailed summaries of Davis and Kerman O&M activities.

Appendix D provides system and site descriptions for PVUSA's host utility sites, and outlines future development plans of PVUSA participants.

Appendix E briefly discusses consensus standards support by PVUSA.

Appendix F lists PVUSA annual reports, topical reports, technical specifications, workshop notebooks, conference papers, and journal articles.

Appendix G is a glossary of important terms and abbreviations that appear in this report.

2

ENGINEERING, PROCUREMENT, AND CONSTRUCTION

This section summarizes 1995 activities in engineering, procurement, and construction. Activities include tracker upgrades for ENTECH EMT-1, array rating for AstroPower EMT-2, module qualification discussions with Golden Photon, and installations of the Amonix and Solar Cells EMT-3 arrays and the Kenetech WindPower PCU. Prior activities are documented in the *1989-1994 PVUSA Progress Reports*.

ENTECH EMT-1 Tracker Upgrades

On May 9, the array's dc tracker controller and drive motors were replaced. This modification to the drive system was previously implemented on the CSW ENTECH system because of problems experienced during high winds at the Fort Davis, Texas, site. The mechanical action for westerly module rotation was changed from a "pull" to a "push" mode. (The motor drives through a mechanical linkage. ENTECH found that exerting force to push rather than pull the CSW ENTECH array to the west was more effective.)

On November 6, PVUSA informed ENTECH that both the east and west end bearing axle assemblies appeared to have failed, causing the end sections to sag about 5 or 6 degrees. ENTECH furnished spacer plates, which were installed on November 13, correcting the sag to about 1 degree. The array was not activated because a roll motor was found to have been burned out. A limit switch had failed with damage to the linkage between the motor and screw jack. ENTECH opted to replace the entire roll motor assembly, with implementation occurring on November 20. The system has tracked well since then. The root cause of the bearing assembly failure is probably the choice of bearing and the axle connection to the array (ENTECH assessment). ENTECH is reviewing the design, and is expected to standardize on larger bearings with a looser fit.

AstroPower EMT-2 Array Rating

The AstroPower installation was completed in November 1994. A rating report was released in May 1995, establishing an array rating of 17.1 kW_{dc} at PVUSA Test Conditions (PTC). The contract value was 19.3 kW_{dc}.

Golden Photon EMT-2 Contracts

The 1989 Photon Energy (later Golden Photon) contract to supply an array was terminated by agreement in July 1993. In March 1995, PVUSA offered to contract with Golden Photon (GP) for qualification of GP modules, stipulating that qualification be completed by September 1, 1995. When GP informed PVUSA in August that module testing would not be completed until November 1995, PVUSA terminated the option. No additional PVUSA contracts with GP are planned.

Amonix EMT-3 Array Installation

The Amonix EMT-3 array was designed to reuse existing EPRI equipment, refurbished to like-new condition. The Amonix contract for a 19.0-kW_{dc} Integrated High-Concentration Photovoltaic (IHCPV) array was targeted for completion on September 1, but installation was delayed by the discovery that the existing EPRI pedestal was structurally inadequate for the new array. The EPRI pedestal was cut off and abandoned, and a new pedestal was installed 10 feet north of the original. A field wet resistance test (FWRT) on September 28 found no insulation problems (the first time in project history), and the array was offered for acceptance testing on October 12. Contract and installation milestones were:

	<u>Contract</u>	<u>Complete</u>
• Contract date	3/10/95	—
• Qualification complete	Prior to contract (1994)	—
• Drawings and calculations submitted	4/3/95	8/18/95
• Installation complete	7/31/95	10/2/95
• System turned over for acceptance testing	9/1/95	10/12/95

The array was accepted on November 21 after a 30-day conditioning period. Amonix is making adjustments to improve power output, and a rating will be established in the spring of 1996.

The array consists of 168 Fresnel lens parquets and PV receiver plates integrated into a structural steel matrix and mounted to a tracking structure. Each Fresnel parquet has an aperture area of 0.7587 m² for a total array aperture area of 127.46 m². The overall tracking structure is 159 m² (13.8-m wide, 11.5-m high) and is attached to a center pedestal via a two-axis mechanical drive. Figure 2-1 shows the completed Amonix IHCPV array at Davis.

Figure 2-1
Amonix 260x EMT-3 Concentrator Array

Amonix has identified¹ two restraints to the commercialization of high-concentration PV systems: the lack of stable, high-performance, commercially available high-concentration solar cells; and the high costs of PV modules, structures, tracking systems, and ancillary equipment.

Amonix believes its 260x IHCPV design, developed with EPRI sponsorship, has the potential for low cost ($< \$2/W$) at multi-megawatt levels. Stable solar cells are available, and the integration of the module housing into the tracker structure reduces costs by eliminating redundant structural components.

Precise alignment of the 168 Fresnel lens parquets and PV receiver plates is necessary to correctly focus sunlight onto the cells. Compensation for gravity sag is a factor during assembly. The array trusses were prestressed in a concave fashion such that the desired flatness would be achieved when fully weighted. Reliability of the computer-controlled tracking system and the two-axis mechanical drive is expected to be demonstrated at PVUSA.

¹ V. Garboushian and S. Yoon, "A Novel High-Concentration PV Technology for Cost Competitive Utility Bulk Power Generation," First World Conference on Photovoltaic Energy Conversion, Waikoloa, HI, December 1994.

Amonix on-site activity included assembly of the integrated array structure, receiver plates, and lens covers on the existing assembly pedestal adjacent to the new main pedestal. The principal Amonix subcontractor was Scientific Engineering, Inc.

The completed installation incorporated components released by EPRI (from its 500x HCPV System at PVUSA Davis) as well as material contributed by PG&E.

A trouble-free FWRT was performed on September 28. Subsequently Amonix replaced four PV receiver plates—one on November 14 (suspect appearance), one on November 21 (cracked cell), and two on December 15 (suspect appearance). Amonix also made minor adjustments to the tracker software.

The array was accepted by PVUSA on November 21 following a 30-day conditioning period, although Amonix was still investigating anomalies in array output. Amonix reported that the standard shimming procedure may not have been followed correctly during alignment on the assembly pedestal since some PV receivers were found to be out of focus. Shims were adjusted from November 28 to December 12, resulting in an improved array output. An array rating will be established in early 1996.

Solar Cells EMT-3 Array Installation

The Solar Cells, Inc. (SCI) purchase contract required SCI to furnish panelized modules and installation materials for a 10.8-kW_{dc} fixed flat-plate, cadmium telluride (CdTe) array to be installed by PVUSA on an existing (EMT-2) support structure of wood trusses. Bechtel installed the system because SCI did not possess a California Contractors License, which the State requires of contractors and installers.

The SCI array consists of 264 modules, arranged in 11 source circuits. Each source circuit has six four-module panels. The technology is polycrystalline thin-film CdTe deposited on glass substrates with ethylene vinyl acetate (EVA)/glass lamination. Each module has an aperture area of 0.67 m². The total array aperture area is 176.88 m². Figure 2-2 shows the completed SCI array.

BOS work was completed by PVUSA in September. SCI panels arrived on September 28, and installation was complete on September 29. A FWRT was conducted on October 2; one module had to be replaced (bad pigtail wire), and five factory wiring splices had to be resealed. The array was accepted on October 3, and the 30-day conditioning period was started. Contract milestones were:

	<u>Contract</u>	<u>Complete</u>
• Contract date	3/10/95	—
• Design complete	6/1/95	4/28/95
• Fabrication complete and shipped	9/1/95	9/28/95

Figure 2-2
Solar Cells EMT-3 Cadmium Telluride Array

The completed installation contains 11 source circuits, although the contract was for 10. One source circuit (24 modules) was added, at the request of SCI, when factory flash tests showed module outputs lower than expected.

Data collection to rate the array started on October 23. The rating report was issued on December 19 and established an array rating of $12.0 \text{ kW}_{\text{dc}}$, which is above the contract value of $10.8 \text{ kW}_{\text{dc}}$ (10 source circuits would have yielded $10.9 \text{ kW}_{\text{dc}}$).

Kenetech WindPower PCU Installation

The Steering Committee, acting on a recommendation from the Technical Review Committee, directed on March 1 that a high priority be given to PCU improvements and/or replacements in 1995.

The project identified two PCUs for possible replacement. These were:

- 100-kW Bluepoint Unit A in the SSI US-1 system. This PCU (one of two in the SSI system) was inoperative. The two units had been rebuilt in January 1993 in an unsuccessful effort to get both PCUs on-line.
- 200-kW Omnion Model 3200 in the IPC US-1 system. This PCU had several operational problems, mostly hardware related, after the array was completed in

the second quarter of 1993. The PCU design became obsolete with the installation of two 275-kW Omnion Model 3200 PCUs at Kerman.

To allow time for evaluation of the installed unit in 1995, the target date for installation of a replacement PCU was September 1995. This limited potential suppliers to a delivery schedule of about 16 weeks. In March, informal inquiries were started with potential suppliers for either a 100-kW or 225-kW unit.

Kenetech WindPower, Inc. (KWI) offered delivery in 14 weeks for either a 100-kW or a 225-kW PCU and also offered some cost share with PVUSA. Based on a unit cost (dollars per kilowatt) comparison, the 225-kW PCU was offered at 66 percent of the 100-kW PCU unit cost. The project selected the 225-kW PCU as a replacement in the IPC system.

Following negotiations, a purchase order (effective May 12) for a 225-kW PCU was placed with KWI for delivery by August 18. A factory test of the PCU was witnessed by PVUSA on August 10. This testing immediately followed an internal KWI factory test, which included an 8-hour burn-in test at full load. Witness testing included an inspection for completeness and workmanship, which found some minor omissions. Dc power was provided by a KWI test unit (a similar PCU programmed to generate dc) large enough to test the PCU at full power. Nine operational tests were performed and included partial and full power efficiency and power quality tests.

Functional tests were performed in the laboratory on a control board identical to the PVUSA unit to check the control software. Tests performed were over/under frequency (level and display), over/under ac voltage (level and display), array overvoltage (level only), and dc ground fault (level only). Some adjustments to the software were required, but the PCU passed the tests. Test results were noted and recorded in a test report. The PCU was delivered to PVUSA Davis on August 15.

In early August, PVUSA prepared a concrete foundation for the new PCU and changed wiring and raceways to accommodate it. PCU installation was completed on August 28 and was followed by start-up testing. The PCU was placed in service on August 30 (Figure 2-3). PVUSA had difficulty interfacing the data acquisition signals due to grounding and noise problems. PVUSA eventually had to add small snubber filters at the data logger to achieve acceptable operation. In early September, a minor adjustment to the software, lowering the wake-up voltage, was made in addition to a fan motor change to reduce vibration (not failure related). The PCU operated very reliably until the end of the year. Warranty service visits were required on December 20 and 28 after several gate fault trips; the fan motor failed and was replaced. No problems have been experienced since the December 20 service visit, during which a modulator circuit board was replaced.

Figure 2-3
Kenetech WindPower 225-kW PCU Retrofit to the IPC US-1 System

Host Utility Sites

Central and South West Services

Installation of the 100-kW_{ac} (nominal) ENTECH system started in August 1994. The array, consisting of 288 ENTECH 21x modules arranged in four 72-module rows, was completed in January 1995. Southwest Technology Development Institute (SWTDI) rated the system at 88 kW_{ac} in February 1995, based on January and February data. Since then, a number of start-up problems were encountered, including 8 modules with cracked lenses, 5 modules with electrical failures, and a number of unresolved ground faults and Omnion PCU trips (see Section 4). In late November, PVUSA published a rating report based on data collected in July and August. The PVUSA rating is 83 kW_{ac}. The minor difference in rating is attributed to differences in the method of measurement and the time of year.

Public Service Company of Colorado

The utility's proposal was not selected for Utility Photovoltaic Group (UPVG) TEAM-UP funding and this, combined with APS going out of business, caused PSCo to re-evaluate their options. Both the location and choice of supplier were examined. Late in December, PSCo awarded a contract to New World Power for a 22 kW (nominal) system using PV modules mounted on five polar trackers. The system, to be installed at a state park campground, is expected to be complete by June 1996.

3

SYSTEM PERFORMANCE

The section discusses key performance characteristics for the following 19 PVUSA systems in operation during 1995:

- 8 EMT arrays in Davis, California
- 1 EMT host array in Maui, Hawaii
- 3 US-1 systems in Davis and 1 US-2 system in Kerman, California
- 6 US host systems in Austin, Texas; Farmingdale, New York; Maspeth, New York; Sacramento, California; and Fort Davis, Texas

The section summarizes the performance of these systems in terms of overall performance, the performance index, energy production and general operation, efficiency, and capacity factor. The second half of the section focuses on the performance of BOS components, including PCUs, trackers, module wiring, module mounting, array support, lightning protection, and grounding. Appendices A and B contain data summaries and comparisons of solar radiation and weather for the various sites. System performance for prior years is documented in the *1989-1994 PVUSA Progress Reports*.

Overall Performance

PVUSA added three systems in late 1995 with a combined capacity of 109 kW. The total capacity of the 19 systems now in operation at eight sites is over 1,800 kW. Another 400 kW are scheduled to be installed in 1996. Combined, PVUSA systems generated almost exactly the same amount in 1995 as they did in 1994: 2.27 million kWh, or enough to satisfy the electricity requirements of about 375 homes, based on an average residential customer load of about 500 kWh/month.

Figure 3-1 depicts cumulative annual generation from 1989 through 1995. 1995 was a landmark year with the project surpassing the 5 million kWh mark early in March, reaching a cumulative total of 7.1 million kWh by year's end (an equivalent savings of over 11,000 barrels of oil for the same generation).

The figure highlights the steady growth experienced in 1995, during which the cumulative generation increased by nearly 50 percent, compared to the cumulative total one year ago. This figure also emphasizes the growing importance of the host

Figure 3-1
PVUSA Cumulative Generation
(7.1 GWh through 1995; Present Capacity 1.8 MW)

sites. Generation from the various host sites had accounted for about 8 percent of the project total as of the end of 1994. In 1995, however, the host sites contributed about 32 percent of the annual generation. The jump in host site generation reflects contributions from SMUD's 207-kW and CSW's 98-kW UPG systems, which completed their first full year of operation in 1995. A smaller, yet still significant amount of energy was generated over part of the year by CSW's new 83-kW ENTECH system.

With partial-year contributions from the new SCI and Amonix arrays, the Davis EMT systems generated 12 percent more than last year and accounted for about 7 percent of the project's generation for 1995. The Davis US systems provided 36 percent of this year's generation, and the Kerman US system accounted for the remaining 26 percent.

Tables 3-1 and 3-2 outline key features of each system. A 7-year performance summary for these systems appears in Table 3-3. Detailed 1995 monthly summaries are included in Appendix B.

Performance Index

The performance index (PI) has been developed by PVUSA over the past two years to replace the previously reported availability statistic. Defined as the ratio of actual

Table 3-1
PVUSA Installed EMT Array Characteristics

System	Installation Date	Orientation ^a	dc (ac) Ratings (kW)	Number of Modules	Module Area (m ²)	Array/Module Area
SSI	1/89	30° FFP	18.7 (18.1)	400	169	1.01
Sovonics Davis	6/89	30° FFP	17.3 (15.9)	1,200	497	1.02
Sovonics Maui	10/89	22° FFP	18.5 (17.6)	1,200	497	1.02
UPG	12/89	30° FFP	15.7 (15.1)	4,992	477	1.03
Solarex	10/90	30° FFP	15.7 (15.1)	336	182	1.15
ENTECH	3/91	2-ax Trk	16.5 (15.6)	60	172	2.09
AstroPower	11/94	30° FFP	17.1 (16.1)	312	292	1.15
SCI	12/95	30° FFP	12.0 (11.2)	264	190	1.02
Amonix	10/95	2-ax Trk	n/a	168	159	1.00

^aFFP = fixed flat plate

2-ax Trk = two-axis tracking

Table 3-2
PVUSA Installed US and Host Utility System Characteristics

System	Installation Date	Orientation ^a	ac Rating (kW)	Number of Modules	Module Area (m ²)	Array/Module Area
IPC Austin	7/92	1-ax Trk	17.9	96	212	1.05
APS Davis	9/92	30° FFP	479	9,600	11,520	1.16
IPC Davis	6/93	1-ax Trk	196	1,100	2,443	1.03
SSI Kerman	6/93	1-ax Trk	498	12,240	5,210	1.08
IPC Maspeth	7/93	10° FFP	12.9	1,008	413	n/a
IPC Farmingdale	8/93	1-ax Trk	17.9 (interim)	96	212	1.05
UPG Sacramento	4/94	1-ax Trk	207	4,800	2,043	n/a
SSI Davis	5/94	1-ax Trk	67	1,984	845	1.08
UPG Ft. Davis	11/94	1-ax Trk	98	2,400	1,022	n/a
ENTECH Ft. Davis	9/95	2-ax Trk	83	288	907	n/a

^aFFP = fixed flat plate

1-ax Trk = one-axis tracking, horizontal N-S axis

Table 3-3
PVUSA Annual Performance Summary^a

	System	1989	1990	1991	1992	1993	1994	1995
ac Energy (kWh)	SSI Davis (EMT-1)	33,391	34,243	31,133	29,261	29,891	30,141	27,119
	Sovonics Davis	25,034	29,037	12,087	12,181	22,758	24,350	22,489
	Sovonics Maui	5,713	29,518	27,319	28,085	32,405	30,760	31,006
	UPG Davis	4,559	29,349	25,823	25,407	25,479	26,537	22,464
	Solarex Davis	n/i	4,715	26,016	22,767	23,572	25,915	21,002
	ENTECH Davis	n/i	n/i	27,558	21,117	20,032	27,258	25,745
	APS Davis	n/i	n/i	n/i	214,508	530,047	650,555	535,129
	IPC Austin	n/i	n/i	n/i	3,127	27,790	26,209	25,732
	IPC Davis	n/i	n/i	23,640	15,600	188,541	168,742	187,335
	SSI Kerman	n/i	n/i	n/i	n/i	647,626	1,016,118	586,570
	IPC Maspeth	n/i	n/i	n/i	n/i	n/r	19,478	14,559
	IPC Farmingdale	n/i	n/i	n/i	n/i	n/r	19,270	11,084
	SSI Davis (US-1)	n/i	n/i	n/i	n/i	n/i	98,995	90,514
	UPG Sacramento	n/i	n/i	n/i	n/i	n/i	99,399	384,380
	UPG Ft. Davis	n/i	n/i	n/i	n/i	n/i	12,071	154,983
	AstroPower Davis	n/i	n/i	n/i	n/i	n/i	1,803	28,785
	ENTECH Ft. Davis	n/i	n/i	n/i	n/i	n/i	n/i	91,602
	SCI Davis	n/i	n/i	n/i	n/i	n/i	n/i	4,519
	Amonix Davis	n/i	n/i	n/i	n/i	n/i	n/i	5,341
Efficiency (%) dc for EMTs ac for USs (in italics)	SSI Davis (EMT-1)	10.7	10.6	10.4	10.1	10.2	10.0	9.7
	Sovonics Davis	3.3	3.1	2.9	2.8	2.6	2.6	2.5
	Sovonics Maui	3.7	3.7	3.4	3.4	3.3	3.4	3.3
	UPG Davis	n/i	3.2	3.0	3.0	2.9	2.8	2.9
	Solarex Davis	n/i	8.8	8.2	7.3	7.4	7.8	7.1
	ENTECH Davis	n/i	n/i	11.2	10.7	11.1	10.7	10.1
	APS Davis	n/i	n/i	n/i	3.8	3.2	3.2	2.8
	IPC Austin	n/i	n/i	n/i	8.5	8.1	8.2	7.6
	IPC Davis	n/i	n/i	n/r	n/r	8.1	7.8	7.2
	SSI Kerman	n/i	n/i	n/i	n/i	9.1	9.0	8.1
	IPC Maspeth	n/i	n/i	n/i	n/i	n/r	3.3	3.0
	IPC Farmingdale	n/i	n/i	n/i	n/i	n/r	8.4	7.8
	SSI Davis (US-1)	n/i	n/i	n/i	n/i	n/i	7.5	6.9
	UPG Sacramento	n/i	n/i	n/i	n/i	n/i	9.4	10.1
	UPG Fort Davis	n/i	n/i	n/i	n/i	n/i	n/r	8.5
	AstroPower Davis	n/i	n/i	n/i	n/i	n/i	5.9	5.5
	ENTECH Ft. Davis	n/i	n/i	n/i	n/i	n/i	n/i	n/r
	SCI Davis	n/i	n/i	n/i	n/i	n/i	n/i	6.5
	Amonix Davis	n/i	n/i	n/i	n/i	n/i	n/i	11.0

Table 3-3
PVUSA Annual Performance Summary^a (Cont'd)

	System	1989	1990	1991	1992	1993	1994	1995
ac Capacity	SSI Davis (EMT-1)	21.4	21.7	19.7	18.5	18.9	19.1	17.2
Factor (%)	Sovonics Davis	21.8	20.9	8.7	8.7	16.3	17.7	16.2
	Sovonics Maui	21.4	19.1	17.7	18.2	21.0	20.0	20.1
	UPG Davis	n/i	22.3	19.5	19.2	19.3	20.1	17.0
	Solarex Davis	n/i	17.8	19.7	17.2	17.8	19.6	15.9
	ENTECH Davis	n/i	n/i	26.8	15.4	14.7	19.9	18.8
	APS Davis	n/i	n/i	n/i	15.3	12.6	15.5	12.8
	IPC Austin	n/i	n/i	n/i	8.5	17.7	16.7	16.4
	IPC Davis	n/i	n/i	n/r	n/r	12.6	9.8	10.9
	SSI Kerman	n/i	n/i	n/i	n/i	23.3	23.3	13.4
	IPC Maspeth	n/i	n/i	n/i	n/i	n/r	13.1	9.8
	IPC Farmingdale	n/i	n/i	n/i	n/i	n/r	12.3	7.1
	SSI Davis (US-1)	n/i	n/i	n/i	n/i	n/i	16.3	15.4
	UPG Sacramento	n/i	n/i	n/i	n/i	n/i	14.1	21.2
	UPG Fort Davis	n/i	n/i	n/i	n/i	n/i	n/r	18.0
	AstroPower Davis	n/i	n/i	n/i	n/i	n/i	10.0	20.4
	ENTECH Ft. Davis	n/i	n/i	n/i	n/i	n/i	n/i	13.8
	SCI Davis	n/i	n/i	n/i	n/i	n/i	n/i	14.1
	Amonix Davis	n/i	n/i	n/i	n/i	n/i	n/i	n/r
Performance	SSI Davis (EMT-1)						88	92
Index (%)	Sovonics Davis						88	91
(Not calc.	Sovonics Maui						92	97
until 1994. In	UPG Davis						95	91
1995, a 5%	Solarex Davis						90	83
PCU low-	ENTECH Davis						67	75
load loss	APS Davis						83	73
adjustment	IPC Austin						84	77
was added,	IPC Davis						31	40
increasing	SSI Kerman						85	51
values by	IPC Maspeth						83	84
5% rel. to	IPC Farmingdale						66	38
'94 results,	SSI Davis (US-1)						60	57
which are	UPG Sacramento						64	81
unchanged	UPG Fort Davis						n/r	63
from prior	AstroPower Davis						78	94
reports)	ENTECH Ft. Davis						n/i	n/r
	SCI Davis						n/i	99
	Amonix Davis						n/i	n/r

^aStart dates are staggered; therefore, some quantities are based on a partial year's performance. Refer to Tables 3-1 and 3-2 for installation dates.

n/i = not installed; n/r = not recorded

to expected generation,¹ it is designed to help assess system reliability ("health") by quantifying the impact of soiling, tracker error, and failure-related reductions in generation. Like the capacity factor and availability, it is dimensionless, ranging from 0 to 100 percent, and can be used over any time interval, including instantaneous.

To avoid penalizing the PV system for externally driven departures from its rated power, the PI (Equation 3.1) adjusts the expected generation to allow for scheduled outages and uncontrollable (weather-related) or irreversible (design- or material-related) effects. Several adjustment factors are included, as defined below. The equation may be tailored to include only those factors considered appropriate for the application. For example, it may not be practical or desirable to measure soiling losses, especially for unattended systems. Instead of being quantified separately, soiling losses then penalize the PI, along with other lumped effects.

Generally, factors that influence generation by less than a few percent are probably not worth measuring, as the ± 4 percent uncertainty in the irradiance measurements alone makes it difficult to isolate smaller variations due to other effects. If the value of a particular adjustment factor is not known, the factor is set at 1.0. However, significant departures from rated power will then be reflected in the PI.

$$PI = \frac{\text{Actual generation}}{\text{Expected generation}} = \frac{\text{Actual generation}}{(\text{Rated power})(\text{Adjustment factors})} = \frac{\text{Actual generation}}{(\text{Rated power})(IA)(TA)(DA)(SA)(BOSA)} \quad (\text{eq. 3.1})$$

IA =	Irradiance adjustment =	Actual/rated irradiance
TA =	Temperature adjustment =	$1 + \beta(T_{\text{mod}} - T_{\text{mod,PTC}})$
		β = temperature coefficient of power, $1/^{\circ}\text{C}$
		$T_{\text{mod}}, T_{\text{mod,PTC}}$ = actual and rated module temperatures, $^{\circ}\text{C}$
DA =	Degradation adjustment =	Present rated power/initial rated power
SA =	Soiling adjustment =	$1 - (\text{fractional soiling losses, relative to rated condition})$
BOSA =	Balance-of-system adjustment =	$1 - (\text{fractional BOS losses, relative to rated condition})$

Although each adjustment factor is dynamic, it is impractical and unnecessary to continuously update certain factors, such as degradation, soiling, and BOS adjustments. They may be measured occasionally (e.g., periodic re-ratings to determine new degradation adjustment factors) or applied as constants (e.g., a lumped factor of 0.90 has been applied to single-axis tracking systems to account for reduced PCU efficiency at low loads, inherent tracking accuracy limits, and field-of-view/shading losses). One change made to the PI calculation in 1995 allows for an additional 5 percent expected loss in generation due to reduced PCU efficiency at low loads. This effect has been incorporated within the BOSA factor for each system. All

¹T.U. Townsend, C.M. Whitaker, H.J. Wenger, and B.K. Farmer, "A New Performance Index for PV System Analysis," First World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, December 1994.

other factors being the same, 1995 values have increased by 5 percent compared to 1994.

Equation 3.1 is useful for real-time calculations (power). An alarmed, color-coded version has been added to the Davis site's system data acquisition system (DAS) display screen to aid in system operations and alert operators in the event of partial and full shutdowns and/or off-design performance.

For longer term analyses (energy), the actual power and actual irradiance terms are integrated to yield actual energy and actual insolation. Insolation is calculated only when systems should be running; that is, dawn, dusk, and periods of scheduled downtime are excluded. Average or estimated values for the adjustment factors are applied. For module temperature, the power-weighted average module temperature is used (Equation 3.2), which weights the effect of temperature-driven changes in system efficiency over extended periods.

$$\bar{T}_{mod} = \frac{\sum (\text{Power} \times T_{mod})}{\text{Energy}} \quad (\text{eq. 3.2})$$

For the PIs calculated for this report, and in general, PVUSA does not adjust for soiling or degradation. Figure 3-2 compares the annual performance indices for the 16 PVUSA-affiliated systems at eight locations that were operating at the beginning of 1995. Interestingly, of the five systems that exceeded a 90 percent annual PI, all were EMT arrays (Sovonics arrays at Maui and Davis; and SSI, UPG, and AstroPower arrays at Davis). Six other systems generated between 70 and 90 percent of their expected amounts; and the remaining five systems generated between 38 and 63 percent of their expected amounts. It should be noted that a system's performance index is not penalized for research-related activities that interrupt operation.

Energy Production and General Operation

Introduction

Electrical energy production generally follows the trend in insolation, except that electrical energy production also reflects outages, limited operation during installation and start-up, and seasonal efficiency variations.

Figure 3-2
1995 PVUSA Performance Indices

Figure 3-3 shows the 1995 monthly ac energy generation by the eight Davis EMT systems. Figure 3-4 shows corresponding data for the three Davis US systems. Figure 3-5 shows the 1995 monthly ac energy generated by the Maui Sovonics system, and for purposes of comparison, includes the Davis Sovonics ac energy generation and Davis site insolation. Figures 3-6 through 3-11 show corresponding data for systems at Kerman, Austin, Farmingdale, Maspeth, Sacramento, and Fort Davis, respectively.

Referenced to the right scale of these figures are lines showing 1995 plane-of-array (POA) insolation and the average insolation over the past several years. For Davis, the average is based on 1989 through 1995; for Maui, the average is based on 1990 through 1995. The measured 30-degree tilt insolation for Davis in 1995 was about 5 percent lower than its seven-year average, with most of the shortfall occurring over the first five months of the year. The measured 22-degree tilt insolation for Maui in 1995 was about 2 percent above its six-year average.

EMT Arrays at Davis

For Davis, the EMT energy production pattern varied fairly smoothly between 1,000 and 3,000 kWh per month. The SSI, Sovonics, and AstroPower arrays did not

Figure 3-3
1995 PVUSA Davis EMT Generation and Insolation

Figure 3-4
1995 PVUSA Davis US System Generation and Insolation

Figure 3-5
1995 Sovonics Generation and Site Insolation, Davis and Maui
(Maui Electric)

POA insolation measured on the array of a horizontal single-axis tracking system

Figure 3-6
1995 Kerman (PG&E) Generation and POA Insolation

POA insolation measured on the array of a horizontal single-axis tracking system

Figure 3-7

1995 Austin (City of Austin) Generation and POA Insolation

POA insolation measured on the array of a horizontal single-axis tracking system

Figure 3-8
1995 Farmingdale (NYSERDA) Generation and POA Insolation

POA insolation measured on a south-facing 10-degree fixed-tilt array

Figure 3-9
1995 Maspeth (NYPA) Generation and POA Insolation

POA insolation measured on the array of a horizontal single-axis tracking system

Figure 3-10
1995 Sacramento (SMUD) Generation and POA Insolation

POA insolation measured on the array of a horizontal single-axis tracking system

Figure 3-11

1995 Fort Davis (CSW) UPG Generation and POA Insolation

experience any significant failures or extended outages, and averaged the equivalent of about 5 peak hours of operation per day, or $5 \text{ kWh/kW}_{\text{rated}}/\text{day}$. The ENTECH, Solarex, and UPG arrays experienced significant disruptions, mostly due to BOS failures, and averaged closer to 4 peak hours of operation per day. The 12-kW_{dc} SCI array was completed at the end of September and rated during November; its output pattern was consistent with the insolation profile, and its generation was comparable to that of the other EMT arrays. (The other EMT arrays were originally rated between 16 and 19 kW. Capacities have degraded to between 13 and 16 kW.)

Persistent fog and cloudy conditions near the beginning of the year masked problems with the ENTECH tracking system, which had just been replaced in November 1994. It was observed, however, that the tracker roll function was erratic, especially under high winds, a characteristic also observed on ENTECH's new system at Fort Davis, Texas. In May, a redesigned tracker motor and drive mechanism was installed, which worked well until mid-November, when the roll motor failed after advancing beyond its limit switch, resulting in one week of downtime. An eight-day disruption occurred in late August-early September, when the array was diverted to test-run the neighboring Amonix array PCU. The system was also down for one week in mid-November after the tracker end bearings were observed to be sagging.

The Solarex array generation was lower than normal, beginning with the last day of August and continuing through mid-November. Initially the array was diverted for one week to test-run the new SCI array PCU. After the array had been reconnected to its normal PCU, the PCU's peak power tracking malfunctioned, operating sporadically while PVUSA and DECC attempted to diagnose the cause. The unit was repaired on November 15, following exchange of a control board, adjustment of suspect control set points, and cleaning of contacts.

A small fire in UPG's main dc collection box disrupted the array output for over half of June. Several terminals and a few blocking diodes, wire leads, and metal oxide varistors (MOVs) needed to be replaced. Although the exact cause is uncertain, it appears a gradual loosening of one or more neutral wire terminations caused high resistances and overheating.

US Systems at Davis

The monthly generation patterns (Figure 3-4) are much less regular for the US systems than for the EMT arrays. The IPC and APS systems experienced several partial and full forced outages during the year due to PCU problems. The SSI Bluepoint PCU was also very unreliable, mostly during the summer months. It did not have any major component failures, but required manual resets nearly every morning at that time of year. As a result of the difficulties experienced by most of the utility-scale system PCUs, some have raised the issue of whether PVUSA's

specifications may need to be modified to better address actual line conditions. At present, power quality studies have not determined whether changes to the specification are warranted.

The IPC Omnion PCU was replaced at the end of August with a KWI PCU. After some initial bugs with signal conditioning and start-up sequencing, the system ran well for most of the rest of the year. Warranty repairs were required on two occasions in October and December to replace failed components. The first event affected the unit's LCD display, fan motors, and start-up functions, and the second event required replacing a failed modulator circuit board and fan motor.

The APS system required one field technician visit and over 50 hours of PVUSA staff time to diagnose and repair various failures in 1995. Line transients continued to trigger fuse openings. There were about a dozen occasions when clearance of fuses, and in some instances additional components, resulted in outages lasting a day or more. As a precaution, the system was turned off for one week in December while strong rainstorms were causing frequent utility disturbances.

Two insolation trend lines are presented in Figure 3-4. The fixed 30-degree tilt insolation corresponds to the APS array orientation, and the one-axis tracking insolation corresponds to the IPC and SSI array orientation.

Maui Electric's Sovonics System at Kihei

Figure 3-5 compares the monthly POA insolation and generation profiles for the Sovonics arrays at Davis and Maui. Unlike the Davis site, the Maui site shows no distinct seasonal trend in either insolation or generation. Because of its lower latitude (20.7 degrees Maui, 38.6 degrees Davis), Maui has less variation in daylight hours than Davis. Overall the 22-degree tilt POA insolation at Maui in 1995 was 7 percent greater than the 30-degree tilt POA insolation at Davis. The Sovonics array generation, however, was 38 percent greater at Maui than at Davis, continuing a multi-year trend of the Maui array operating reliability at a 30 percent (relative) higher efficiency than the Davis array. Other than a large dip in February—the result of a three-day outage of unspecified cause and a partial outage caused by a module junction box failure—the array operated at a consistent monthly pace. A minor dip in output occurred during June, July, and August as a result of two additional module junction box failures.

PG&E's SSI US-2 System at Kerman

Figure 3-6 shows the monthly generation and POA insolation for the SSI US-2 system at Kerman. The match between the generation and insolation trends is satisfactory over the first five months, but for most of the rest of the year, the generation is far less than expected, resulting in an annual production of just 51

percent of the expected total. The plant experienced several multi-day outages when one or both PCUs would either run briefly or not run at all. Repairs were often delayed or hampered due to the site's remote, unattended status. Maintenance activities and grid-support performance issues are detailed in Sections 4 and 5, but this plot is significant in that it clearly shows the periods and approximate magnitudes of the lost generation.

City of Austin's IPC System at Austin

Figure 3-7 shows the somewhat irregular monthly generation and POA insolation profiles for the IPC system at Austin. The insolation profile is not as smooth as PVUSA's other sites, but this is likely because the system's one-axis tracker was malfunctioning for an unknown time until a position sensor was replaced at the end of August (the second position sensor failure in 3.5 years).

Overall the PV system generated about 77 percent of its expected amount for the year. The lost generation due to tracker errors is hard to estimate because a reference tracker does not exist at this site. However, the ratio of actual insolation relative to that on a fixed horizontal plane is available. The relative gain in insolation for the tracking system relative to a fixed horizontal orientation was about 25 percent, but it should have been approximately 31 percent according to long-term data. This suggests a generation shortfall of as much as 6 percent could be attributable to tracker error. Much of the remaining shortfall was related to PCU downtime.

Over the first few months of the year, the PCU tripped off-line frequently, prompting a field repair trip and necessitating some PCU component replacements. The PCU operated reliably until December, when it resumed tripping off line for unknown reasons and would operate for only short periods. (The City of Austin has since reported that after a manual reset during the second week of 1996, the unit began to operate properly again.)

NYSERDA's IPC System at Farmingdale

Figure 3-8 shows the monthly generation and POA insolation for NYSERDA's IPC US-1 one-axis tracking system at Farmingdale, New York. A variety of data acquisition, tracker, and PCU problems have resulted in an incomplete 1995 performance summary.

The insolation profile is abbreviated because data logger errors began corrupting temperature and irradiance signals during August. The PCU was off line from the beginning of the year until Omnion made a repair trip in late April. The system was down again over the last three months of 1995 due to a PCU shutdown of unspecified cause.

Although tracker position is not monitored on this system, irradiance data indicate the tracking system has a history of not operating up to its potential. The irradiance profiles on clear days have not demonstrated the symmetrical mid-morning and mid-afternoon peaks characteristic of one-axis trackers, and the potential benefit of tracking has not been realized. Based on long-term average data for nearby New York City, the POA insolation should be around 27 percent greater than the fixed horizontal insolation. In 1994, the POA insolation was only 11 percent greater than the fixed horizontal insolation, and in 1995, the POA insolation was 2 percent less than the horizontal insolation (based on a 64 percent complete data set).

Although construction was completed during the summer of 1993, NYSERDA has not yet accepted the system from IPC, and PVUSA has not rated the system. An interim rating of 17.9 kW has been used for performance calculations, since this was the rating for the identically sized PVUSA host system installed by IPC for the City of Austin. An effort to improve PCU performance and repair the tracker and DAS was initiated in the fall. At NYSERDA's request, AWS Scientific assessed outstanding items and helped to develop a repair plan involving IPC, Omnion, and the Southwest Technology Development Institute (SWTDI). In December, SWTDI reported they had repaired and recalibrated the DAS. As of the end of 1995, however, PVUSA was still unable to collect data.

NREL/NYPA's IPC System at Maspeth

Figure 3-9 shows the monthly generation and POA insolation for the joint NREL/NYPA system installed by IPC at Maspeth, New York. This system is roof-mounted at a fixed-tilt angle of 10 degrees atop a New York City Transit Authority warehouse. This orientation does not maximize annual generation, but helps boost summertime output to better match the building's electricity demand. The low-profile design reduces wind loading and structure cost, and is pitched steeply enough to shed water and collect less dirt than a horizontal surface. The annual POA insolation for 1995 was about 14 percent greater than for a fixed horizontal surface.

Using data from June 1995, PVUSA rated the system at 12.9 kW. Previously, PVUSA had been using NREL's initial 1993 estimate of 17 kW to describe this system. Most of the decrease is due to Staebler-Wronski degradation, characteristic of amorphous silicon, in the two years elapsed between ratings.

This year's generation and insolation profiles track fairly closely, with the only notable exceptions occurring in February and August. In both cases PCU shutdowns lasting several days were fixed by manually restarting the unit. The February outage was caused by snow that covered the panels for at least two days, making it impossible for the PCU to overcome internal losses and synchronize with the grid; the data set indicated there were several false PCU start-up attempts.

SMUD's UPG System at Sacramento

Figure 3-10 shows the monthly generation and POA insolation for SMUD's UPG system in Sacramento, California. This was the first full year of operation for this one-axis tracking system, which was installed at SMUD's Hedge substation for its potential additional grid-support value.

A rating of 207 kW was calculated this year, using May data. (A preliminary rating of 213 kW had been used since October 1994.) Overall the system generated 81 percent of the energy it was expected to produce, with much of the lost generation a result of PCU-related downtime. The system was down for the first two weeks of the year, continuing an outage that began in November 1994. A PCU circuit board was replaced in mid-January to enable a previously installed auto-restart feature to work properly. A few subsequent trips required manual restarts, including several in February, one in March that resulted in two weeks of downtime, and another in August that resulted in three days of downtime. Some of the reduced generation earlier in the year was the result of a tracker program error, but the program was modified in late April, and the tracker operated properly afterward.

CSW's UPG System at Fort Davis

Figure 3-11 shows the monthly generation and POA insolation for CSW's one-axis tracking UPG system installed in November 1994 at its Solar Park site near Fort Davis, Texas.

The generation and insolation patterns are very irregular for the UPG system, partly because of poor data availability and partly because of lost generation. Phone line interference has occasionally corrupted data or prevented access to the site's computer. There were numerous PCU-related partial and full outages, two lightning-related incidents that resulted in system protection equipment and source circuit damage, as well as tracker problems similar to those experienced over the first few months of the year at the SMUD site. The system was rated at 98 kW using June data. Overall the system generated only 63 percent of the amount it was expected to produce over the year. Energy data for the last three months are believed to be erroneously high, perhaps by 50 percent, due to what was later determined to be a malfunctioning signal-conditioning resistor.

Data for CSW's other Solar Park PV system, from ENTECH, are not included on the plot. The ENTECH system ran intermittently after initial start-up in January, requiring field work on several occasions to address module and tracking system failures and recurring PCU trips. It was disrupted by lightning-related damage on at least two occasions, and ran without interruption during just one month, August. Nevertheless the system still generated about 92,000 kWh, or an equivalent annual capacity factor of almost 14 percent, based on a system rating of 83 kW. The system rating was calculated in November using August data.

Efficiency

Efficiency is calculated as the ratio of monthly dc energy (ac energy for US systems) produced to monthly POA insolation during hours when the PCU is operating. POA for the concentrator arrays refers to direct normal insolation. For the ENTECH and Amonix concentrator arrays, which move on two-axis tracking structures, the efficiency calculations are further limited to data collected between 9 a.m. and 3 p.m. PST, when intermodule shading does not occur. For the flat-plate arrays, POA refers to either global tilt or global one-axis tracking.

Figure 3-12 shows 1995 average efficiencies for 17 systems at eight sites. For the EMT arrays, dc efficiencies are reported because the emphasis is on comparing *module* performance, albeit in a grid-connected system setting. For the US systems, ac efficiencies are reported because the emphasis is on *system* performance. PCU efficiencies of about 90 to 95 percent are responsible for the difference between dc and ac efficiencies.

Figure 3-12
1995 PVUSA System Efficiencies
EMTs: dc USs: ac

A wide range of annual average efficiencies are evident in Figure 3-12. The highest efficiencies correspond to single-crystal silicon cell types. The highest efficiency, 10.1 percent, is for the ENTECH concentrator array, which uses Solarex single-crystal cells mounted below a 22x lens.

The SMUD UPG system, which uses SSI single-crystal silicon modules, apparently operated at almost as high an efficiency on an ac basis as the ENTECH array did on a dc basis. This high result for the SMUD system must be viewed as uncertain, however, because similar or identical modules in other systems using SSI modules all operated at notably lower efficiencies. These include SSI's three EMT and US systems at Davis and Kerman and UPG's system at Fort Davis. Not even the Davis EMT array, at 9.3 percent dc efficiency, was very close to the Sacramento system's apparent efficiency, and the others ranged from 7 to 8.5 percent. While a relative drop of about 10 percent could be accounted for in the case of the Davis arrays due to long-term degradation, the Sacramento result is still substantially higher than that measured for either of the newer Kerman or Fort Davis systems. Calibration errors in the SMUD power or irradiance signals may be responsible for the discrepancy.

The efficiency of four of the five systems with polycrystalline silicon (poly-Si) modules was about 7 percent. The four systems use either cut wafer or drawn ribbon cell manufacturing techniques. The fifth poly-Si EMT array, from AstroPower, has a somewhat lower 5.5 percent dc efficiency. AstroPower uses a new low-cost method of creating a "thick-film" cell by sintering a layer of poly-Si directly onto a low-cost substrate. SCI's new polycrystalline thin film CdTe/CdS array averaged 6.5 percent dc efficiency over its first three months of operation. Unlike crystalline Si technologies, the CdTe array efficiency does not show any sensitivity to temperature, at least over the temperatures that prevailed during the fall and early winter.

The lowest efficiencies, averaging around 3 percent, correspond to the five amorphous silicon-based (a-Si) systems. These include tandem-junction a-Si EMT modules from Sovonics at Davis and Maui, and from UPG at Davis. A US system at Davis consists of single-junction a-Si modules by APS. The remaining a-Si system consists of tandem-junction modules made by Sovonics' successor company, USSC, and installed by IPC in Maspeth.

Figures 3-13 and 3-14 show the monthly efficiency history for each system. The seasonal and long-term trends seen in these plots were analyzed in detail in the 1993 *PVUSA Progress Report* and are shown here to illustrate a continuation of the trends that have developed over the past few years. Some of the sharper disruptions were caused by partial system failures that may not be indicative of module problems. Such was the case with the Solarex Davis dropoff during September through November, which resulted from trouble with the DECC PCU. PCU problems also impacted the APS Davis system, which operated at three-quarter power from July to mid-September. There was also a one-month dip during June

Figure 3-13
PVUSA EMT Array dc Efficiencies

Figure 3-14
PVUSA US and Host Utility System ac Efficiencies

1995 for the UPG EMT array, which ran at partial power for about two weeks after a junction box fire.

Data collection began in 1995 from the SCI EMT array at Davis and the CSW UPG system at Fort Davis. Collection of full-month data did not commence until October for the SCI array, and other than the fact that its efficiency was steadily in the range of 6 to 6.5 percent, little else can be inferred at this stage. The CSW UPG efficiency pattern was more irregular, and these data are somewhat uncertain because of incomplete records and an unverified ac power calibration in place after mid-September.

Capacity Factor

Introduction

The capacity factor is calculated as the dimensionless ratio of energy produced over a given time, divided by the product of the system rating and the time interval. Monthly or annual time intervals are commonly used, although other time intervals, such as peak load periods only, may be specified as well. The capacity factor helps utility planners and operators understand characteristic output patterns of PV systems and their match with demand patterns.

Annual capacity factors for each system are listed in Table 3-3. Monthly capacity factors during 1995 for seven of the eight EMT arrays at Davis are shown in Figure 3-15 (capacity factors for the Amonix array are not included because the array was in a start-up and testing mode through the end of 1995 and had not yet received a final rating); monthly capacity factors during 1995 for the three Davis US systems are shown in Figure 3-16; and monthly capacity factors during 1995 for the Kerman system and six host utility systems are shown in Figure 3-17. The trends are the same as observed for monthly generation, but are normalized to a dimensionless 0 to 100 percent scale. The capacity factor is a function of system reliability, rating basis, and sunlight availability. Sunlight availability varies widely and is, in turn, dependent on the time period, local climate, and system orientation. Therefore, wide swings in capacity factor are common for PV systems.

EMT Arrays at Davis

Except for ENTECH, the EMT arrays shown in Figure 3-15 normally exhibit similar monthly capacity factor trends, varying smoothly from about 5 to 10 percent in the winter to more than 25 percent in the summer. These arrays—from SSI, Sovonics, UPG, Solarex, AstroPower, and SCI—are identically oriented at a fixed 30-degree tilt, and other than a few one- or two-month irregularities for the UPG and Solarex arrays, each demonstrated good reliability. The 1995 annual capacity factor for these

Figure 3-15
1995 PVUSDA Davis EMT Array Capacity Factors

Figure 3-16
1995 PVUSA Davis US System Capacity Factors

Figure 3-17
1995 PVUSA Host Utility System Capacity Factors

arrays ranged from 16 to 20 percent, a slight drop from past years, but generally consistent with results dating from 1989.

The ENTECH concentrator array uses a two-axis tracking system and lenses to capture direct normal insolation only. In the absence of failures, this type of system exhibits a wider seasonal swing than a fixed flat-plate system, as evident in Figure 3-15. In the Davis climate the concentrator array should also achieve about a 10 percent (relative) higher annual capacity factor than the fixed arrays. However, the array's annual capacity factor in 1995 was 19 percent, about the same as for the fixed arrays. This was because the ENTECH array experienced somewhat more downtime than the other arrays, both scheduled (eight days) and failure-related (about two weeks).

US Systems at Davis

Figure 3-16 illustrates 1995 monthly capacity factors for the US systems at Davis. The APS system is oriented at a fixed 30-degree tilt, while the IPC and SSI systems are oriented to track about a horizontal north-south axis. In the absence of failures the tracking systems' capacity factor profile should exhibit a wider seasonal swing than the fixed-tilt system. The SSI system's 30 percent capacity factor in June indicates the advantage of the one-axis system over a fixed-tilt system in the summer. The expected patterns were interrupted by several irregularities in 1995.

Monthly Capacity Factors for US and EMT Systems Not at Davis

Figure 3-17 compares 1995 monthly capacity factors for seven PVUSA systems installed at locations other than Davis. These include systems at Kerman and Sacramento, California; Farmingdale and Maspeth, New York; Austin and Fort Davis, Texas; and Kihei (Maui), Hawaii.

The Maspeth and Maui systems are oriented at fixed-tilt angles; the other five systems are oriented to track about a horizontal north-south axis. The Maui system's capacity factor pattern was fairly flat, centered on an average monthly capacity factor of about 20 percent. Although the Maspeth system pattern appears to be relatively flat (pattern compressed somewhat because of the plot scale), it still experienced a 3 to 1 ratio in its summer-to-winter capacity factors. Its annual average of just 10 percent reflects a long-term degradation of 25 percent over its first two years of operation. The reduction in rated power is likely to be caused by a combination of light-induced degradation, soiling, and module failures. Except for the SMUD UPG system, the capacity factor patterns for each of the tracking host site systems were disrupted by lengthy outages resulting from a variety of causes.

Capacity Factors During PG&E's Peak Periods

Capacity factors over shorter time intervals can be much higher than the monthly capacity factors shown in Figures 3-15 through 3-17. Figure 3-18 illustrates the capacity factors for each array in PG&E's service territory during PG&E's peak periods (weekdays in May through October, 12 p.m. to 6 p.m. PDT). Results for 1995 are compared with the 1991-1994 average. Within the PG&E service territory, peak-period capacity factors approaching 70 percent are possible for fixed arrays that face south (although 60 percent has been more typical), and capacity factors as high as 75 percent have been recorded for two-axis tracking arrays. As in prior years, significant downtime limited the 1995 peak-period capacity factors for the ENTECH and IPC systems. The APS peak-period capacity factor for 1995 was also somewhat lower than expected, partly because of failures, and partly because it is based on initial capacity; this system's capacity has decreased by 20 to 25 percent after three years of operation.

Figure 3-18
Summer Peak-Period Capacity Factors for PVUSA Systems in PG&E's Service Territory

BOS Experience

Power Conditioning Units

In 1995, PVUSA pulled together much of the data and experience gained over the operating lives of the power conditioning units (PCUs) and conducted some additional power quality tests as part of a special report on this topic.² Some of the data and information have been summarized for this report.

All of the PVUSA systems include a PCU. PCUs convert the dc power produced by a PV system to the ac power used in electric utility systems. After the PV modules and array structures, the PCU is generally the most significant contributor to the total system cost.

There are six different PCU models at PVUSA's Davis and Kerman sites. Each of the eight EMT arrays at Davis is connected to a DECC 25-kW PCU. The US system PCUs at Davis and Kerman were furnished as part of competitively bid turnkey systems. Data are also presented in this report for PCUs at several host utility sites. More detailed information is documented in the topical report.

During 1995, one US-1 PCU was replaced with a unit manufactured by KWI, as described in Section 2.

Summary of PCU Characteristics. The characteristics of the six PCU models at Davis and Kerman are highlighted in Table 3-4.

PCU Efficiency. Figure 3-19 shows efficiency as a function of power (normalized to the PCU's rated ac power). The curves are fits to several days to a month of data, and include transformer losses. The curve for the DECC EMT inverter is an average of five units, and the SSI Bluepoint curve is for only one of the two units operating.

The shapes of the curves are similar. Some, such as the Omnion units for IPC and Kerman, are noticeably flatter (i.e., constant efficiency) above 25 percent of rated power. The efficiencies of all of the Davis and Kerman PCUs are 92 ± 4 percent above 40 percent of rated power. The newly installed KWI unit has the lowest efficiency among PCUs at Davis and Kerman. Two of the host utility PCUs have lower efficiencies.

² W.J. Stolte, *PVUSA Experience with Power Conversion for Grid-Connected Photovoltaic Systems*, DOE/AL/82993-26, November 1995.

Table 3-4
Characteristics of Davis and Kerman PCUs

	EMT	US-1				US-2
Supplied by	PVUSA	IPC	PVUSA ^a	SSI	APS	SSI
PCU Manufacturer	DECC	Omnion	KWI	Bluepoint	APS	Omnion
Manufacturer's Rating	25 kW dc	200 kW ac	225 kW ac	200 kW ac	500 kW ac	550 kW ac
PV System Rating @ PTC	12 to 19 kW dc	196 kW ac	196 kW ac	134 kW ac	479 kW ac	498 kW ac
Unit Configuration	1 x 25 kW dc	1 x 200 kW ac	1 x 225 kW ac	2 x 100 kW ac	4 x 125 kW ac	2 x 275 kW ac
Type of Commutation	Self	Self	Self	Line	Line	Self
Switching Device	Transistor	IGBT	IGBT	SCR	SCR	IGBT
Wake-up Sensing	Array voltage	Array voltage	Array voltage	Pilot cell	Pilot cell	Array voltage
Maximum Power Tracking	Yes	Yes	Yes	Fixed voltage	Fixed voltage	Yes
Efficiency ^b	94.1%	93.6%	91.8%	93.9%	96.1%	93.3%
Current Unbalance ^b	3.0%	2.0%	2.4%	2.3%	0.3%	0.4%
THD Current ^b	5.5%	2.5%	3.3%	-	3.5 to 5.5%	2.5 to 5.5%
THD Voltage ^b	0.6 to 0.8%	1 to 1.5%	-	-	0.8 to 1.2%	2.5%
Power Factor ^c	1.0	1.0	1.0	0.8 to 0.9	0.85 to 1.0	1.0
Run-On Time, seconds	1.5	0.03 to 0.11	2.5	0.03	0.1 to 0.12	-
Enclosures, kW/ft ²	2.2	3.1	5.2	2.0	5.5	4.9
Cooling	Unventilated	HVAC	Forced air	Forced air	Forced air	HVAC
Location	Under array	In sunlight	In sunlight	In sunlight	Under array	In sunlight

^a Replaced IPC Omnion PCU (August 1995).

^b In region near rated power.

^c At more than 40% rated power.

Figure 3-19
PCU Efficiencies as a Function of Power

Some care should be taken in generalizing these efficiency characteristics. As shown, PCU efficiency is a strong function of power level expressed as a percentage of full rated power. To a lesser extent, efficiency is also a function of dc and ac voltage levels. In addition, variations can occur from unit to unit. The left graph in Figure 3-20 shows efficiency data (for June 1995) for two "identical" Omnion PCUs, procured at the same time by CSW. The units are connected in parallel at the ac line so that the ac voltages are the same. The average dc voltages are similar ($\pm 353 V_{dc}$ for UPG and $\pm 377 V_{dc}$ for ENTECH). The right graph in Figure 3-20 shows efficiency data for two "identical" DECC PCUs. These were also manufactured at the same time, are paralleled on the ac side, and are co-located. The modules (single- and polycrystalline silicon) have the same irradiance, and have similar average dc voltages ($\pm 141 V_{dc}$ for SSI and $\pm 156 V_{dc}$ for Solarex). Despite the similarities, differences exist in the efficiency characteristics of these pairs of identical PCUs. The ac outputs for the DECC units were not calibrated (except at the factory, since dc data were of primary interest for the EMT arrays), which may play a part. Calibration frequency and procedures for the host utility PCUs are not known.

Figure 3-20
Efficiency as a Function of Power for Two Pairs of "Identical" PCUs

PCU Power Factor. Figure 3-21 shows the power factors of the US and the Austin PCUs as functions of power. The data clearly show the difference between the line-commutated units with fixed capacitors and the self-commutated, pulse-width-modulated units. Two Omnion PCUs (IPC and Kerman) and the KWI PCU power factors are nearly identical and have a power factor above 0.99 for power levels greater than 10 percent of rated power. The power factor for the Austin Omnion PCU rises somewhat more slowly, reaching 0.99 at 20 percent of rated power. The data for the SSI Bluepoint PCU are for one of two units operating but with the capacitors for both units connected, and thus the operating power factor is lower than designed. Neither of the current-source PCUs meets the power factor specification at low power.

PCU Harmonics. Voltage and current total harmonic distortion (THD) measured at Davis and Kerman generally conform to IEEE 519-1992. THD data for KWI are from factory testing. The magnitudes of the harmonic currents are relatively constant as a function of power. The PCU power levels are relatively low compared with those of the connected utility lines and thus do not greatly affect the voltage harmonics. The data in Table 3-4 should be used with caution, since THD can be affected by power level, dc and ac voltage levels, and the impedance of the utility line.

Other PCU Characteristics. Unbalance among the ac output phase currents ranges from less than 0.3 percent to 2.4 percent for the US systems. Unbalance for the DECC units ranges from 1.4 to 5.1 percent, with an average of 3 percent.

Figure 3-21
PCU Power Factors as a Function of Power

Tests performed during start-up showed that the PCUs disconnect and do not run-on upon loss of the utility line voltage (and when no load is present). However, special tests on the DECC PCUs resulted in run-on for up to several minutes when the connected load was 10 to 20 percent above the power being generated by the PCU. Given the correct load impedance, any of the PCUs might run-on. Run-on continues to be a concern for utility companies.

Magnetic field data on the DECC EMT units were collected, and the relatively low magnitudes were judged by PVUSA to be of minimal concern.³

Tracking Systems

The following paragraphs summarize recent PVUSA experience with tracking systems at Davis and Kerman. PVUSA systems that track the sun are Amonix EMT-3, ENTECH EMT-1, IPC US-1 and SSI US-1 at Davis, and SSI US-2 at Kerman.

Amonix EMT-3. The Amonix IHCPV array requires an accurate two-axis tracker, with no more than a 1-degree error for acceptable operation. The tracking system consists of a PC-based Advanced Thermal Systems, Inc. controller and two ac motors

³ G.J. Chang and C. Jennings, *Magnetic Field Survey at PG&E Photovoltaic Sites*, DOE/AL/82993-12, August 1994.

that drive a Peerless Winsmith gear assembly. Tracking is open-loop, using a PC clock as the basis for tracker position. The PC tracker controller and two tracker motors obtain their power from an uninterruptible power supply (UPS).

PVUSA has limited experience with this recently completed system (operations began in October 1995). Amonix "fine-tuned" and calibrated the tracker between October and December. No meaningful data can be presented since Amonix continued to align the structure (tracker) throughout the remainder of the year.

ENTECH EMT-1. The ENTECH EMT-1 system is a 22x linear concentrator configured with 60 modules mounted on a single-row structure. The two-axis active tracker tilts the whole row for elevation position and rolls each of the 60 modules for azimuth position. The tracking system consists of a dc-powered Prime microprocessor controller unit, a 1/3-hp 12-Vdc tilt-drive motor, a 1/20-hp 12-Vdc roll-drive motor, and two 60-Ah batteries. The batteries provide power to the tracking system while it is operational during daylight hours. The battery charger is disconnected from the grid during daylight hours and connected to the grid at night to charge the batteries. This configuration is designed to isolate the system from effects of any transients and noise on the grid during tracking.

The original tracking system supplied by ENTECH included an ac roll motor, an ac tilt motor, and an ac-powered controller. It experienced intermittent problems, believed to be associated with ac noise. The tracker control board had been shipped back and forth to the supplier for repair, but the problems lingered. In 1994, ENTECH modified the tracking system to a dc-powered tracker controller, a dc roll motor, and a dc tilt motor. The new tracker controller showed improved workmanship, configuration, and operation. Since the installation of the new tracking system in May 1994, the tracker had only minimal downtime. The roll function failed on two occasions due to limit switch failure, and separately it failed to track accurately when the wind speeds were above 20 miles per hour. PVUSA, with ENTECH's assistance, resolved each of the problems in a timely and satisfactory manner. ENTECH has demonstrated their enthusiasm in keeping the Davis installation operational with minimum downtime. ENTECH's response and support to the PVUSA project are outstanding and commendable.

The azimuth of the 60 modules can be adjusted individually, and the whole structure can be adjusted in elevation to accurately aim at the sun. Aiming errors of one degree or less do not significantly affect module performance.

One drawback to the ENTECH tilt-roll tracking system is that during early mornings and late afternoons, module-to-module shading occurs. This shading limits the duration of energy capture for the system.

IPC US-1. The IPC US-1 system has 11 rows of one-axis tracking structures with 1,100 flat-plate Mobil Solar modules. The one-axis active tracker consists of a tracker controller, a winch drive, and a steel cable driving the tracker rows. The microprocessor-based tracker controller uses a clock-based algorithm for tracker position. It employs a back-tracking logic to mitigate the impact of row-to-row shading during the early mornings and late afternoons. The tracker can travel from -60 degrees to +60 degrees of horizontal.

If there is a failure in the tracking system, the system is still operational but generates less than expected amounts of energy (the amount depends on where the array is pointing). There is negligible power drop with aiming inaccuracy less than 5 degrees. The actual gain was zero at IPC's single-axis tracking system as a result of tracker downtime, and the actual gain at SSI's single-axis tracking system was only 15 percent. The shortfall is mostly due to aiming error, but may also be attributed in part to field-of-view differences, mechanical tracking limits, and PSP soiling.

PVUSA experience with the IPC tracker is good, with only a few failures and repairs required. Scheduled maintenance items included checking the tracker clock and resetting or recalibrating the tracker position at least once a month. When the power to the tracker system is disconnected, such as during a utility outage, the tracker loses its position and remains lost through the day. It automatically resets and properly tracks the following day. There were two occurrences of component failure in the tracker controller. Both occurrences required replacement of input and output modules (isolation relays), which were difficult to find and obtain. Another IPC-recommended preventive maintenance item is the annual tensioning of the tracker drive cable, which requires specially skilled craft and is not inexpensive. The cable tension must be between 28,000 and 36,000 pounds to keep the mid-span sag between 5.8 and 7.5 in.

SSI US-1 and SSI US-2. The SSI US-1 system has eight rows of one-axis tracking structures with 3,968 flat-plate SSI modules. The SSI US-1 one-axis passive tracking system consists of 32 Robbins Sunseeker tracker actuators filled with R-22 refrigerant. Four actuators reside on each of the eight rows in the array field or one tracker actuator per 52.8 m² of array area.

The 500-kW (nominal) SSI US-2 system has 8-1/2 rows of one-axis tracking structures with 12,240 flat-plate SSI modules. Like the SSI system at Davis, the Kerman system is a one-axis passive-tracking system. It is a larger system, consisting of 77 Robbins Sunseeker tracker actuators filled with refrigerant R-134a. Nine actuators reside on each of the eight full rows, and five actuators reside on the half-row (i.e., one tracker actuator per 67.7 m² of array area).

During the construction and start-up activities for the SSI US-1 and US-2 systems, 10 to 15 percent of the actuators failed primarily due to leaks in their seals. An accurate count is not available since the systems were still undergoing start-up and the contractor, SSI, had responsibility for maintenance. After system acceptance the number of actuator failures diminished. The SSI US-1 trackers operated without any failure-related incidents in 1995. The SSI US-2 trackers operated with one failure-related incident in 1995. SSI predicts less than a 6 percent annual failure rate for the passive trackers. This equates to 1.9 and 4.6 failures per year for US-1 Davis and US-2 Kerman, respectively.

The failure of one actuator may not necessarily cause system downtime. One row requires only one actuator to track the sun (two for US-2). However, one tracker actuator that is "frozen" can prevent the row from rotating and causes a stair-step position of the particular row. The "frozen" actuator causes high force or pressure in adjacent actuators through the structural steel mechanical link. If not corrected immediately, the failed actuator may cause failure of the adjoining actuators. However, like IPC, complete tracker failure results only in reduced energy output.

The Robbins Sunseeker tracker actuators at Davis and Kerman have an aiming accuracy, respectively, of 10 and 5 degrees lagging on clear warm days. The Davis and Kerman trackers operate more accurately during warm weather (summer months) than in cold weather (below 40 degrees F).

At Kerman the potential benefit of single-axis tracking over horizontal was calculated to be 41 percent (based on data from NREL), but the actual plane of array insolation showed a gain of only 27 percent. A closer inspection of the Kerman data set showed an excellent correspondence between the POA, fixed horizontal, and optimally-tracked reference instruments over the noontime period. This suggests the shortfall probably was not the result of measurement error. Note that the Kerman system's passive tracker still outperformed its predecessor (SSI US-1) at the Davis site.

Lessons Learned with Trackers. The gain for a fixed-tilt system over a horizontal system can be expected to be about 15 percent, and the additional gain of a one-axis tracker over a fixed-tilt system is about 20 to 25 percent.

POA data indicate that the SSI US-1 system collected approximately the same amount of solar radiation as an ideal horizontal fixed flat-plate system. The shortfall is basically attributable to the inaccuracy of the SSI tracking system and row-to-row shading. The SSI US-1 trackers are lagging by as much as 10 degrees during warm sunny days. This lagging inaccuracy gets worse (lags by more than 10 degrees, or may be immobile facing west) during overcast and cold days.

Data for the IPC system regarding the solar radiation (plane-of-array) that it collected between 1991 and 1995 are inconclusive. The system (including the trackers) was down for several months due to array junction box and wiring harness modification (1992-1993), inverter intermittent shutdowns (1993-1995), and PCU replacement (1995).

At Sacramento, the potential gain was estimated to be 49 percent (see Figure A-2), similar to the nearby Davis site. The actual gain was 31 percent. At Austin, the potential gain was 27 percent, and the actual gain was 16 percent (see Figure A-2). For Farmingdale, a 28 percent tracking gain was expected, but not enough actual data were available to make a meaningful comparison. At Fort Davis, the potential gain for single-axis tracking was calculated to be 40 percent, with an adjusted actual gain of 36 percent. (The actual figure includes a 15 percent adjustment to allow for missing data. Given the relatively high adjusted figure, it seems likely that a large share of the missing data were overcast or nighttime values.)

Concentrator systems with medium- to high-concentration ratios must be aimed accurately toward the sun, usually within one degree. A two-degree inaccuracy for a concentrator system could cause considerable power drop and may render the system inoperable. A five-degree aiming inaccuracy for a one-axis tracking flat-plate system yields negligible power drop.

Concentrator systems that rely on direct normal irradiance (DNI) do not generate power when DNI drops to negligible values. One-axis tracking flat-plate systems, however, can operate on diffuse irradiance, which can be 150 W/m² even with negligible DNI.

Maintenance for tracking systems at Davis have not been excessive. Specific maintenance costs for trackers have been insignificant when compared to the PCU maintenance cost. See Section 4 for details.

Module Wiring

PVUSA flat-plate PV systems contain from 264 to 12,240 modules per array. PVUSA contractors panelized modules in the factory for eight of ten flat-plate systems. Panelized modules required less field labor for installation. Panels shipped with modules preassembled and prewired (interconnecting wires) were the usual choice for the PVUSA PV contractor since field labor is expensive and field wiring is more prone to errors. The PVUSA memorandum of understanding (MOU) with various crafts usually dictate that electricians perform the field installation work of panels. The use of connectors for interconnecting panels (in the field) adds to material costs but reduces field labor costs and wiring errors.

Connecting low voltage modules in series reduces the number of field wires from the array to the dc collection box or to the inverter. Examples of this module wiring scheme include IPC, SSI US-1, and SSI US-2. All of these three systems use modules with open circuit voltage of approximately 9 V. The source circuit could be segmented in such a way that each segment has an open circuit voltage less than 50 V (above which requires gloves), thus reducing the hazard during construction as well as during maintenance. The SSI US-2 Kerman array is a good example of a well-designed PV wiring system. On each tracker structure, the modules are connected 5 in parallel and 8 in series. Between each tracker structure, two plug-in connectors (Cam Lok) are installed and provide a convenient point of segmenting the circuit to less than 50 V open circuit. This wiring facilitates maintenance and testing such as I-V curves and field wet resistance tests.

Connectors used in outdoor environments must be selected and applied with great care to avoid water intrusion, leakage current, and potential safety hazard. PVUSA experience with connectors is both good and bad, depending on the care exercised in selecting the connector. The SCI and Amonix arrays use plug-in type connectors for panel-to-panel connections. These connectors were preinstalled at the factory, ready to be plugged in the field. The connectors were suitable for outdoor installation, but were expensive. On the other hand, the APS system had inexpensive plug-in connectors that were neither tested nor qualified for outdoor use. APS retrofitted the connectors to satisfy specifications. The field re-work was time consuming and costly. Module connectors that are rated for outdoor use should be used.

Module-to-module wiring, if correctly specified for the anticipated environment and not accessible to unqualified persons, does not need to be enclosed in raceway. PVUSA experience with factory-installed and unprotected wiring has been excellent. Examples are the UPG and the SCI shop-fabricated and preassembled panels. The panel support was used as the raceway for module-to-module wiring. Reports of rodent damage at some PV sites (at Georgia Power, squirrels chew on the insulation of the power cables) indicate that this possibility should be checked and raceway furnished if necessary. Module junction boxes have frequently been sources of problems for PVUSA systems. Problems include melting (due to loose connections), loose covers, cracked cases, and leaking cable entries. PVUSA experience is that module pigtails, connected by splice or by connector, are more trouble free than junction boxes. However, module replacement requires more field labor when wire splices are used.

Module Mounting

One of the most economical means of module attachment to the structures at PVUSA involved the use of modern adhesives. Adhesives were used to attach support hardware directly to the module backs, in one case eliminating the need for module framing. Examples are the module attachment used by APS on their US-1

system, and by UPG and SCI for their EMT arrays. Module damage during installation has been minor and acceptable for both framed and unframed modules. Module mounting should allow easy removal and replacement of failed or damaged modules in the field.

Array Support

The array structures and their foundations cost between 11 and 13 percent (of system cost) for PVUSA US systems.⁴ System efficiencies range from 4.0 to 9.8 percent (PTC). On the basis of \$/kW, structure and foundation costs are inversely proportional to system efficiency.

Using longer panels in fixed flat-plate arrays gives a longer slant height, resulting in shorter array row length and fewer, larger foundations. Panel length and weight also have an impact on installation and maintenance costs. The APS array utilizes a lightweight structure, with a slant length of 40 feet, and has received favorable comment. Slant heights will vary with module type and weight as well as the constraints for optimum installation and maintenance costs.

Some general comments on array supports include

- Economies are possible by using structural designs that integrate the structural elements of both the support frame and the panel frame.
- Some PVUSA manufacturers did not allow sufficient tolerance in panel attachments (to the support structure), which hampered the field alignment of panels.
- Detailed erection procedures also facilitate installation.
- Wood structures installed by PVUSA for the EMT systems did not provide a saving over steel structures.

For one-axis tracking systems, costs appear to favor center-balanced panels mounted on a horizontal center support tube. Primary vertical supports of both steel posts and wood poles have been used. UPG pioneered a wood pole design at Sacramento using standard utility poles and pole-installation techniques in 1994. UPG repeated it for installations in Texas and elsewhere. However, some wood poles used at Sacramento are reported as having sunk. Critical factors are soil conditions and installation methods.

Steel screw anchor foundations have been tried at Davis and function adequately. Installation was fast, taking only minutes to install each anchor, but requires special equipment during the process. Screw anchors cannot be used if soil conditions are

⁴C. Jennings, A.B. Reyes, and K.P. O'Brien, "PVUSA Utility-Scale System Capital and Maintenance Costs," First World Conference on Photovoltaic Energy Conversion, Waikoloa, HI, December 1994.

not suitable. Soil must not be corrosive or the cost of epoxy coating makes steel screw anchors uneconomic. PVUSA specifies a 20-year life for its systems. Safety margins should be established by pull tests on steel screw anchors before designs are accepted.

Lightning and Transient Protection

Modeling indicates that attempting to completely protect a large array field against direct strikes is not likely to be cost-effective. MOVs offer some protection against lightning-induced transients at relatively low cost.⁵ Direct lightning strikes on arrays at Fort Davis, Texas, in 1995 caused damage even though non-MOV transient protection was in place.

PVUSA Davis uses conventional air terminals on its office building roof but not on the array structures. The project uses conventional low-energy (up to a few thousand joules) MOVs to limit voltage transients induced by nearby lightning strikes. The Davis, California area has an isokeraunic level of 5, and no on-site lightning strikes have been observed in the past eight years. The Sacramento installation, which is not far from Davis, has experienced one lightning strike.

Users of MOVs should consider two cautions. These components can age—particularly when exercised—allowing conduction at progressively lower voltages. Failures can be catastrophic and damage other nearby components. PVUSA recommends compartmentalizing or surrounding the MOV by a metal container or fire-resistant material.

Commercial distribution class surge arresters were installed on the 12 kV side of each US-1 step-up transformer. The intent was to prevent surges caused by line switching and gate firing transients from adjacent PCUs from damaging the connected PCU. To date, PVUSA has had no PCU failures attributable to these causes, except fuses on the APS system, which is a common occurrence.

Grounding Practice

System Grounding. Ten of the twelve Davis and Kerman PVUSA systems are configured with a neutral that is solidly grounded. The neutral of a bipolar system is a natural point to connect to ground. For PVUSA systems, this neutral is also monitored and gives a shutdown signal to the PCU and an alarm indication of dc ground fault for current above the set point. Most inverter designs favor the neutrals to be grounded in the inverter only for the inverter and are conducive to monitoring ground currents.

⁵*Photovoltaic System Grounding and Fault Protection Guidelines*, Sandia National Laboratories report, SAND83-7025, February 1985, pp. 5-88 to 5-131.

The IPC dc system was originally designed as a three-wire bi-polar system, but was reconfigured as a mono-polar system when the KWI PCU was installed. The negative pole is solidly grounded. So far, no problems have resulted from this grounding method.

The APS dc system has a derived neutral—it utilizes two diodes in series, two resistors in series, and two MOVs in series across the positive and negative poles. The center connection of the diodes, resistors, and MOVs is the neutral and is solidly grounded. Failure of these components has occurred and caused a fire in the dc disconnect switch where these are located. Such a design must be carefully evaluated to prevent damage to components.

Equipment Grounding. All the PV systems at PVUSA used the steel in each array foundation (rebar or pipe) as a ground electrode.⁶ This is a PVUSA standard practice. Annual readings of the resistance of the grounding system to earth are consistently low at Davis. Readings range from 0.05 to 3.00 ohms. A reading of 5 ohms or less is considered good engineering practice. The NEC allows a reading of 25 ohms or less. Section 7 discusses the details and results of PVUSA ground resistance testing.

PVUSA PV systems use the array structural steel as grounding conductor. This practice has worked well, since connections (nuts, bolts, and grounding jumpers) are selected to suit the environment.

Module frames made of aluminum should not be installed directly on steel supports, since dissimilar metals making physical contact corrode. To avoid corrosion problems, a nonconductive spacer and a separate ground connection should be employed.

⁶ Ibid., p. 4-30 and Appendix C.

4

MAINTENANCE

This section describes maintenance activities during 1995 at the Davis, Kerman, and project participants' sites. The section also reports on the status of the maintenance database, summarizes module replacement history, and presents estimates of maintenance costs at the Davis and Kerman sites. Prior maintenance activities are documented in the 1989-1994 *PVUSA Progress Reports*.

Maintenance Activities During 1995

One of PVUSA's objectives is to assess the maintenance requirements of PV systems within an electric utility setting. Summarized below are failure-related and scheduled maintenance activities during 1995 for the eight Davis EMT systems and their associated PCUs, the three Davis US-1 systems, the Kerman US-2 system, and the PVUSA host utility systems. Appendix C contains details of activities at Davis and Kerman.

EMT Arrays

Table C-1 indicates the labor hours associated with preventive and failure-related maintenance.

SSI

One shattered module was replaced; the cause is unknown.

Sovonics

Insulating compound was applied to a burnt Tefzel spot on the module to repair a frame-to-module ground fault.

UPG

Figure 4-1 shows the effects of a fire in the dc collection box, which destroyed wiring, terminals, blocking diodes, and metal oxide varistors. In June, PVUSA replaced the damaged components and reset the system.

Figure 4-1
Effects of a Fire in UPG dc Collection Box

Solarex

The array operated without any failure-related maintenance.

ENTECH

The ENTECH tracking system had three unscheduled 1995 downtimes. In January, the tracker roll function failed, which was attributed to the tracker moving beyond its limit switch. A new dc roll motor was installed to correct the failure. It operated well from January until March, when it started tracking inaccurately during wind speeds above 20 mph. A new 12-V_{dc} roll motor was installed on May 9 and tracked accurately through October. In November, while the tracker was manually stowed to replace failed tracker end bearings, the roll motor coupling failed. The coupling failure may be attributable to the failure of the west limit switch mechanism. ENTECH opted to furnish an upgraded roll motor assembly, rather than fix the failed unit. The tracker operated properly for the remainder of the year.

AstroPower

The array operated without any failure-related maintenance.

SCI

The array operated without any failure-related maintenance.

Amonix

The tracker program failed on September 29 (prior to PVUSA acceptance), requiring reprogramming. Four receiver plates were identified as having defects (e.g., cracked cell, defective secondary optical element, and cell discoloration) and were replaced in November and December. The receiver plates were replaced under warranty.

EMT PCUs

Synchronization errors were the predominant failure-related events in 1995 for the eight DECC model 61635 PCU. Synchronization errors usually occur in the early morning when there is insufficient irradiance and the PCU attempts to start but fails because it cannot deliver power to the grid.

- The SSI PCU experienced 12 synchronization errors that in each case required a manual reset to restore operations. Also, SSI required seven additional resets after miscellaneous shutdowns.
- The ENTECH PCU required 10 resets after synchronization errors.
- The PCU connected to the Solarex array failed once after a synchronization error, once after a line disturbance, and once after an error shutdown. All three events required a manual reset to restore operations. PCU A2J8 card contacts were cleaned to correct the peak-power tracking problem.
- The Sovonics PCU was reset 13 times after miscellaneous shutdowns. On May 17, a logic card from the SCI PCU was interchanged into the Sovonics PCU, and the damaged logic card was returned to DECC Helionetics for repair.
- The UPG PCU was reset twice to replace control fuses and five times after miscellaneous shutdowns.
- The AstroPower PCU was reset 13 times due to synchronization errors and was off line twice to replace control fuses.
- On August 29, the Amonix PCU was started using power from the ENTECH array. The PCU was not peak power tracking until a DECC field representative identified the problem on October 22 as a bad chip on a logic card, which was subsequently replaced on October 27. The Amonix PCU was reset once after a synchronization error, once after a PG&E line disturbance, and twice due to grid overvoltage. A burnt wire on the PCU capacitor bank was repaired on November 15.
- The SCI PCU was initially energized using the Solarex array on September 6; however, the PCU would not start because the dc contactor would not close

during the start-up routine. A teleconference troubleshooting effort with DECC on September 27 resulted in the identification of a loose connector and adjustment to a logic card potentiometer, providing an initial start-up. An additional start-up problem with peak power tracking was resolved on October 21 by a DECC field representative. One synchronization error occurred on October 11.

Davis US-1 Systems

SSI

- PCU B was successfully reset 55 times after miscellaneous shutdowns.
- Eight modules and two bypass diodes failed and were replaced.
- The enclosure fan on PCU B failed and was replaced on September 25.
- A burnt wire on a capacitor bank was repaired.
- PCU A remained "mothballed" during 1995 with no present plans for repair.

APS

- PG&E line disturbances continued to be problematic for the PCU; ten occurrences resulted in 23 cleared ac rectifier fuses. There are 12 ac rectifier fuses in the PCU, three each in the four inverter enclosures. The likelihood of line disturbances is increased during storms. PVUSA has begun manually shutting down the APS PCUs during storms to mitigate PCU problems.
- PCU #1 failed on August 1; troubleshooting efforts by PVUSA were unsuccessful. On September 12, a factory service representative was on site to diagnose the failure and calibrate the meters, reference voltages, and currents. PCU #1 has performed satisfactorily since September 12.
- PCU #3 failed on August 8, requiring the replacement of a dc fuse and the dc contactor bridge before operations could resume.
- Various PCUs were manually reset 24 times after miscellaneous shutdowns or failures to start up in the morning.
- One cracked module was replaced.
- A fire in the dc switch of PCU #4 occurred in October and was repaired. Failed protection diodes were the cause of the fire and subsequent failures during the following months.
- A ground fault occurred on PCU #4 in the dc switch enclosure, which resulted in the failure of a dual pack diode, wiring, and varistors. Additionally, an internal

diode across the dc filter, dc filter fuse, and rectifier fuse were replaced before proper operation of PCU #4 could resume.

IPC with Omnion PCU (January 1995 through July 1995 only)

- On 48 occasions, miscellaneous Omnion PCU shutdowns required manual resets.
- On five occasions the Omnion PCU shut down due to enhanced irradiance and required resets.
- Sixteen bridge boards were replaced; fifteen boards were removed and shipped to Omnion for repairs, and one board was repaired on site.
- In June all of the ribbon cable connectors were cleaned and reseated.
- All of the U-2 chips on the bridge boards were socketed, and a new e-prom was installed.
- Omnion was on site two days in February to repair the PCU. The problem was traced to a gate power supply chip; upon chip replacement, the PCU was reset.
- A final Omnion PCU failure occurred in mid-July, after which PVUSA decided to abandon any further repairs pending replacement of the PCU with a KWI unit.
- The data logger failed and was replaced in late July.

IPC with KWI PCU (September 1995 through year end)

- On three occasions input/output modules failed in the tracker controller and were replaced.
- The tracker controller required manual resets on eight occasions.
- Dc ground faults in two rows were investigated and identified as a failed varistor and a failed module. The module was replaced.
- A second failed module was bypassed.
- A KWI PCU was installed and operational on August 31. The KWI PCU replaced the existing Omnion PCU; the Omnion PCU was abandoned in place.
- During the first month of operation the KWI PCU tripped four times for line disturbances or ground faults.
- A reprogrammed chip was installed by KWI to eliminate manual reset requirements following a line disturbance.
- A failed component in the KWI display board was replaced.

- KWI performed warranty repairs to the PCU, replacing a modulator circuit board and a failed cooling fan.

Kerman US-2

Kerman remains a frustrating system to keep running. Two dominant factors impact the inverter availability. The first is the frequent inverter trips for actual or "detected" faults. Detected faults can be the result of noise, transducer malfunction, signal discontinuity, or program errors. Often the trips lock out the inverter, preventing automatic restart. Inverter component failures have been a significant factor, but array source circuit problems may be a contributing cause.

The second dominant factor is related to remote resets. The control scheme allows limited reset for system trips from the Dispatch Office due to the belief that any trip significant enough to require a reset should be investigated prior to restart. Getting the Kerman PV Power Plant online has a lower priority than other grid problems or outages. Consequently, as a result of nuisance trips, failure to acknowledge trips and execute a remote manual reset, and real equipment failure, the inverters were down about 30 percent of the time for unit 1 and 51 percent for unit 2.

Improving system reliability requires knowledge of the root cause of failure. Unfortunately this is difficult at Kerman due to its remote location. The following types of problems, however, have been typical:

- Loose connections within groups of modules burn and corrode until the module fails due to the heating of the connections, or a bypass diode fails and the module burns up.
- A source circuit fuse clears, causing an excessive voltage imbalance.
- Inverter trips result when the control system detects an electrical condition that the control program deems unacceptable.

Specific activities this year were:

- Either one or both PCUs were inoperable for some period on 219 days. Days of downtime reflect the time to notice the failure, and to effect repair or reset.
- The Fresno dispatch operator remotely reset one or both PCUs on 36 occasions. On 41 occasions the PCUs required manual resets after local inspection or repair.
- Six fuses for HVAC, control, or source circuit were replaced.
- PCU #2 shut down on nine consecutive days for overtemperature before a problem with the HVAC circuit was corrected.

- Three dc voltage imbalances on PCU #1 were individually resolved by either replacing a source circuit fuse or replacing a module with a failed termination. PVUSA performed diagnostic current-voltage (I-V) curves and source circuit current and voltage measurements to help isolate the voltage imbalance.
- The PLC in PCU #1 was returned to Omnion for reprogramming and battery replacement.
- Two days of PCU downtime can be attributed to either the SCADA unit or PCU inadvertently being left in the local position. It normally is in the remote mode.
- Dc ground fault indications caused one shutdown of PCU #1 and 13 shutdowns of PCU #2. No dc array ground faults were identified in September and October. The neutral current sensor (LEM) in PCU #2 was replaced on 11/17/95 to correct the ground fault shutdowns.
- On four occasions Fresno Substation Maintenance either exchanged or replaced circuit boards in the PCUs.
- All of the ribbon cable connectors were cleaned and reseated on two occasions during troubleshooting efforts.
- Omnion was on site in September to troubleshoot and replace a voltage regulator board in PCU #2.
- One failing tracker was replaced.

PVUSA Host Utility Systems

Owing to logistics, utility priority, and incomplete submittal of quarterly and annual maintenance logs, it is difficult to capture accurate data for host utility system maintenance activity. The data received at PVUSA must be used with caution in assessing system reliability or maintenance requirements, but may be used as an indicator of issues encountered in PV system maintenance. A list of maintenance highlights for CSW UPG and ENTECH systems (most complete available) follows.

CSW UPG

- One module fell from the array because of loose fastening hardware; a subsequent inspection identified 22 other loose fasteners.
- Four failures occurred with the tracker programmable logic controller (PLC) but were resolved by adding a ferroresonant transformer to the PLC's ac input line.
- The PLC and several PVX2000 ground fault disconnect devices were damaged by two lightning strikes, one in July and another in August. The first strike short-circuited one source circuit and burned a hole through a panel adjacent to one of the PVX2000 devices. The second strike damaged two more PVX2000 devices and

resulted in the exchange of all of the PVX2000 units with disconnects and 60 A dc fuses.

- In September the tracker motor ac fuses were replaced, and the PLC's output modules were reprogrammed to correct a tracking error.

CSW ENTECH

- A number of problems occurred between start-up and May, including eight modules with cracked lenses, five modules with electrical failures, unresolved ground faults, wind-related tracker drive problems, and unexplained PCU trips.
- Several modules were replaced between May and August.
- Between May and August, the tracker roll drive was upgraded to a larger, 1,500 pound ball screw jack, after problems with strong west winds (similar to the Davis site). This modification included changing the motor rotation counter's reed switch, adding an external east limit switch, and adding east and west limit mechanical stops. A software error that had allowed the roll angle to drift up to 0.75 degrees during the day was also corrected.
- Lightning strikes in August damaged 5 more modules in addition to 13 replacement modules. CSW made a detailed report on its experience to the TRC on June 6.
- A row junction box fire in November caused one half of the array to be down until the box was repaired in early 1996. The fire is believed to have been caused by a failed fuse block connection or possibly another lightning strike.

Maintenance Database

The database now contains 2,399 maintenance records starting from July 1989. The database includes maintenance logs from Davis EMT-1, EMT-2, EMT-3, and US-1 systems. Kerman US-2 is also included and kept current by the input of log forms faxed to the Davis site by Fresno Substation Maintenance personnel.

The database operates within a Windows "point and click" environment and minimizes the need to type repetitive entries. Through normal commands, queries of any subsection may be accomplished. Figure 4-2 shows the current maintenance report and inspection sheet.

Module Replacement History

Module reliability has improved dramatically in the last two decades. PVUSA experience indicates that, in general, module reliability is very good. PVUSA module failures are consistent with the average failure rate of 0.01 percent per year. In 1995, the overall failure rate at Davis and Kerman was about 8 per 10,000 modules (0.08 percent), which is less than in prior years. The high module reliability

PVUSA O&M REPORT AND INSPECTION SHEET					
Log # _____		Date: _____		Start Time: _____	
Stop Time: _____					
Site: ☐ EMT-1 ENT ☐ EMT-1 SX ☐ EMT-3 AMNX ☐ MAUI ☐ US2-KERMAN ☐ EMT-1 SOV ☐ EMT-1 UPG ☐ I.C BLDG ☐ US1-IPC ☐ EMT-2 ASTRO ☐ EMT-1 SSI ☐ EMT-3 SCI ☐ US1-APS ☐ US1-SSI ☐ Other _____					Type of Maintenance: ☐ Planned-Preventive ☐ Unplanned-Failure Related ☐ Research Related
Description of Event:					
☐ BOS Failure ☐ Erosion Problem ☐ Inverter Failure ☐ Pump Failure ☐ Routine Inspect. ☐ Sych Error ☐ Clearance ☐ Exchange Equip. ☐ Line Disturbance ☐ PV Sys Problem ☐ Routine Maint. ☐ Vegetation Problem ☐ DAS Problem ☐ Facility Improvement ☐ Module Failure ☐ PV Workshop ☐ Security Problem ☐ DAS Upgrade ☐ FWRT ☐ Non-Routine Maint. ☐ Read Meters ☐ Safety Problem ☐ Other _____					
Action Taken:					
☐ Adjust ☐ Disconnect ☐ Modify ☐ Procurement ☐ Other: _____ ☐ Calibrate ☐ Inspect ☐ Repair ☐ Supervise/Buddy _____ ☐ Clean/Wash ☐ Install ☐ Replace ☐ Test _____ ☐ Connect ☐ Load ☐ Reset ☐ Warranty _____					
System Involved:		Subsystem(s) Involved:			
System: ☐ DAS ☐ PCU ☐ PV Module ☐ Support Structure ☐ Other: _____ _____ _____ _____	AC Electrical: ☐ Circuit Brkr. ☐ Fuse ☐ Inverter ☐ Relaying ☐ 12kV Transf. ☐ Other: _____ _____ _____	DC Electrical: ☐ Blocking Diode ☐ Bypass Diode ☐ Bypass Diode ☐ Combiner Box ☐ Fuse ☐ Interconnect ☐ Movistor ☐ Switch ☐ Other: _____ _____ _____	Tracker: ☐ Actuator/Seal ☐ Bearings ☐ Clock ☐ Controller ☐ Lubricate ☐ Motor Drive ☐ Receiver ☐ Sensor ☐ Stow ☐ Wake-up ☐ Winch ☐ Other _____	Site: ☐ Buildings ☐ Drainage ☐ Fences ☐ Erosion Ctrl ☐ Pest Ctrl. ☐ Pumps ☐ Roads ☐ Security ☐ Veggie Ctrl ☐ Other: _____ _____	Site DAS: ☐ Computer ☐ Datalogger ☐ MD9 ☐ Pyranometer ☐ Sensor ☐ Software ☐ Thermocouple ☐ Transducer ☐ Weather Sta. ☐ Wiring ☐ Other: _____ _____
Downtime:					
Problem Occurred:		Downtime Hours:		Present Status:	
Date: _____	Partial System: _____	Whole System: _____	Whole system On	☐ Whole system On	
Time: _____			Partial system Off	☐ Partial system Off	
			Whole system Off	☐ Whole system Off	
Materials and Labor					
PVUSA WBS:		Work Done by:		Materials/Parts Used:	
☐ BSD ☐ KEY-2 ☐ BSK ☐ KEY-2K ☐ DAS ☐ MTN ☐ DASK ☐ SAF ☐ EMT-2 ☐ SAFK ☐ EMT-3 ☐ SPD ☐ EVA ☐ SPK ☐ KEY-1 ☐ _____		☐ BEV ☐ DJS ☐ DLM ☐ KOB ☐ PAH ☐ RSR ☐ TUT ☐ _____		_____ _____ _____	
				Materials Cost:	
				Equipment Cost:	
Total Force: _____		Hours per Person: _____		Total Cost: _____	
		Work Complete:		Labor Cost: _____	
		☐ Yes ☐ No			

Figure 4-2
PVUSA Maintenance Report and Inspection Sheet

demonstrated the value of requiring module qualification tests. The majority of failures were related to BOS components. Wiring and connection failures, tracking system misoperation, and PCU problems required the most O&M effort. Higher than normal rates for some of the EMTs reflect the early production aspect of the technology. Figure 4-3 is a running history of module replacements for the EMT and US systems closely monitored by PVUSA.

Only the two Sovonics EMT arrays have had a significant number of module defects. About 82 of its 1,200 Davis modules (1.2 percent per year) have been replaced due to cosmetic delaminations or blisters on the Tefzel cover (79 modules) and complete failures (6 modules). Additionally, PVUSA found a bullet hole in another module (it was still operating) and used a nonconductive silicone compound to seal the hole. Of the 1,200 Maui modules, 51 (0.9 percent per year) had failed junction boxes. Most were replaced, but a few were repaired by cleaning and rewiring the connections. None of the Maui modules have experienced cover delaminations.

Figure 4-3
Cumulative Module Replacement/Repair Histories through 1995

Only three of the 400 Siemens modules have failed (0.15 percent per year); one failure was caused by a bullet hole. Only three of 4,992 UPG modules have been replaced (0.01 percent per year), all due to cracked glass. Only one of 336 Solarex modules has failed (0.08 percent per year), its cover glass shattered by an unknown cause. The 60 modules on the ENTECH array have not suffered any failures.

APS amorphous glass-on-glass modules have the highest failure rate of the utility scale systems. The large glass-on-glass module appears to be susceptible to cracks that develop in the front and back glass. To date these are the only known module failures. Due to the large number of modules in parallel (240), individual module problems are too small to be measured or to be of much consequence. APS failure rate has been 0.14 percent per year.

The MV-55J crystalline silicon module used by SSI at Kerman and Davis has been in production in nearly the same configuration for some time. Consequently module failures are few. However, PVUSA has experienced a relatively high number of failures related to source circuit design, bypass diode failure, and unreliable connections. The modules are paralleled in groups of four (Davis) and five (Kerman). When there is simultaneously a module and a bypass diode failure in the group, the other modules are unable to carry the string current and burn up, resulting in the loss of all four or five parallel modules. Failure rates are 0.13 percent and 0.03 percent per year for Davis and Kerman, respectively.

IPC uses the large area Mobil modules. These modules are currently marketed in a slightly different form by ASE Americas. The failures to date have been two ground faults between the frame and module edge. Annual failure rate is about 0.1 percent.

Maintenance Costs

The maintenance database enables PVUSA to track maintenance costs at Davis and Kerman. As can be seen in Figure 4-2, maintenance costs are segregated by type: planned-preventive, unplanned-failure related, and research-related. Research-related maintenance activities at Davis and Kerman will not occur for mature, commercial US systems.

Tables 4-1, 4-2, and 4-3 summarize maintenance costs for APS US-1, IPC US-1, and SSI US-1 systems, respectively. Project and vendor labor hours were included and assigned a cost of \$50/hour. Most materials were supplied under warranty.

The Kerman US-2 system provides the best PVUSA test bed for realistically predicting maintenance costs. Kerman is an unstaffed facility that is remotely monitored and operated. Table 4-4 summarizes 1995 maintenance costs at Kerman.

Maintenance

Table 4-1
1995 APS US-1 Maintenance Costs

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Preventive Monthly Labor ^a (hr)	Preventive-related Monthly Material ^a (\$)	Preventive Maintenance Total (¢/kWh)	Cumulative Preventive Maintenance (¢/kWh)	Failure-related Monthly Labor ^a (hr)	Failure-related Monthly Material ^a (\$)	Failure-related Total (¢/kWh)	Cumulative Failure-related Maintenance (¢/kWh)	Cumulative Total Cost (¢/kWh)
January	17,221	17,221	0.50	0.00	0.15	0.15	0.50	0	0.15	0.15	0.29
February	28,651	45,872	0.50	0.00	0.09	0.11	0.00	0	0.00	0.05	0.16
March	47,258	93,130	2.50	0.00	0.26	0.19	0.60	0	0.06	0.06	0.25
April	56,506	149,636	3.00	0.00	0.27	0.22	0.30	0	0.03	0.05	0.26
May	69,951	219,587	0.75	0.00	0.05	0.17	0.95	0	0.00	0.05	0.22
June	60,112	279,699	3.00	0.00	0.25	0.18	1.95	350	0.74	0.20	0.39
July	59,563	339,262	0.50	0.00	0.04	0.16	7.55	440	1.37	0.41	0.57
August	49,893	389,155	0.50	0.00	0.05	0.14	14.16	351	2.12	0.63	0.77
September	47,254	436,409	1.00	0.00	0.11	0.14	175.19	70	18.69	2.58	2.72
October	40,497	476,906	0.75	0.00	0.09	0.14	17.20	725	3.91	2.70	2.83
November	42,926	519,832	0.70	0.00	0.08	0.13	10.30	197	1.66	2.61	2.74
December	14,876	534,708	5.50	0.00	1.85	0.18	0.20	0	0.07	2.54	2.72

^a Costs include materials provided by PVUSA, subcontract factory service representatives, and materials provided under warranty.

Table 4-2
1995 IPC US-1 Maintenance Costs

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Preventive Monthly Labor ^a (hr)	Preventive-related Monthly Material ^a (\$)	Preventive Maintenance Total (¢/kWh)	Cumulative Preventive Maintenance (¢/kWh)	Failure-related Monthly Labor ^a (hr)	Failure-related Monthly Material ^a (\$)	Failure-related Total (¢/kWh)	Cumulative Failure-related Maintenance (¢/kWh)	Cumulative Total Cost (¢/kWh)
January	2,139	2,139	0.25	0.00	0.58	0.58	1.75	0.00	4.09	4.09	4.68
February	10,221	12,360	0.25	0.00	0.12	0.20	35.37	0.00	17.30	15.02	15.22
March	24,051	36,411	3.00	0.00	0.62	0.48	1.40	0.00	0.29	5.29	5.77
April	28,146	64,557	6.50	0.00	1.15	0.77	5.93	35.36	1.18	3.50	4.27
May	2,835	67,392	0.50	0.00	0.88	0.78	6.60	87.68	14.73	3.97	4.75
June	19,876	87,268	12.25	0.00	3.08	1.30	7.40	12.00	1.92	3.50	4.81
July	20,961	108,229	0.25	0.00	0.06	1.06	1.30	0.00	0.31	2.89	3.95
August	0	108,229	1.25	0.00	—	1.12	6.00	40.00	0.00	3.20	4.32
September	34,672	142,901	0.25	0.00	0.04	0.86	4.00	40.00	0.84	2.59	3.45
October	29,852	172,753	0.25	0.00	0.04	0.72	0.50	0.00	0.21	2.16	2.87
November	21,097	193,850	0.25	0.00	0.06	0.64	0.00	0.00	0.17	1.92	2.57
December	4,555	198,405	12.00	0.00	13.17	0.93	30.60	297.00	46.15	2.80	3.73

^a Costs include materials provided by PVUSA, subcontract factory service representatives, and materials provided under warranty.

Table 4-3
1995 SSI US-1 Maintenance Costs

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Preventive Monthly Labor ^a (hr)	Preventive-related Monthly Material ^a (\$)	Preventive Maintenance Total (¢/kWh)	Cumulative Preventive Maintenance (¢/kWh)	Failure-related Monthly Labor ^a (hr)	Failure-related Monthly Material ^a (\$)	Failure-related Total (¢/kWh)	Cumulative Failure-related Maintenance (¢/kWh)	Cumulative Total Cost (¢/kWh)
January	2,318	2,318	0.00	0.00	0.00	0.00	0.50	0	2.16	1.08	1.08
February	4,294	6,612	0.00	0.00	0.00	0.00	0.10	0	0.70	0.45	0.45
March	6,854	13,466	2.00	0.00	1.46	0.74	12.00	1,100	24.80	12.85	13.59
April	11,075	24,541	7.00	0.00	3.16	1.83	1.65	60	1.29	7.63	9.46
May	12,426	36,967	0.25	0.00	0.10	1.25	0.40	0	0.16	5.12	6.37
June	14,642	51,609	10.25	0.00	3.50	1.89	0.40	0	0.14	3.71	5.59
July	10,631	62,240	4.50	0.00	2.12	1.93	0.80	0	0.38	3.14	5.07
August	8,994	71,234	0.10	0.00	0.06	1.69	1.10	0	0.00	2.82	4.51
September	6,874	78,108	0.00	0.00	0.00	1.54	7.05	810	16.91	4.06	5.60
October	6,265	84,373	0.00	0.00	0.00	1.43	0.30	0	0.24	3.77	5.20
November	3,949	88,322	4.50	0.00	5.70	1.62	0.00	0	0.00	3.61	5.23
December	1,773	90,095	10.25	0.00	28.91	2.16	0.90	0	2.54	3.59	5.74

^a Costs include materials provided by PVUSA, subcontract factory service representatives, and materials provided under warranty.

Table 4-4
1995 Kerman Maintenance Costs

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Preventive Monthly Labor ^a (hr)	Preventive-related Monthly Material ^a (\$)	Preventive Maintenance Total (¢/kWh)	Cumulative Preventive Maintenance (¢/kWh)	Failure-related Monthly Labor ^a (hr)	Failure-related Monthly Material ^a (\$)	Failure-related Total (¢/kWh)	Cumulative Failure-related Maintenance (¢/kWh)	Cumulative Total Cost (¢/kWh)
January	16,249	16,249	4.00	0.00	1.23	1.23	8.60	0	2.65	2.65	3.88
February	29,020	45,269	4.00	0.00	0.69	0.88	78.02	0	13.44	9.57	10.45
March	55,068	100,337	8.00	0.00	0.73	0.80	8.65	12	0.81	4.76	5.56
April	89,672	190,009	4.00	0.00	0.22	0.53	2.93	0	0.16	2.59	3.12
May	97,774	287,783	4.00	0.00	0.20	0.42	2.25	0	0.12	1.75	2.17
June	89,294	377,077	12.00	0.00	0.67	0.48	0.70	0	0.04	1.34	1.82
July	24,501	401,578	4.00	0.00	0.82	0.50	7.75	331	2.93	1.44	1.94
August	24,831	426,409	4.00	0.00	0.81	0.52	26.05	400	0.00	1.76	2.27
September	44,640	471,049	8.00	0.00	0.90	0.55	93.05	25	10.48	2.58	3.14
October	50,521	521,570	4.00	0.00	0.40	0.54	6.60	0	0.65	2.40	2.93
November	26,551	548,121	4.00	0.00	0.75	0.55	3.20	148	1.16	2.34	2.88
December	23,842	571,963	56.00	0.00	11.74	1.01	0.00	0	0.00	2.24	3.25

^a Costs include materials provided by PVUSA, subcontract factory service representatives, and materials provided under warranty.

^b Travel costs incurred to support activities are not included.

Figure 5-1
Kerman Substation Transformer #2 1995 Daily Peak Load (30-Min Avg)
and Kerman 1995 Daily Peak Ambient Temperature (10-Min Avg)

Figure 5-3 shows that the peak transformer loads occur in the late afternoon during the summer months (typically between 3 and 5 p.m. local standard time), 2-4 hours earlier than the fall/winter/spring peaks.

Because of the PV system's single-axis tracking, there is still a significant amount of system output capability at the time of peak loads. Figure 5-4 shows the transformer load duration curve (load values plotted in order from highest load to smallest) and the plane of array irradiance coincident with each load value. (Usually PV plant output is plotted against the load duration curve, but due to the significant plant downtime, a more informative comparison of transformer load to available irradiance is provided.) Approximately 82 percent of the irradiance values on the plot are above 500 W/m^2 ; 62 percent are above 800 W/m^2 . As the 800 W/m^2 represents 80 percent of the plant's rating irradiance, a functioning plant could be expected to produce from 70 percent to over 80 percent of its rated output at this irradiance, depending on the temperature.

Figure 5-2
Kerman PV Plant 1995 Daily Peak Output (10-Min Avg)
and 1995 Daily Peak Plane of Array Irradiance (10-Min Avg)

Figure 5-3
Time of Occurrence of Kerman Transformer #2 Peak Daily Load

Figure 5-4
Transformer Load Duration Curve and Coincident Irradiance

Seasonal Performance

Figure 5-5 represents three typical summer days' PV output and transformer load profiles (typical for a normally operating PV plant). The transformer load without PV is also shown. This is a conservative estimate of "PV-less" load since it's simply the numerical addition of plant output measured at the plant to the transformer load measured at the transformer. There would actually be some additional load at the transformer if the PV were not present due to line and substation losses (roughly 10 kW at 3 MW of feeder load, according to Wenger and Hoff²). These summer profiles show that, due to its use of single-axis trackers, the plant still has substantial output at the time of the daily peak loads. The plots also show the characteristic afternoon reduction in output due to high ambient and array temperature.

Figure 5-6 shows similar profiles for three typical winter days. The 1995 winter was marked by record-breaking rainfall throughout most of California. The associated cloud cover made it difficult to find clear winter days with normal plant operation. These plots show that plant output does not match peak loads, which tend to occur just before sunrise and just after sunset. However, as shown in Figure 5-1, transformer capacity is not an issue during these months.

² H.J. Wenger and T.E. Hoff, *The Value of Photovoltaics in the Distribution System—The Kerman Grid-Support Project*, DOE/AL/82993/20, May 1995.

Figure 5-5 Typical Kerman Substation and PV Plant Summer Performance (Standard Time)

Figure 5-6
Typical Kerman Substation and PV Plant Winter Performance
(Standard Time)

Voltage Support

A plant outage that occurred on May 1 was investigated to determine the cause of the outage. In addition to generating daily files containing 10-minute averages, the data collection computer at the Kerman site also stores 5-second (nominal) samples of all data channels for a period of time. Normally only the 10-minute average files are downloaded; the 5-second data are discarded approximately every month. To investigate this outage, 5-second samples of several channels were downloaded from the control computer.

At 10:02:35 a cloud-enhanced irradiance of over 1,500 W/m² was measured by two separate pyranometers. The PCU tripped off per design due to dc overcurrent sometime prior to the next SCADA reading taken at 10:02:41. Feeder voltages measured before and after the trip are shown in Table 5-1 and Figure 5-7. The table shows pre- and post-trip average feeder voltages and plant output (due to the presence of clouds, plant output—and therefore feeder voltage—was changing fairly rapidly) as well as the last readings prior to trip. These data are also converted to 120-V basis to compare with previous results.³ Based on the pre- and post-trip averages, a loss of 149 kW in generation resulted in a 1-V reduction in feeder voltage (120-V basis). Considering the last readings prior to the trip compared to the post-trip average, a 271-kW reduction in generation resulted in a 1.5-V reduction in feeder voltage, consistent with the earlier results⁴ that voltage support to the feeder is directly proportional to plant output and independent of feeder load.

Table 5-1
Voltage Support Data

	Phase A Voltage (V)	Phase B Voltage (V)	Phase C Voltage (V)	PCU 1 (kW)
Last Reading prior to trip	12,349	12,066	12,289	271
Average from 9:55:01 - 10:02:35	12,288	12,033	12,226	149
Average from 10:02:41 - 10:09:59	12,185	11,919	12,121	0
120-V Basis				
Last Reading prior to trip	118.8	116.1	118.3	271
Average from 9:55:01 - 10:02:35	118.2	115.8	117.7	149
Average from 10:02:41 - 10:09:59	117.3	114.7	116.6	0

³ Ibid.

⁴ Ibid.

Figure 5-7
Voltage Support Example

Externality Value

Wenger and Hoff also presented an estimate of the value of the reduced emissions from conventional power plants as a result of the energy production from the plant.⁵ Their results were based on 20-year simulations, but information was provided to estimate the savings based on 1995 production. Based on a total 1995 production of 587 MWh, Table 5-2 shows the emission savings and value. With a value of just under 1.1 ¢/kWh, a total value of \$6,301 is achieved for the year. The plant's low output for the year contributed to a rather low value. Figure 5-8 shows the percentage contribution of each emission type to the total value. Note that these values do not strictly scale to the previous results due to the assumptions made in the simulation program regarding changing fuel usage over the 20-year analysis period compared to the assumption for 1995.

⁵ Ibid.

Table 5-2
Estimated Emission Savings

	Particulate	NO _x	ROG	SO ₂	CO ₂	Total
lb/MWh	0.037	1.508	0	0.478	248	
Tons Avoided	0.01	0.44	0.00	0.14	72.73	
\$/lb (\$1995)	2.31	3.98	2.28	0.92	0.017	
¢/kWh	0.00009	0.0060	0	0.0004	0.0042	0.0107
\$	\$50	\$3,520	\$0	\$258	\$2,473	\$6,301

Figure 5-8
Externality Value Contributed by Emission Type (percent of \$6,303)

Future Plans

The level of effort planned for 1996 is that necessary to ensure safe operation of the plant. The plant will continue to be operated by the local PG&E operating department and maintained by the local PG&E maintenance crew. Scheduled maintenance will continue, and failed components will be repaired or replaced. Plant data will continue to be collected and analyzed as a basis for quantifying performance and maintenance costs. Since the nontraditional benefits valuation has been completed, additional data on the distribution system and substation will not be collected.

6

DATA ACQUISITION AND ANALYSIS

This section briefly describes PVUSA's data acquisition systems (DASs) for the Davis and Kerman sites. The section includes information on the DAS upgrade in 1995 and the Kerman SCADA network. The evolution of PVUSA's DAS is summarized in the 1989-1994 *PVUSA Progress Reports*, and DAS lessons learned are documented in the topical report *PVUSA Instrumentation and Data Analysis Techniques for Photovoltaic Systems*.

System Description

Data acquisition for PVUSA is centered at Davis and consists of a Windows for Work Groups local area network of personal computers collecting data from Campbell Scientific, Inc. (CSI) data loggers. Kerman data are collected with a utility-type supervisory control and data acquisition (SCADA) system and stored locally on a personal computer running QNX, a small, real-time operating system. Kerman and host utility PV system data are transmitted at night via modem to Davis for later analysis and reporting.

The Davis DAS network uses one CSI data logger for each PV system, one for the solar/weather instruments, and one for utility grid monitoring. Monitoring at PVUSA host utility sites is performed by remote CSI data loggers that communicate with the Davis site via a telephone modem.

Data channels on the CSI data loggers are scanned every 5 seconds and averaged over 10 minutes. Five-second sample data from the Davis site are displayed on a central computer screen. Audible alarms and visual alarms displayed at the top of the screen inform the site operator if there are system problems. In a background operation on the data acquisition computer (DAC), 10-minute average data are collected every 20 minutes and appended to daily files for each site.

With each data scan, the Davis data loggers monitor 18 channels for each EMT system. A greater number of channels are monitored for the US systems (depending on the system) using expanded data loggers capable of scanning more than 100 input signals.

The DAS monitors ac and dc voltage, current, and power; fault current; daily ac kWh; module and ambient temperature; plane-of-array (POA), horizontal, direct

normal, and global normal irradiance; wind speed and direction; and rainfall. In addition, the DAS monitors several status signals on each PCU, including on/off, error off, recycle, and smoke alarm.

Daily data files on the DAC are quality-checked and loaded into a Structured Query Language (SQL) database for reporting and analysis. Summary queries are used to compile relevant performance statistics such as energy production, insolation, and meteorological information. The summary program can be run for any interval of days and any number of PV systems.

A Basic Measurement Instruments (BMI) 8010 PQNode provides high-frequency monitoring of utility-line power quality at Davis and Kerman. Data from the BMI 8010 are collected by computer either through a direct serial connection or through a dial-up modem. At Davis, the 8010 data are collected every 3 hours by a dedicated 386 computer running the PQNode application and system software called PASS. (PASS is a multifunction program whose capabilities include real-time data plots, historical plots, power quality reports, and database functions, such as archiving.) PG&E's Research and Development Department collects Kerman PQNode data by modem at night. Snapshot 12-kV line data are sampled by exception to defined thresholds, every half hour, or when triggered manually.

DAS Upgrade in 1995

PVUSA continued upgrading the DAS in 1995 to more effectively manage the data collected from additional and modified EMT, US, and host utility installations. Activities completed in 1995 include installing an additional computer, reconfiguring existing machines, redeveloping the database, and upgrading the data logger firmware and software.

To support expanded database operations for new PV systems being monitored by PVUSA, a new database computer with more memory, more disk space, and a faster processor than its predecessor was purchased. This computer includes a Pentium 90-MHz processor, with a 1.6-GB hard disk and 16-MB RAM. The 50-MHz 486 computer that was previously used for the database has been reconfigured as the raw data archive and Kerman data download computer.

The Gupta SQLBase database installed in 1994 was replaced with a Microsoft Access database in October 1995. There were three areas of increasing concern related to the Gupta database: maintenance, reliability and data organization. Maintenance was an issue because the Gupta database engine stored all data in a single database file, which became a problem as the file grew to be a significant portion of the available hard disk space (800 MB at four-month intervals). This created a shortage of disk space whenever data older than four months needed to be analyzed. It also prevented the configuration data (systems installed, ratings, architecture, and other

relatively stable information) from being maintained independently from the performance data. The reliability of the Gupta database was poor enough that three database files were corrupted in 1995, resulting in delays of several weeks as archived raw data were reloaded into the database and new reports generated. Data organization used in the Gupta database was designed with too much flexibility, which resulted in inefficient data storage and retrieval.

The new database design was initially implemented as a stopgap measure after the Gupta database engine started crashing repeatedly. When the improvements in processing speed (10x), disk usage (5x), and ease of development (two weeks to equivalent report generation) of the stopgap database were recognized, it was cleaned up and put into permanent use.

This result was not entirely unexpected, as the new database incorporates lessons learned from the previous design and implementation. With respect to maintenance, the data are stored in multiple database files to keep the per-file size at a fraction of the whole database size, and keep static data separate from performance data. This separation of concerns was not possible using the Gupta database system. Access supports this architecture well, allowing a single query to extract data from the multiple database files easily. Reliability of Access in maintaining the maintenance database for PVUSA over the last two years has been good, and the effect of any failures is expected to be contained by keeping the data in independent database files. The simplified version of the earlier architecture now stores data much more efficiently (42 MB/month vs. 200+MB/month), but requires somewhat more work to maintain whenever systems are added or data processing algorithms are modified. The improved maintenance and performance characteristics for frequent operations so far appear to compensate for the additional maintenance required for new systems.

The firmware (operating software encoded in PROM chips) and software (installation-specific configuration) for the CSI data loggers at the Davis site were upgraded in 1995 to improve reliability and maintainability. The new firmware includes features designed to simplify data identification when it is archived, and a bug fix for a timekeeping problem that has recurred on the first day of each year. The new software utilizes the features supported by the new firmware, and removes the ability to archive the 5-second data samples, which was of minimal utility and the source of several maintenance and reliability problems.

Kerman SCADA System Operation

The Kerman US-2 installation uses the PG&E SCADA network. The Kerman SCADA system is a state-of-the-art, utility-grade system that allows remote plant operation by the local distribution office similar to other generating and substation facilities. SCADA permits operator functions and data acquisition and monitoring to

MAIN BKR
89-1
REMOTE
MAIN BK
RESET
REENABLE
RESTART
NORMAL
INVERTER #1 ON
52-1
REMOTE

1475
VOLTS
D 12.0
B 11.0
C 12.1
WATTS 90.14
VARS -10.10
D 4.0
B 4.0
C 4.0
TEMP -5.1
AMPS 27.1
WATTS 47.43
VARS 36.0
SYNC FAIL NORMAL

WIND SPEED
WIND DIRECTION
BANK TEMP -1
BANK TEMP -2
BANK TEMP -3

TRACK ANGLES
11.1
12.0
13.0
14.0
15.0
16.0
17.0
18.0
19.0
20.0
21.0
22.0
23.0
24.0
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90.0
91.0
92.0
93.0
94.0
95.0
96.0
97.0
98.0
99.0
100.0

RESET
REENABLE
RESTART
NORMAL
INVERTER #2 ON
52-2
REMOTE
VOLTS
D 367.9
B 360.1
C 361.6
TEMP -0.0
AMPS 70.6
WATTS 40.03
VARS 36.0
SYNC FAIL NORMAL

Figure 6-1
Remote Status Display for Kerman SCADA System

7

SPECIAL TESTS

This section summarizes special tests performed in 1995, including I-V curve traces, power quality (PQ) measurements, soiling studies, ground resistance testing, and APS soil anchor corrosion testing. Special tests for prior years are documented in the 1989-1994 *PVUSA Progress Reports*.

I-V Curves

Current-voltage (I-V) curve tests are conducted on completed arrays to obtain snapshot data for diagnostics and baseline rating estimates. I-V curve tests also may detect wiring and module deficiencies in installed PV dc circuits. I-V tests are performed as part of PVUSA's field acceptance testing. In 1995, SCI and Amonix curves were taken for field acceptance; ENTECH and Solarex curves were taken for diagnostic purposes.

Initial I-V curves for both SCI and Amonix were useful for prediction of array rating. A sample curve for the SCI array (11 source circuits, CdTe) is shown in Figure 7-1. Normalized power for the array translates to 12.1 kW_{dc}, consistent with the 12.0-kW_{dc} PTC rating established in a separate rating report issued on December 19.

The back-contact cell used by Amonix has been under development for some time. I-V curves of cells and modules were measured at PG&E's PV Test Facility in San Ramon, CA, since 1990 and reported by Rosen et al.¹ I-V curves on the Amonix array represent measurements of new and unique technology using equipment designed for flat-plate systems. The electrical characteristics of the back-contact cells when connected to a capacitive I-V curve tracer like the DS600 may interact with the measuring equipment. Figure 7-2 shows an I-V curve taken with a DS600 capacitive I-V curve tracer. Note the square-edged anomalies in the curve. A subsequent curve shown in Figure 7-3 displayed no such problem. A teleconference with Clin Lashway, the DS600 designer, indicated that the problem in the curve may be related to random noise generated in the array. Testing with an oscilloscope to capture high-speed data will proceed in 1996 as equipment and weather conditions permit.

¹ P.B. Rosen, C.M. Whitaker, H.J. Wenger, *EPRI High Concentration PV Module—1991 Performance*, PG&E Report #007.5-92.11, July 1992.

Figure 7-1
SCI Array I-V Curve

Figure 7-2
Amonix Source Circuit I-V Curve with "Noise"

Figure 7-3
Amonix Source Circuit I-V Curve without "Noise"

Initial Amonix I-V curves such as that shown in Figure 7-4 suggest an array rating of $16.8 \text{ kW}_{\text{dc}}$. Recent I-V curves taken after some array adjustments by Amonix present a similar rating around $16.3 \text{ kW}_{\text{dc}}$. The final, more rigorous rating for the array has not yet been calculated but will be expected to be in the vicinity of these numbers.

ENTECH EMT-1 array performance is down from earlier years, which prompted an investigation of string currents. These string current data proved inadequate to determine any problems in the system, so array I-V curves were measured. Individual I-V curves of source circuits showed healthy strings with differing peak power voltages and currents. Mismatch and lens soiling losses are suggested as part of the reduction in array peak power.

Multiple I-V curves taken during the same day may be used to determine other operating parameters such as voltage and current temperature dependencies. Figure 7-5 shows the change in Amonix voltage and current as a function of module back temperature at constant irradiance.

Figure 7-4
Initial Amonix Array I-V Curve

Figure 7-5
Effect of Amonix Module Temperature on V_{oc} and I_{sc}
At Constant Irradiance ($\sim 950 \text{ W/m}^2$)

Power Quality Testing

Installation of the KWI PCU to replace the Omnion 3200 at IPC US-1 generated an additional task of PCU acceptance. Acceptance testing of new PV systems at PVUSA consists of a series of operational and functional tests, ending with power quality (PQ) measurements. PQ testing utilizes portable equipment connected to the 12-kV output of the system under consideration. Harmonic spectra from low to 100 percent power levels are recorded. PVUSA has used BMI 3060 and 4800 portable power quality instruments for field acceptance tests as well as a BMI 8100 PQNode (at the site instrumentation and control building), which monitors the total US system output at the grid intertie. The BMI equipment suffers from narrow bandwidth (4 to 3,000 Hz) and has been replaced for field acceptance testing with an HP 35665A Dynamic Signal Analyzer, a spectrum analyzer with state-of-the-art current toroids, and high-voltage probes. Unfortunately, time of year, weather, sun angle, and scheduling have resulted in little opportunity for PQ data collection. The most consistent overall measure of PQ was with the BMI 8100.

In mid-December 1995, several attempts were made to measure KWI PCU PQ using the spectrum analyzer and wide-bandwidth probes. Measurements in the field and with the PQNode indicated values above acceptable limits. Figure 7-6 is a presentation of PQNode data measured at about 50 percent power. The current waveform is noticeably nonsinusoidal and has significant THD. Within days, a control component failed in the PCU, causing the device to recycle every few minutes. Post-repair PQ is greatly improved with the current THD near 3 percent at 50 percent power as seen in Figure 7-7. Note the 3 percent current THD waveforms are nearly sinusoidal and relatively smooth.

Failures at IPC and SSI US-1 have shown the value of monitoring THD current and voltage. PQ measurements are made automatically every 30 minutes by the PQNode software. The 30-minute sample is a snapshot and gives voltage and current waveforms as well as THD.

On an occasion where only the SSI US-1 system was on-line, the current THD was seen to be 30 to 40 percent above average or acceptable levels. Investigation of the data showed a change in the SSI US-1 capacitor filter that resulted in a loss of effectiveness in removing the higher-order harmonics. Repair of the filter wiring renewed the filter effectiveness, reducing the current total harmonic content to acceptable levels below the 5-percent limit suggested by IEEE 519-1992.

Figure 7-6
Pre-Repair KWI Current Waveforms at about 50 Percent Power

Figure 7-7
Post-Repair KWI Current Waveforms at 50 Percent Power (3 Percent THD)

Soiling

Power and energy losses due to the buildup of dirt and other contaminants can be significant and are commonly asked about by visitors and system designers. Soiling losses vary considerably depending on many factors and must be considered with respect to the cost of maintaining clean arrays. Contributing effects include the local climate; the nature of activities from neighboring farms, vehicles, and birds; soil particle properties; collector surface properties; structure orientation; and long-term mechanical and chemical surface actions. These effects make it difficult to predict soiling losses for a given system.

At the Davis site, precipitation is rare during the summer months, and PVUSA noted power losses of as much as 19 percent can occur when arrays have been left uncleaned for several months.² Ordinarily, soiling losses are much less significant, averaging perhaps 5 percent annually for a broad range of sites with more even seasonal rainfall patterns.

PVUSA does not routinely clean its arrays, but performs spot cleaning as needed to assist with diagnostic work such as I-V curves and field wet resistance tests (FWRT), or to wash visibly heavy buildup at times when rain is unlikely. The project's water tank and pump are only capable of spraying surfaces up to about 12 feet high; taller structures such as Amonix EMT-3 and APS US-1 arrays require rented equipment. In addition, PVUSA's extremely hard well water has often been observed to leave a visible white residue. For more critical cleaning applications, softer water has been brought in from other supplies such as city water from deep wells obtained from the mains via a hydrant in downtown Davis.

In 1995, most of the arrays were manually cleaned at least once during the summer. The SCI and Amonix EMT arrays were each washed several times to support start-up and rating activities. A detailed comparison was undertaken during August on the fixed, 30-degree tilt EMT-1 array from SSI, which consists of 400 microgridded single-crystal silicon modules.

The SSI EMT-1 array had been cleaned thoroughly by rain in mid-June, and after being washed again on August 21, the steady state efficiency increased by 6 percent. This result was somewhat lower than expected, since the array was visibly soiled after approximately 2 months of drought. Furthermore, an initial before/after "snapshot" suggested a change of 12 percent, but this brief comparison may have been influenced by irradiance fluctuations or temporarily cooler operating temperatures as the water evaporated. The improvement of 6 percent was gauged by calculating PTC ratings using 2 days' worth of data both before and after the cleaning. In its cleaned condition, the array's updated rating of 16.2 kW_{dc} indicates it has

² 1993 PVUSA Progress Report, pp. 5-15 and 5-16.

continued to degrade at a slow annual rate of about 2 percent since its rating was last updated in October 1993. This is identical to the array's overall 2 percent annual degradation rate over its first 6.67 years of operation, and is consistent with other recent reports of long-term poly- and single-crystal silicon array degradation rates.³

Ground Resistance Testing

Ground resistance testing is conducted to ensure personnel safety (maintaining low-ground grid resistance) and proper operation of electronic equipment. Ground resistance is measured according to the IEEE 80-1986 standard "Fall of Potential" method, using a Biddle ground resistance micro-ohmmeter or equivalent.

Ground resistance readings were taken at the PVUSA Davis site periodically since 1988. Readings were taken at 22 strategically located points: eleven in the US-1 area, nine in the EMT area, and two in the sump pump area.

Readings were taken in November 1995, November 1994, September 1993, August 1992, and October 1988. Readings ranged between 0.05 ohms and 3.0 ohms. These readings suggest that the integrity of the grounding system has been good over the 7-year period (the NEC allows a reading of 25 ohms or less; good engineering practice allows a reading of 5 ohms or less).

APS Soil Anchor Corrosion Testing

The test is conducted annually to quantify the corrosion rate of the APS soil anchors in mils per year. The site soil conditions at Davis are highly corrosive, and PVUSA established during construction that possibly 15 percent of the soil anchors may have 8 or 9 mils of epoxy coating, less than the specified 15 mils. The soil anchor test therefore provides a basis for determining the integrity of the epoxy-coated soil anchors.

Figure 7-8 shows the locations of the cathodic test stations. Each test station has four anchors and one zinc anode. Table 7-1 shows the current readings between the anodes and the soil anchors. The soil anchor current reading for a particular soil anchor has increased year after year. The test data reflect readings of the anodic current in milliamperes and should be converted to a corrosion rate expressed in mils per year. To convert the current readings (in milliamperes) to mils per year, PVUSA uses the following equation:

$$\text{Corrosion rate (mils/year)} = \frac{\text{Current (mA)} \times 0.492}{\text{Surface Area of the Soil Anchor (ft}^2\text{)}}$$

³ A.R. Rosenthal, "Lessons Learned from 15 Years of PV System Testing," presented at the NREL PV Performance and Reliability Workshop, Golden, CO, September 1995.

where the surface areas of the perimeter and inner soil anchors are 9 and 5 ft², respectively.

Figure 7-8
APS Soil Anchor Test Stations

There is no pass/fail value. The intent is to conduct the tests at periodic intervals to observe an annual trend in the corrosion rate. An increasing corrosion rate may indicate that the soil anchor coating is deteriorating and extensive corrosion may be occurring. One ampere-year of anodic current flow consumes 20.11 pounds of iron.

Based on a 20-year design life for the array, PVUSA established an acceptable corrosion rate of 1 mil/year (1 mpy) or less. Translating 1 mpy into anodic current flow values, each 9 ft² and 5 ft² anchor is allowed a maximum of 18.29 and 10.16 mA, respectively. Through 1995, anodic current flow readings have been below the maximum allowable. Since the soil anchors at PVUSA have not exceeded maximum allowable corrosion rates, they are expected to be adequate through the design life.

Table 7-1
APS Soil Anchor Current Readings

Current Readings (mA) between Anchor and Zinc		Test Site 1	Test Site 2	Test Site 3	Test Site 4	Test Site 5	Test Site 6	Test Site 7
8/6/92	Anchor 1	0.000	0.031	0.065	0.320	0.000	0.000	0.150
	Anchor 2	0.020	0.005	0.035	0.240	0.013	0.000	0.011
	Anchor 3	0.004	0.015	0.080	0.190	0.070	0.000	0.000
	Anchor 4	0.012	0.020	0.450	0.220	0.070	0.000	0.000
7/27/93	Anchor 1	0.015	0.573	0.472	1.921	0.013	0.001	0.241
	Anchor 2	0.320	0.640	0.613	1.261	0.337	0.001	0.365
	Anchor 3	0.209	0.337	0.597	0.601	0.081	0.001	0.097
	Anchor 4	0.052	0.918	1.102	0.609	0.110	0.001	0.013
8/15/94	Anchor 1	0.017	1.334	3.620	3.160	0.068	0.000	0.182
	Anchor 2	0.314	0.766	3.350	1.140	0.757	0.000	0.521
	Anchor 3	0.143	0.451	1.050	0.471	0.347	0.000	0.205
	Anchor 4	0.036	0.830	1.750	0.606	0.275	0.000	0.048
9/15/95	Anchor 1	0.165	1.340	2.730	3.225	0.024	0.009	0.145
	Anchor 2	0.529	0.843	1.713	1.860	0.620	0.008	0.580
	Anchor 3	0.480	1.282	1.250	0.806	0.585	0.006	0.074
	Anchor 4	0.312	1.215	2.637	0.710	0.470	0.005	0.053

8

SAFETY

This section summarizes PVUSA's 1995 safety program activities. Prior activities are documented in the *1989-1994 PVUSA Progress Reports*.

The good safety record and orderliness of site operations were affirmed by Bechtel Safety and Health's favorable site safety and health review on August 22 and zero accident award certificate; the California Energy Commission's due diligence inspection (documented in a July 6 memo), and PG&E's environmental assessment for the City of Davis (issued August 23). Safety program activities in 1995 included:

- The Safety Committee met on August 22.
- Numerous subcontractor (tool box) and site staff safety (refresher) meetings were conducted.
- Site employees attended the following off-site safety seminars sponsored by the Safety Center in Sacramento, CA:
 - Introduction to Safety
 - Regulatory Introduction and Overview
 - Getting People Involved
- The hot line tools, grounding sets, and protective rubber gloves were tested in accordance with CalOSHA requirements.
- The master copy of the PVUSA Safety and Health Action Plan was updated to include the handling and disposal of CdTe modules.

No lost time accidents or first aid cases occurred at Davis or Kerman in 1995.

9

PROJECT TRANSITION

In 1994, PG&E decided to relinquish management of the PVUSA project. This section describes the selection of CEC and SMUD as the new co-managers, and reviews the activities endorsed in 1995 by the SC and undertaken by PG&E, the CEC, and SMUD to transition PVUSA over to the new team. The status of the transition and future plans are also addressed. The target transition date was December 29, 1995.

Identifying New Management

To better prepare for a more competitive electric utility environment, PG&E management decided in 1994 to decrease research and development of renewable energy technologies, and at the end of 1995 to relinquish management of the PVUSA project. In consideration of the Project's future, PVUSA hired a consulting firm, UNISUN, to conduct a survey of all parties who were currently or potentially interested in PVUSA. The survey's goal was to solicit ideas and options on how the project might evolve to maximize its value to the nation's electric utilities and the PV industry, and to identify potential agencies for management.

From UNISUN's comprehensive effort came the overwhelming message that the Davis test site plays a key role in fielding new technologies and is contributing to one of the best long-term databases available. UNISUN also evaluated several management options. At the end of 1994, the SC requested CEC and SMUD, based on their expressed interest, to communicate about potentially co-managing the program. This looked to be a favorable combination, with each bringing its complementary strengths.

The Steering Committee met in March, and recommended that a plan proposed by SMUD and CEC to co-manage the project be pursued and further developed. The plan called for linkages to other programs and users, continuation of training and education, and general program direction in line with the UNISUN findings. The first priority and indication of commitment would be for SMUD and CEC to develop a proposal to DOE for 1996 funding. The Steering Committee set a criterion—that SMUD submit a proposal to DOE before the next meeting in June. Progress on identifying and resolving issues would also be reviewed at the June meeting. The National Renewable Energy Laboratory was also interested in seeing the project

continue and offered to consider management should the CEC/SMUD plan, for whatever reason, not work out.

SMUD, CEC, and PG&E collaborated on preparing the DOE proposal in April, and it was reviewed in May. The Steering Committee reviewed the essence of the proposal at their June meeting. The proposal calls for SMUD to operate and maintain the site, and manage the day-to-day activities. They projected a need for seven full-time equivalent people, and an annual budget of approximately \$1.3 million to maintain and operate the site, collect and evaluate data, and manage the program. DOE anticipated review to be complete and to issue a letter of intent in early October. The Steering Committee approved CEC and SMUD as project managers beginning January 1, 1996. The SMUD proposal was submitted to DOE on June 16. An information bulletin was jointly issued in early August announcing the planned transition.

Transition Activities

Once new management was identified, a comprehensive transition schedule was laid out to identify all the activities that needed to occur and guide the parties to the targeted year-end date. The transition was kicked off in July with logistics planning and various preparatory activities. Transition activities identified, in semi-chronological order, include:

- Perform site due diligence evaluation (CEC).
- Verify ability to assign remaining warranties.
- Conduct site inventory.
- Perform environmental assessment.
- Estimate site decommissioning and restoration costs.
- Estimate liquidation value.
- Prepare and submit budget request for 1996 (CEC).
- Negotiate and assign site lease.
- Craft transition agreement between PG&E and CEC.
- Discuss future relationship with EPRI.
- Conduct site familiarization and training.
- Obtain PG&E management approval.
- Obtain Energy Commission approval.
- Implement power purchase and operating agreements.

- Consolidate project documents at the Davis site.
- Post for and obtain staff.
- Implement new support subcontracts.

Along with the Steering Committee, PG&E is interested in the research results and supportive of seeing the project successfully continue and flourish. Both CEC and PG&E have extended considerable effort in the evaluation, planning, and transition efforts. Many of the activities are those typical in any property transaction. Most of these efforts were completed or well under way by the time the Steering Committee reconvened in October. At that time, CEC presented a timeline for various tasks if PVUSA were to be brought before the Commission at their December 13, 1995 business meeting, the last one of the year. All parties agreed to work toward this goal. In mid-November, DOE issued a letter of intent to SMUD, allowing accrual and reimbursement of expenses provided a contract is eventually executed.

Under the transfer agreement PG&E will donate all the property improvements, photovoltaic systems, and personal property to the CEC for the continuation of the research. Included in the personal property are all engineering, research, and correspondence documents as well as existing data collected from the systems. In return, PG&E will continue as a member in good standing with full benefits accorded thereto, and contribute an annual fee based on the value of net power generated from the site.

Status and Plans

Unfortunately, two of the many contracts that the CEC must approve were not worked out sufficiently to present to the Commission for approval in December. Consequently, at a late hour, consideration of PVUSA was taken off CEC's December 13, 1995 agenda and placed on the January 17, 1996 agenda. Despite several briefings to the Policy Committee and Commissioners, as the date drew near, several questions began emerging. Significant discussion ensued at the meeting, resulting in a recommendation to postpone consideration until February 14, 1996 to allow additional fact finding. Subsequently, unanimous approval was granted on February 14. PG&E management approval was obtained in December.

An early transition date of May 1, 1996 is now planned, which allows time for contracts to be executed and staff to be put in place after the CEC meeting. The actual transition date may also depend on approval from the California Public Utilities Commission.

In the interim PG&E has offered to continue managing the project and keep the Davis site operating at a minimum maintenance level (support PV systems operation and data collection only). Although details of agreements and transitions

often require more time and attention than planned, the transition should occur this spring.

The Department of Energy remains supportive of PVUSA, provided substantial exchange (support/feedback) continues between PVUSA and utilities/end users, and the program closely integrates its functions with the Department program. As reported in the 1994 *PVUSA Progress Report*, the Steering Committee has endorsed some general new directions for PVUSA. These directions are based on the reconnaissance work performed by UNISUN. The PVUSA program will continue to educate utilities and other users on PV technology to allow planning, purchasing, and operating systems with a greater level of confidence and success. The areas of focus endorsed by the Steering Committee include

1. Continue as a user-driven, rather than supplier-driven, program.
2. Use the Davis site, as a well-equipped testing facility, for continued long-term performance evaluation of modules and systems, and for testing—and possibly qualifying—components, either cooperatively or on a fee-for-service basis with manufacturers.
3. Emphasize nearer-term interests, including smaller system configurations and short-term component testing.
4. Continue technology transfer through reports, assistance, and workshops, and increase linkages to other regional and national programs in order to provide synergy and avoid possible duplication of efforts.

These general directions will be revisited and formalized, and specific strategies for implementation developed once the CEC and SMUD officially assume management.

10

TECHNOLOGY TRANSFER ACTIVITIES

This section describes 1995 activities in the area of technology transfer. The following activities are covered: workshops, topical reports and publications, conferences and papers, presentations, meetings, and site tours. A comprehensive list of PVUSA publications is provided in Appendix F. Technology transfer activities for prior years are documented in the 1989-1994 *PVUSA Progress Reports*.

Workshops

The PVUSA project team conducted two workshops (Figure 10-1):

- The PVUSA Balance-of-System and Procurement Workshop was held at the Davis site on January 23-24. In addition to PVUSA team members, Brian Champion (West Texas Utilities), Dave Collier (SMUD), Mark O'Neill (ENTECH), Mike Stern (UPG), and Raju Yenamandra (SSI) gave presentations on balance-of-system designs and lessons learned associated with PVUSA Davis and host utility systems.
- Nineteen participants attended a PVUSA workshop at the Davis site on PV Power Conversion, Data Collection, and System Rating on June 14-15.

Topical Reports, Specifications, and Publications

In 1995, the PVUSA project team issued six topical reports, one model technical specification, and authored one article.

The six topical reports issued are:

- *Emerging Photovoltaic Module Technologies at PVUSA—A Five-Year Assessment*
- *The Value of PV in the Distribution System—The Kerman Grid-Support Project*
- *Photovoltaic Balance-of-System Designs and Costs at PVUSA*
- *PVUSA Instrumentation and Data Analysis Techniques for Photovoltaic Systems*
- *PVUSA Experience with Power Conversion for Grid-Connected Photovoltaic Systems*
- *PVUSA Procurement, Acceptance, and Rating Practices for Photovoltaic Power Plants*

BOS and Procurement Workshop

PV Power Conversion, Data Collection, and System Rating Workshop

Figure 10-1
PVUSA Workshop Participants

A model technical specification for a turnkey PV power system was issued in November.

Brian Farmer authored an article "Moving Photovoltaics from the Lab to Utility Application" which was published in *The Electricity Journal*, Volume 8, Number 2, March 1995.

Conferences and Papers

The PVUSA project team attended two workshops and three conferences, and presented a number of papers.

- In January, Tom Hoff presented a paper titled "Reducing Distribution System Losses" at the IEEE PES Winter Power Meeting in New York.
- In April, Brian Farmer presented a paper titled "Performance and Value Analysis of the Kerman 500 kW Photovoltaic Power Plant" at the American Power Conference in Chicago.
- In May, Walt Stolte presented a paper titled "Inverter Performance Comparison at PVUSA" at the 13th NREL PV Program Review Meeting in Lakewood, Colorado.
- In July, Tony Reyes presented "PVUSA Experience with Power Conditioning Units" and Chuck Whitaker presented "Acceptance Testing and Rating Grid-Connected PV Systems: Experience at PVUSA," at the ASES Solar '95 Conference in Minneapolis.

Presentations and Meetings

The PVUSA project team made several presentations and participated in a number of meetings, as follows:

- Project personnel attended Soltech '95 and the UPVG Annual Meeting, held concurrently in San Antonio, Texas on April 11-13. Brian Farmer gave a presentation at Soltech on the recent results and future directions of PVUSA. PVUSA sponsored a booth at the exhibit hall to support its new member campaign.
- Brian Farmer gave a presentation in July on PVUSA and U.S. experience with interconnection requirements at the Grid Connection of PV Systems Workshop, sponsored by the Centre for PV Devices and Systems at the University of New South Wales in Australia.
- Christina Jennings gave a presentation on PVUSA Utility-Scale System Preventive and Failure-Related Maintenance at the NREL PV Performance and Reliability Workshop in September.

- A video conference with PVUSA stakeholders was held on February 15 to discuss development of a joint SMUD/CEC project management plan. As presented, SMUD would be responsible for all day-to-day management and operations including all contracting with DOE, utilities, and subcontractors. The CEC would hold title to property and provide guidance in long range planning. Approval by SMUD managers to "enter into negotiations" was received.
- PG&E Project Management met with CEC and SMUD representatives in Sacramento on March 22. Project management transition specifics were discussed.
- Chuck Whitaker attended the SCC 21 Standards Meeting in June at NREL in Golden, CO.
- Chuck Whitaker attended the UPVG Engineering and Specifications Work Group Meeting on September 5-6 in Golden, CO.
- Brian Farmer and Chuck Whitaker attended an IEEE SCC 21 Standards Meeting on November 6-7 in Las Cruces, NM.
- Chuck Whitaker attended the IECTC 82 Working Group 3 Standards Meeting in October at the 13th European Solar Energy Conference in Nice, France.
- The TRC and SC met three times in 1995.

PVUSA Davis Site Tours

In 1995, PVUSA hosted 82 tours of the Davis site, for a total of 392 visitors. Tour highlights included visits by an Australian group led by the Honorable Colin Barnett, Leader of the House in the Australian Legislative Assembly, and a visit by a Chinese delegation sponsored by the DOE.

Tours of the PVUSA Davis facility are conducted by appointment, Monday through Thursday, 12:30-3:30 p.m. Arrangements may be made by contacting the site by phone (916) 753-0725 or fax (916) 753-8469. Tours range in duration from 30 to 60 minutes, and large groups (20 or more) can be accommodated with adequate notice.

KEY FINDINGS AND CONCLUSIONS

This section summarizes the key findings and conclusions from PVUSA work in 1995. Areas covered include engineering, procurement, and construction; system performance; maintenance; Kerman grid-support performance; data acquisition and analysis; special tests; safety; and project transition.

Engineering, Procurement, and Construction

EMT Arrays

The 20-kW (nominal) rating of EMT arrays at PVUSA Davis appears to furnish arrays that are large enough to provide a meaningful test of emerging PV technologies. The 1995 findings are:

- *ENTECH EMT-1*: The dc tracking system appears to perform better than the ac tracking system it replaced.
- *AstroPower EMT-2*: The original (1989) AstroPower AP-M38 (104-cm² cells) modules became obsolete and AstroPower, by agreement, substituted AP-M7225 (225-cm² cells) modules late in 1993. The array was installed and became operational on November 18, 1994.

The original AstroPower system was scheduled to be turned over to PVUSA on April 30, 1990, so that delivery was 53 months late from the date proposed in the 1989 contract. PVUSA worked closely with AstroPower in quality assurance and quality control areas and monitored module quality continuously, at the factory, during the fabrication process. The quality of the Davis AP-M7225 modules is much better than the AP-M38 modules delivered to VEPCO in 1993.

The PVUSA AstroPower array appears to be a good product, although the modules are still below the efficiency levels proposed in 1989.

- *Golden Photon EMT-2*: In December 1994, PVUSA reopened an invitation to GP for an array. GP did not have a product ready. The TRC asked PVUSA to sponsor module qualification testing. The offer was extended, but by August, GP could not support it. This effort to develop a thin-film CdTe module and production facility spanned eight years but produced neither qualified modules nor an array for PVUSA. This example highlights the difficulty of getting a product out of the research and development stage to a commercial reality.

- *Amonix EMT-3*: The original 1992 contract for a 20-kW_{dc} (PTC) 260x point focus concentrator was canceled by PVUSA in May 1993 due to lack of funds. However, in June 1993, Amonix certified both its module qualification and a 1-kW demonstration. PVUSA placed a new contract in March 1995 with Amonix for a 19-kW_{dc} (PTC) 260x concentrator, which was installed in October 1995. This effort to develop a 260x concentrator for PVUSA spanned 35 months and resulted in a completed array. Due to some unexpected performance issues, the array has not yet been rated.
- *Solar Cells EMT-3*: PVUSA ended the original contract (for a 19.7-kW_{dc} CdTe array) in July 1993 when SCI advised an installation schedule slip of five months from May to September 1994. The module qualification portion of the contract (but not the 1-kW demonstration) was completed in May 1993. Following negotiations in 1995, PVUSA purchased components for a 10.8-kW_{dc} array, which was installed by PVUSA and became operational on October 3, 1995. The installation of the SCI components was quick (less than two days), efficient, and simple. In December 1995, the array was rated at 12.0 kW_{dc} at PTC. In summary, the two contracts spanned a period of 43 months from March 1992 to September 1995.

PVUSA experience with its 11 EMT procurements (5 EMT-1, 3 EMT-2, and 3 EMT-3) is that buyers of emerging module technologies will find it prudent to require a degree of field demonstration of module durability before placing an order. This demonstration should:

- Take place after module qualification is complete.
- Be of a minimum rating of 1 kW; larger if possible.
- Include the tracking system if one is to be furnished.

Buyers of emerging PV system technologies may need both patience and the ability to absorb lengthy schedule slips. PVUSA experienced the schedule delays shown in Table 11-1.

US Systems

The IPC system was retrofitted with a KWI PCU. As with any retrofit, field tie-ins and reconfiguration had to be identified and effected. The dc input rating of the PCU required that the source circuit be mono-polar. Minimum field work was targeted, and resulted in using the existing wires from the array dc switches to the dc collection box.

One minor oversight was that the blocking diodes were not interchangeable. Field wiring of the dc collection box deviated from the design to accommodate this oversight.

Delivered on schedule, the PCU had a smooth start-up and reliable operation, but harmonics may be a concern and efficiency appears significantly less than proposed.

Table 11-1
PVUSA Schedule Delays for EMT Arrays

System	Number of Months Delayed Based on Proposed Installation Date
EMT-1	
ARCO/SSI	1
UPG	1
ECD/Sovonics	5
Solarex	22
ENTECH	12
EMT-2	
ARCO/SSI	Withdrew
AstroPower	53
Photon Energy/GP	Funds withdrawn
EMT-3	
SCI	18 ^a
Sun Power	Withdrew
Amonix	16 ^a

^a Includes appropriate delay time from first contract, cancelled in May and July 1993.

System Performance

Combined, PVUSA's PV systems generated 2.27 million kWh in 1995, and have generated a cumulative total of 7.1 million kWh since 1989.

With 109 kW of new capacity from three systems added in 1995, PVUSA is now affiliated with 19 systems at eight sites across the U.S. with a combined capacity of over 1,800 kW. Two more systems totaling nearly 400 kW are scheduled to be installed in 1996.

At the Davis site, fixed-tilt systems generated about 5 kWh per kW of rated capacity per day, for systems in good operating condition. This figure may increase by about 0.75 kWh/kW/day at the best U.S. locations in the desert Southwest, and by about 1 kWh/kW/day for tracking systems.

Several systems were rated in 1995. Two new systems were rated as shown in Table 11-2.

Table 11-2
Ratings for New Systems

Supplier	Location	Rating (PTC)
ENTECH	CSW, Fort Davis, TX	83 kW _{ac}
SCI	PG&E, Davis, CA	12.0 kW _{dc} (11.2 kW _{ac})

Final ratings were also calculated for the previously installed systems shown in Table 11-3.

Table 11-3
Ratings for Previously Installed Systems

Supplier	Location	Rating (PTC)
AstroPower	PG&E, Davis, CA	17.1 kW _{dc} (16.1 kW _{ac})
IPC	Maspeth, NY	12.9 kW _{ac}
UPG	SMUD, Sacramento, CA	207 kW _{ac}
UPG	CSW, Fort Davis, TX	98 kW _{ac}

System efficiencies ranged from about 3 percent for systems consisting of amorphous silicon type modules to 6-8 percent for polycrystalline silicon and CdTe/CdS types, and 7-10 percent for single-crystal silicon types. Unlike nearly all silicon-based PV modules, the efficiency of the new CdTe/CdS array is not sensitive to temperature. The UPG amorphous silicon array at Davis has also shown a negligibly small sensitivity to temperature.

Annual capacity factors ranged from 7 to 21 percent, although monthly capacity factors for several systems exceeded 30 percent during the summer. Demonstrating the good match between solar energy availability and electricity demand, the peak period capacity factors for several of the systems in PG&E's service territory were in the 50-66 percent range.

The performance index (PI), defined as the ratio of actual to expected generation, averaged 74 percent for 16 of PVUSA's 19 systems that were in operation as of the beginning of 1995. Insufficient data were available to calculate PIs for CSW ENTECH, NYSERDA IPC, and Davis Amonix. Five systems operated at better than 90 percent, which PVUSA considers a minimum benchmark for reliable systems. As they allow for normal losses due to poor weather, inherent BOS limitations, and long-term degradation, the PI results are a good quantitative indicator of system reliability.

This year's results suggest there is considerable room for improvement for many of the PV systems, particularly the larger utility-scale systems such as Kerman.

BOS

Lessons learned from the performance of BOS components are as follows:

- Generally, modules that are panelized and prewired at the factory reduce field labor. However, assembly of panels in the field, especially large-area or heavy modules should not be ruled out. It may be less costly for large and heavy modules to be panelized on-site or at a nearby assembly shop.
- Panel-to-panel wire connections are easily accomplished in the field with plug-in connectors. Using plug-in connectors decreases field labor, but connectors can be expensive and must be rated or tested for outdoor use. Plug-in connectors are easy to install and facilitate maintenance work, especially in diagnosing array problems.
- Savings can be realized if module or panel supports are integrated into the array structure. Further savings can be realized by using commercially available structural elements.
- Lightning and/or surge suppressors such as MOVs should be carefully selected for proper rating. Several events at PVUSA support shielding or segregating MOVs such that a failure, usually causing a fire, is contained or does not propagate to other wiring or components.

Maintenance

PVUSA continues to track maintenance for Davis, Kerman, and host sites. Owing to its attended operation and research nature, the Davis database is the most complete. Kerman and other host sites are reported with less attention to detail by O&M personnel.

Kerman, which has unattended operation and a 500-kW nominal size, provides the most credible data on mature system maintenance cost. The total annual maintenance cost for 1995 was 3.2¢ per kWh (1.0¢ per kWh preventive, 2.2¢ per kWh failure-related). Higher than expected maintenance at Kerman resulted from PCU problems primarily located in the control system or instruments and their signal conditioning. However, the cumulative failure-related maintenance cost after 30 months of operation is 1.1¢ per kWh (up from 0.67¢ per kWh a year ago). One failure of a tracker actuator occurred, which is less than the 6 percent annual failure rate predicted by SSI. Failure-related 1995 costs averaged 2.7¢ per kWh for IPC and APS and were 3.6¢ per kWh for SSI US-1. Major problems associated with keeping the systems running (for APS and IPC) and poor SSI US-1 performance have driven the

maintenance costs up from the traditionally estimated value of less than 1¢ per kWh.

Module failures are less frequent than previous years, averaging 8 per 10,000 modules. At SSI US-1 and Kerman, module failures resulted from bypass diode and module connection failures. BOS failures continue to be the most frequent problem, primarily caused by the PCU.

The EMT PCUs continued to be reliable, but required manual resets on the occasional synchronization errors or start-up problems. The SSI Bluepoint PCU continues to work reliably except for wake-up problems. APS is prone to problems associated with line disturbances, resulting in five occurrences of cleared fuses and failed protection electronics. The IPC Omnion PCU required frequent attention, logging 48 resets and several board repairs. Installation of the KWI PCU appears to have solved some of the IPC PCU issues. Kerman PCUs were plagued with shutdowns, with 36 remote resets, 41 manual resets, and several occurrences of control board failures or communications problems. An extensive treatise of the PCUs in use by PVUSA is documented in the topical report on PCUs.¹

Kerman Grid-Support Performance

The poor plant performance experienced during peak load summer months underscores the need for high system reliability and timely repairs. Plant downtime during the critical top 100 hours of the load duration curve has a detrimental effect on the plant's calculated value related to transmission system, substation, system capacity, and other value components. Fortunately, the available irradiance indicates that the value of a properly operating plant would have been similar to previous years. Once the problems hampering the plant in 1995 are addressed, future years will show once again the high value of distributed PV generation at Kerman.

Data Acquisition and Analysis

PVUSA implemented three significant changes to its Davis DAS in 1995. First, a new database processing computer with a faster processor, more main memory, and more disk space was installed to support analysis of data over longer periods. Second, a new implementation of the master performance database was installed for better processing speed, reliability, and maintainability. This database replaces the one that was installed in 1994, which suffered from poor vendor support and unanticipated limitations in maintainability and efficiency. Finally, the firmware in all data loggers at the Davis site was upgraded to improve performance and maintainability, and eliminate a minor timekeeping problem.

¹W.J. Stolte, *PVUSA Experience with Power Conversion for Grid-Connected Photovoltaic Systems*, DOE/AL/82993-26, November 1995.

Special Tests

PVUSA measures I-V curves at initial array installation and periodically thereafter to track degradation and system failures. Measurements made of the Amonix and SCI arrays produced rating figures similar to values determined by the regression of performance data. I-V curves of ENTECH and Solarex arrays were measured to support troubleshooting low power output. The value of I-V curves for troubleshooting appears to justify the specialized equipment and trained personnel.

Acceptance testing of the KWI PCU requires a measurement of THD for voltage and current at or near full power. PQ testing with a BMI 8100 PQNode showed excessive harmonic distortion near half load. Investigation of the excessive harmonics resulted in a field repair to the KWI PCU. Measurements subsequent to field repairs are 1 and 3 percent for voltage and current, respectively.

Ground resistance tests taken at the Davis site continue to show readings between 0.05 and 3.0 ohms, much less than the NEC standard of 25 ohms and within PG&E's 5 ohm standard practice. Measurements of ground resistance are made with a Biddle ground resistance micro-ohmmeter using the IEEE 80-1986 "Fall of Potential" method.

Steel, such as rebar or pipe, in the array foundation has proved to be an adequate grounding electrode at the Davis site. The structural steel, if supplied with proper hardware, can be used as the grounding conductor. Connection of dissimilar metals should be avoided. Such connections do not provide a good grounding path, and can lead to corrosion.

During construction, 15 percent of the APS soil anchors were found to have less than the 15 mils of epoxy coating specified. The soil anchor corrosion rates are estimated by periodically monitoring the cathodic currents flowing between selected soil anchors and test anodes. Readings of current in amperes are proportional to a corrosion rate in mils per year. The APS screw anchors have shown minimal anodic current, suggesting that the anchors will deliver the expected 20-year life.

Soiling of arrays reduces system output significantly during the most productive times of the year. Providing realistic values to designers and engineers is necessary for realistic simulation and designs. Nominal values of soiling are given as 5 percent annually. The SSI EMT-1 array was washed twice during the summer to determine the amount of soiling. If PTC ratings of the system output are taken before and after washing, the soiling is calculated as 6 percent for a visibly soiled array. Calculation of the system rating also shows the PTC rating has consistently degraded 2 percent annually for reasons other than soiling.

Safety

PVUSA continued to emphasize safety training and documentation. There were no CalOSHA-reportable incidents, and no lost time accidents or first aid cases at Davis or Kerman in 1995. A safety inspection of the Davis site was conducted, and numerous safety meetings and training sessions were attended by PVUSA personnel.

Project Transition

Due primarily to delays in various contract negotiations, a new target date of April 1, 1996 was established to transfer project management from PG&E to the CEC-SMUD team. In the interim PG&E has offered to continue managing the project and keep the Davis site operating at a minimum level.

Appendix A

WEATHER DATA

Table A-1 compares totals for several weather characteristics at the Davis site from 1989 through 1995. Table A-2 compares totals for the Maui site from 1990 through 1995. Table A-3 lists totals for the Austin site through 1995. Table A-4 lists totals for the Kerman site beginning in July 1993. Table A-5 lists totals for the Farmingdale site in 1994 and 1995. Table A-6 lists totals for the Maspeth site in 1994 and 1995. Table A-7 lists totals for the Sacramento site dating from mid-September 1994. Table A-8 lists 1995 data for the Fort Davis site. Detailed 1995 monthly weather and performance summaries for all eight sites are included in Appendix B. Certain quantities are measured only at some sites; for example, precipitation is measured only at the PVUSA Davis and Fort Davis sites. Also, because of the wide variety of fixed and tracking PV systems installed at Davis, a greater number of insolation orientations are measured there. All instruments at Davis are cleaned regularly. Radiation instruments are calibrated annually to NREL reference; other weather instruments are calibrated semiannually by PG&E's meteorological group.

Table A-1
PVUSA Davis Weather Summary

	1989	1990	1991	1992	1993	1994	1995
Insolation, kWh/m ²							
Global horizontal (long-term = 1,838)	1,812	1,890	1,877	1,827	1,801	1,872	1,773
Global 30° tilt	2,104	2,213	2,123	2,038	2,036	2,122	1,989
Single-axis tracking (horiz. N-S axis)	N/A	N/A	2,707	2,498	2,593	2,748	2,603
Global normal	2,982	3,185	3,044	2,819	2,900	3,052	2,823
Direct normal	2,189	2,509	2,260	1,839	2,064	2,289	2,123
Average T _{ambient} , °C (long-term = 15°C)	14.9	15.7	15.6	16.3	15.7	15.1	16.3
Minimum T _{ambient} , °C	-6.4	-9.7	-6.0	-2.9	-4.8	-2.5	-1.3
Maximum T _{ambient} , °C	43.7	42.7	43.8	41.7	42.4	40.5	41.8
Average wind speed, m/s	2.9	3.2	3.2	3.0	2.9	2.9	3.1
Maximum wind speed, m/s	17.5	13.7	14.1	15.1	13.6	14.2	17.8
Rainfall, in. (long-term = 18 in.)	11	15	11	20	24	23	24

Table A-2
PVUSA Maui Weather Summary

	1990	1991	1992	1993	1994	1995
Insolation, kWh/m ²						
Global horizontal (long-term average = 2,009 kWh/m ²)	2,122	2,075	2,070	2,098	2,065	2,057
POA (global 22° tilt)	2,078	2,158	2,148	2,180	2,146	2,139
Average T _{ambient} , °C ^a	28	28	28	27 ^b	27	28
Minimum T _{ambient} , °C ^a	16	17	16	15 ^b	13	15
Maximum T _{ambient} , °C ^a	44	42	43	40 ^b	43	42
Average wind speed, m/s	3.0	3.5	3.7	3.7	3.2	3.6
Maximum wind speed, m/s	14.7	14.0	13.3	13.1	14.4	12.4

^a Maui data logger temperature measurements have tended to read 5 degrees C higher than expected.

^b June-July 1993 data not available.

Table A-3
PVUSA Austin Weather Summary

	1993	1994	1995
Insolation, kWh/m ²			
Global horizontal (long-term average = 1,700 kWh/m ²)	1,615	1,525	1,599
POA (single-axis tracking (horiz. N-S axis))	1,955	1,847	1,855
Average T _{ambient} , °C (long-term = 20°C)	23	21	23
Minimum T _{ambient} , °C	-1	-2	-8
Maximum T _{ambient} , °C	42	43	45
Average wind speed, m/s	1.8	1.8	1.7
Maximum wind speed, m/s	7.7	9.2	10.6

Table A-4
PVUSA Kerman Weather Summary

	1993 July-December	1994	1995 ^a
Insolation, kWh/m ²			
Global horizontal (Fresno long-term average = 1,899 kWh/m ²)	895	1,835	1,781
Single-axis tracking (horiz. N-S axis)	1,317	2,534	2,513
Average T _{ambient} , °C (Fresno long-term average = 17°C)	20	8	19
Minimum T _{ambient} , °C	-3	-2	2
Maximum T _{ambient} , °C	42	42	43
Average wind speed, m/s	2.4	2.6	2.6
Maximum wind speed, m/s	10.6	11.4	12.7

^a Data availability was 95 percent in 1995.

Table A-5
PVUSA Farmingdale Weather Summary

	1994	1995 ^a
Insolation, kWh/m ²		
Global horizontal (long-term average = 1,460 kWh/m ²)	1,366	1,340 (estimated)
Single-axis tracking (horiz. N-S axis)	1,504	1,723 (estimated)
Average T _{ambient} , °C (long-term = 13°C)	N/A	N/A
Minimum T _{ambient} , °C	N/A	N/A
Maximum T _{ambient} , °C	N/A	N/A
Average wind speed, m/s	1.6	1.7 (incomplete)
Maximum wind speed, m/s	12.4	10.4 (incomplete)

^a Data availability was 64 percent in 1995. Insolation totals are patched with data from the nearby Maspeth site.

Table A-6
PVUSA Maspeth Weather Summary

	1994	1995
Insolation, kWh/m ²		
Global horizontal (long-term average = 1,460 kWh/m ²)	1,298	1,223
POA	1,448	1,391
Average T _{ambient} , °C (long-term = 13°C)	14	15
Minimum T _{ambient} , °C	-17	-10
Maximum T _{ambient} , °C	39	44
Average wind speed, m/s	3.2	3.2
Maximum wind speed, m/s	10.9	20.3

Table A-7
PVUSA Sacramento Weather Summary

	1994 (8/16 – 12/31)	1995
Insolation, kWh/m ²		
Global horizontal (long-term average = 1,788 kWh/m ²)	513	1,668
Single-axis tracking (horiz. N-S axis)	657	2,501
Average T _{ambient} , °C (long-term = 16°C)	16	18
Minimum T _{ambient} , °C	-1	1
Maximum T _{ambient} , °C	41	44
Average wind speed, m/s	2.0	2.6
Maximum wind speed, m/s	12.7	19.0

Table A-8
PVUSA Fort Davis Weather Summary

	1995
Insolation, kWh/m ²	
Global horizontal (El Paso long-term average = 2,082 kWh/m ²)	1,968
Single-axis tracking (horiz. N-S axis)	2,762 (estimated)
POA tracking (horiz. N-S axis)	2,272 (incomplete)
Average T _{ambient} , °C (El Paso long-term average = 17°C)	16
Minimum T _{ambient} , °C	-8
Maximum T _{ambient} , °C	37
Average wind speed, m/s	3.1
Maximum wind speed, m/s	18.0

Figure A-1 shows the monthly insolation during 1995 at the Davis site for five orientations: global horizontal, global 30-degree tilt, global normal, direct normal, and global north-south single-axis.

As expected, global normal was the orientation with the highest annual quantity of insolation. The next best orientation was the global single-axis, which received 92 percent of the global normal insolation. Direct normal insolation was 75 percent of the global normal, global 30-degree tilt insolation was 71 percent, and global horizontal was 63 percent.

Figure A-1 also shows that the largest differences between the various orientations occur in the summer months. During the summer, tracking surfaces are able to capture insolation by following the sun's wide arc. For fixed-tilt surfaces, the summer sun is positioned "behind" the POA for more than 2 hours a day, and the incidence angles are relatively large during all but the noon hours.

During the winter, the "view" or incidence angle differences between the various orientations become less important because of generally cloudy weather. Much of Davis' rainfall occurs then, and there are often prolonged periods of heavy fog. The amount of insolation for every orientation, especially direct normal, is reduced greatly during overcast periods.

The global 30-degree tilt insolation showed the least seasonal variation, with a peak monthly insolation about three times greater than the lowest monthly insolation. The single-axis insolation exhibited the widest seasonal swing, with a peak monthly insolation about five times greater than the lowest monthly insolation. During the summer, the single-axis orientation received nearly as much insolation as the best orientation (global normal), but in the winter it approached the worst orientation (global horizontal).

Figure A-1
1995 PVUSA Davis Insolation

Although the horizontal orientation generally received less insolation than the other orientations, during the summer months it actually received slightly more than the fixed 30-degree tilt orientation. During the summer, the solar incidence angles are smaller on the horizontal surface than on the fixed 30-degree tilt surface. During the winter, incidence angles are always large on the horizontal surface (at least 60 degrees). Because of these large incidence angles and because of short (9.3 hours during winter compared with 14.6 hours in summer) and often cloudy days, the horizontal surface receives considerably less insolation in winter than at other times of the year.

Figures similar to Figure A-1 are not shown for PVUSA's other sites because fewer irradiance measurements are made at these sites. However, figures showing trends in 1995 monthly POA insolation for these sites are included in Section 3 as overlays with the monthly generation trends.

Figure A-2 shows the 1995 daily average insolation for several orientations and sites. Both 1995 and long-term data are shown for the global horizontal orientation at each site, and a mixture of fixed-tilt, single-axis tracking and direct normal data are shown, depending on the measurements made at a given site.

Figure A-2
1995 PVUSA Site Insolation Comparisons

The 1995 global horizontal insolation was less than the long-term average at each site. In some cases, such as Maui, the shortfall was insignificant (1 percent), but at two other sites, the insolation was considerably below normal—the Austin site received 11 percent less than normal, and the Maspeth site was 17 percent less than normal. At Farmingdale, the estimated shortfall was 8 percent, a figure based partly on data patched from the nearby Maspeth site (over one-third of the Farmingdale data set was missing due to DAS problems).

The other sites' global horizontal insolation ranged between 3 percent less than normal at Davis and 7 percent less than normal at Sacramento. Part of the shortfall at each site except for Davis is probably attributable to PSP maintenance. At the Davis site's rooftop monitoring station, the PSPs are cleaned at least three times per week and recalibrated annually. The uncertainty associated with the Davis results is on the order of ± 4 percent. At the other sites, PSP cleaning is sporadic, and some of the PSPs have not been calibrated for 3 years.

The benefit of tracking varied at the different sites. At the Davis site, the potential gain in insolation for single-axis trackers over the horizontal orientation was 47 percent. The actual gain was zero at IPC's single-axis tracking system as a result of

tracker downtime, and the actual gain at SSI's single-axis tracking system was only 15 percent. The shortfall may be attributed in part to field of view differences, mechanical tracking limits, and PSP soiling, but is mostly due to aiming error.

At Kerman, the potential benefit of single-axis tracking over horizontal was calculated to be 41 percent (based on data from NREL), but the actual plane of array insolation showed a gain of only 27 percent. A closer inspection of the Kerman data set showed an excellent correspondence between the POA, fixed horizontal, and optimally-tracked reference instruments over the noontime period. This suggests the shortfall probably was not a result of measurement error. Note that the Kerman system's passive tracker still outperformed its predecessor (SSI US-1) at the Davis site.

At Sacramento, the potential gain as shown on Figure A-2 was estimated to be 49 percent, similar to the nearby Davis site. The actual gain was 31 percent. At Austin, Figure A-2 indicates a potential gain of 27 percent and an actual gain of 16 percent. For Farmingdale, a 28 percent tracking gain was expected, but not enough actual data were available to make a meaningful comparison. At Fort Davis, the potential gain for single-axis tracking was calculated to be 40 percent, with an adjusted actual gain of 36 percent. (The actual figure includes a 15 percent adjustment to allow for missing data. Given the relatively high adjusted figure, it seems likely that a large share of the missing data was overcast or nighttime values.)

Direct normal insolation (DNI) is measured at the Davis, Kerman, and Fort Davis sites. DNI data for Kerman are not included because the tracker was determined to be off-target for too many hours to make a meaningful summary. The Davis site received about 3 percent less DNI than its 7-year average of 6.0 kWh/m²/day, but this result is not unusually low, as the standard deviation of the annual DNI for Davis since 1989 has been ± 7 percent. The Fort Davis site was very clear. At an average daily DNI of 6.9 kWh/m², it received over 18 percent more DNI than the Davis site. This result agrees very well with the average daily DNI for the nearest location with long-term data, El Paso, at 6.7 kWh/m²/day.

After insolation, ambient temperature and wind speed are the most important weather-related influences on system power output. Crystalline silicon-based PV output drops approximately 0.5 percent for each 1 degree C of temperature increase, while output for amorphous silicon-based PV modules drops approximately 0.1 to 0.25 percent for each 1 degree C of temperature increase. SCI's new CdTe/CdS array has not demonstrated any sensitivity to temperature over its first three months of operation. Figure A-3 compares 1995 average and extreme temperatures at the various PVUSA sites. Valid temperature data were not available for the Farmingdale site.

Figure A-3
1995 PVUSA Temperature Comparisons

Figure A-4 compares 1995 average and peak (10-minute average) wind speeds for the various sites. The average wind speed ranged from 1.7 m/s (4 mph) at the Austin and Farmingdale sites, to 3.6 m/s (8 mph) at the Maui site. Record-high winds were recorded at the Davis site this year, with the lifetime peak 10-minute average increasing from 17.5 to 17.8 m/s (40 mph). The Davis peak wind speed was still less than that recorded at three other sites. Ten-minute averages of 18, 19, and 20.3 m/s (40 - 45 mph) were recorded at the Maspeth, Sacramento, and Fort Davis sites, respectively.

Peak wind speeds of shorter duration than 10 minutes can be considerably higher. At the Davis site, a study conducted this year found that peaks of 5-second duration were typically about 50 percent higher than the sustained 10-minute average, consistent with NASA data.¹ This suggests brief wind gusts of approximately 60 mph have occurred at the Davis, Maspeth, Sacramento, and Fort Davis sites.

¹"Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development," NASA Technical Paper 1359, December 1978.

Figure A-4
1995 PVUSA Wind Speed Comparisons

The effects of wind speed on PV system output are more difficult to quantify, primarily because the effects are nonlinear and are influenced somewhat by module construction, array orientation, and wind direction, especially at lower wind speeds. For a typical framed crystal silicon-based PV module, increasing wind speed from 0 to 1 m/s at 1,000 W/m² irradiance can reduce module temperature by 20 degrees C (increasing power by 8 to 10 percent), while increasing wind speed from 4 to 5 m/s at the same irradiance may reduce module temperature by only 2 degrees C (increasing power by up to 1 percent).²

² A. Roger and C. Maguin, "Photovoltaic Solar Panels Simulation Including Dynamical Thermal Effects," *Solar Energy*, vol. 29, no. 3, pp. 245-256.

Appendix B

DETAILED MONTHLY WEATHER AND PERFORMANCE SUMMARIES

Tables B-1 through B-3 contain 1995 monthly data on solar resource, site weather, and system performance for the Davis site.

Similar data are listed in Tables B-4 through B-6 for the Maui site, B-7 through B-9 for the Austin site, B-10 through B-12 for the Kerman site, B-13 through B-15 for the Maspeth site, B-16 through B-18 for the Farmingdale site, B-19 through B-21 for the Sacramento site, and B-22 through B-24 for the Fort Davis site. (Fewer quantities are measured at the host utility sites.)

Array and system efficiencies are based on the module area times the number of modules in the system.

Maximum wind speeds are maximum 10-minute averages, not peak gust speeds.

Average module temperature is weighted with respect to system power per the following equation:

$$\bar{T}_{\text{mod}} = \frac{\sum (\text{Power} \times T_{\text{mod}})}{\text{Energy}}$$

Table B-1
1995 PVUSA Davis Solar Resource Data

	Global Normal		Global 30° Tilt		Global Horizontal		Direct Normal		Global One-Axis Tracking	
Month	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	1,155	60	1,045	55	663	41	901	26	712	48
February	1,122	99	1,010	84	689	64	961	67	849	90
March	1,156	162	1,185	132	1,079	116	993	115	1,068	166
April	1,187	240	1,154	180	1,039	171	1,007	172	1,149	245
May	1,230	294	1,200	205	1,124	210	958	199	1,158	285
June	1,232	350	1,209	222	1,186	239	993	279	1,186	340
July	1,229	377	1,157	235	1,144	251	975	302	1,236	369
August	1,154	372	1,136	243	1,006	234	964	310	1,099	358
September	1,156	312	1,112	217	925	181	962	252	1,009	282
October	1,098	271	1,044	194	786	136	930	206	909	219
November	1,098	200	957	145	617	88	908	141	760	139
December	1,267	90	1,047	72	622	46	923	53	696	62

Table B-2
1995 PVUSA Davis Weather Data

Month	Ambient Temperature (°C)			Wind Speed (m/s)		Precipitation
	Min.	Avg.	Max.	Avg.	Max.	Total (in./mo)
January	0	10	18	4.2	13.7	6.7
February	-1	10	23	2.0	8.9	1.7
March	0	11	22	4.2	17.8	7.9
April	2	14	29	4.1	11.8	0.9
May	5	17	35	2.7	9.9	1.1
June	8	21	42	3.6	13.5	0.8
July	11	24	42	2.9	8.7	0
August	9	24	40	2.9	10.8	0
September	10	21	38	2.4	9.2	0
October	2	18	34	3.1	15.9	0.1
November	2	14	27	2.3	12.3	0
December	1	10	22	3.2	15.8	4.8
Annual	-1	16	42	3.1	17.8	24
1989-95						
Extreme	-10		44		17.8	min 11, max 24
Average	-5	16	42	3.0	15.1	18
Std.dev. of avg.	±3	±0.5	±1	±0.1	±1.6	±5

Table B-3
1995 PVUSA Davis Performance Data

Month	System	Mod. Temp. Wt. Avg. ^a (°C)	Effic. ^b (%)	ac Energy (kWh)	Max ac Power (kW)
January	SSI EMT-1	24	(10.8)	740	16.7
	Sovonics	25	(1.7)	351	12.1
	UPG	21	(3.1)	675	12.7
	Solarex	24	(8.6)	605	14.6
	ENTECH	32	(9.8)	104	15.4
	APS	24	3.6	17,276	375.2
	IPC	18	8.7	2,257	132.5
	SSI US-1	18	7.0	2,318	50.6
	AstroPower	22	(5.8)	721	18.3
February	SSI EMT-1	31	(10.8)	1,268	17.9
	Sovonics	30	(2.0)	710	12.7
	UPG	31	(2.9)	1,061	12.8
	Solarex	30	(8.4)	1,058	14.7
	ENTECH	45	(11.1)	1,124	18.7
	APS	31	3.4	28,723	379.2
	IPC	30	8.7	10,338	175.8
	SSI US-1	30	7.8	4,294	54.3
	AstroPower	29	(5.9)	1,268	18.7
March	SSI EMT-1	31	(10.6)	2,099	19.4
	Sovonics	31	(2.2)	1,389	15.3
	UPG	31	(2.8)	1,688	14.3
	Solarex	30	(8.3)	1,778	16.4
	ENTECH	39	(11.1)	1,537	19.0
	APS	32	3.3	47,334	419.4
	IPC	31	8.0	24,476	183.4
	SSI US-1	30	8.3	6,854	73.8
	AstroPower	29	(6.0)	2,001	20.3

Table B-3
1995 PVUSA Davis Performance Data (Cont'd)

Month	System	Mod. Temp. Wt. Avg. ^a (°C)	Effic. ^b (%)	ac Energy (kWh)	Max ac Power (kW)
April	SSI EMT-1	36	(10.4)	2,313	19.2
	Sovonics	35	(2.5)	1,916	15.0
	UPG	36	(2.8)	2,096	14.0
	Solarex	35	(8.1)	2,167	16.4
	ENTECH	44	(11.8)	1,789	19.9
	APS	36	3.3	56,506	420.9
	IPC	35	7.5	28,146	184.2
	SSI US-1	34	7.0	11,075	78.4
	AstroPower	34	(5.8)	2,524	20.3
May	SSI EMT-1	43	(9.9)	2,944	18.8
	Sovonics	42	(2.7)	2,344	15.2
	UPG	43	(2.8)	2,552	14.5
	Solarex	41	(7.9)	2,519	15.8
	ENTECH	53	(11.2)	2,917	18.6
	APS	43	3.2	69,942	419.7
	IPC	36	7.3	2,968	186.2
	SSI US-1	41	6.8	12,426	78.5
	AstroPower	40	(5.8)	3,055	19.1
June	SSI EMT-1	45	(9.7)	2,911	17.6
	Sovonics	43	(2.8)	2,666	15.4
	UPG	41	(2.4)	1,013	13.8
	Solarex	43	(7.6)	2,704	15.2
	ENTECH	52	(10.7)	3,839	18.8
	APS	47	3.1	60,143	422.0
	IPC	51	6.4	20,238	187.8
	SSI US-1	44	6.6	14,721	75.7
	AstroPower	41	(5.6)	3,110	18.4

Table B-3
1995 PVUSA Davis Performance Data (Cont'd)

Month	System	Mod. Temp. Wt. Avg. ^a (°C)	Effic. ^b (%)	ac Energy (kWh)	Max ac Power (kW)
July	SSI EMT-1	51	(9.3)	3,204	17.1
	Sovonics	48	(2.9)	2,894	15.1
	UPG	51	(3.0)	2,563	14.9
	Solarex	49	(7.5)	2,815	14.9
	ENTECH	58	(10.0)	4,007	16.9
	APS	51	2.6	59,714	371.5
	IPC	52	7.4	21,381	188.5
	SSI US-1	49	7.1	10,726	72.0
	AstroPower	46	(5.5)	3,448	19.1
August	SSI EMT-1	51	(9.1)	3,226	15.9
	Sovonics	48	(2.8)	2,889	14.9
	UPG	52	(2.8)	3,045	14.3
	Solarex	49	(7.1)	2,734	13.9
	ENTECH	56	(9.5)	3,568	16.0
	APS	50	2.0	50,330	410.8
	IPC	n/a	0	0	0
	SSI US-1	48	7.0	9,080	64.7
	AstroPower	45	(5.2)	3,402	16.9
September	SSI EMT-1	49	(8.3)	2,668	15.8
	Sovonics	47	(2.4)	2,363	13.8
	UPG	51	(2.8)	2,689	13.7
	Solarex	48	(4.6)	1,771	12.9
	ENTECH	53	(6.8)	2,272	14.8
	APS	47	2.5	47,471	360.7
	IPC	50	7.6	23,043	155.0
	SSI US-1	44	6.5	6,963	55.3
	AstroPower	45	(5.0)	3,007	15.9
	SCI	n/a	n/a	237	12.1
	Amonix	n/a	n/a	374	17.9

Table B-3
1995 PVUSA Davis Performance Data (Cont'd)

Month	System	Mod. Temp. Wt. Avg. ^a (°C)	Effic. ^b (%)	ac Energy (kWh)	Max ac Power (kW)
October	SSI EMT-1	41	(9.4)	2,665	15.9
	Sovonics	40	(2.6)	2,342	13.9
	UPG	45	(2.9)	2,447	13.4
	Solarex	38	(3.2)	785	8.9
	ENTECH	48	(10.4)	2,829	15.8
	APS	41	2.7	40,497	339.4
	IPC	n/a	6.8	29,852	170.8
	SSI US-1	36	5.5	6,265	47.2
	AstroPower	38	(5.4)	2,785	16.7
	SCI	n/a	(6.2)	1,874	11.9
	Amonix	43	n/a	2,581	17.8
November	SSI EMT-1	36	(10.2)	2,131	15.3
	Sovonics	35	(2.4)	1,860	12.7
	UPG	39	(3.0)	1,614	11.9
	Solarex	34	(6.3)	1,321	12.6
	ENTECH	40	(9.1)	844	13.8
	APS	36	3.3	42,926	324.1
	IPC	n/a	7.4	21,097	130.3
	SSI US-1	29	5.1	3,949	32.4
	AstroPower	33	(5.6)	2,348	16.4
	SCI	36	(6.6)	1,644	11.5
	Amonix	43	n/a	1,902	16.4
December	SSI EMT-1	25	(10.6)	949	17.7
	Sovonics	24	(1.7)	777	12.8
	UPG	27	(3.1)	1,013	13.3
	Solarex	24	(7.3)	731	13.2
	ENTECH	36	(10.7)	902	17.7
	APS	27	3.6	14,876	324.4
	IPC	14	6.5	4,555	123.4
	SSI US-1	18	6.3	1,773	41.2
	AstroPower	23	(5.4)	1,107	18.3
	SCI	26	(6.6)	764	12.4
	Amonix	35	n/a	484	17.2

^aAverage module temperature, weighted with respect to system power.

^bFor EMTs, dc efficiencies are shown in parentheses. For US systems, ac efficiencies are shown in italics.

Table B-4
1995 PVUSA Maui Solar Resource Data

Month	Global 22° Tilt		Global Horizontal	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	1,218	162	984	127
February	1,178	167	1,026	141
March	1,197	191	1,121	179
April	1,197	186	1,169	192
May	1,196	184	1,291	206
June	1,105	169	1,206	198
July	1,083	176	1,190	202
August	1,126	182	1,155	196
September	1,146	194	1,139	189
October	1,205	193	1,022	168
November	1,168	158	960	127
December	1,092	179	905	133

Table B-5
1995 PVUSA Maui Weather Data

Month	Ambient Temperature (°C)			Wind Speed (m/s)	
	Min.	Avg.	Max.	Avg.	Max.
January	15	25	36	4.2	10.7
February	16	25	34	4.2	10.9
March	17	26	38	3.7	11.3
April	19	26	40	4.0	11.2
May	17	27	40	3.7	10.9
June	20	29	42	3.1	10.8
July	21	30	42	3.4	10.9
August	20	29	42	3.5	12.4
September	21	29	40	3.5	10.7
October	20	29	42	3.4	10.5
November	19	28	38	3.0	8.8
December	18	27	37	3.5	10.8

Table B-6
1995 PVUSA Maui Sovonics Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	dc Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	40	3.4	2,543	17.3
February	40	3.0	1,780	17.4
March	43	3.4	2,933	17.9
April	41	3.5	2,844	18.9
May	41	3.5	2,940	17.5
June	44	3.2	2,495	15.9
July	45	3.1	2,480	15.9
August	45	3.1	2,588	16.2
September	47	3.4	2,815	16.9
October	46	3.4	2,528	18.8
November	45	3.1	2,248	15.9
December	46	3.4	2,813	16.3

^aAverage module temperature, weighted with respect to system power.

Table B-7
1995 PVUSA Austin Solar Resource Data

Month	Global Single-Axis Tracking		Global Horizontal (Long-Term Avg. in [])	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	869	115	755	86 [84]
February	925	94	813	74 [99]
March	1,012	124	967	104 [140]
April	1,069	188	1,041	156 [152]
May	1,088	173	1,077	151 [179]
June	1,096	231	1,129	193 [196]
July	1,043	206	1,112	204 [206]
August	1,076	174	1,076	184 [189]
September	982	173	977	148 [152]
October	1,006	170	1,013	138 [130]
November	854	114	746	88 [93]
December	830	93	627	75 [81]

Table B-8
1995 PVUSA Austin Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [1])			Wind Speed (m/s)	
	Min.	Avg.	Max.	Avg.	Max.
January	1	14 [10]	29	1.5	6.9
February	3	16 [12]	31	1.4	7.1
March	1	18 [15]	37	2.1	6.7
April	10	23 [20]	35	2.0	6.6
May	15	27 [24]	37	2.0	8.0
June	18	30 [28]	40	1.8	6.1
July	24	33 [29]	45	1.8	6.2
August	24	33 [29]	42	1.3	6.7
September	12	30 [26]	43	1.2	10.6
October	8	24 [21]	38	1.4	6.6
November	3	18 [15]	31	1.6	6.5
December	-8	15 [11]	35	1.6	7.0

Table B-9
1995 PVUSA Austin IPC Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	30	8.2	1,324	15.7
February	36	8.0	1,267	15.8
March	39	7.7	1,272	16.3
April	41	7.7	2,502	17.6
May	44	7.5	2,530	16.8
June	48	7.4	3,430	16.7
July	52	7.1	2,467	15.5
August	51	7.2	2,618	16.4
September	49	7.4	2,705	15.8
October	43	7.7	2,768	16.4
November	33	8.1	1,926	15.8
December	31	7.8	919	14.6

^aAverage module temperature, weighted with respect to system power.

Table B-10
1995 PVUSA Kerman Solar Resource Data

Month	Global Single-Axis Tracking (Reference Tracker)		Global Horizontal (Fresno Long-Term Avg. in [1])	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	713	57	624	49 [63]
February	833	80	789	63 [90]
March	1065	174	1,022	102 [146]
April	1125	238	1,048	174 [189]
May	1246	292	1,153	218 [232]
June	1169	312	1,158	230 [243]
July	1117	348	1,086	248 [248]
August	1066	339	984	227 [223]
September	997	283	992	171 [177]
October	877	212	795	134 [133]
November	725	131	608	80 [81]
December	648	65	610	49 [59]

Table B-11
1995 PVUSA Kerman Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [1])			Wind Speed (m/s)	
	Min.	Avg.	Max.	Avg.	Max.
January	2	13 [7]	22	3.0	12.4
February	2	14 [10]	23	1.7	9.9
March	2	15 [12]	25	3.1	11.9
April	5	17 [16]	31	3.1	11.2
May	3	20 [20]	37	3.1	10.3
June	10	23 [23]	41	3.0	12.4
July	15	26 [28]	43	3.0	7.6
August	13	27 [27]	42	2.6	6.9
September	8	24 [24]	40	2.6	6.5
October	5	18 [18]	35	2.0	7.0
November	4	15 [12]	27	1.8	9.0
December	3	14 [7]	33	2.1	12.7

Table B-12
1995 PVUSA Kerman SSI Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	21	10.1	16,249	339
February	29	9.5	29,020	429
March	35	9.6	70,600	493
April	39	9.0	89,672	493
May	44	8.1	97,774	468
June	45	8.8	89,294	507
July	52	7.8	24,501	420
August	52	7.6	24,831	419
September	45	7.8	44,640	365
October	40	7.0	50,521	320
November	30	5.9	26,551	214
December	24	7.7	23,842	297

^aAverage module temperature, weighted with respect to system power.

Table B-13
1995 PVUSA Maspeth Solar Resource Data

Month	Global 10° Tilt		Global Horizontal (New York City Long-Term Avg. in [])	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	646	54	511	41 [54]
February	896	82	733	65 [71]
March	980	121	838	105 [109]
April	1,174	154	1,064	139 [138]
May	1,118	141	1,043	133 [165]
June	1,140	147	1,071	141 [170]
July	1,168	161	1,002	152 [186]
August	1,135	186	990	166 [167]
September	1,066	128	918	110 [129]
October	967	99	807	80 [99]
November	717	56	555	44 [60]
December	578	57	402	40 [50]

Table B-14
1995 PVUSA Maspeth Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [])				Wind Speed (m/s)	
	Min.	Avg.		Max.	Avg.	Max.
January	-9	5	[0]	19	3.5	8.0
February	-13	1	[1]	14	3.6	9.9
March	-6	8	[5]	24	3.3	8.8
April	-4	12	[11]	26	3.3	10.5
May	9	19	[17]	34	2.9	8.8
June	15	24	[22]	39	2.9	7.7
July	19	29	[25]	44	2.8	9.9
August	18	28	[24]	40	3.1	7.5
September	12	22	[20]	35	2.9	7.2
October	8	19	[14]	32	3.1	20.3
November	-2	8	[9]	25	3.4	11.3
December	-8	2	[3]	15	3.7	8.8

Table B-15
1995 PVUSA Maspeth IPC Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	15	2.5	502	8.1
February	19	2.6	623	11.0
March	27	2.8	1,365	12.2
April	35	2.9	1,800	16.2
May	40	2.9	1,668	15.0
June	47	3.0	1,571	14.7
July	51	3.1	2,116	14.8
August	50	3.0	1,160	13.4
September	40	2.9	1,500	13.9
October	36	3.0	1,187	11.9
November	19	2.6	551	9.3
December	11	2.6	565	7.1

^aAverage module temperature, weighted with respect to system power.

Table B-16
1995 PVUSA Farmingdale Solar Resource Data

Month	Global Single-Axis Tracking (POA)		Global Horizontal (New York City Long-Term Avg. in [])		
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	
January	503	55	572	41	[54]
February	706	75	718	74	[71]
March	953	114	858	113	[109]
April	988	150	969	149	[138]
May	1,080	151	1,054	148	[165]
June	1,061	161	1,064	165	[170]
July	n/a	205	1,267	192	[186]
August	n/a	n/a	984	166	[167]
September	n/a	n/a	825	110	[129]
October	n/a	n/a	n/a	80	[99]
November	n/a	n/a	n/a	44	[60]
December	n/a	n/a	n/a	40	[50]

Table B-17
1995 PVUSA Farmingdale Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [])				Wind Speed (m/s)	
	Min.	Avg.		Max.	Avg.	Max.
January	-10	3	[0]	n/a	1.9	8.6
February	-15	-1	[1]	18	1.8	10.4
March	-8	6	[5]	21	1.6	7.3
April	-6	9	[11]	23	1.9	6.6
May	4	15	[17]	36	1.6	5.7
June	9	22	[22]	n/a	1.8	7.7
July	12	27	[25]	n/a	1.7	6.0
August	13	25	[24]	n/a	2.0	6.9
September	14	n/a	[20]	n/a	2.1	5.0
October	n/a	n/a	[14]	n/a	n/a	n/a
November	n/a	n/a	[9]	n/a	n/a	n/a
December	n/a	n/a	[3]	n/a	n/a	n/a

Table B-18
1995 PVUSA Farmingdale IPC Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	0	0	0	0
February	0	0	0	0
March	0	0	0	0
April	28	8.6	427	18.2
May	33	8.4	2,487	20.2
June	38	8.0	2,327	19.2
July	37	5.6	2,895	19.9
August	n/a	n/a	2,248	19.8
September	n/a	n/a	701	20.9
October	0	0	0	0
November	0	0	0	0
December	0	0	0	0

^aAverage module temperature, weighted with respect to system power.

Table B-19
1995 PVUSA Sacramento Solar Resource Data

Month	Global Single-Axis Tracker (POA)		Global Horizontal (Sacramento Long-Term Avg. in [])	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	681	46	614	42 [59]
February	753	82	701	64 [84]
March	930	134	924	107 [133]
April	1,072	208	997	160 [177]
May	1,099	246	1,135	195 [223]
June	1,143	292	1,127	224 [237]
July	1,109	318	1,071	234 [245]
August	1,040	294	1,006	221 [217]
September	919	235	895	171 [171]
October	816	172	758	128 [124]
November	674	110	586	79 [72]
December	604	46	576	42 [53]

Table B-20
1995 PVUSA Sacramento Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [])			Wind Speed (m/s)	
	Min.	Avg.	Max.	Avg.	Max.
January	1	12 [7]	21	4.1	16.6
February	1	12 [10]	25	1.3	9.9
March	2	13 [12]	24	3.2	18.3
April	4	15 [15]	29	3.2	9.5
May	7	18 [18]	36	2.6	8.5
June	9	21 [22]	44	3.2	11.8
July	13	25 [24]	43	2.9	10.6
August	11	25 [24]	42	2.6	11.3
September	10	22 [22]	39	2.3	7.5
October	7	19 [18]	35	1.9	10.8
November	6	15 [12]	29	1.4	8.4
December	1	12 [7]	22	2.3	19.0

Table B-21
1995 PVUSA Sacramento UPG Performance Data

Month	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	19	10.3	1,173	134
February	26	10.6	3,828	160
March	28	11.0	19,560	216
April	33	10.8	38,410	233
May	40	10.3	37,013	231
June	42	10.2	54,053	240
July	47	9.9	64,541	217
August	48	9.9	53,564	215
September	45	9.7	46,618	196
October	38	10.2	35,764	170
November	31	9.4	21,041	128
December	20	7.8	7,481	118

^aAverage module temperature, weighted with respect to system power.

Table B-22
1995 PVUSA Fort Davis Solar Resource Data

Month	Global Single-Axis Tracker (UPG array POA)		Global Horizontal (El Paso Long-Term Avg. in [])	
	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)	Peak Irradiance (W/m ²)	Insolation (kWh/m ²)
January	891	110	813	122 [108]
February	1,177	142	1,038	107 [126]
March	1,262	250	1,034	174 [183]
April	1,288	299	1,093	206 [213]
May	1,252	303	1,140	224 [242]
June	1,284	271	1,232	203 [240]
July	1,303	231	1,188	221 [229]
August	1,349	250	1,204	190 [211]
September	1,177	97 (inc.)	1,209	150 [177]
October	1,069	230	997	162 [152]
November	907	160	844	114 [114]
December	939	132	799	95 [99]

Table B-23
1995 PVUSA Fort Davis Weather Data

Month	Ambient Temperature (°C) (Long-Term Avg. in [])				Wind Speed (m/s)	
	Min.	Avg.		Max.	Avg.	Max.
January	-6	6	[6]	23	3.3	17.1
February	-4	11	[9]	22	3.0	9.7
March	-8	12	[13]	28	3.3	15.1
April	-2	15	[17]	27	4.0	13.1
May	7	21	[22]	34	4.1	13.7
June	10	22	[27]	33	3.0	12.4
July	13	24	[28]	37	2.9	10.2
August	14	23	[27]	33	2.7	11.3
September	3	20	[24]	34	2.4	10.4
October	2	16	[18]	28	2.6	11.6
November	-1	12	[11]	25	2.7	15.5
December	-6	8	[7]	23	2.7	18.0

Table B-24
1995 PVUSA Fort Davis Performance Data

Month	System	Mod. Temp. Wt. Avg. ^a (°C)	ac Efficiency (%)	ac Energy (kWh)	Max ac Power (kW)
January	UPG	n/a	n/a	9,593	98
	ENTECH	n/a	n/a	n/a	n/a
February	UPG	27	9.5	14,537	102
	ENTECH	19	n/a	519	54
March	UPG	33	8.2	13,479	105
	ENTECH	22	n/a	1,174	97
April	UPG	39	7.7	20,061	105
	ENTECH	26	6.6	11,236	96
May	UPG	43	7.6	21,330	105
	ENTECH	42	9.6	12,016	92
June	UPG	48	7.5	17,809	104
	ENTECH	49	8.3	10,215	87
July	UPG	51	6.8	7,638	98
	ENTECH	51	8.6	12,965	89
August	UPG	48	6.9	12,110	108
	ENTECH	47	9.7	12,536	89
September	UPG	49	7.5	7,924	n/a
	ENTECH	44	9.6	8,888	91
October	UPG	41	9.4	23,807	88
	ENTECH	44	8.2	14,299	92
November	UPG	32	10.9	17,281	83
	ENTECH	28	7.9	2,734	89
December	UPG	25	n/a	20,383	95
	ENTECH	17	n/a	3,822	45

^aAverage module temperature, weighted with respect to system power.

Appendix C

DETAILED SUMMARIES OF DAVIS AND KERMAN MAINTENANCE ACTIVITIES

Tables C-1, C-2, C-3, and C-4 summarize 1995 maintenance activities for the Davis and Kerman sites.

Table C-1

1995 Maintenance Activities for PVUSA Davis EMT Arrays

Event	Date; Number of People x Time (default is 1 person)
ENTECH EMT-1 <i>Preventive Maintenance: 11.6 hr</i> Inspected array, checked tracker alignment and battery Checked tracker gear oil, lubed bearings Adjusted PCU start-up voltage, inspected array, calibrated tracker controller Inspected PCU <i>Failure-Related Maintenance: 18.73 hr</i> Reset tracker controller Reset PCU due to sync error shutdown Warranty installation of a new tracker motor and drive Reset PCU due to line disturbance (auto reset) End bearing axle failed—system stowed until repaired Roll motor failure inspection and replacement Realigned 13 modules after roll motor replacement <i>Research-Related Maintenance: 10.7 hr</i> Installed and calibrated new e-prom in tracker controller I-V curves Ac/dc calibration Disconnected PCU for PQ testing at IPC	monthly; 4.2 hr total quarterly; 4.1 hr total semi-annual; 3 hr total two-year; 0.3 hr total 10 occurrences; 3.33 hr total 10 occurrences; 1.55 hr total 5/8-9; 8 hr 6/6; 0.05 hr 11/6; 0.3 hr 11/13, 11/20; 2.5 hr total 11/30; 3 hr 7/25; 0.8 hr 12/1; 0.8 hr 12/6; 9 hr 12/7; 0.1 hr
SSI EMT-1 <i>Preventive Maintenance: 0.5 hr</i> Inspected array and adjusted PCU operating voltage <i>Failure-Related Maintenance: 4.7 hr</i> Reset PCU due to sync error shutdowns Reset PCU due to line disturbance Reset PCU due to inverter failure Replaced shattered module <i>Research-Related Maintenance: 24.1 hr</i> Calibrated PCU Disconnected PCU for PQ testing at IPC	9/25; 0.5 hr 12 occurrences; 1.8 hr total 3 occurrences; 1.5 hr total 4 occurrences; 0.4 hr total 8/21; 1 hr 12/5; 24 hr 12/7; 0.1 hr
Solarex EMT-1 <i>Preventive Maintenance: 0.5 hr</i> Inspected array and adjusted PCU operating voltage <i>Failure-Related Maintenance: 2 hr</i> Reset PCU due to line disturbance Reset PCU due to sync error shutdowns Reset PCU due to inverter failure Investigated PCU peak power tracking problem Cleaned PCU A2J8 card contacts <i>Research-Related Maintenance: 0.6 hr</i> Disconnected PCU to compare signal conditioning method for ac power Disconnected PCU for PQ testing at IPC	9/25; 0.5 hr 6/6; 0.1 hr 10/3; 0.1 hr 10/4; 0.3 hr 11/7; 1 hr 11/15; 0.5 hr 11/6; 0.5 hr 12/7; 0.1 hr

Table C-1
1995 Maintenance Activities for PVUSA Davis EMT Arrays (Cont'd)

Sovonics EMT-1 <i>Preventive Maintenance: 0.8 hr</i> Inspected array and adjusted PCU operating voltage <i>Failure-Related Maintenance: 6.7 hr</i> Reset PCU due to line disturbance Reset PCU due to dc overvoltage Applied insulating compound to burned Tefzel spot Installed logic card from Solar Cells PCU Reinstalled loose modules <i>Research-Related Maintenance: 0.1 hr</i> Disconnected PCU for PQ testing at IPC	9/25; 0.8 hr 5 occurrences; 4.5 hr total 8 occurrences; 0.95 hr total 4/6; 0.25 hr 5/17; 0.5 hr 11/6; 0.5 hr 12/7; 0.1 hr
UPG EMT-1 <i>Preventive Maintenance: 0.5 hr</i> Inspected arrays and adjusted PCU operating voltage <i>Failure-Related Maintenance: 9.45 hr</i> Reset PCU due to misc. shutdowns Reset PCU and replaced fuse Fire in dc collection box Inspected burnt dc collection box Repaired burnt dc collection box <i>Research-Related Maintenance: 0.1 hr</i> Disconnected PCU for PQ testing at IPC	9/25; 0.5 hr 5 occurrences; 0.45 hr total 2 occurrences; 0.8 hr total 6/9; 0.2 hr 6/22; 2 hr 6/29; 6 hr + \$58 12/7; 0.1 hr
AstroPower EMT-2 <i>Preventive Maintenance: 0.75 hr</i> Inspected array and adjusted PCU operating voltage Tighten support bolts <i>Failure-Related Maintenance: 3 hr</i> Reset PCU due to sync error shutdowns Replaced 3 ac fuses in PCU Replaced 1 amp fuse in PCU <i>Research-Related Maintenance: 24 hr</i> Calibrated PCU	4/20; 0.25 4/27; 0.5 13 occurrences; 1.8 hr total 3/6; 1 hr + \$15 6/12; 0.2 hr + \$1.25 12/4; 24 hr

Table C-1
1995 Maintenance Activities for PVUSA Davis EMT Arrays (Cont'd)

Amonix EMT-3 <i>Preventive Maintenance: 2.3 hr</i> Adjusted PC board R4 and R11 Washed array lenses Inspected electrical cables and elevation ball screw, checked grease oil <i>Failure-Related Maintenance: 25.85 hr</i> Reset tracker-off sun Reset PCU due to grid overvoltage Reset PCU due to sync error Reset PCU due to line disturbance Replaced burnt wire on PCU capacitor bank CAC Swapped thermocouple connection to t/c #2 Warranty repairs-four receiver plates replaced <i>Research-Related Maintenance: 7.75 hr</i> Verified thickness of Amonix pedestal Tested Amonix PCU using ENTECH array Investigated PCU peak power tracking problem Checked Voc, Voper, Ioper I-V curves	9/28; 1 hr 10/16; 1 hr 11/9; 0.3 hr 2 occurrences; 0.9 hr total 2 occurrences; 0.2 hr total 10/5; 0.1 hr 10/24; 0.1 hr 11/13; 0.3 hr 11/15; 0.25 hr 11/14,11/20,12/15 (2 receiver plates); 24 hr 1/13; 0.25 hr 8/29; 1.5 hr 8/30; 4.5 hr 11/7; 0.5 hr 11/16; 1 hr
SCI EMT-3 <i>Preventive Maintenance: 3.5 hr</i> Washed array Adjusted PC board R4 and R11 <i>Failure-Related Maintenance: 9.1 hr</i> Troubleshoot SCI PCU with Nick Olney via telephone Reset PCU due to sync error <i>Research-Related Maintenance: 0.6 hr</i> Tested Solar Cells PCU using Solarex array	10/17, 11/9; 2.5 hr 9/28; 1 hr 9/26, 9/27; 9 hr total 10/11; 0.1 hr 8/31, 9/26; 0.6 hr

Table C-2
1995 Maintenance Activities for PVUSA Davis US-1

Event	Date; Number of People x Time (default is 1 person)
APS <i>Preventive Maintenance: 19.15 hr</i> Cleaned PCU filters and test emergency lights Adjusted PCU operating voltages Inspected array and tested PCU smoke detectors Tested soil anchors Inspected and lubricated dc switches Calibrated protective relays Clearance for 12-kV trip relay calibration Clearance for connecting UPS power to IPC 51 relays Clearance for SSI transformer tap change Disconnected PCU due to line disturbance <i>Failure-Related Maintenance: 54.7 hr</i> Manually reset inverters PCU #4 REC fuses blown Replaced diodes, resistors, and MOVs after dc switch fire Replaced broken module PCU #1 REC fuses blown Exchanged PC boards and troubleshoot Replaced F8 fuse in PCU #3 Vendor repaired PCU #1 and #4 PCU # 2 REC fuses blown Diagnosed and repaired fire damage in dc switch <i>Research-Related Maintenance: 0.8 hr</i> Disconnected PCU for PQ data for KWI	monthly; 5.25 hr total quarterly; 0.75 hr total semi-annual; 3 hr total annual; 5 hr total 3/16; 2 hr 4/12; 2.5 hr 5/2; 0.25 hr 9/6; 0.1 hr 11/9; 0.2 hr 12/11; 0.1 hr 24 occurrences; 4.7 hr total 4 occurrences; 2 hr total + \$301 3 occurrences; 10.5 hr total + \$300 7/24; 4 hr + \$200 7/25, 8/1; 7 hr + \$232 7/26, 8/9; 7 hr 8/9; 0.5 + \$6 9/12, 9/13; 8 hr + \$7,524 10/9, 10/24; 1 hr + \$129 11/2, 11/6; 10 hr total + \$197 12/7, 12/28; 0.8 hr
IPC <i>Preventive Maintenance: 36.5 hr</i> Cleaned PCU filters and set tracker clock Inspected modules and source circuits Tensioned tracker cable, lubed tracker bearings, and replaced winch oil Manually disconnected source circuits Inspected and lubed dc switches Calibrated protective relays Clearance for 12 kV trip relay calibration Connected UPS power to 51c relays Clearance for connecting UPS power to 51 relays Clearance for SSI transformer tap change	monthly; 2.7 hr semi-annual; 3.5 hr semi-annual; 20.5 hr total + \$26 3 occurrences; 0.25 hr total 3/16; 2 hr 4/19; 6 hr 5/2; 0.25 hr 9/6; 1 hr 9/6; 0.1 hr 11/9; 0.2 hr

Table C-2
1995 Maintenance Activities for PVUSA Davis US-1 (Cont'd)

IPC Failure-Related Maintenance: 82.2 hr Manually reset inverter Removed and replaced repaired bridge boards Replaced I/O modules in tracker controller Reset tracker Investigated dc ground fault Reset PCU and opened dc circuits due to enhanced irradiance Reset KWI PCU due to misc. shutdowns Troubleshoot Omnion PCU via teleconference Vendor repaired Omnion PCU Troubleshoot tracker problems Installed new e-prom Cleaned ribbon cable connectors Inspected final Omnion PCU failure Repaired failed data logger Troubleshoot DAS grounding problem Replaced component in KWI display board Replaced damaged module Bypassed shorted module Warranty repairs to KWI PCU and PQ testing Research-Related Maintenance: 9 hr PQ testing for acceptance of KWI	48 occurrences; 8.05 hr total 3 occurrences; 8 hr total + \$70 3 occurrences; 2.5 hr total + \$53 8 occurrences; 3.6 hr total 5 occurrences; 7.75 hr total + \$80 5 occurrences; 1.1 hr total 4 occurrences; 1.1 hr total 2/9; 8 hr 2/13, 2/14; 8 hr + \$1,351 4/18; 0.5 hr + \$12 5/3; 0.5 hr 6/2; 2 hr 7/17; 0.5 hr 7/28; 2 hr 9/6; 0.5 hr 10/20; 0.3 hr 12/6; 6.3 hr + \$297 12/6; 1.5 hr 12/20, 12/28; 20 hr 12/7; 9 hr
SSI Preventive Maintenance: 24.1 hr Lubricated tracker bearings and inspected array Inspected and lubricated dc switches Calibrated protective relays Clearance for 12 kV trip relay calibration Changed transformer taps and associated clearances Clearance for connecting UPS power to 51 relays Failure-Related Maintenance: 20.65 hr Reset Inverter "B" after unit failed to "wake up" Replaced 8 burned modules and two bypass diodes Replaced PCU 'B' enclosure fan Repaired burnt wire on cap bank Research-Related Maintenance: 0.6 hr Disconnected PCU for PQ data for KWI	semi-annual; 10.25 hr total + \$20 3/16; 2 hr 4/12; 7 hr 5/2; 0.25 hr 7/6, 11/9; 4.5 hr 9/6; 0.1 hr 55 occurrences; 7.3 hr total 2 occurrences; 10.6 hr total + \$2,200 9/25; 2 hr + \$50 12/8; 0.75 hr 12/7, 12/28; 0.6 hr

Table C-3
1995 Maintenance Activities for PVUSA Davis BOS

Event	Date; Number of People x Time (default is 1 person)
<i>Preventive Maintenance: 83.65 hr</i> Read meters and reported to PG&E Power Control Dept. Checked fire extinguishers, emergency lights, security system; maintained site vehicles; lubricated sump pump bearings Checked safety boxes and perimeter fence Provided vegetation control; cut fire breaks, mowed site Performed major cleaning of visitor center and I&C building Inspected and maintained UPS Calibrated protective relays in I&C building Calibrated 480-V EMT breakers in I&C building Calibrated 12-kV trip relays Clearance on switch #20013 for calibrations of 12-kV trip relays Calibrated meteorological station Relocated sump microswitches Non-routine maintenance; lamps, doorstops, sheet metal roofing Repaired sea van storage room doors Cleaned mud from sump Bladed roads and reshaped ditches Cleaned out water trailer Repaired erosion damage adjacent to driveway barricade PG&E replaced meters with demand metering	monthly; 1.2 hr total monthly; 12 hr total + \$70 quarterly; 1.5 hr total annual; 9 hr total + \$1,828 annual; \$200 semi-annual; 1 hr total 4/19; 5.5 hr 4/20, 4/19; 20.2 hr total 5/2; 10 hr 5/2; 1.25 hr 5/8; 2 hr + \$70 7/13; \$671 7/14; \$962 8/1; 1 hr 8/1; \$1,324 8/10; \$1,132 9/26; 3 hr 9/26; \$1,947 12/26; 1 hr
<i>Failure-Related Maintenance: 10.05 hr</i> Reset plant after loss of site power events Replaced fuse in sump pump control cabinet Repaired water trailer lights Replaced failed water trailer pump Reset NIP tracker	5 occurrences; 4.15 hr total 1/6; 0.5 hr 11/2; 2 hr 11/30; 3.3 hr + \$253 12/15; 0.1 hr
<i>Research-Related Maintenance: 7.2 hr plus 2 hr/wk (ongoing)</i> Exchanged logic control cards on DECC PCUs Monitored site power quality, processed data Clearance on all EMTs to measure the 480-V system voltage Measured resistance to ground of US-1 and EMT systems Disconnected 12 kV switchgear for SSI transformer tap change	6 occurrences; 3 hr total ongoing; 2 hr/wk 10/26; 1 hr 11/6; 3 hr 11/9; 0.2 hr

Table C-4
1995 Maintenance Activities for Kerman US-2

Event	Date; Number of People x Time (default is 1 person)
Preventive Maintenance: 141.45 hours Inspected system operation via Davis computer Routine inspection of PCUs and array DAS maintenance Monthly Inspection and Maintenance Quarterly Inspection and Maintenance Semi-annual Inspection and Maintenance Annual Inspection and Maintenance	469 occurrences; 23.45 hr total 2 occurrences; 1.2 hr total 9/15, 11/3; 0.8 hr 48 hr total 16 hr total 8 hr total 44 hr total
Failure-Related Maintenance: 117.4 hours Remotely reset one or both inverters Manually reset one or both inverters Replaced blown fuses Replaced PC boards with spares Troubleshoot PCU #2 with Omnion by teleconference Repaired loose module connection Removed, reprogrammed, and replaced PCU #1's PLC Removed actuator, shipped, repaired, and replaced Performed I-V curves on all monopoles Checked voltages and currents on all monopoles Exchanged PLC between PCU #1 and PCU #2 Cleaned ribbon cable connectors and reseated Exchanged PC boards between PCUs Vendor repair of PCU #2 Performed monopole isolation tests to find source of dc ground fault Replaced LEM on PCU #2 to correct ground fault problem	36 occurrences; 13.1 hr total 41 occurrences; 8.1 hr total 6 occurrences; 8.2 hr total + \$51 3 occurrences; 13.2 hr total 2/1; 24 hr 7/6; 0.5 hr 7/26; 5 hr + \$317 8/1; 12 hr + \$400 8/23; 8 hr 8/23; 4 hr 9/7; 1.2 hr 9/7; 1 hr 9/8; 10/30; 10.3 hr 9/25; 12 hr + \$4,052 10/30; 2.8 hr 11/17; 3 hr + \$148
Research-Related Maintenance: 9.25 hours Reset 1 axis tracker Reset DNI tracker DAS backups Clean pyranometers	7/5; 0.5 hr 7/5; 0.25 hr monthly; 8.0 hr monthly; 0.5 hr

Appendix D

ADDITIONAL PVUSA TEST SITES

This appendix includes system and site descriptions for PVUSA's host utility sites and outlines future development plans of PVUSA participants.

System and Site Descriptions

Participating utilities have the opportunity to install host systems in their service territories as part of the PVUSA project. To the extent possible, these host systems duplicate existing systems at the Davis site. The host systems, which allow PVUSA to compare similar systems under different operating conditions, are described below. Figure D-1 shows a map of all PVUSA test sites.

Central and South West (CSW), Fort Davis, Texas

Two nominal 100-kW systems were installed in 1994-95 at the 25-acre Fort Davis Solar Park located in the hills of west Texas. Each system delivers dc power at approximately 800 V to separate Omnion Series 3200 PCUs. Each PCU connects to the utility through its own 380 V/12 kV step-up transformer. Presently, the site is frequently but not continuously staffed, and CSW monitors operations daily. The site also includes wind and solar dish Stirling engine demonstration systems and a visitors' shelter.

UPG's system consists of 2,400 SSI modules mounted on 10 rows of motor-driven single-axis trackers. This system first paralleled in September 1994 and was accepted in November 1994. In September 1995, PVUSA issued a report to CSW detailing the system's PTC rating of $98 \pm 2 \text{ kW}_{ac}$. Performance data from June 1995 were used to calculate the rating.

During the fall of 1994, ENTECH began installing a system consisting of 4 two-axis tracking rows, each with 72 line-focus 21x concentrator modules. This system first paralleled in January 1995, and after a series of start-up hurdles, the system was accepted in September. Using data from parts of July and August, both PVUSA and SWTDI came up with consistent ratings of 83 kW_{ac} . PVUSA's rating of $83 \pm 4 \text{ kW}_{ac}$ was detailed in a November report to CSW.

PVUSA SITE DATA

Status through 12/95; 19 Systems Totaling 1,820 kW

Figure D-1
Map of PVUSA Test Sites

City of Austin, Texas

This 17.9-kW system is located at the City of Austin Convention Center. The system consists of 96 Mobil Solar modules, a 25-kW Omnion PCU, an IPC horizontal single-axis structure and motor-driven tracker, and a PVUSA-specified DAS. In this configuration the PV system operates in parallel with the utility's service to provide supplemental power for the convention center's daytime electrical requirements.

The array is configured in one row, oriented on a horizontal north-south axis. The array is located on top of the convention center's eastern wall. The tracker drive controller and array monopole disconnect are located at the southern end of the row, with the tracker winch in the middle of the row, west of the center pedestals. The PCU, dc disconnect switches, and DAS are located inside the convention center. The system is checked routinely by convention center staff and monitored remotely by the city's Electric Department.

Maui Electric, Hawaii

The 17.6-kW array is located just north of Kihei, Maui, in one corner of an area previously used as a U.S. Air Force experiment station. The array consists of 1,200 Sovonics EMT modules similar to those in the Sovonics array at Davis. The modules are tilted at 22 degrees on a fixed, south-facing structure designed by Sovonics. The system's 25-kW DECC PCU converts 300 V_{dc} input power to 480 V_{ac} for the Maui Electric grid. The system is monitored remotely by Maui Electric.

Virginia Electric Power Company (VEPCO)

In 1995, VEPCO ended operations at its Vista PV site and canceled its membership in PVUSA. Although construction had been complete for over a year on VEPCO's PVUSA host 20-kW Astropower EMT-2 array, the array was never approved for full operation due to extensive module, wiring, and junction box failures noted during field wet resistance tests. Dismantling preparations began during the fall, and PVUSA's DAS was returned for possible use at another host site.

NREL/New York Power Authority (NYPA), Maspeth, New York

This 17-kW system is part of the National Renewable Energy Laboratory (NREL) amorphous-silicon project. The NYPA demand-side management PV application is located atop a New York City Transit Authority materials warehouse in Maspeth, New York. The array supplies power to meet the warehouse's daytime electrical needs. The system consists of 14 rows of USSC Model UPM-880 amorphous-silicon modules at a fixed 10-degree tilt, and a 25-kW Omnion inverter. Transit Authority staff monitor and maintain the system.

After two years of operation, system power has decreased by nearly 25 percent from NREL's initial 17 kW_{ac} rating. The present PTC rating of 12.9 ±0.7 kW_{ac} was calculated by PVUSA using data from June 1995. The results were detailed in an August report to NREL.

New York State Energy Research and Development Authority (NYSERDA)

NYSERDA's 20-kW IPC PVUSA host system is one of three installed in 1993 at the State University of New York's (SUNY's) Farmingdale campus on Long Island. The PVUSA system is similar to the City of Austin host system, with single-axis tracking, 96 Mobil Solar modules, and an Omnion PCU. PCUs and data acquisition for all three systems are located in a modified "Seatainer" trailer approximately 500 feet from the array. The weather station is installed on the roof of an adjacent building approximately 8 meters above grade.

The site is monitored by Ascension Technology for NYSERDA, with maintenance handled by SUNY staff and by subcontractor company Sunshine Plus. Operation has

been intermittent and performance has been poor since the system connected to the grid in August 1993. The system has not been accepted by NYSERDA nor rated by PVUSA, because there have been a number of recurring problems with the PCU, long-standing deficiencies with the tracker, and unreliable signals and communications with the DAS. In the fall of 1995, NYSERDA hired AWS Scientific to assess the system and coordinate an effort with IPC to bring the system up to design performance.

Sacramento Municipal Utility District (SMUD)

The SMUD 200-kW host system was installed by UPG. The system is located at the Hedge substation on Sacramento County's southeast border. The system began operating in April 1994, but full data collection did not begin until mid-October 1994.

The SMUD system has 4,800 SSI M55 modules arranged in 20 rows; 1/3-hp motors rotate each row about a north-south axis. A single tracker controller regulates simultaneous movement of the motors. Each row has 10 sections, and each section has 24 modules in series. The entire array is supported by wooden utility poles and has a centerline of rotation 5 feet above ground level.

The PCU is a 250-kW Omnion Series 3200. The array has a standard PVUSA DAS and SMUD's SCADA system for remote operations. The site is also spot-checked by SMUD staff.

A PTC rating of $207 \pm 6 \text{ kW}_{ac}$ was calculated by PVUSA using data from June 1995. The results were detailed in an August report to SMUD.

PG&E Kerman, California

In 1993, SSI installed a 500-kW US-2 system near the town of Kerman, 15 miles west of Fresno, California. This grid-support system operates in parallel with PG&E's 12.47-kV service supporting a transformer in the Kerman substation. Featured are 12,240 SSI M55VJ PV modules, two 275-kW Omnion Series 3200 PCUs, a Robbins one-axis passive tracker system, and a utility-grade SCADA system. System operation began in June 1993.

Other Host Utility Sites

Other host utility sites scheduled for future operation are described below.

DOD, Yuma, Arizona

The Department of Defense Tri-Service Review Panel awarded to the Utility Power Group a contract to design and install a versatile PV/battery grid-interactive system,

to be completed by December 1996. The system will consist of a nominal 450-kW fixed array of SSI frameless modules and a redundant pair of 450 kW KWI PCUs that may be paralleled to supply as much as 900 kW when powered by additional battery reserves.

Public Service Company of Colorado, Aurora, Colorado

In December, the Public Service Company of Colorado selected New World Power to supply a 22-kW PVUSA host system to be installed in Cherry Creek State Park. The system will employ several single-axis tracking pedestals inclined at an angle equal to the Earth's polar axis. The system is scheduled for completion in June 1996.

Appendix E

CONSENSUS STANDARDS SUPPORT

This appendix briefly discusses the changes that took place in 1995 in national standards for the qualification of flat-plate PV modules and development of a PV system field acceptance guideline. The development of module qualification tests for acceptance of PV modules by PVUSA is documented in the *1989-1994 PVUSA Progress Reports*.

PV Module Qualification

Both national and international standards for PV module qualification continued in active development in 1995. Based in large part on the experience of PVUSA and its suppliers, the Institute of Electrical and Electronic Engineers (IEEE) developed IEEE 1262 — *IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules* to cover the qualification of flat-plate modules. This standard was approved by the IEEE standards board in December 1995.

PVUSA is an active supporter of efforts to develop consensus national standards for the PV industry. The two PV systems installed at Davis in 1995 (Solar Cells and Amonix) had their modules qualified to draft standards, as described in Appendix E of the *1994 PVUSA Progress Report*. Essentially the flat-plate modules met the requirements of the NREL IQT (SERI/TR-213-3624) 1990 with some PVUSA requirements added. However, in the PVUSA Model Technical Specification (MTS) issued in late 1995, PVUSA's present requirements for module qualification are stated as follows:

Excerpt from PVUSA MTS:

7.0 MODULE AND SYSTEM TESTING

7.1 MODULE QUALIFICATION TESTS

Perform qualification tests to establish the acceptability of the design, materials/manufacturing process of the modules to be furnished. Conduct the tests on modules produced from the CONTRACTOR'S production line and with stabilized peak power outputs within 10% of the contract values. The test modules shall, at a minimum, pass the tests specified in this document. After the module qualification tests have been passed, no changes in design,

materials, or manufacturing process are allowed, unless submitted to the OWNER for review and acceptance. The OWNER may require requalification after review of the changes.

Concentrator modules shall successfully pass the tests described in *Qualification Tests for Photovoltaic Concentrator Cell Assemblies and Modules*, Sandia Report #SAND92-0958.UC.272, printed October 1992. Flat-plate modules shall successfully pass the tests described in IEEE P1262 July 21, 1995, *IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules*, or their equivalent.

COMMENT: A final version of IEEE P1262 is expected to be approved and issued by IEEE in 1996. The approved document should then be referenced; that is, IEEE 1262, not IEEE P1262.

Qualification Test Certification shall be submitted per Appendix K and IEEE P1262. Use Appendix K forms if the IEEE P1262 forms are not used.

The OWNER reserves the right to witness any or all of the tests. No exception will be allowed to the requirements of this section.

PV System Field Acceptance Testing

PVUSA (Chuck Whitaker and Brian Farmer) is spearheading the development of a field testing standard for IEEE currently titled P1373 *Recommended Practice for Field Test Methods and Procedures for Grid-Connected Photovoltaic Systems*. This document details procedures of tests that are to be performed prior to utility interconnection, upon initial start-up, and periodically throughout the life of the system. It also provides a system rating procedure. It is based on the test procedures and requirements provided in the PVUSA US-2 Technical Specification (Kerman). The document is being rewritten to remove the Technical Specification's contractual language, remove references to PVUSA-specific criteria and equipment, generalize the procedures, and accommodate different procedures and methods used by other organizations. It is anticipated that this document will be issued as an approved standard in late 1996 or early 1997.

Appendix F

PVUSA PUBLICATIONS

This appendix lists annual reports, topical reports, technical specifications, workshop notebooks, conference papers, and journal articles produced by PVUSA from 1988-1995. All conference papers and journal articles are copyrighted by the sponsoring organization and are properly obtained from the copyright owner.

Reports, specifications, and notebooks are free to PVUSA members. If you would like membership information or have questions about PVUSA publications, please contact the PVUSA project office at (916) 753-0725.

Annual Reports

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Topical Reports

Alternatives to Herbicide Use at PVUSA Davis, H.C. Appleton and M. Waaland, PG&E Report #009.4-94.2, July 1994.

Audible Noise Study, PVUSA Power Conversion Units, P.Y. Lee, PG&E Report #007.3-91.3, March 1991.

Davis PV Plant Operation and Maintenance Manual, PVUSA Project Team, DOE/AL/82993-13, September 1994.

Emerging Photovoltaic Module Technologies at PVUSA—A Five-Year Assessment, T.U. Townsend, DOE/AL/82993-18, April 1995.

Experimental Design for Testing Alternatives to Herbicide Use at PVUSA Davis, H.C. Appleton and M. Waaland, PG&E Report #009.4-90.7, June 1990.

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The PV Grid-Support Project at Kerman Substation: Project Plan, T.E. Hoff et. al., PG&E Report #007.5-92.5, June 1992.

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PVUSA Instrumentation and Data Analysis Techniques for Photovoltaic Systems, J.D. Newmiller et. al., DOE/AL/82993-25, November 1995.

PVUSA Procurement, Acceptance, and Rating Practices for Photovoltaic Power Plants, R.N. Dows and E.J. Gough, DOE/AL/82993-21, October 1995.

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The Value of Photovoltaics in the Distribution System—The Kerman Grid-Support Project, H.J. Wenger and T.E. Hoff, DOE/AL/82993-20, May 1995.

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Model Technical Specification for a Turnkey PV Power System, R.N. Dows and E.J. Gough, DOE/AL/82993-27, November 1995.

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PV Power Conversion, Data Collection, and System Rating, June 1995.

PV Balance-of-System and Procurement, January 1995.

PV Construction and Safety, September 1994.

Grid-Support PV, June 1994.

PV Power Plant Design, Operation and Maintenance, April 1993.

Conference Papers and Journal Articles***General Interest***

"Experience Gained from the First Three Years of the PVUSA Project (1988-1990)," E.J. Gough, P.A. Hutchinson, T.U. Townsend, T.R. Candelario, and B.K. Farmer, 53rd American Power Conference, Chicago, IL, May 1991.

"Initial Results from the Photovoltaics for Utility Scale Applications (PVUSA) Project," S.L. Hester, F.W. Hay, T.U. Townsend, W.T. Clements, and W.J. Stolte, 1990 AIChE Summer Conference, San Diego, CA, August 1990.

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Appendix G

TERMS AND ABBREVIATIONS

APS	Advanced Photovoltaic Systems, Inc.
ASES	American Solar Energy Society
a-Si	Amorphous silicon
BMI	Basic Measurement Instruments, Inc.
BOS	Balance-of-system. All equipment and associated labor not part of the actual PV array, such as the support structure, power conditioning unit, and utility grid interconnection equipment
CalOSHA	California Occupational Safety and Health Association
Capacity Factor	Ratio of actual ac energy production (kWh), in any time interval, divided by the product of the ac rating (kW) and the number of hours in that interval
CdS	Cadmium sulfide
CdTe	Cadmium telluride
CEC	California Energy Commission
CSI	Campbell Scientific, Incorporated
CSW	Central and South West Services, Inc.
DAC	Data acquisition computer
DAS	Data acquisition system
DECC	Delta Electronic Control Corporation
DNI	Direct normal insolation
DOD	U.S. Department of Defense (Tri-Service PV Review Panel)

DOE	U.S. Department of Energy
Efficiency	Ratio of monthly energy produced to monthly POA insolation during hours when the PCU is operating
EFG	Edge-defined film-fed growth
EMF	Electric and magnetic fields
EMT	Emerging module technology
EPRI	Electric Power Research Institute
EVA	Ethylene vinyl acetate
FWRT	Field wet resistance test
GP	Golden Photon, Inc.
Hz	Hertz, unit of frequency, cycles per second
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IHCPV	Integrated high-concentration photovoltaic
IPC	Integrated Power Corporation
I/O	Input/output
I-V	Current-voltage
JPL	Jet Propulsion Laboratory
KWI	Kenetech WindPower, Inc.
MOV	Metal-oxide varistor
MSEC	Mobil Solar Energy Corporation
NEC	National Electric Code
NREL	U.S. National Renewable Energy Laboratory (formerly Solar Energy Research Institute)

NWP	New World Power Corporation
NYPA	New York Power Authority
NYSERDA	New York State Energy Research and Development Authority
O&M	Operation and maintenance
PC	Personal computer
PCU	Power conditioning unit. Contains a dc-to-ac inverter, system protection and control, and maximum power-tracking circuits
PG&E	Pacific Gas and Electric Company
PI	Performance Index
PLC	Programmable logic controller
POA	Plane of array
Poly-Si	Polycrystalline silicon
PQ	Power quality
PSCo	Public Service Company of Colorado
PTC	PVUSA test conditions, defined as 1,000 W/m ² POA irradiance for flat-plate modules, 850 W/m ² direct normal irradiance for concentrators, 20°C ambient temperature, and 1 m/s wind speed
PV	Photovoltaic
SC	PVUSA Steering Committee
SCADA	Supervisory Control and Data Acquisition
SCI	Solar Cells, Inc.
SCR	Silicon-controlled rectifier
SDG&E	San Diego Gas and Electric
Si	Silicon
SMUD	Sacramento Municipal Utility District

SNL	Sandia National Laboratories
SQL	Structured Query Language
SRP	Salt River Project
SSI	Siemens Solar Industries, Inc. (formerly ARCO Solar, Inc.)
STAR	Solar Test and Research Facility, managed by Arizona Public Service
STC	Standard test conditions, defined as 1,000 W/m ² POA irradiance for flat plate modules, 850 W/m ² direct normal irradiance for concentrators, 25°C or 28°C cell temperature, and air mass 1.5 spectrum
SWTDI	Southwest Technology Development Institute
T&D	Transmission and distribution
tbd	To be determined
THD	Total harmonic distortion
TRC	PVUSA Technical Review Committee
UPG	Utility Power Group
UPVG	Utility Photovoltaic Group
US	Utility-scale
USSC	United Solar Systems Corporation
VA	Volt ampere, unit for apparent power
VAR	Volt-ampere reactive, unit for reactive power
VEPCO	Virginia Electric Power Company