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1993
PVUSA Progress Report

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1993 PVUSA Progress Report

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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 photovoltaic (PV) electric generation systems and recent developments in module technology. This report updates the progress of the PVUSA project, reviews the status and performance of all PV installations during 1993, and summarizes key accomplishments and conclusions for the year.

BACKGROUND

For several years forecasts have indicated that PV could become a significant utility resource within the next decade, but stable prices and good availability of fossil fuels have deferred these expectations. As a result, the market is still in its infancy, with present capacity of grid-connected PV systems in the United States less than 12 MW, and world sales of only about 60 MW per year.

Nonetheless, certain markets are fostering strong growth in the PV industry, and environmental pressures to develop renewable energy continue to rise. In addition, recent trends in financial and utility transmission and distribution (T&D) markets indicate PV is poised for a rapidly expanding role within electric utilities, and government and utility interest in PV is high. Bringing this technology into the utility mainstream, however, will require knowledge of PV operational characteristics in a utility system and confidence in predicting PV performance, reliability, and economics.

The PVUSA project has five objectives 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

- To evaluate the performance, reliability, and cost of promising PV modules and balance-of-system (BOS) components side-by-side at a single location
- To assess PV system operation and maintenance (O&M) in a utility setting
- To compare PV technologies in diverse geographic areas
- To provide U.S. utilities with hands-on experience in designing, procuring, and operating PV systems
- To document and disseminate knowledge gained from the project

PVUSA participants include the U.S. Department of Energy, the California Energy Commission, the Electric Power Research Institute (EPRI), Pacific Gas & Electric (PG&E), and 11 utilities and other energy-related agencies. PG&E leads the PVUSA Project Team, which manages daily activities and facilitates technology transfer.

PROJECT SCOPE

PVUSA consists of two types of demonstrations: emerging module technologies (EMTs), which are unproven but promising state-of-the-art PV technologies in 20-kW (nominal) arrays; and utility-scale (US) systems, which represent more mature PV technologies in 200- to 500-kW (nominal) turnkey systems. The most recent highlight of the PVUSA project is the siting of one US system at a key location in a distribution system to allow testing and evaluation of grid-support benefits. In addition, several PVUSA participants have installed EMT arrays or US systems in their service areas.

PVUSA's primary test site is in Davis, California. The Davis site has five EMT arrays and three US systems. 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). In 1993, two systems totaling 700 kW were added, increasing PVUSA's total capacity to 1300 kW, with four more systems totaling 250 kW nearing completion. In California, PV systems are operated or are under construction by PG&E and the Sacramento Municipal Utility District (SMUD). Additional PV systems are being operated or installed in Hawaii by Maui Electric, in Texas by the City of Austin, in Virginia by the Virginia Electric Power Company (VEPCO), and in New York by the New York State Energy Research and Development Agency (NYSERDA) and the New York Power Authority (NYPA).

Tables ES-1 and **ES-2** show PVUSA suppliers of EMT, US, and host utility systems; completion dates; PV technologies employed; and system efficiencies and sizes. All completion dates in this report are as of December 1993.

PVUSA suppliers include:

- Advanced Photovoltaic Systems (APS)
- AstroPower
- ENTECH
- Golden Photon (GP)
- Integrated Power Corporation (IPC)
- Siemens Solar Industries (SSI)
- Solar Cells, Inc. (SCI)
- Solarex
- Sovonics
- Utility Power Group (UPG)

Table ES-1
PVUSA EMT and US Systems at Davis and Kerman

Completion Date	Supplier	Technology	System Efficiency (%)[a]	Power (kW)[a]
		Davis EMT Systems		
	EMT-1			
1/89	Siemens Solar (ARCO)	Microgridded single-crystal silicon	11.1 dc	18.7 dc
6/89	Sovonics-Davis	Tandem junction amorphous silicon	3.5 dc	17.3 dc
12/89	Utility Power Group	Tandem junction amorphous silicon	3.3 dc	15.7 dc
10/90	Solarex	Bifacial polycrystalline silicon	8.6 dc	15.7 dc
3/91	ENTECH	22x linear concentrator, crystalline silicon	11.3 dc	16.5 dc
	EMT-2			
3rd Q/94[b]	AstroPower	Thin-film polycrystalline silicon on ceramic	7.4[c] dc	19.3[c] dc
		Davis and Kerman US Systems		
	US-1			
2nd Q/94[d]	Siemens Solar	Single-crystal silicon, one-axis passive tracking, Bluepoint PCU	10.0[c] ac	174[c] ac
2nd Q/93	Integrated Power Corp.	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.0 ac	196 ac
3rd Q/92	Advanced Photovoltaic Systems	Amorphous silicon, fixed tilt, APS PCU	4.2 ac	479 ac
	US-2 Kerman			
2nd Q/93	Siemens Solar	Single-crystal silicon, one-axis passive tracking, Omnion PCU	9.8 ac	498 ac

a Based on PVUSA Test Conditions (PTC) and total array area, where PTC are defined as 1000 W/m^2 plane of array irradiance, 20°C ambient temperature, and 1 m/s wind speed. (For concentrators, a direct normal irradiance of 850 W/m^2 is used.)

b PVUSA estimate. AstroPower made extensive product changes in 1993. A new schedule has not been issued.

c Based on supplier's estimate (system yet to be accepted by PVUSA).

d PVUSA project estimate as of December 1993.

Table ES-2
PVUSA Host Systems

Completion Date	Host Utility Sponsor	Supplier	Technology	System Efficiency (%)[a]	Power (kW)[a]
10/89	Maui Electric	Sovonics EMT-1	Tandem junction amorphous silicon	3.7 dc	18.5 dc
1/94[b]	VEPCO	AstroPower EMT-2	Thin-film polycrystalline silicon on ceramic	7.4[c] dc	20[c] dc
7/92	City of Austin	IPC US-1	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.4 ac	17.9 ac
8/93	NYSERDA	IPC US-1	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.4[c] ac	20[c] ac
7/93	NYPA (NREL)	IPC	Fixed flat plate amorphous silicon	5[c]	17[c]
3/94[b]	SMUD	UPG	Single-crystal silicon (SSI), one-axis active tracking, Omnion PCU	11[c]	200[c]
3/94[b]	DOD	To be determined	To be determined	tbd	150
7/94[b]	CSWS	To be determined	To be determined	tbd	100
7/95[b]	PSCC	APS	Single or tandem junction amorphous silicon	tbd	50

a Based on PVUSA Test Conditions (PTC) and total array area, where PTC are defined as 1000 W/m^2 plane of array irradiance, 20°C ambient temperature, and 1 m/s wind speed. Generally EMTs are rated on array dc output and USs are ac-rated (determined by contract).

b PVUSA project estimate as of December 1993.

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

ACCOMPLISHMENTS

The most significant accomplishments in 1993 are listed below.

Procurement and Installation

US Systems. In June, a US-1 system supplied by Integrated Power Corporation (IPC) was completed at the Davis site. The system was rated at 196 kW, 16 kW above its design rating of 180 kW. Also in June a US-2 system supplied by Siemens Solar Industries (SSI) was completed in Kerman, California. This system—the nation's first grid-support application—was rated at 498 kW, 2 kW below its design rating of 500 kW. The Kerman plant was completed on schedule, 9 months after construction began and 15 months after SSI's bid was selected.

Host Systems. Nominal 20-kW systems were installed by AstroPower at a VEPCO site in North Anna, Virginia, and by IPC at two sites in New York: a NYSERDA site in Farmingdale, and an NYPA site in Maspeth (Queens). At year's end AstroPower and VEPCO were negotiating remaining work and conditions for full start-up and final acceptance; this system is expected to be on-line in early 1994. Both IPC projects came on-line in late summer of 1993. Because of delays in acquiring phone lines at the sites, data acquisition activities began just before year's end at the Farmingdale site, and began in November at the Maspeth site via a cellular phone. A 200-kW US-2 system under construction by Utility Power Group (UPG) for SMUD was about 75 percent complete by the end of the year, with system start-up expected in early 1994.

Performance

PVUSA systems in Davis, Maui, Austin, and Kerman generated 1624 MWh in 1993—enough to satisfy the electricity requirements of about 270 homes. Since the project's initial generation of electricity in 1989, PVUSA systems have supplied more than 2500 MWh through 1993, offsetting the need for more than 4000 barrels of oil through conventional generation.

PVUSA systems operated at annual capacity factors averaging 20 percent, and with summer afternoon peak-period capacity factors as high as 78 percent. During the first 6 months of operation the Kerman plant had an availability of 90 percent or better, as high as any other PVUSA system.

Equipment for continuous monitoring of 12-kV line power quality was installed at the Davis and Kerman sites, and has yielded valuable information for analyzing PV system responses to varying grid conditions.

Safety

An "Injury and Illness Prevention Program" and a "Safety and Health Action Plan" were completed in October.

Technology Transfer

PVUSA staff issued 12 technical reports and papers, gave presentations and participated at several conferences, conducted two PV workshops, hosted tours for more than 750 visitors at Davis and Kerman, and continued participation on two PV standards committees.

Planning

The PVUSA team developed a near-term strategy to continue monitoring the project's existing systems, with an emphasis on technology transfer. In 1994, several workshops and major topical reports are planned in the areas of O&M, construction and safety, BOS, EMT performance evaluation, and data acquisition. The evaluation of Kerman benefits will be ongoing.

CONCLUSIONS

PVUSA is providing valuable services and information to advance utility knowledge and use of PV technology. In 1993, the project made good progress toward meeting its five objectives. Numerous lessons learned from procuring and operating nearly a dozen PV systems, some for as long as 5 years, are being applied by PV suppliers and utility users. PVUSA provides a test bed for manufacturers to field new products, encourages technology improvements and cost reductions, and serves as a channel for developing uniform specifications for utilities and the PV industry.

Based on the 500-kW Kerman and 200-kW SMUD projects, today's cost for a turnkey PV system is approximately \$8–\$9/W. The 500-kW Kerman grid-support application is demonstrating that PV systems can be installed in 9 months or less, and can be operated reliably through remote means. Early data indicate an average O&M cost of about \$0.01/kWh. This figure reflects start-up activities and is not necessarily indicative of long-term trends.

Preliminary results from special tests conducted by PG&E also indicate the Kerman PV plant provided substantial local T&D benefits during the critical peak period in summer 1993. These tests assessed local reliability benefits, voltage support, load matching, line-loss savings, power quality, and substation transformer O&M cost savings. Work to date is preliminary; a workshop and full report are planned for 1994.

O&M experience indicates that, in general, module reliability has been very good—only about 3 percent of PVUSA's O&M time has been spent on module failures, and the overall annual failure rate has been about 2.6 per 10,000 modules. The majority of the failures experienced have been related to BOS components. Wiring and connection failures, tracking system failures, and power conditioning unit (PCU) failures have required the most O&M effort.

Considerable development work remains before the next set of EMTs is ready for validation and field testing. Five of six EMT-2 and EMT-3 contracts established since 1989 have become inactive. Procurement has been slowed by funding hurdles and difficulties in meeting module performance targets and in passing factory qualification testing.

Significant difficulties have been encountered in trying to start up and maintain each US system's PCU. Problems have been encountered with overheating, responding to grid transients, and achieving acceptable power quality. Limited availability of commercial PCUs for large-scale PV applications mirrors the limited market utilities have presented for these products. Major initiatives to develop performance standards, encourage cost reductions, and improve reliability and power quality would boost the commercial use of PV systems.

Because procurement and installation of most systems were completed in 1993, PVUSA will shift its focus in 1994. In the coming year a significant part of PVUSA's efforts will be focused on technology transfer and production of a series of technical reports and workshops.

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Section 1
INTRODUCTION

The following section provides information on PVUSA's goals and scope, technologies, project sites, schedule, participants, and funding.

BACKGROUND

With the cost of photovoltaic (PV) modules continuing to decline and environmental awareness increasing, PV could be a significant source of power within the next decade. However, acceptance of this technology by the utility industry requires knowledge of PV operational characteristics in a utility system and confidence in predicting the performance, reliability, and lifetime economics of PV.

PVUSA is a national public-private partnership that is assessing and demonstrating the viability of utility-scale PV electric generating systems. PVUSA offers utilities the hands-on experience needed to evaluate and utilize 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 laboralories, and the PV industry that will be necessary for successful development and commercialization of utility PV systems. The specific objectives of PVUSA are

- To evaluate the performance, reliability, and cost of promising PV modules and BOS components side-by-side at a single location
- To assess PV system operation and maintenance (O&M) in a utility setting
- To compare PV technologies in diverse geographic areas
- To provide U.S. utilities with hands-on experience in designing, procuring, and operating PV systems
- To 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 yet been field tested. The 20-kW size of the EMT arrays was selected to demonstrate ease of manufacture and allow a statistically credible evaluation, while minimizing the risks associated with a new technology.

PVUSA is fielding 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 scale-up. The lessons learned by manufacturers are important input for PV technology commercialization decisions. EMTs also allow PVUSA to establish baseline information regarding 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 full array. In addition EMTs have provided PVUSA with the opportunity to create and establish procedures for performing and tracking O&M costs for PV systems, which were then used as a basis for developing corresponding procedures for US systems.

US systems offer valuable information for utilities. 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. The US 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 satisfactory system protection requirements, installation requirements and costs, system performance, O&M costs, and grid interaction. These systems incorporate innovative BOS designs that are expected to lead to cost-effective approaches for utility applications. They also provide both the project participants and the PV industry with experience in commercial procurement and construction practices.

One US system (US-2 Kerman) has been strategically sited within a utility's distribution system to allow detailed study of the impact of PV on the local grid. This grid-support system will allow verification of several potential benefits of distributed PV as well as 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 located at PVUSA's main demonstration site in Davis, California, shown in **Figure 1-1**. In addition a 500-kW US system has been installed near the town of Kerman, 15 miles west of Fresno, California. In this grid-interactive configuration the PV system operates in parallel with the utility's 12.47-kV service, supporting a transformer bank in the Kerman substation. The focus of the Kerman installation is to evaluate the costs and benefits of distributed PV generation that is strategically located in an electric transmission and distribution (T&D) system. **Figure 1-2** shows the Kerman site.

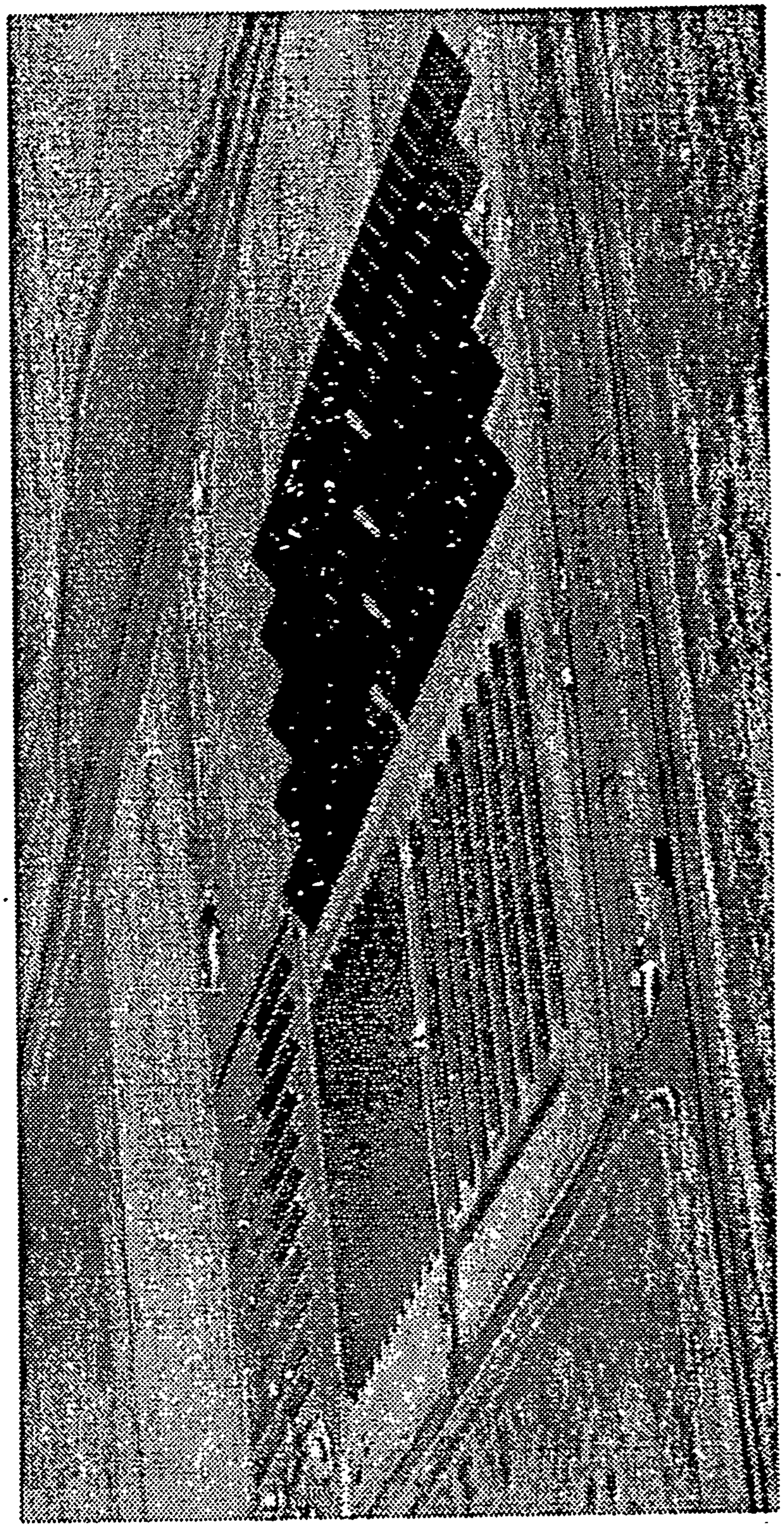


Figure 1-1
PVUSA Davis, September 1992

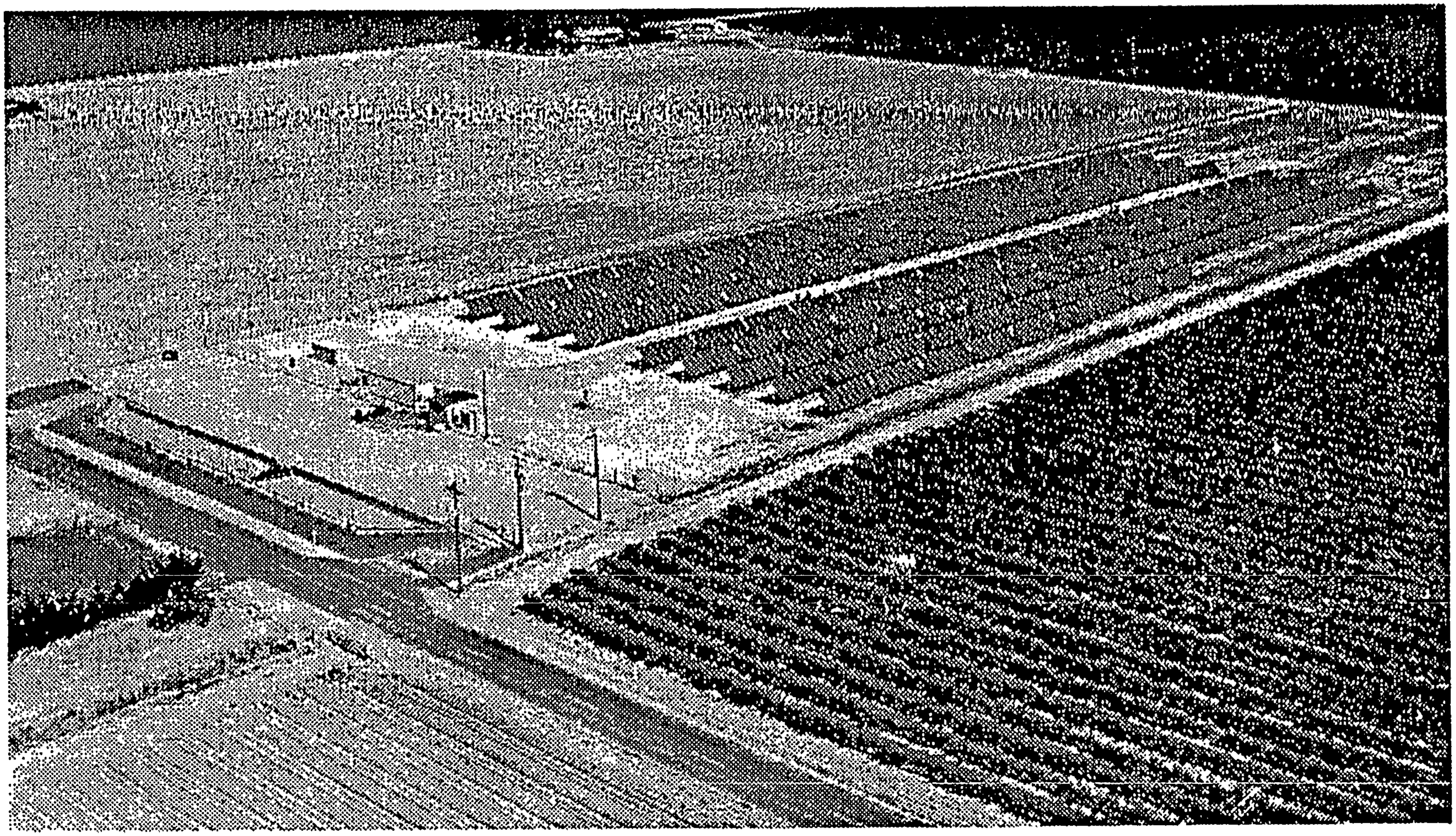


Figure 1-2
PVUSA Kerman, January 1993

In addition to the Davis and Kerman sites, several utilities are hosting PVUSA systems in their service territories. PVUSA also cooperatively monitors other PV systems of utility interest. Maui Electric/State of Hawaii installed an 18.5-kW dc EMT system in 1989, and the City of Austin, Texas, completed installation of a 17.9-kW ac US system in 1992. In 1993, 20-kW systems were installed by Virginia Electric Power Company (VEPCO), New York Power Authority (NYPA), and the New York State Energy and Research Development Authority (NYSERDA), and a 200-kW system is being installed by the Sacramento Municipal Utility District (SMUD). In addition Central and South West Services (CSWS), the Public Service Company of Colorado (PSCC), and the Department of Defense (DOD) have indicated they intend to host PVUSA systems. **Tables 1-1, 1-2,** and **1-3** show PVUSA EMT, US, and host system suppliers; completion dates; PV technologies employed; and system efficiencies and sizes.

PVUSA suppliers include:

- Advanced Photovoltaic Systems (APS)
- AstroPower
- ENTECH
- Golden Photon (GP)
- Integrated Power Corporation (IPC)
- Siemens Solar Industries (SSI)
- Solar Cells, Inc. (SCI)
- Solarex
- Sovonics
- Utility Power Group (UPG)

Table 1-1
PVUSA Davis EMT Systems

Completion Date	Supplier	Technology	dc System Efficiency (%)[a]	dc Power (kW)[a]
	EMT-1			
1/89	Siemens Solar (ARCO)	Microgridded single-crystal silicon	11.1	18.7
6/89	Sovonics-Davis	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			
3rd Q/94[b]	AstroPower	Thin-film polycrystalline silicon on ceramic	7.4[c]	19.3[c]

a Based on PVUSA Test Conditions (PTC) and total array area, where PTC are defined as 1000 W/m^2 plane of array irradiance, 20°C ambient temperature, and 1 m/s wind speed. (For concentrators, a direct normal irradiance of 850 W/m^2 is used.)

b PVUSA estimate. AstroPower made extensive product changes in 1993. A new schedule has not been issued.

c Based on supplier's estimate (system yet to be accepted by PVUSA).

Table 1-2
PVUSA Davis and Kerman US Systems

Completion Date	Supplier	Technology	ac System Efficiency (%)[a]	ac Power (kW)[a]
	US-1			
2nd Q/94[b]	Siemens Solar	Single-crystal silicon, one-axis passive tracking, Bluepoint PCU	10.0[c]	174[c]
2nd Q/93	Integrated Power Corp.	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.0	196
3rd Q/92	Advanced Photovoltaic Systems	Amorphous silicon, fixed tilt, APS PCU	4.2	479
	US-2 Kerman			
2nd Q/93	Siemens Solar	Single-crystal silicon, one-axis passive tracking, Omnion PCU	9.8	498

a Based on PVUSA Test Conditions (PTC) and total array area, where PTC are defined as 1000 W/m^2 plane of array irradiance, 20°C ambient temperature, and 1 m/s wind speed.

b PVUSA project estimate as of December 1993.

c Based on supplier's estimate (system yet to be accepted by PVUSA).

Table 1-3
PVUSA Host Systems

Completion Date	Host Utility Sponsor	Supplier	Technology	System Efficiency (%)[a]	Power (kW)[a]
10/89	Maui Electric	Sovonics EMT-1	Tandem junction amorphous	3.7 dc	18.5 dc
1/94[b]	VEPCO	AstroPower EMT-2	Thin-film polycrystalline silicon on ceramic	7.4[c] dc	20[c] dc
7/92	City of Austin	IPC US-1	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.4 ac	17.9 ac
8/93	NYSERDA	IPC US-1	Ribbon silicon (Mobil Solar EFG), one-axis active tracking, Omnion PCU	8.4[c] ac	20[c] ac
7/93	NYPA (NREL)	IPC	Amorphous silicon	5[c]	17[c]
3/94[b]	SMUD	UPG	Single-crystal silicon (SSI), one-axis active tracking, Omnion PCU	11[c]	200[c]
3/94[b]	DOD	To be determined	To be determined	tbd	150[b]
7/94[b]	CSWS	To be determined	To be determined	tbd	100[b]
7/95[b]	PSCC	APS	Single or tandem junction amorphous silicon	tbd	50[b]

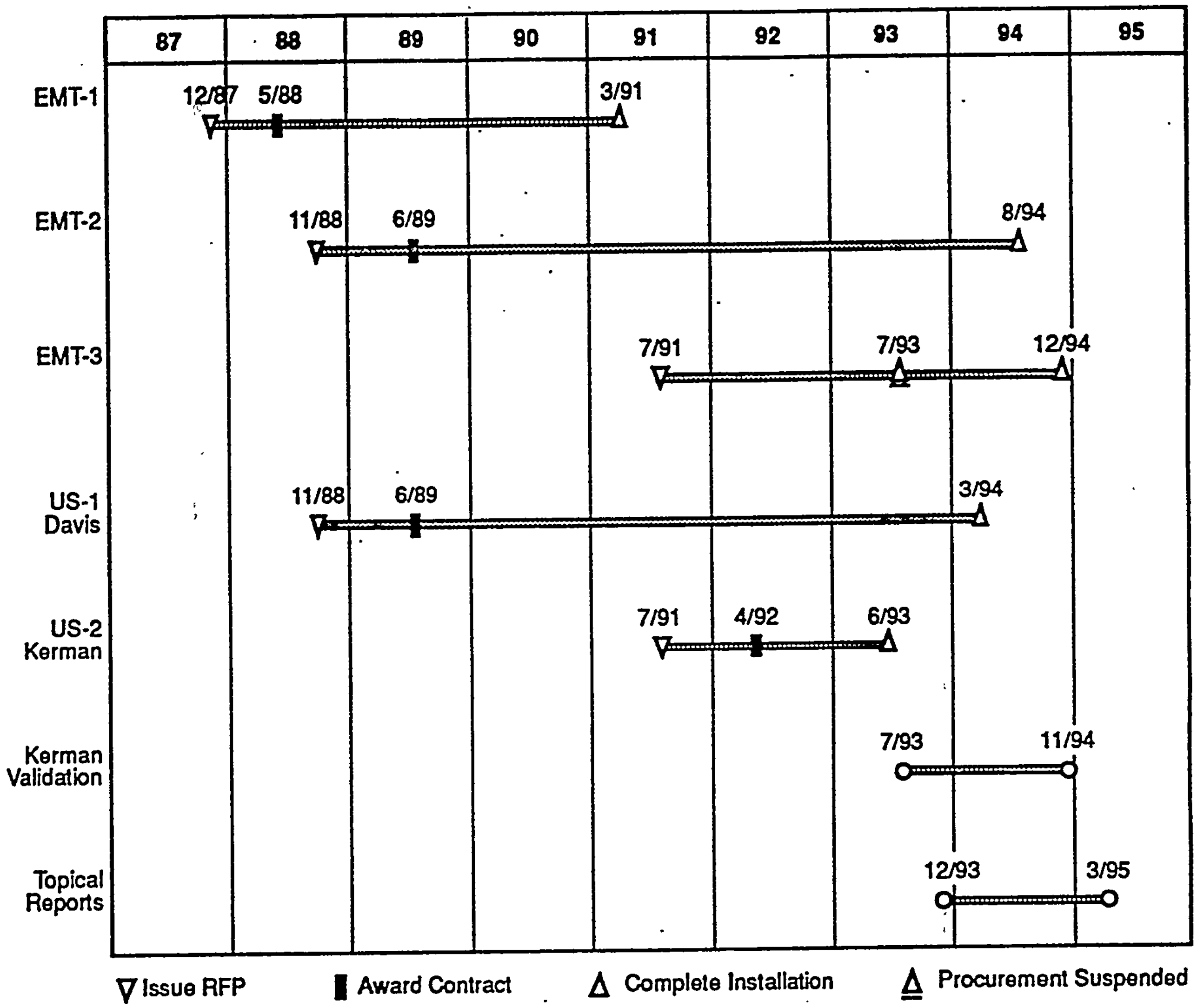
a Based on PVUSA Test Conditions (PTC) and total array area, where PTC are defined as 1000 W/m^2 plane of array irradiance, 20°C ambient temperature, and 1 m/s wind speed. Generally EMTs are rated on array dc output and USs are ac-rated (determined by contract).

b PVUSA project estimate as of December 1993.

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

SCHEDULE

Figure 1-3 provides an overall schedule of PVUSA activities, except for those of host utilities.



Completion dates do not apply to host systems.

Figure 1-3
PVUSA Overall Schedule

EMTs

At Davis, EMT-1 consists of five 20-kW (nominal) arrays. Except for AstroPower EMT-2, all EMT-2 and EMT-3 contracts have been terminated or suspended primarily because of unacceptable delays in supplier schedules. All EMT arrays are installed with PVUSA-supplied BOS components, including Delta Electronic Control Corporation (DECC) Helionetics inverters of 25-kW nominal size. The EMT-1 arrays were completed in early 1991; installation of the AstroPower array is scheduled for 1994.

US Systems

US-1 at Davis consists of a 479-kW fixed amorphous silicon system, a 196-kW active-tracking crystalline silicon system, and a 200-kW (nominal) passive-tracking crystalline silicon system. US-2 at Kerman consists of a 498-kW passive-tracking crystalline silicon system. By year's end, two US-1 systems at Davis and the US-2 system at Kerman were completed. The third US-1 system is expected to be completed in early 1994. Testing, data collection, and analysis for the Kerman benefits validation were initiated after start-up of the plant and are scheduled to continue through the summer of 1994.

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 draw together its experience in key areas. Efforts in 1994 will focus on developing certain topical reports based on the many years of experience gained. Workshops associated with these reports also are being contemplated. Monthly updates and other forms of technology transfer will continue.

PARTICIPANTS AND FUNDING

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

Government Agencies/Research Institutes

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

Utilities/Other Agencies

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

Participation by additional utilities and research organizations is encouraged. For more information please contact the PVUSA project office, (510) 866-5569.

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.

Total project expenditures are approximately $29 million (financial) **[*What does "financial" mean or refer to?*]** through the end of 1993. Project costs for 1994 are currently estimated at $2.7 million. Funding committed by PVUSA sponsors is shown in **Table 1-4**.

Table 1-4
Funds Committed Through 1993 by PVUSA Sponsors

Organization	Amount (millions of dollars)	Percent
PG&E	9.5	33
DOE	14.3	50
EPRI	3.4	12
CEC/California	1.3	4
Other Cosponsors	0.3	1
Total	28.8	100

REPORT FORMAT

This report describes PVUSA activities during 1993 and is divided into the following sections:

This section (Section 1) discusses PVUSA's goals and scope, technologies, project sites, schedule, participants, and funding.

Section 2 summarizes 1993 procurement, construction, and installation activities and discusses the Kerman system.

Section 3 describes the objectives and results of factory and field qualification tests and summarizes results of field acceptance and performance testing.

Section 4 briefly describes PVUSA's data acquisition systems (DAS) for the Davis and Kerman sites.

Section 5 provides key performance results for installed EMT-1 and US systems, summarizes overall performance for the year, and reports on energy production, efficiency, capacity factor, and system availability.

Section 6 describes major O&M activities, provides results of maintenance cost analyses, and discusses improvements to the O&M database.

Section 7 summarizes special tests, including current-voltage (I-V) curve traces, electric and magnetic field (EMF) tests, infrared camera scans, and power quality measurements.

Section 8 describes other 1993 project activities, including project planning, technology transfer, and workshops.

Section 9 provides key findings and conclusions.

Section 10 presents recommendations for future work.

Appendix A contains weather data.

Appendix B contains detailed monthly weather and performance summaries.

Appendix C contains detailed 1993 O&M summaries.

Appendix D contains information on PV systems monitored by PVUSA at various sites.

Appendix E contains a schematic of the PVUSA module qualification test sequence.

Appendix F lists technology transfer activities during 1993.

Appendix G contains definitions of technical terms and abbreviations that appear in this report.

Section 2

ENGINEERING, PROCUREMENT, AND CONSTRUCTION

No new procurement activity was initiated in 1993. In May, PVUSA's Steering Committee indicated that each pending contract needed to complete qualification testing by July 2, 1993, for PVUSA to maintain its overall schedule and remain within its expected budget. This section summarizes activity in 1993 on existing EMT-2, EMT-3, US-1, and US-2 procurements, and reviews construction activities.

ENGINEERING AND PROCUREMENT

EMT-2

- In July, PVUSA and Golden Photon (GP) agreed to terminate their contract for a 20-kW EMT-2 system because GP's schedule had slipped by more than four years. GP had been unable to complete module qualification and was in the process of restarting its operations at a new location. PVUSA indicated a willingness to open a dialogue with GP at some future date, should GP have a product to offer.

  Termination of GP leaves AstroPower as the only EMT-2 contract. In August 1992, PVUSA and SSI agreed to suspend their contract until SSI has a suitable product to offer. In November 1993, SSI informed PVUSA it was not yet prepared to offer a product, and a contract amendment was issued in December that canceled SSI EMT-2.

- AstroPower's efforts to satisfy the VEPCO requirements delayed the schedule for the 20-kW PVUSA array. The completion target slipped to November 29, 1993, and then was postponed indefinitely. AstroPower correspondence, late in 1993, indicated the possibility of a proposal to substitute AP-M7225 modules (with 225-cm^2 cells) for the AP-M38 modules (with 104-cm^2 cells) ordered by PVUSA. In late 1993, AstroPower began development of a quality assurance and control program for AP-M38 and AP-M7225 modules.

EMT-3

The EMT-3 procurement process is illustrated in **Figure 2-1**.

- Sun Power, as previously reported, withdrew from its contract in 1992.
- PVUSA notified Amonix on May 19, 1993, that PVUSA would not continue its contract past the module qualification stage due to reductions in the PVUSA program. Amonix, however, certified completion of both its module qualification and the 1-kW demonstration in June 1993.
- Solar Cells, Inc., (SCI) certified completion of its module qualification on May 5, 1993, but indicated it expected installation of its 20-kW EMT-3 system at Davis to be delayed from April 1994 to September 1994. PVUSA responded that a September 1994 delivery was unacceptable. SCI was notified in July 1993 that its contract would not be continued beyond module qualification. The notification also indicated PVUSA's willingness to open a dialogue with SCI at some future date, should SCI have a product to offer.

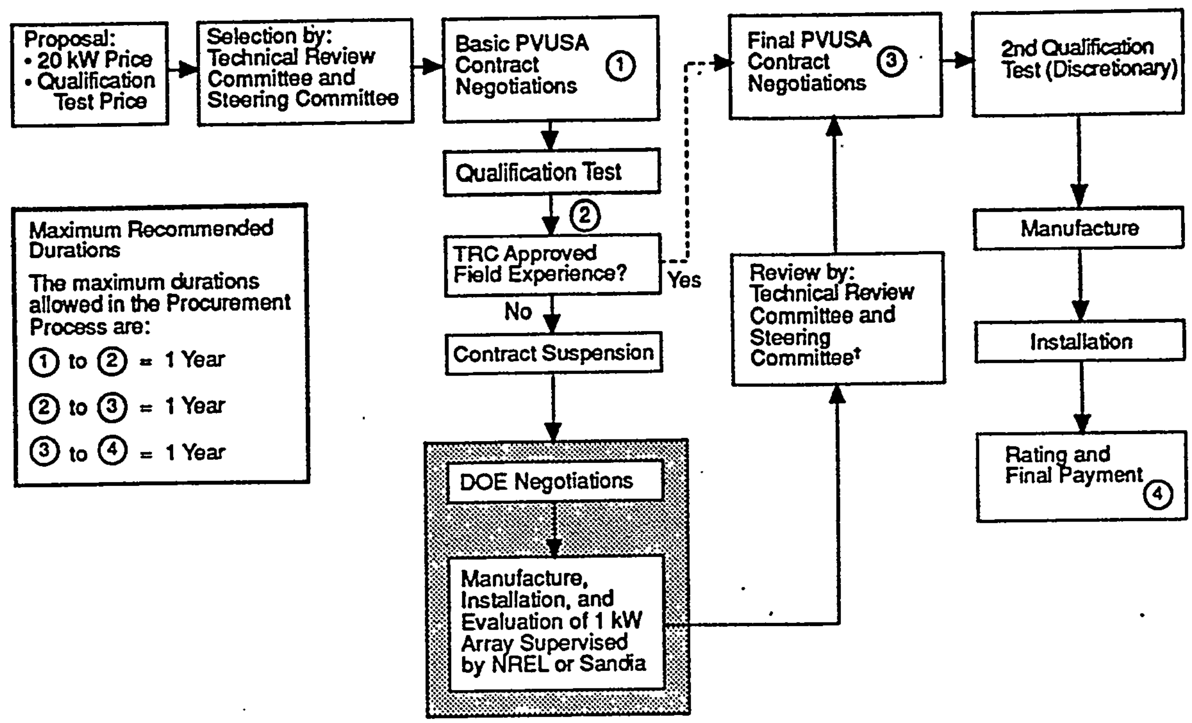


Figure 2-1
PVUSA EMT-3 Procurement Process

† Amonix notified 5-19-93 that phase ③ would not take place;
Solar Cells Inc. notified 7-30-93 that phase ③ would not take place.

CONSTRUCTION

Progress in construction was attained in the following areas:

EMT-2

No construction activity took place on the EMT-2 arrays due to continued delays by PV manufacturers.

EMT-3

No construction activity occurred for the EMT-3 arrays.

US-1 (Davis)

- SSI installed their repackaged Bluepoint Associates inverter 'A' in January, passed PG&E's functional tests, and received permission to operate the inverter unattended. SSI was unable to achieve reliable operation because of several problems with the PCU and the array. A field wet resistant test (FWRT) identified more than 60 failures involving wiring, modules, and bypass diodes. The FWRT failures may have contributed to an excessive number of ground fault trips and numerous fuse, instrumentation, and inverter component failures. SSI repaired the failures and successfully passed a second FWRT of the repaired components. SSI replaced six modules that were ruined because of failed or missing bypass diodes. Also, several dc current transducers were replaced. During late summer both the 'A' and 'B' inverters ran intermittently. Bluepoint Associates returned in October to troubleshoot and reset both PCUs. The reliability of both PCUs improved considerably during October, but questions concerning the future of the system remain. Current estimates call for closure of the contract in the first quarter of 1994.

  The R-134A single test actuator that was installed last year was replaced with the original R-22 tracking actuator, and the actuator reflectors were restored to the original galvanized steel. SSI used the test actuator in an attempt to improve cold weather performance. Other measures tried included adding heat-absorbing coatings to the evaporator tubes, varying the R-22 gas/oil ratio, and using stainless steel reflectors. No measurable improvement was obtained in cold weather performance.

- IPC completed rewiring the array's 1100 modules, which had been retrofitted with standard junction boxes in place of the original innovative interconnection disks that developed problems. The system passed the FWRT, with minor failures that were corrected. A series of initial PCU trips due to high irradiance were corrected by installing a new EPROM with modified logic for "abort power" trips. The ac and dc metering calibrations were completed before the PVUSA performance rating period (June 18 to July 17). The system was rated at 196 kW ac under PVUSA test conditions. Shortly thereafter the PCU began to trip off-line with increasing regularity, most often because of overheating. Eventually, control board "bridge fault" failures caused the PCU to shut down completely. The system was down for much of August and September and was not repaired until November 5. The problems were traced to failed circuit boards, which were replaced.

Host Sites

- NYSERDA's IPC US-1 host system was completed in early 1993. However, an agreement to parallel with the grid was not granted by Long Island Lighting Company (LILCO) until August 1993. The NYSERDA DAS is in place, but a phone line must be installed before data can be transmitted to Davis; installation is scheduled for November. NYSERDA reports the system is experiencing problems associated with its Omnion PCU tripping off-line. IPC is investigating the problem. Ascension Technology is performing data analysis for the four NYSERDA systems.

- VEPCO completed installation of an AstroPower 20-kW EMT-2 host array at their North Anna site in April 1993. The expected power is about 25 percent below target, and VEPCO delayed accepting the array due to visual defects in the modules. In November 1993, VEPCO and AstroPower reached an agreement in principle on components as a basis for accepting the array, and VEPCO has ordered a DAS in preparation for data transfer to Davis. System testing is scheduled for early February 1994.

- NREL completed installing its 20-kW IPC/USSC system at a NYPA site in Maspeth, New York, in July. The system is a rooftop mount 10° fixed tilt (vs. 40° latitude) to compensate for wind loading and roof load-bearing capacity requirements. The array contains no roof penetrations and is grid-connected to Consolidated Edison. After two months of operation, NREL indicated the system generated about 17.9 kW at 1000 W/m^2 plane of array (POA) irradiance. The NYPA DAS system was supplied by PVUSA through Southwest Technology Development Institute. A cellular phone will be used to download data to NREL.

- SMUD announced plans in June to construct a 200-kW system at their Hedge substation site. By late September the system was 50 percent completed, with completion of the array field scheduled for November. Delivery of the PCU was scheduled for early December with system start-up in February 1994.
- City of Austin has experienced nearly trouble-free operation during the fourth quarter of 1993; the exception was the need to recalculate set points for the tracker.
- PSCC has completed the PV interface diagram and IJB drawings for inclusion in the APS contract. PSCC has obtained fault current and maximum load information for their tie-in point at Fort St. Varian.
- DOD Yuma, Arizona: In late 1993, PVUSA furnished comments on the DAS portion of the draft RFP.

US-2 (Kerman)

- Construction of the PV array field was completed in December 1992. **Figure 2-2** provides a single-line diagram of the Kerman electrical system. Construction continued in early 1993 with the installation of the Omnion inverters and the 12.47-kV switchgear. Construction was completed in early April. The start-up period of 30 days was extended to 110 days due to various problems, including
  - Excessive high-frequency harmonic distortion, which was solved by adding capacitive filtering to both inverters
  - A circulating neutral current that prevented both inverters from operating simultaneously, which was solved by adding a 480-V isolation transformer between Inverters 1 and 2
  - Inverter high-temperature trips, which were solved by replacing the air conditioning units with new units of greater capacity

Details and analysis of the construction and start-up are described in a technical paper entitled "Construction of the 500-kW ac Kerman Photovoltaic Power Plant" presented at the "Power-Gen '93" conference in Dallas, Texas, on November 17, 1993. The paper addressed the following lessons learned:

- Turnkey PV plants (500–1000 kW) for grid support can be installed in 9 months, from award to commercial operation.
- With more standardized plant designs and advanced planning, the design and installation period could be significantly reduced. Advanced planning should address site selection, land acquisition, and the permitting process, and should include initial work on establishing engineering design documents. Procurement of long-lead items (e.g., PCUs, outdoor switchgear, and battery systems) also must be addressed in project planning.

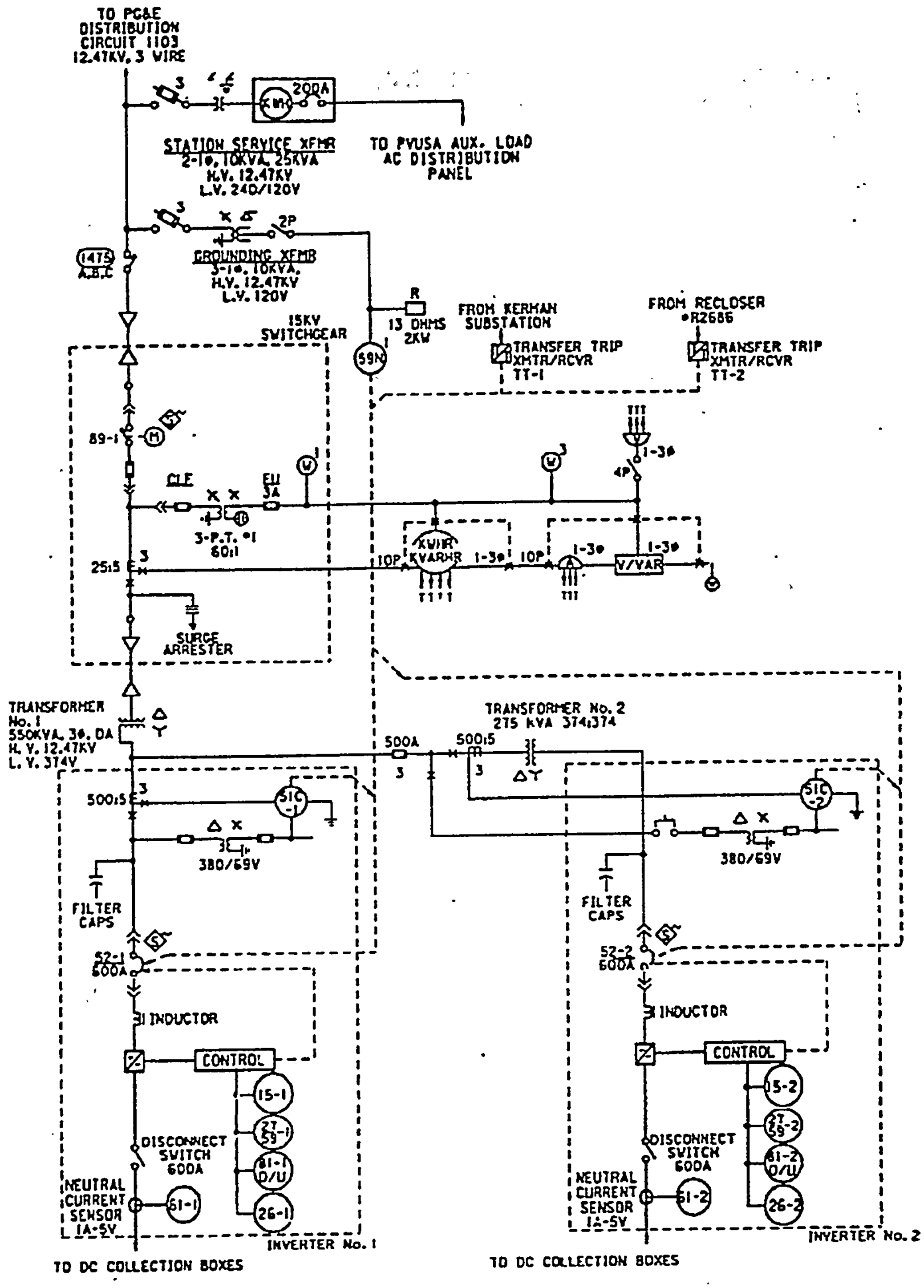


Figure 2-2
Kerman Single-Line Diagram

- The significant shortening of the schedule for the Kerman project, compared with earlier PVUSA systems, can be attributed to several key factors, including earlier and clearer definitions of system design and performance expectations, use of specific commercially proven components, and utilization of existing utility substation design standards and practices.
- A high level of review and discussion of vendor system design before system components were fabricated proved highly valuable. No modifications to the array dc system were required, although four defective modules were replaced.
- Because of the large number of mechanical and electrical components and connections, on-site quality control and inspection of installation activities proved critical.
- Support and enthusiasm from SSI and Omnion regarding design and design safety reviews, safety programs, and system testing significantly contributed to the completion of the conditional operation period on June 14, 1993.
- Incentives and penalties in commercial terms of contracts for turnkey PV systems can positively affect schedules.
- Because the availability of inverters for PV application is limited, attention should be given to the effect of required factory tests on delivery. When two or more inverters are connected in parallel, the parallel configuration should be demonstrated in factory testing before shipment. Full-load factory testing is also desirable to demonstrate the adequacy of inverter cooling at the highest specified site-ambient temperatures.
- A training program for utility operators should be developed and implemented during construction and start-up phases to provide operators with hands-on experience, promote operator confidence, and obtain valuable feedback. Safety programs also should be emphasized.

A formal dedication was held at the site on May 17, 1993 (see **Figure 2-3**), and construction activity ended with site demobilization on June 17, 1993. Intermittent site activities after June 17 included PVUSA special testing and SSI warranty repairs. A 30-day rating period ended on August 1, 1993. The Kerman plant was rated at 498 kW ac under PVUSA test conditions (PTC).

After the plant became operational, PG&E conducted a series of special tests involving the Kerman distribution feeders, Kerman substation transformers, and other adjacent substations. Data were collected through the spring, summer, and fall to form a basis for analyzing the distribution system benefits of the Kerman PV plant.

Figure 2-3
Kerman Dedication
May 1993

Section 3

FACTORY QUALIFICATION AND FIELD ACCEPTANCE TESTS

This section describes the objectives and results of factory and field qualification tests, and summarizes field acceptance and performance testing during 1993.

OBJECTIVES

To ensure the safe, reliable operation of PV technologies supplied to the project, PVUSA has developed a set of factory and field qualification tests for PV modules. These tests, which are based on existing and proposed industry standards, address module durability, reliability, electrical performance, mechanical strength, safety, and corrosion resistance. PVUSA is using experience gained through these tests to offer input to industry standards. In addition to ensuring that PV modules meet PVUSA requirements, such qualification testing also will be necessary in the long term to satisfy utilities that PV can be operated safely and reliably during lifetimes anticipated to exceed 20 years in most utility settings.

A diagram of the PVUSA factory module qualification test sequence is shown in **Figure E-1.** In addition to the factory module qualification tests, PVUSA has developed PCU factory acceptance tests. These tests provide assurance that equipment and components satisfy specification requirements, although the lack of a large dc power source usually limits the scope of PCU testing. Modification to the equipment or component, if necessary, is accomplished more effectively at the factory. PVUSA has the option to have Project Team members witness the factory tests.

Field tests include installed component inspections, array field wet resistance tests (FWRTs), array field I-V curves, a system performance test, system rating measurements, system functional tests, system power quality tests, and a preparallel test and inspection. These tests verify that installed systems and components fulfill required specifications and are ready for operation.

FACTORY QUALIFICATION TESTS

EMTs

Factory module qualification tests for EMT-2 and EMT-3 systems were conducted in early 1993. In February 1993, the PVUSA TRC directed the Project Team to establish a schedule for completion of factory module qualification testing by July 1, 1993. This schedule provided sufficient time to manufacture and install EMT systems, and will allow PVUSA to monitor and evaluate EMT systems for at least two years. The cutoff date was set as a result of delays in factory qualification tests on EMT-2 and EMT-3 modules, and those delays have affected PVUSA strategic planning and goals.

In May 1991, AstroPower received a variance on the factory module qualification tests after consultation between the Project Team and the TRC. AstroPower was required to obtain initial values of power within 20 percent of the proposed average for installed modules. AstroPower completed module qualification testing and certified results on March 22, 1993.

Amonix completed module qualification testing and certified results on June 25, 1993; however, Bechtel notified Amonix that the PVUSA SC would not exercise the option of a 20-kW array because of budget constraints.

Solar Cells, Incorporated (SCI) reported satisfactory completion of module qualification tests in May 1993. Installation of the Davis SCI EMT system was forecast for September 1994, which is unacceptable to PVUSA. Thus the project opted not to proceed with a 20-kW array.

Golden Photon (GP) was unable to meet the July 1, 1993, deadline set by the PVUSA TRC to complete qualification tests. Subsequently this contract was terminated by mutual agreement between PVUSA and GP.

PCU FACTORY TEST

On January 6 and 7, 1993, PVUSA team members witnessed factory-testing of one Omnion PCU supplied by SSI for the Kerman US-2 turnkey system. Testing of a second Omnion PCU was conducted by Omnion personnel only; PVUSA waived its option to witness the tests, and instead accepted a certified report of the factory tests.

The second rebuilt Bluepoint inverter "A" was factory-tested on January 15, 1993; testing was witnessed by PVUSA Project Team members. Because only a minimal amount of power (3 kW) was available, testing was limited to demonstrating proper operation and function of the PCU.

At both Omnion and Bluepoint, factory tests were conducted on only one of two units to be deployed in the field; the final field configuration was not simulated. In retrospect, simulating the field configuration at the factory may have uncovered problems encountered later in the field.

FIELD ACCEPTANCE AND PERFORMANCE TESTS

To verify the integrity of electrical insulation (environmental seal) for installed PV systems, PVUSA conducts a FWRT (wet megger) on the entire array before the system is accepted. PVUSA developed this test based on a similar test done at the Jet Propulsion Laboratory. In the PVUSA test the environmental seals of installed PV modules and their interconnecting wiring/components are checked by measuring the level of array leakage current. Excessive leakage current can indicate a mechanism for corrosion, and, in extreme cases, can represent a shock hazard. The test has proven to be highly effective in detecting quality control problems in manufacturing and installation processes. After the initial FWRT, PVUSA periodically repeats the test on sections of each array to ensure safe, reliable operation and detect any deterioration in system components. **Figure 3-1** shows wet megger testing at Davis.

Figure 3-1
Field Wet Resistance Testing at APS US-I

During 1993, FWRTs were conducted for the IPC, SSI, and APS US-1 systems at Davis. Results are summarized below.

IPC completed a retrofit of the module junction box and associated wiring work that was begun in late 1992. Array FWRTs were conducted in March and April of 1993. A total of 31 failures were found. Three modules had scratches on the back skin, and one had a broken conductor strip. These four modules were replaced. The remainder of the failures were due to poor junction box seals, which were resealed and retested.

In March 1993, FWRTs at SSI identified 66 failures. Fifty-four module failures involved junction box seals, 48 of which were resealed and passed retesting. Six modules were replaced because their seals could not be repaired in the field. Twelve bypass diodes that failed were replaced.

FWRTs were conducted at APS on the blue connector repairs. No failures were detected after testing a 50 percent sample of the repairs.

For Kerman, FWRTs were completed December 30, 1992. The tests identified five failures out of 12,240 modules. The failed modules were repaired or replaced.

Two US systems were completed during 1993. Before a new system is accepted, it must be shown to operate automatically according to contract specifications. In addition to the FWRT procedure, a series of functional tests are conducted to confirm proper operation. Many of the factory functional checks are verified in the field after final installation. The following areas are field tested:

- Protective relaying
- Synchronization with the grid
- Islanding
- Automatic start-up and shutdown
- Power quality
- I-V curves
- System power rating

The first four tests are functional tests conducted in conjunction with regional utility personnel before permission to parallel is given. These tests verify safety and control functions provided by the power conditioning unit (PCU), and are completed before a system is allowed to operate unattended. The final three tests are performance tests—power quality, I-V curves, and system power ratings—and are conducted during a 30-day period after a system becomes operational, or is connected with the utility distribution system to generate power (i.e., commercial operation).

Highlights of the field acceptance and performance tests for the Davis IPC US-1 and Kerman SSI US-2 systems follow.

Kerman Start-up

The PCUs for the IPC (Davis) and SSI (Kerman) US systems are based on the Omnion Model 3200. The Model 3200 consists of multiple insulated-gate bipolar transistor bridges. These bridges are connected in parallel, but firing-control logic differs between the Kerman and Davis units. In addition the Kerman system consists of two separately controlled 275-kW units operating in parallel and connected via a common transformer bus. During initial field tests the inverter neutral current became extremely high when firing of a positive pole on one PCU occurred simultaneously with firing of a negative pole on the other PCU. The problem was resolved by installing an isolation transformer between one inverter and the bus. No problems occurred on the Davis system.

Line-powered equipment exhibited sensitivity to harmonics when the first inverter was started up. This was also the last problem solved before final acceptance. The specification for harmonic distortion does not account for effects of high frequencies, generally in the firing frequency of the bridges. The high-frequency harmonics were mitigated by adding inverter filter capacitors.

Abnormal weather conditions in late spring caused a problem with inverters tripping. Rapid changes in irradiance due to cloud enhancement caused power levels to briefly exceed the inverter's 300-kW limit. The problem was resolved by modifying the control logic in the inverters and increasing the portion of array temporarily disconnected during such conditions.

An inverter filter capacitor failure occurred when the capacitor current exceeded the capacitor rating. This was resolved by installing capacitors with adequate ratings.

A problem of Inverter 1 tripping (15 trips) with an "ac overvoltage" message was caused by a cleared fuse on the neutral wire from Inverter 1 to the main transformer resulting in erroneous reference control-voltage readings.

PCU overtemperature that resulted in tripped inverters was traced to undersized air conditioning units. This problem was resolved by replacing the air conditioners with larger units and modifying control circuitry.

An Inverter 2 electronic current transducer failure occurred when loose power bus hardware that resulted in heating, coupled with small tolerances between the bus and transducer, caused the transducer to melt and short to the bus. High voltage then carried into the control boards, damaging several circuit boards and the transducer.

Several array problems were traced to loose factory wire connections.

Three 60-A fuses in the dc source circuits opened. Although the cause is unknown, the fuses were replaced.

Power Quality

During 1993, power quality tests were conducted for the Kerman SSI US-2 and Davis IPC US-1 systems. Both systems met contract requirements based upon IEEE 519 recommendations for power quality. The IEEE recommendation for harmonics was adopted by the project as a minimum requirement. The performance parameters appear in **Table 3-1**. Power quality testing of Davis IPC was carried out quickly and with acceptable results using a BMI 3060A, the industry test equipment standard. Initial test results at Kerman were within acceptable limits. However, customer complaints about high-frequency "noise" required additional testing, installation of filter capacitors, inverter rework, and retesting to confirm acceptable performance.

Table 3-1
1993 PVUSA Power Quality Tests on SSI Kerman and IPC Davis Systems

Parameter	Required Values	SSI's Values[a]	IPC's Values
Current			
THD[b]	≤ 5%	4.1%	2.4%
Any single harmonic	≤ 3%	2.5%	Not Available
Voltage			
THD	≤ 3%	1.8%	1.1%
Any single harmonic	≤ 1%	1.0%	Not Available
Power factor	≥ 0.95 (lagging)	Not Available	1
dc current injection	< 0.5%	Not Available	0
Phase current balance	< 0.5%	Not Available	0.2%

a Measurements taken with one power conditioning unit operational.
b Total harmonic distortion, average.

I-V Curves

Current-voltage (I-V) curves are measured for each source circuit. Contractors are notified of any anomalies detected in the curves. Often variations in a curve indicate the location and type of failure. If possible, the contractor is directed to the module or group of modules where the problem is located. Davis IPC I-V curves taken August 30, 1993, did not disclose any failures. Kerman I-V curves showed several module problems that were verified with a clamp-on current gun. Subsequent module replacement resolved the problems. Some of the modules were connected by wire terminal screws with stripped threads. These poor connections (wire terminations) were factory connections, and field repairs were made by the contractor. Other module problems included open circuit modules that had not been detected previously. (See also discussion in Section 7.)

System Power Ratings

After a contractor has completed a system, PVUSA imposes a 30-day conditioning period to perform "shakedown" tests, calibrate instruments, and stabilize module power. The final step before acceptance of an EMT or US system is then a 30-day performance test period. During the performance test period, data are gathered to determine the system rating. Sufficient data are collected to provide a statistically meaningful database upon which a nonlinear regression is made. System power output is determined as a function of irradiance, ambient temperature, and wind speed. Screening criteria are applied to the data set to ensure sufficient clear-sky irradiance data are recorded during the performance period.

PVUSA calculates expected power from a PV system by normalizing to PVUSA test conditions (PTC), where PTC are defined as 1000 W/m^2 plane of array (POA) irradiance, 20°C ambient temperature, and 1 m/s wind speed. For concentrators, a direct normal irradiance of 850 W/m^2 is used. The PTC power rating is one factor considered in determining the payment a supplier receives.

PTC power ratings are lower than power ratings under standard test conditions (STC) because during field operation cell temperatures are usually 20°C or more above STC temperatures. STC are defined as 1000 W/m^2 POA irradiance, 25 or 28°C cell temperature, and air mass 1.5 spectrum. For concentrators, a direct normal irradiance of 850 W/m^2 is used.

The Kerman SSI US-2 and Davis IPC US-1 systems were rated in 1993. Based on data collected during June and July, the Kerman system was rated at 498 kW under PTC, 2 kW under its design rating, and was accepted in December. Based on data collected during June and July, the Davis

IPC US-1 system was rated 196 kW PTC, exceeding its contractually required power rating of 180 kW. However, the system's performance was subsequently limited by various problems with its Omnion PCU. A 2 percent power loss from an apparent control board problem affected data recorded at the end of the performance period. Shortly thereafter the PCU experienced frequent control-related failures during operation. Frequent nuisance trips eventually required manual shutdown and a request for warranty service from IPC. Warranty repair work is ongoing, and data and system performance are presently being evaluated for winter cloud effects.

To model the instantaneous output of a system under any ambient conditions, PVUSA uses the equation shown below (**Equation 3-1**) to model PV power as a function of POA irradiance, ambient temperature, and wind speed (measured at 10 m above ground). The equation has two principal uses: to calculate expected power under PTC for vendor acceptance tests, and to track variations in PTC performance over longer periods.

The useful range of Equation 3-1 depends on the linearity of the system with respect to changes in irradiance, ambient temperature, and wind speed. The range is also dependent on the distribution of conditions that make up the data set. PVUSA has found this model to be accurate for rating systems under PTC, especially when the data set has a concentration of samples with conditions near PTC.

Equation 3-1 describes ac power as a function of POA irradiance, ambient temperature, and wind speed. A linear regression is performed on test data to determine the constants a, b, c, and d. With these constants known, the ac rating is calculated by evaluating Equation 3-1 at PTC.

$$ac_{power} = I_{POA}(a + bI_{POA} + cT_{amb} + dW) \qquad (3\text{-}1)$$

where
ac_{power} = power, kW
I_{POA} = POA irradiance, W/m^2
T_{amb} = ambient temperature, °C
W = wind speed, meters/second
a, b, c, d = regression constants derived from operational data

Table 3-2 shows coefficients derived from regression analysis for the 30-day performance period for Davis IPC US-1 and Kerman SSI US-2. The last column of Table 3-2, r^2, is the statistical coefficient of determination. Its value ranges from 0 to 1.00 and is an indicator of how well the fitted equation describes the actual data. Values greater than 0.90 generally indicate a satisfactory correlation between the equation and the actual data.

Table 3-2
Power Equation Coefficients for Two US Systems

System	Coefficient A	Coefficient B	Coefficient C	Coefficient D	PTC Rating	r^2
IPC US-1	282.14	-70.152	-0.89798	1.5824	196 ±3 kW	0.98
SSI US-2	701.1	-142.2	-3.384	6.412	498 ±6 kW	0.97

Section 4
DATA ACQUISITION AND ANALYSIS

This section briefly describes PVUSA's data acquisition systems for the Davis and Kerman sites.

Data acquisition for PVUSA is centered at Davis. The Davis system consists of a network of Campbell Scientific (CSI) data loggers—one for each PV system, one for the solar/weather instruments, and one for utility grid monitoring. Monitoring at other PVUSA sites is performed by remote Campbell data loggers that communicate with the Davis site via a telephone modem.

Additional high-frequency utility-line monitoring is provided by a BMI 8010 PQNode. PQNode data are handled separately from other data collected through the Campbell data loggers. Snapshot 12-kV line data are sampled by exception to defined thresholds or when triggered manually.

Data channels are scanned every five seconds and averaged over 10 minutes. Five-second sample data from the Davis site are displayed on a central computer screen (data acquisition computer, or DAC). Ten-minute average data are relayed to the DAC every 20 minutes and appended to daily files for each site. Remote systems are automatically polled once each night to transfer the previous 24 hours of data.

The Davis data loggers for all EMT systems monitor 24 channels with each data scan. For the US systems a greater number of channels depending on system configuration are monitored, using expanded data loggers capable of scanning more than 100 input signals.

The data acquisition system (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. The DAS also monitors several status signals on each PCU, including on/off status, error off, recycle, and a 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.

PVUSA is upgrading the DAS to allow more effective monitoring of existing and future EMT and US installations; the upgrade is scheduled for completion in early 1994. Activities completed in 1993 include installing an Ethernet local area network, a Magneto Optical drive system, and a master database; and converting to Windows™-based, object-oriented programming techniques. Remaining tasks include installing one additional computer, reconfiguring existing machines, developing additional real-time display software, and providing training for project staff in SQL and DAS systems.

The Windows for Work Groups™ environment makes it possible to network the Davis site computers, enhances the system's architectural flexibility, and improves productivity. The new database system uses SQL to merge data from all project sites into a single database. SQL permits users to develop ad hoc queries for studying aspects of various systems' performance. (In the past, few custom queries were done because of the time required to perform nonstandard calculations.) In addition SQL allows various reporting functions to be automated with pull-down menus. Sample queries are shown in **Figures 4-1** and **4-2**.

Query Result Window

Result Edit

Acronym	Latitude	Longitude	Timezone	Description
MAUI	20.75	156.44	10	Maui Host Site
DAVIS	38.58	121.73	8	The main PVUSA site
NYSERDA	40.66	73.62	5	Host Site: New York State Energy Research and Development Authority
AUSTIN	30.3	97.7	6	Austin Convention Center PV Host System.
KERMAN	36.76	120.04	8	Kerman US-2
VEPCO	38.07	77.8	5	Virginia Power Host System

Figure 4-1
Results of Ad Hoc Query: Site Information

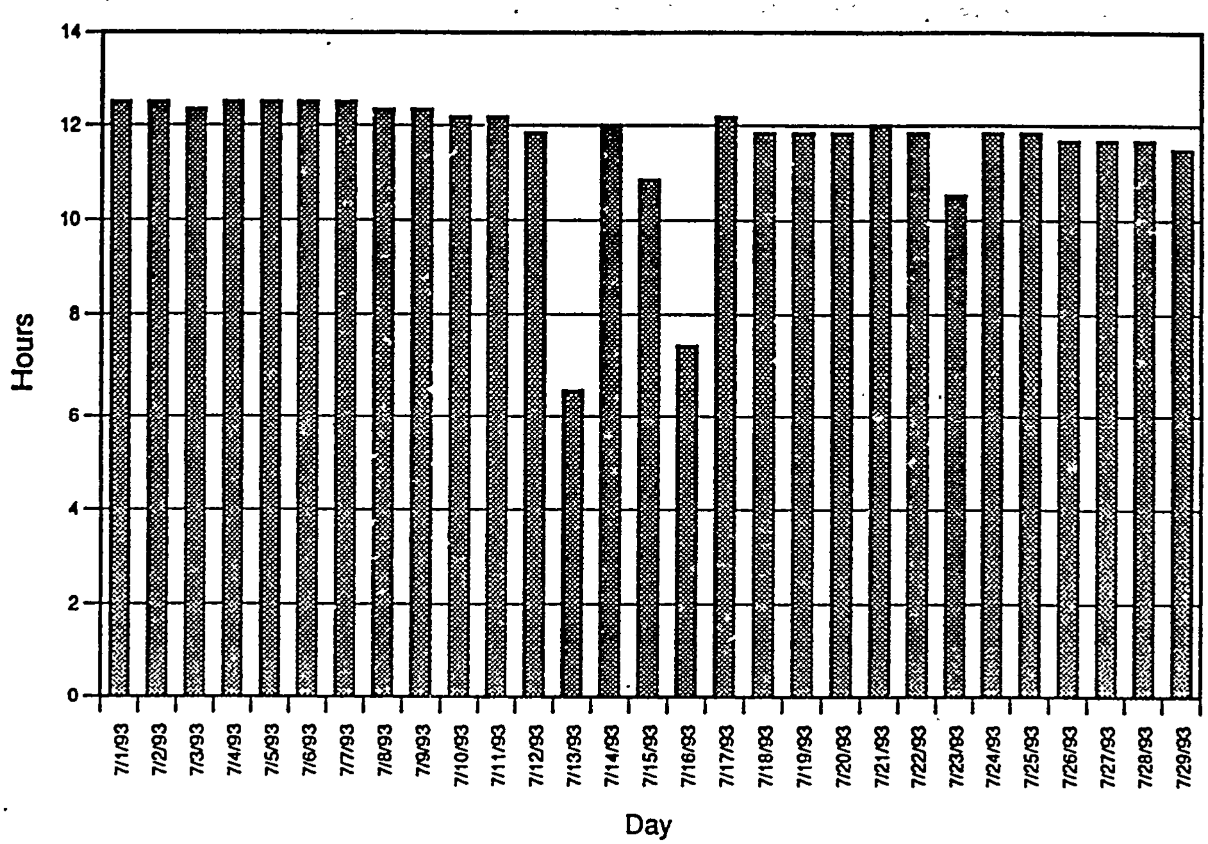


Figure 4-2
Results of Ad Hoc Query: Kerman PCU Availability

Unlike the Davis systems, the Kerman US-2 installation utilizes the PG&E's Supervisory Control and Data Acquisition (SCADA) network. The Kerman SCADA system is a state-of-the-art, utility-grade system that facilitates integration of PV systems into the utility grid. A schematic of the Kerman system appears in **Figure 4-3**. SCADA allows operator functions and data acquisition and monitoring to be performed remotely; operator functions are routinely performed from the Fresno distribution operator's office. An additional feature of the Kerman SCADA system is that it allows O&M personnel to locally monitor system performance for troubleshooting purposes by plugging a laptop computer into the main SCADA unit.

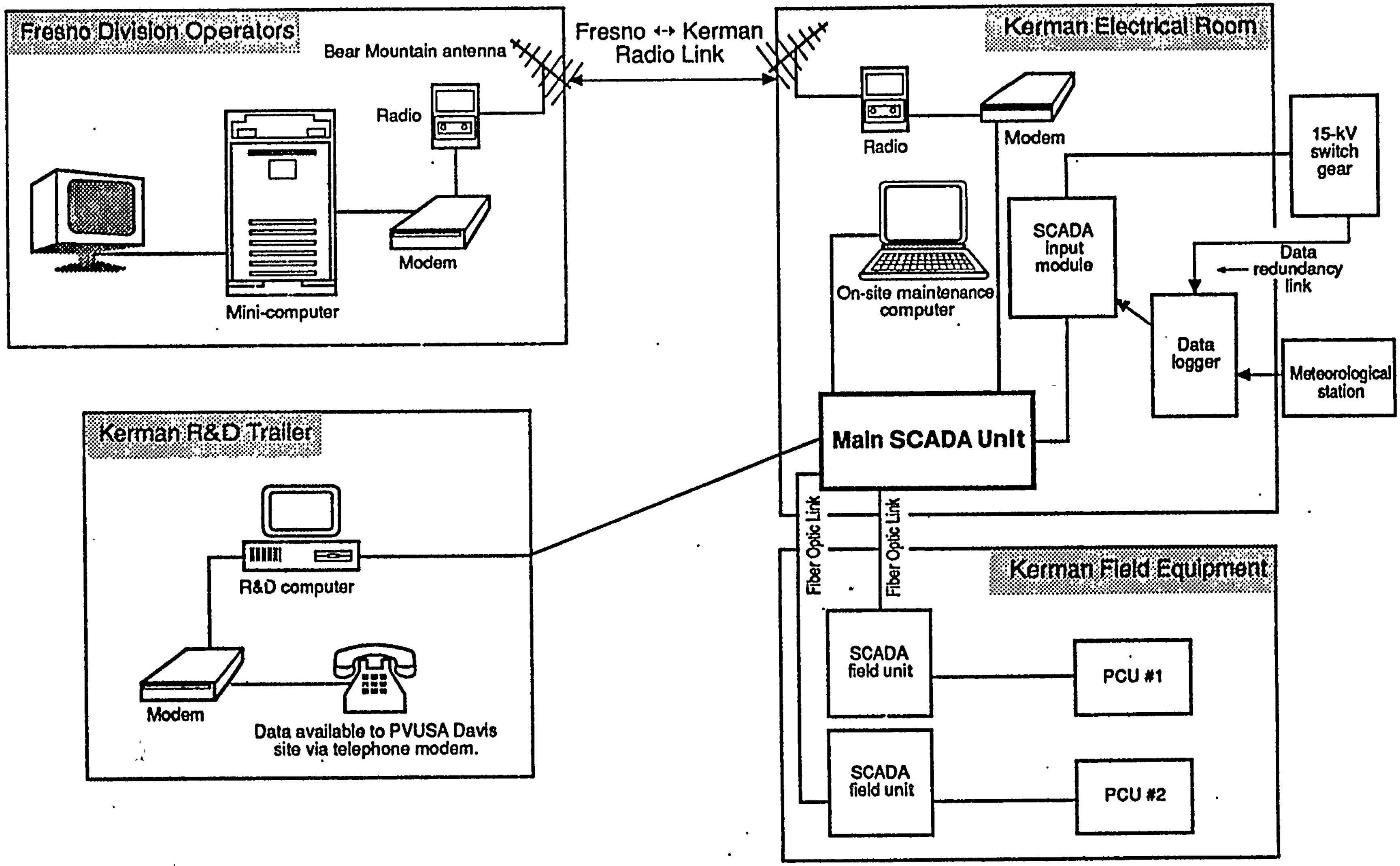


Figure 4-3
Kerman SCADA system diagram showing radio link to Fresno and simultaneous R&D data acquisition.

The main SCADA unit at Kerman, which is located in the electrical room, monitors 130 data points from the 12-kV switchgear, two field units, and a meteorological station. The field units, which are located next to the PCUs and connected to the electrical room via fiber optic cable, monitor dc and ac current, voltage, power, PCU status, POA irradiance, and array temperature. Total plant ac output (watts and VARs) is redundantly monitored by a Campbell Scientific data logger, which also collects and conditions meteorological data. The main SCADA unit transmits these data to PG&E division operators in Fresno and the PG&E Research and Development database computer at the Kerman site.

Data are transmitted from the Kerman electrical building to the Fresno office via the Bear Mountain receiver station using a 900-MHz radio link, then by modem to the Fresno SCADA system. Division operators remotely monitor all system functions; they also start, stop, and reset each PCU and open or close the 12-kV disconnect.

At the same time data are transmitted to Fresno, data also are supplied to a database computer located in the research trailer at the Kerman site. Using commercially available software, the database logs data from all points every 5 seconds; 10-minute averages of these values are then computed and stored. The averages are downloaded daily via modem to the PVUSA project site in Davis, where they are analyzed with other host site data.

Operation of the combined SCADA/data collection system during the first 6 months has raised a question of data reliability. Although the SCADA system has been continuously operable and has performed well for real-time operation and control, the data files used for more comprehensive plant evaluation have contained some erroneous or missing data. Overall availability of Kerman data for the third quarter was 96 percent, compared with PVUSA's CSI equipment that continues to demonstrate 99.99+ percent availability. Due to the complex nature of processing and transmitting the data from source to user, the problem area(s) are not easily identified. PVUSA continues to investigate the cause of the data problems.

Table 4-1 shows a sample monthly summary report for all systems currently monitored by PVUSA using the SQL database and query software. With the new database, summary outputs are better presented, primarily because of the linkage between the Windows™ environment and the report generator.

Table 4-1
Monthly Summary Report of PVUSA PV Systems

PVUSA Performance Summary

12/1/93 through 12/31/93 — Printed 1/18/94 12:00 AM

Site		Minimum	Average	Maximum		
AUSTIN	Ambient Temperature (deg C):	2	15	28	Raw Weather Data Availability:	100%
	Wind Speed (m/s):	0.0	1.4	6.1	% Weather Data Used:	82%
	Global Horizontal Irradiance (W/m^2):			690.3	Global Horizontal Insolation (kWh/m^2):	65.8

System	DC Rating (kW)	AC Rating (kW)	Module Area (m^2)	Weighted Mod. Tmp. (deg C)	POA Insolation (kWh/m^2)	Captured Insolation (kWh)	Max POA Irradiance (W/m^2)	DC Energy (kWh)	DC Eff. (%)	Max DC Power (kW)	AC Energ (kWh)	Max AC Power (kW)	PCU Eff. (%)	AC Eff. (%)	AC Cap. Factor (%)	Sys. Avail. (%)	Data Used (%)	Raw Data Availability (%)
AUSTIN	19.0	17.9	212	28	83.5	17494.8	936.0	1674	9.57	18.8	1478		88	8.4	11.1		29	100

Site		Minimum	Average	Maximum		
DAVIS	Ambient Temperature (deg C):	-4	6	19	Raw Weather Data Availability:	100%
	Wind Speed (m/s):	0.0	2.5	9.8	% Weather Data Used:	80%
	Global Horizontal Irradiance (W/m^2):			587.0	Global Horizontal Insolation (kWh/m^2):	51.7

System	DC Rating (kW)	AC Rating (kW)	Module Area (m^2)	Weighted Mod Tmp. (deg C)	POA Insolation (kWh/m^2)	Captured Insolation (kWh)	Max POA Irradiance (W/m^2)	DC Energy (kWh)	DC Eff. (%)	Max DC Power (kW)	AC Energ (kWh)	Max AC Power (kW)	PCU Eff. (%)	AC Eff. (%)	AC Cap. Factor (%)	Sys. Avail. (%)	Data Used (%)	Raw Data Availability (%)
EMT1ENT	16.5	15.6	172	35	42.4	6823.2	864.0	907	13.29	19.0	1106	18.1	94	12.4	9.5	41	20	100
EMT1SOLI	15.7	15.1	182	24	77.9	14022.8	898.0	1215	8.66	13.9	1011	13.1	82	7.1	9.0	67	23	100
EMT1SOV	17.3	15.9	497	23	79.6	37316.1	911.0	760	2.04	11.8	807	11.0	90	1.8	6.8	58	45	100
EMT1SSI	18.7	18.0	169	24	77.3	12871.5	885.0	1427	11.09	16.1	1210	15.1	84	9.3	9.0	73	25	100
EMT1UPG	15.7	15.1	477	25	78.4	35596.2	895.0	1034	2.91	12.1	1002	11.7	92	2.7	8.9	76	51	100
US1APS	504.0	479.0	11520															
US1IPC	208.0	196.0	2443															

Site		Minimum	Average	Maximum		
KERMAN	Ambient Temperature (deg C):	1	8	22	Raw Weather Data Availability:	100%
	Wind Speed (m/s):	0.0	1.9	8.5	% Weather Data Used:	88%
	Global Horizontal Irradiance (W/m^2):			596.2	Global Horizontal Insolation (kWh/m^2):	51.1

System	DC Rating (kW)	AC Rating (kW)	Module Area (m^2)	Weighted Mod. Tmp. (deg C)	POA Insolation (kWh/m^2)	Captured Insolation (kWh)	Max POA Irradiance (W/m^2)	DC Energy (kWh)	DC Eff. (%)	Max DC Power (kW)	AC Energ (kWh)	Max AC Power (kW)	PCU Eff. (%)	AC Eff. (%)	AC Cap. Factor (%)	Sys. Avail. (%)	Data Used (%)	Raw Data Availability (%)
KERMAN	539.4	498.0	5075	22	59.5	297458.4	672.1	32459	10.91	332.0	30094	310.1	92	10.0	8.1	93	68	100

Site		Minimum	Average	Maximum		
MAUI	Ambient Temperature (deg C):	17	26	38	Raw Weather Data Availability:	100%
	Wind Speed (m/s):	0.0	3.3	12.1	% Weather Data Used:	83%
	Global Horizontal Irradiance (W/m^2):			916.0	Global Horizontal Insolation (kWh/m^2):	135.6

System	DC Rating (kW)	AC Rating (kW)	Module Area (m^2)	Weighted Mod. Tmp. (deg C)	POA Insolation (kWh/m^2)	Captured Insolation (kWh)	Max POA Irradiance (W/m^2)	DC Energy (kWh)	DC Eff. (%)	Max DC Power (kW)	AC Energ (kWh)	Max AC Power (kW)	PCU Eff. (%)	AC Eff. (%)	AC Cap. Factor (%)	Sys. Avail. (%)	Data Used (%)	Raw Data Availability (%)
MAUI	18.5	17.6	497	44	176.4	87169.8	1119.0	2943	3.38	17.7	2745	16.6	93	3.1	21.0	89	46	100

Section 5
SYSTEM PERFORMANCE

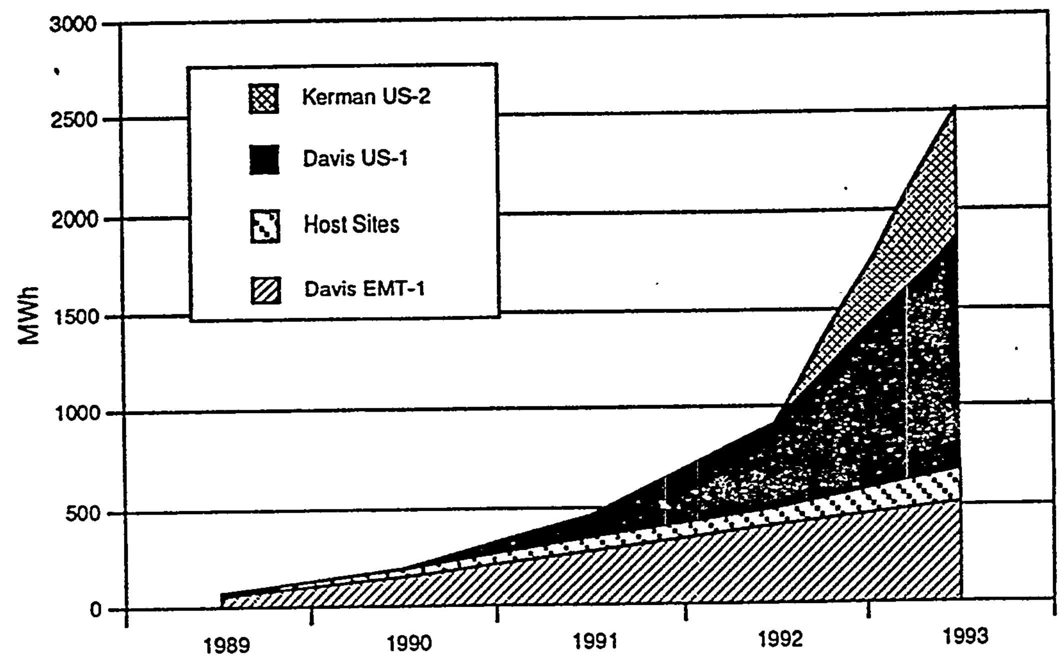
The following section discusses key performance areas for the PVUSA systems in operation during 1993: five EMT-1 arrays in Davis, California; one EMT-1 host array in Maui, Hawaii; two US-1 systems in Davis; one US-1 host system in Austin, Texas, and one US-2 system in Kerman, California. An overall summary is presented first, followed by monthly plots detailing electrical generation and insolation, efficiency, capacity factor, and availability. Two additional performance measures have been added to this report that have not been included in previous PVUSA reports: long-term efficiency degradation and solar radiation-weighted capacity factors. (These new measures are defined below in the subsections titled "Efficiency" and "Capacity Factor.") Solar radiation and weather data summarics and comparisons for Davis, Maui, Austin, and Kerman sites are included in Appendix A.

OVERALL PERFORMANCE

PVUSA's operating capacity more than doubled in 1993. The total capacity of the ten systems in operation at the Davis, Maui, Austin, and Kerman sites is now about 1300 kW. One year ago the total capacity was about 600 kW. Another 250 to 500 kW are scheduled to be installed in 1994.

Combined, PVUSA's systems at Davis, Maui, Austin, and Kerman generated 1.62 million kWh, enough to satisfy the electricity requirements of about 270 homes, based on an average residential customer load of about 500 kWh/month. The EMT-1 systems at Davis accounted for about 7 percent of this total, the US-1 systems in Davis accounted for about 49 percent, the Maui EMT and Austin US host sites each contributed about 2 percent, and the Kerman US-2 system supplied the remaining 40 percent.

Figure 5-1 depicts cumulative annual generation from 1989 through 1993. Through 1993, PVUSA's various systems had generated a cumulative total of over 2.5 million kWh (an equivalent savings of over 4000 barrels of oil for the same generation). The figure also highlights the rapid growth seen in 1993: that is, while it took 4 years to reach the 1 million kWh milestone (reached in March 1993), it took less than 6 months to reach the 2 million kWh mark. In addition, the cumulative total will have surpassed 3 million kWh before this report is distributed in early 1994.



	1989	1990	1991	1992	1993
Kerman US-2	0	0	0	0	647.626
Davis US-1	0	0	113.040	412.680	1206.926
Host Sites	5.713	35.231	62.550	93.762	154.281
Davis EMT-1	62.984	160.328	282.945	394.036	515.768

Figure 5-1
PVUSA Cumulative Energy Production

Tables 5-1 and **5-2** outline key features of each system. A 5-year performance summary for these systems appears in **Table 5-3**. Detailed 1993 monthly summaries are included in Appendix B.

Table 5-1
PVUSA Installed EMT Array Characteristics

	SSI	Sovonics *D=Davis* *M=Maui*	UPG	Solarex	ENTECH
Installation date	1/89	6/89 *D* 10/89 *M*	12/89	10/90	3/91
Orientation[a]	30° FFP	30° FFP *D* 22° FFP *M*	30° FFP	30° FFP	2-ax Trk
dc [ac] ratings (kW)	18.7 [18.1]	17.3 [15.9] *D* 18.5 [17.6] *M*	15.7 [15.1]	15.7 [15.1]	16.5 [15.6]
Number of modules	400	1200 *D,M*	4992	336	60
Module area (m^2)	169	497 *D,M*	477	182	172
Array/module area	1.01	1.02 *D,M*	1.03	1.15	2.09

[a] FFP = fixed flat plate
2-ax Trk = two-axis tracking

Table 5-2
PVUSA Installed US System Characteristics

	IPC Austin	APS Davis	IPC Davis	SSI Kerman
Installation date	7/92	9/92	6/93	6/93
Orientation[a]	1-ax Trk'	30° FFP	1-ax Trk	1-ax Trk
ac rating (kW)	17.9	479	196	498
Number of modules	96	9600	1100	12,240
Module area (m^2)	212.1	11,520	2443	5075
Array/module area	1.05	1.16	1.03	1.08

[a] FFP = fixed flat plate
1-ax Trk = one-axis tracking, horizontal N-S axis

Table 5-3
PVUSA Annual Performance Summary[a]

	System	1989	1990	1991	1992	1993
ac Energy (kWh)	SSI Davis EMT-1	33,391	34,243	31,133	29,261	29,891
	Sovonics Davis	25,034	29,037	12,087	12,181	22,758
	Sovonics Maui	5,713	29,518	27,319	28,085	32,405
	UPG	4,559	29,349	25,823	25,407	25,479
	Solarex	n/i	4,715	26,016	22,767	23,572
	ENTECH	n/i	n/i	27,558	21,117	20,032
	APS	n/i	n/i	n/i	214,508	530,047
	IPC Austin	n/i	n/i	n/i	3,127	27,790
	IPC Davis	n/i	n/i	23,640	15,600	188,541
	SSI Kerman US-2	n/i	n/i	n/i	n/i	647,626
Efficiency (%)	SSI (dc)	10.7	10.6	10.4	10.1	10.2
	Sovonics Davis (dc)	3.3	3.1	2.9	2.8	2.6
	Sovonics Maui (dc)	3.7	3.7	3.4	3.4	3.3
	UPG (dc)	n/i	3.2	3.0	3.0	2.9
	Solarex (dc)	n/i	8.8	8.2	7.3	7.4
	ENTECH (dc)	n/i	n/i	11.2	10.7	11.1
	APS (ac)	n/i	n/i	n/i	3.8	3.2
	IPC Austin (ac)	n/i	n/i	n/i	8.5	8.1
	IPC Davis (ac)	n/i	n/i	n/r	n/r	8.1
	SSI Kerman US-2 (ac)	n/i	n/i	n/i	n/i	9.1
ac Capacity Factor (%)	SSI	21.7	21.7	19.7	18.5	18.9
	Sovonics Davis	21.8	20.9	8.7	8.7	16.3
	Sovonics Maui	21.4	19.1	17.7	18.2	21.0
	UPG	n/i	22.3	19.5	19.2	19.3
	Solarex	n/i	17.8	19.7	17.2	17.8
	ENTECH	n/i	n/i	26.8	15.4	14.7
	APS	n/i	n/i	n/i	15.3	12.6
	IPC Austin	n/i	n/i	n/i	8.5	17.7
	IPC Davis	n/i	n/i	n/r	n/r	12.6
	SSI Kerman US-2	n/i	n/i	n/i	n/i	23.3
Availability (%)[b]	SSI	n/r	83	80	81	80
	Sovonics Davis	n/r	80	35	37	72
	Sovonics Maui	n/r	74	71	73	85
	UPG	n/r	86	83	85	85
	Solarex	n/r	83	76	75	76
	ENTECH	n/r	n/i	69	46	41
	APS	n/r	n/i	n/i	80	64
	IPC Austin	n/r	n/i	n/i	73	73
	IPC Davis	n/i	n/i	n/r	n/r	40
	SSI Kerman US-2	n/i	n/i	n/i	n/i	92

a Start dates are staggered; therefore, some quantities are based on a partial year's performance. Refer to Tables 5-1 and 5-2 for installation dates.

b Availability defined as the percentage of daylight hours during which a system supplies net power to the grid. This quantity not measured in 1989.

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

ELECTRICAL ENERGY PRODUCTION

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 5-2 tracks the 1993 monthly ac energy generated by the five EMT systems in Davis. **Figure 5-3** shows corresponding data for the three US systems in Davis. **Figure 5-4** shows the 1993 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 5-5** and **5-6** show the corresponding data for the Austin and Kerman systems, respectively.

Referenced to the right scale of these figures are lines showing plane-of-array (POA) insolation (this quantity includes all daylight hours—between sunrise and sunset) and the average insolation over the past several years. For Davis, the average is based on 1989 through 1993, and for Maui, the average is based on 1990 through 1993. The measured 30° tilt insolation for Davis was about 3 percent less than the 5-year average. The measured 22° tilt insolation for Maui was about 2 percent greater than the 4-year average.

For Davis, the EMT energy production pattern varies fairly smoothly between 1000 and 3000 kWh/month and averages about 1900 kWh/month. There are a few notable deviations from the insolation trend line:

- The Sovonics array's energy production is relatively low in June. At the end of May a junction box connection failed in one of the array's 1200 modules, reducing the system's power output by about 16 percent until repairs were made in mid-July.
- Repeated tracker controller failures forced the ENTECH array out of service during many of the clear hours this year, making its August generation of over 4000 kWh appear to be an anomaly, rather than the norm. The ENTECH concentrator array operates on direct normal insolation, which varies more seasonally than the global 30° tilt insolation used by the other EMT arrays. Consequently the concentrator system may typically generate 25 percent less than a comparably sized flat-plate array during the cloudy winter months, but is capable of generating 25 percent more per month during the summer. On an annual basis the direct normal insolation for 1993 was nearly equal to the global 30° tilt insolation used by the other EMT arrays.
- The Solarex array's energy production was about 14 percent lower than expected between late March and mid-July while 2 of its 14 source circuits were out of service. One circuit was lost when water intruded into an intermediate junction box, shorting several terminals and damaging diodes, terminal blocks, and wiring. Another circuit was inadvertently left switched out following troubleshooting of the junction box failure. Both circuits were restored in mid-July.

- Each array's generation was about 11 percent lower than expected in May. Nearly four days' data were lost during the Memorial Day weekend as a result of a malfunction in the DAS.

Of the Davis US systems shown in **Figure 5-3**, only the APS system was in operation for the full year. The IPC system was completed in June, and the SSI system was available for only limited periods while start-up and testing activities continued. The upper insolation trend line corresponds to the IPC system's one-axis orientation, and the lower insolation trend line corresponds to the APS system's fixed 30° orientation.

The generation patterns of the APS and IPC systems are not consistent with their insolation trends. The APS system has been vulnerable to fluctuations and transients on the 12-kV distribution line that serves the Davis site. It tripped off-line about ten times during 1993 as a result of 12-kV disturbances, and tended to blow several fuses with each occurrence. On several occasions other components including circuit breakers, switches, contactors, movistors, diodes, and rectifiers were damaged as well. Partial or full outages resulting from these failures significantly reduced generation in April, May, June, July, and September. APS and PVUSA are discussing ways to make the PCU less susceptible to grid-induced failures.

The IPC system began delivering start-up and testing energy in April, and the system was completed in mid-June. Unfortunately the system's Omnion PCU began tripping off-line with increasing regularity after the first month of operation, most often as a result of overheating. The system was repaired in November, but it continued to trip off-line frequently through the end of the year with dc overvoltage errors indicated. Omnion is investigating the cause of the trips.

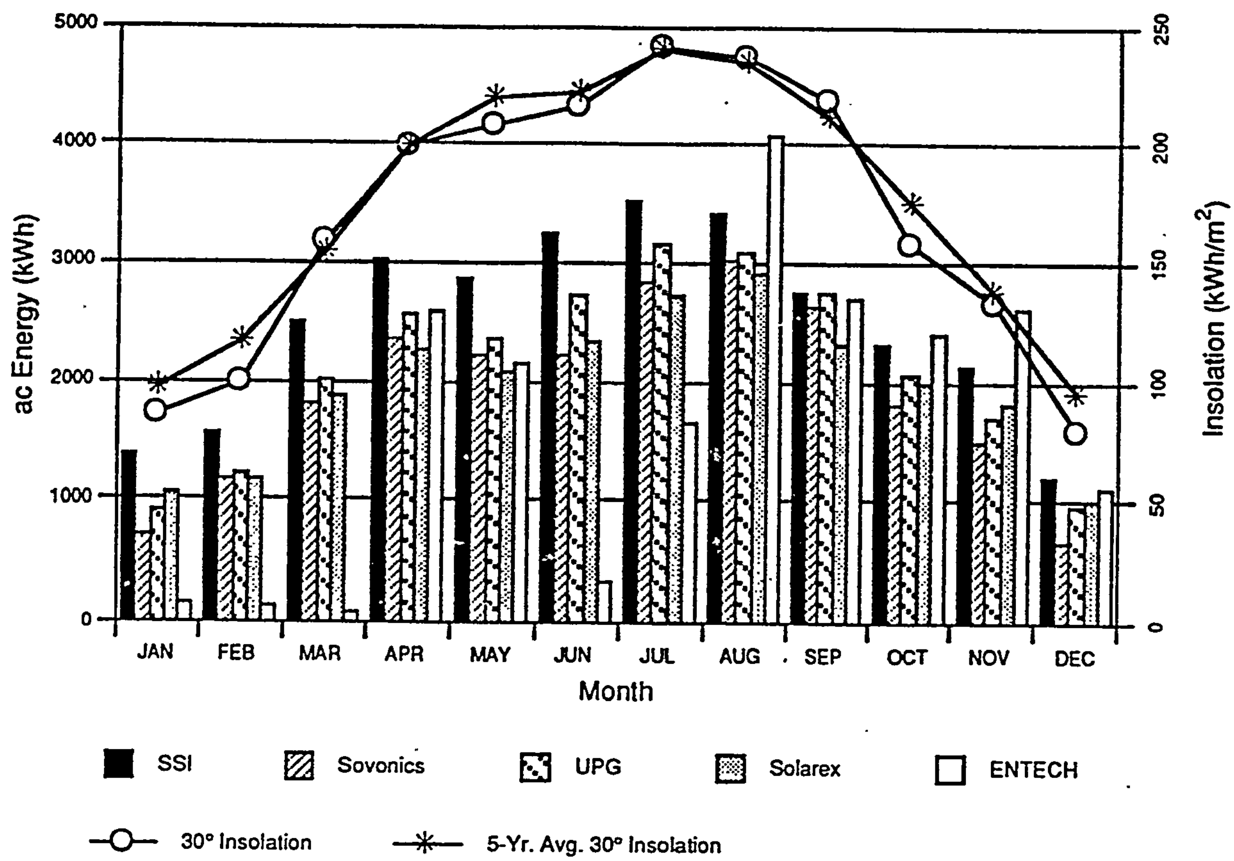


Figure 5-2
PVUSA Davis Generation and Insolation
1993 EMT Output

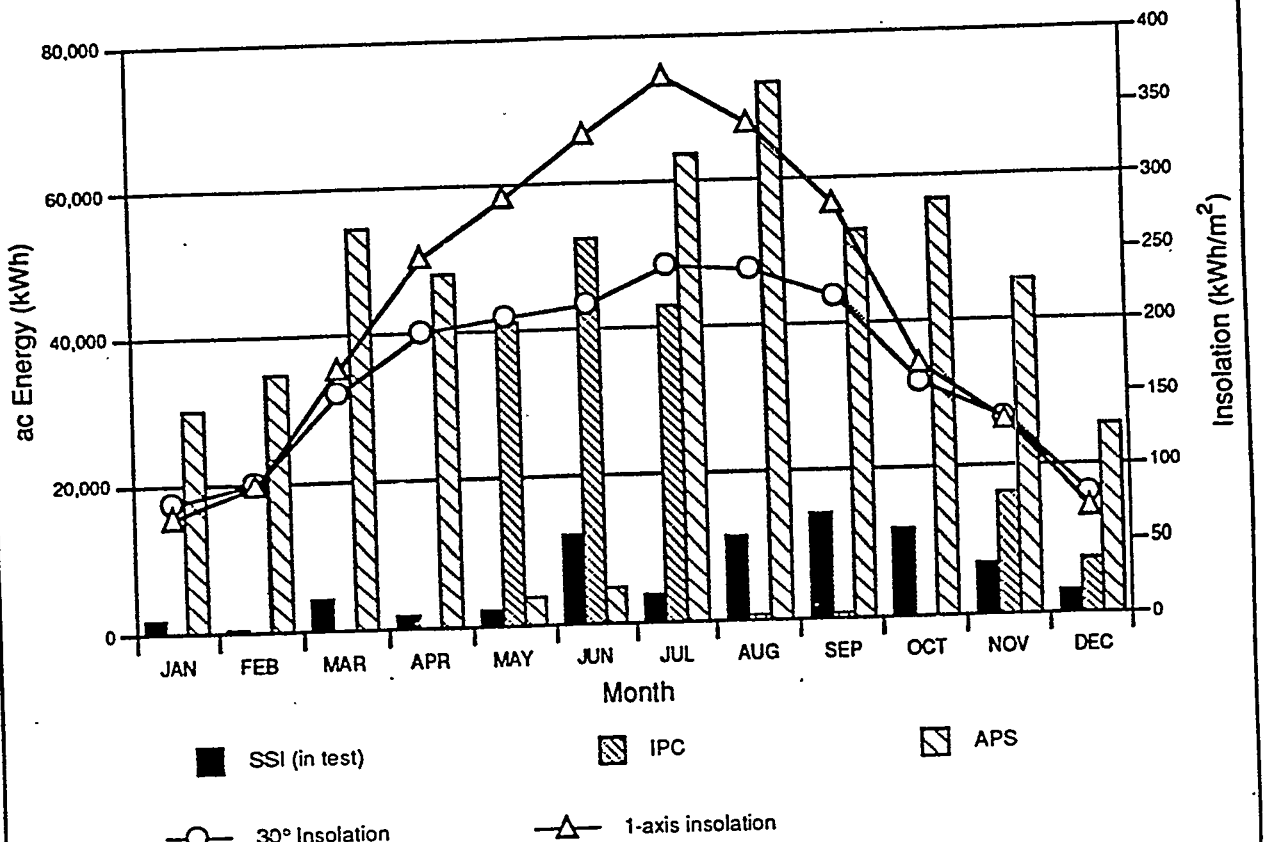


Figure 5-3
PVUSA Davis Generation and Insolation
1993 US Output

Figure 5-4 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° Maui, 38.6° Davis), Maui has less fluctuation in day length than Davis. Overall the 22° tilt POA insolation at Maui in 1993 was about 7 percent greater than the 30° tilt POA insolation at Davis, but the Maui array's generation was 42 percent greater than the Davis array. The Maui array's performance was better mainly because its average efficiency was about 29 percent higher than the Davis array. Its availability was about 18 percent higher as well.

The relatively flat monthly insolation pattern at Maui in 1993 was consistent with that site's 4-year average insolation trend. The relative heights of the generation bars and the 1993 insolation trend line indicate that generation was significantly lower than expected in only 2 months, April and July. In April the system output was about 15 percent lower than expected because of two failures of module junction boxes. In July the output was about 20 percent lower than expected because of another module failure and because the system tripped off-line for several days during the Fourth of July weekend.

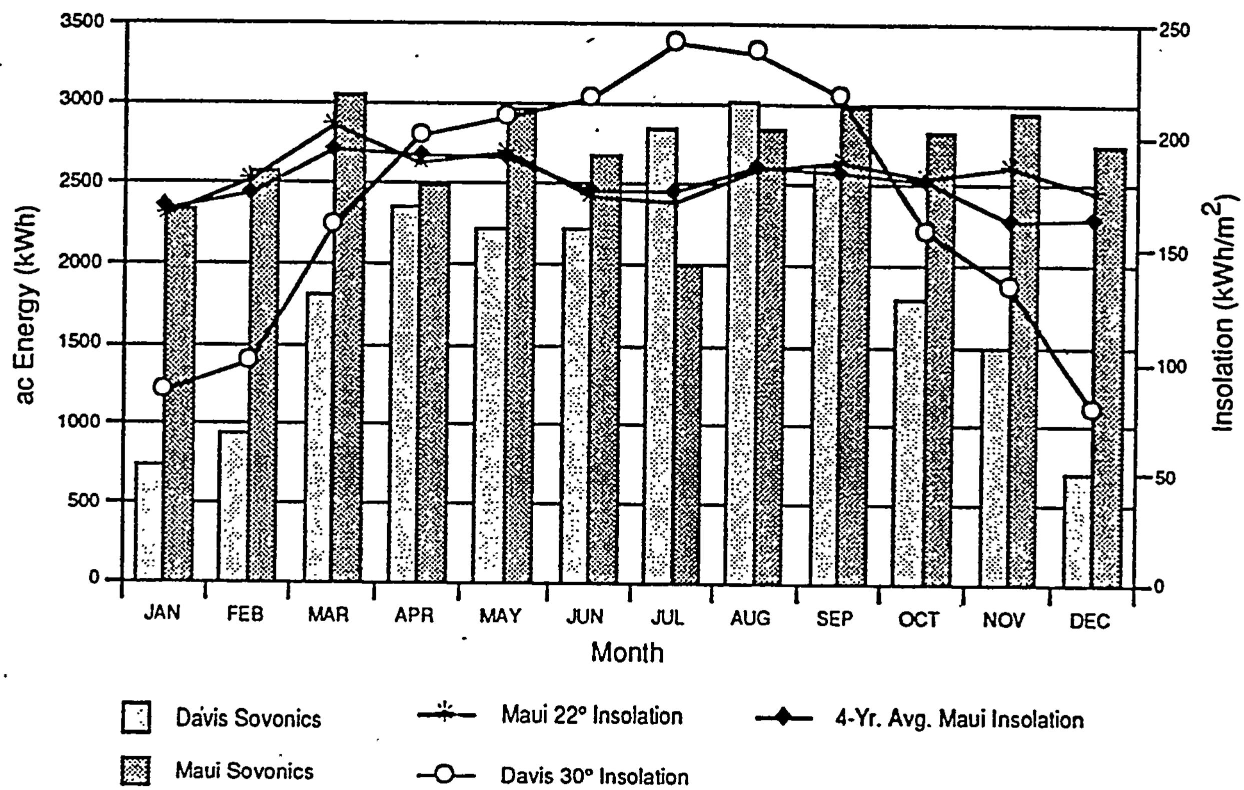


Figure 5-4
Sovonics Generation and Site Insolation
Davis and Maui, 1993

Figure 5-5 shows the monthly generation and POA insolation for the IPC US-1 system at Austin. As the figure indicates, an unusual dip occurs in the June insolation relative to the surrounding months. A detailed check of the data for that month, however, reveals no gaps or out-of-range values, just very few clear days. The relative heights of the generation bars and the insolation trend line indicate that there were 5 months with notably reduced generation: February, April, May, June, and July. The City of Austin reported several instances of partial and full outages during these months resulting from tracker controller problems, a switchgear wiring failure, and PCU shutdowns. The generation pattern during the latter part of the year was very consistent with the insolation pattern.

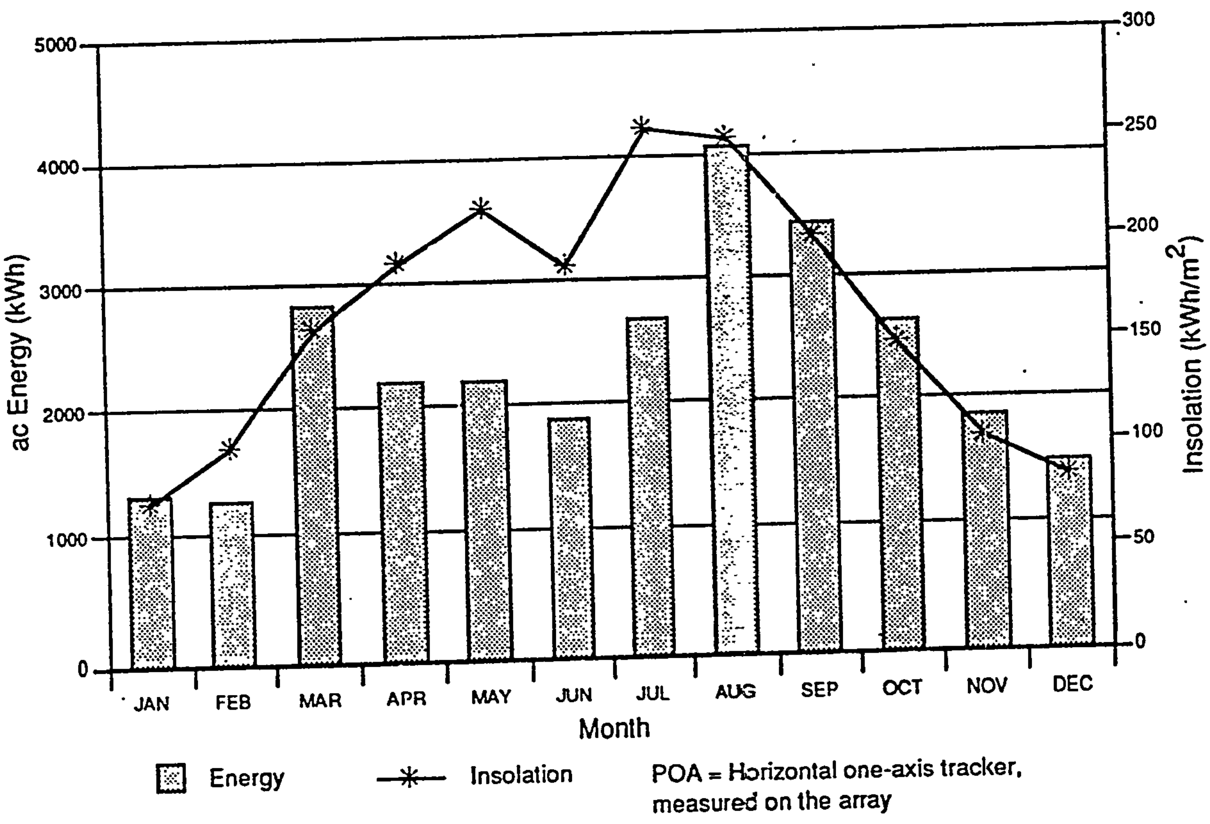


Figure 5-5
Austin Generation and POA Insolation, 1993

Figure 5-6 shows the monthly generation and POA insolation for the SSI US-2 system at Kerman. Only data beginning with the first full month of system operation are shown. (About 135 MWh were generated during start-up activities in April through June.) The overall match between the generation and insolation trends is very good. However, relative to the insolation line, there was a small drop in output in August and September due to module failures and scheduled outages for research activities.

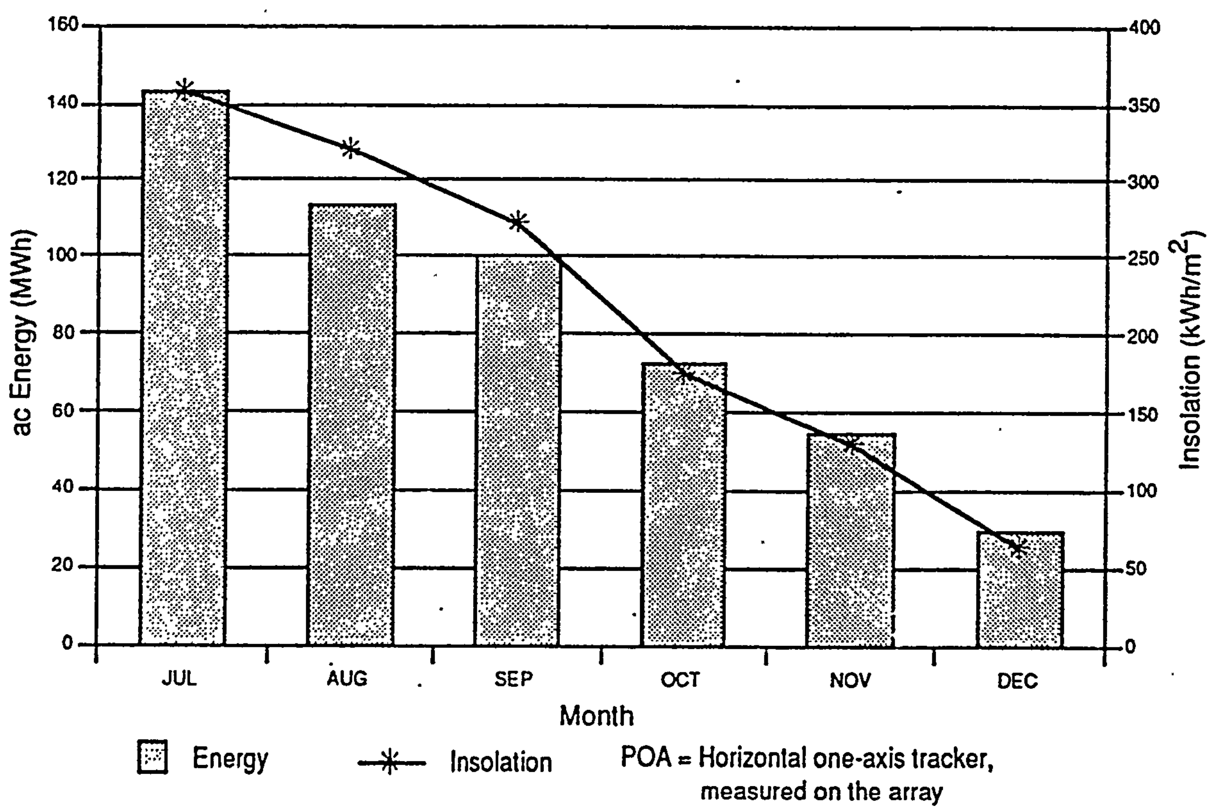


Figure 5-6
Kerman Generation and POA Insolation, 1993

EFFICIENCY

The efficiency for all arrays, except the ENTECH array, is calculated as the ratio of monthly dc (ac for US systems) energy produced to monthly POA insolation during hours when the PCU is operating. The ENTECH array, which uses a 22x concentrating lens and two-axis tracking structure, partially shades itself and its pyrheliometer during the early and late hours of the day. Therefore, its efficiency calculations are based on data collected between 9 a.m. and 3 p.m. PST, when shading does not occur. Also, the term "POA" for the ENTECH array refers to direct normal insolation. For the other arrays, POA refers to either global 30° tilt or global one-axis tracking.

Figure 5-7 shows a history of monthly average dc efficiencies for the EMT arrays. **Figure 5-8** compares estimates of long-term changes in efficiency for the EMT arrays. **Figure 5-9** shows ac efficiencies for the US systems. Dc efficiencies are reported for the EMT arrays because the emphasis is on comparing *module* performance, albeit in a grid-connected system setting. Ac efficiencies are reported for the US systems because the emphasis is on *system* performance.

In **Figure 5-7**, three groupings are apparent. In the first group the arrays with the highest efficiency, from SSI and ENTECH, are based on single-crystal silicon (Si) PV cells. They normally range between 10 and 12 percent efficiency, with the ENTECH array efficiency equal to, or higher than, the SSI array efficiency during each month that both systems have been in operation. The ENTECH array efficiency fluctuates more than the SSI array efficiency because its module temperature fluctuates more under the same weather conditions. The ENTECH array's peak efficiency of over 13 percent in January 1993 is somewhat of an anomaly because the array operated for only 18 of 299 daylight hours during the month, under very clean and cold conditions. With 5 years of data now available, the SSI array appears to be developing a slow annual decrease in efficiency. This possibility is examined in more detail below in the discussion of **Figure 5-8**.

In the second group the next highest efficiency is achieved by the Solarex polycrystalline Si array. It has averaged around 8 percent efficiency, with a seasonal variation similar to that of the single-crystal Si technologies. The apparent decline in efficiency in 1992 and 1993 is largely because the array operated for long periods during these years without 1 or 2 of its 14 source circuits. All source circuits were repaired and active as of mid-July 1993.

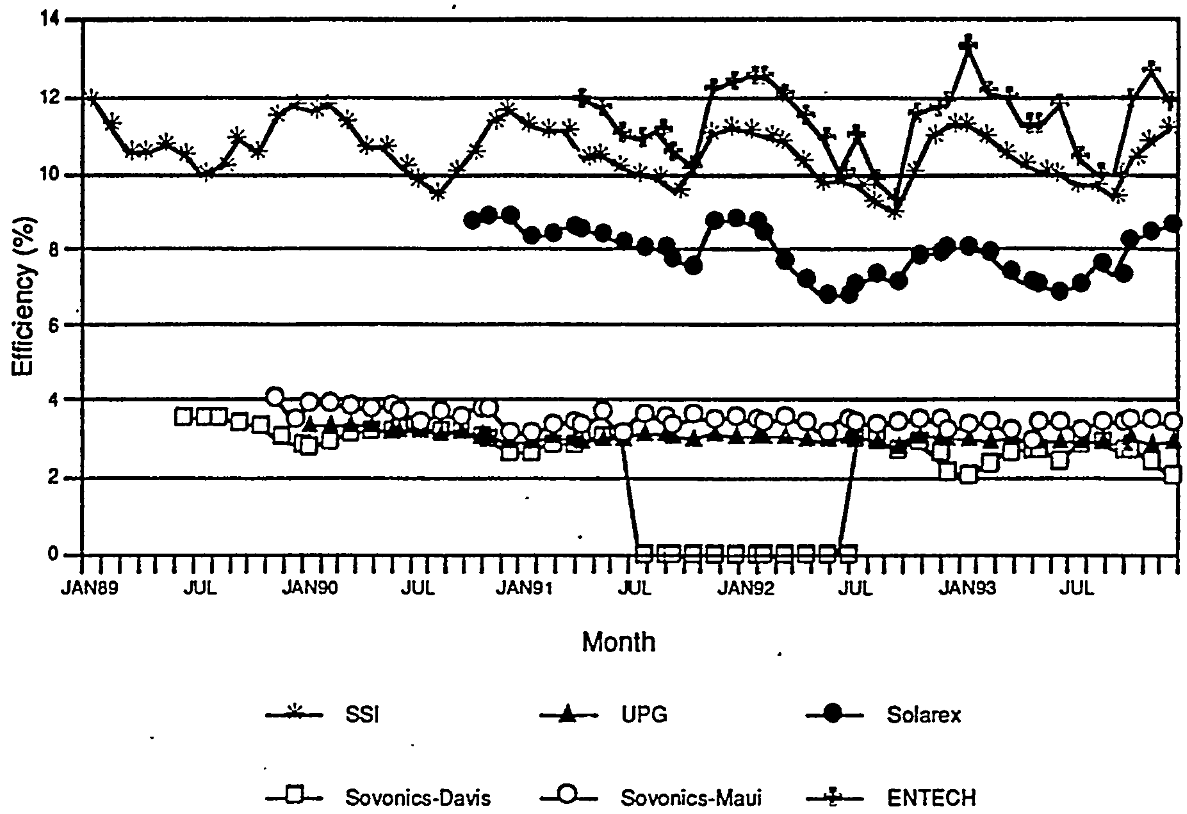


Figure 5-7
PVUSA EMT Array dc Efficiencies

In the third group the lowest efficiencies are exhibited by the three amorphous silicon (a-Si)-based EMT arrays. The Maui Sovonics and UPG arrays have demonstrated very consistent monthly efficiencies, except that the Maui array has operated at a reduced efficiency on several occasions as a result of module failures.

The Davis Sovonics array was out of service from July 1991 through June 1992. Its efficiency has also tended to fluctuate seasonally but in the opposite direction of the crystal Si technologies. This pattern may reflect the Sovonics array's sensitivity to variations in the spectral distribution of solar radiation, where a greater proportion of the ultraviolet wavelengths favored by the Sovonics technology is available in the summer. Because of its tropical latitude and consistent climate, the Maui site may not experience the same seasonal shifts in spectral distribution as the Davis site.

Another possibility is that the Sovonics array may be more sensitive to light-induced degradation that is later offset by summertime thermal annealing. This effect, however, has not been measured.

The long-term performance trends of the EMT arrays suggest degradation may be occurring at a slow rate, even for the single-crystal SSI array. **Figure 5-8** shows the results of detailed estimates of the long-term degradation of efficiency for the EMT arrays. To establish the estimates, 2 months, April and October, were chosen for each year that data were available for each array. The efficiencies for these months were adjusted from their measured energy-weighted-average module temperature to a common 45°C reference, using a temperature coefficient of 0.4 percent/°C for the single-crystal and polycrystalline Si arrays, and 0.25 percent/°C for the a-Si arrays. April and October were chosen because the arrays are normally very clean during those months, an abundance of clear days typically occur, operating temperatures are fairly cool (about 45°C), and month-to-month spectral variations are nearly eliminated. A few points were deleted due to failure-related full or partial outages, and the efficiency was adjusted upward on three of the Solarex array's months to account for missing source circuits. Also, no points were included within the first 6 months of installation for the a-Si arrays.

A straight-line fit yielded the degradation rates shown in the center of each horizontal bar. To illustrate the uncertainty associated with each estimate, the degradation rate is bounded by one standard deviation. (The uncertainty of PVUSA's dc efficiency measurements is ±4 percent.) These results indicate that, for the 3–5-year study period for these arrays, the three a-Si arrays' degradation rates are the highest, averaging about 3 percent, but these results are not very consistent. The degradation rates for the three single-crystal and polycrystalline Si arrays range between 0 and 2 percent, but these rates are too small to be considered significant or conclusive at this time.

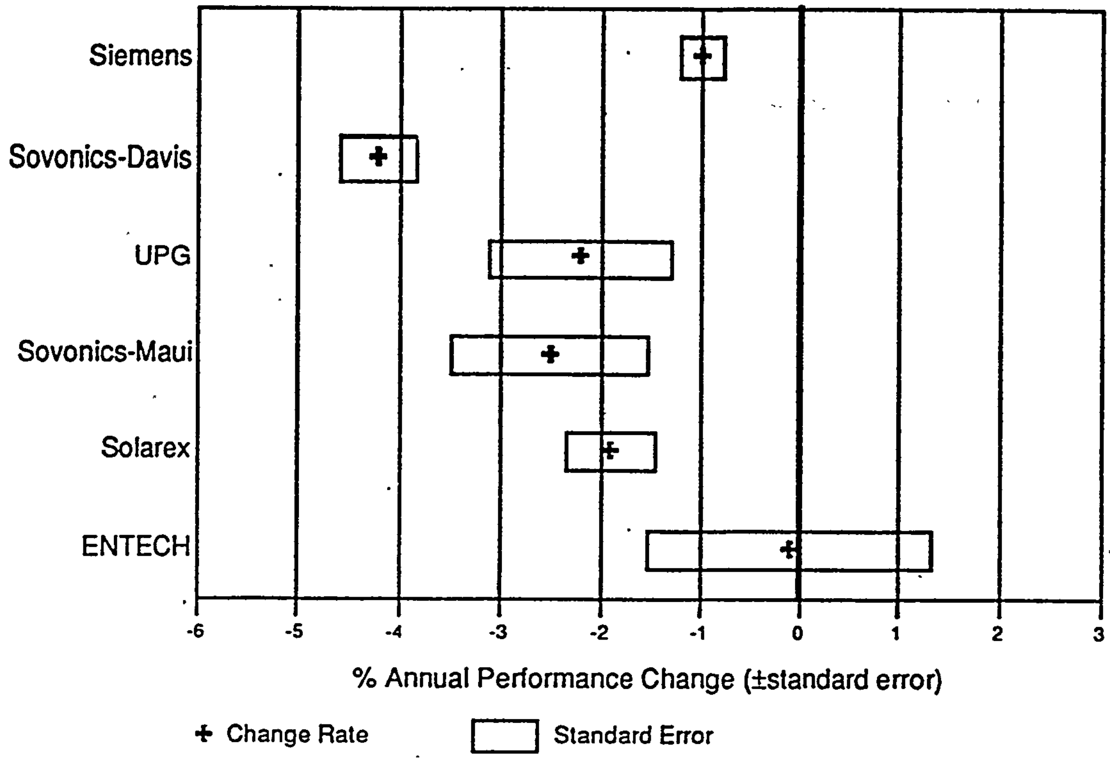


Figure 5-8
Long-Term EMT Array Performance Change

Figure 5-9 shows the ac efficiency histories of the US systems at Davis, Austin, and Kerman. The efficiency of the Kerman array, which uses single-crystal Si cells, has averaged between 8 and 10 percent, improving with the approach of winter as temperatures drop and more frequent rain reduces soiling losses. The polycrystalline Si-based IPC arrays at Austin and Davis have exhibited similar efficiencies, averaging about 8 percent. The Davis IPC system was out of service due to a PCU failure for all of October.

The efficiency of the APS system at Davis appears to be declining throughout the year, with one discontinuity in June when the system was down. However, a distinct increase occurred in October after a thorough rain at the beginning of the month provided the first cleaning for the system in 4 months. Even after accounting for lower temperatures during the days after it rained, the temperature-adjusted increase in efficiency was calculated to be about 19 percent. This result does not suggest that the effect of soiling is always this severe. It does, however, indicate that for typical California Central Valley conditions, there may be a substantial benefit in cleaning the panels to improve system output during summer peak load hours.

After the October cleaning the system's estimated degradation over its first year was calculated to be about 11 percent. It is common for a-Si systems to degrade by 20 percent during their first year. However, the baseline calculations for the APS system were performed after most of the panels had been exposed in a short-circuited condition for about 4 months, and any degradation that may have occurred then was not measured. Even with 11 percent degradation over the first year, the APS system's present rating would still be about 7 percent above the system's original target capacity of 400 kW.

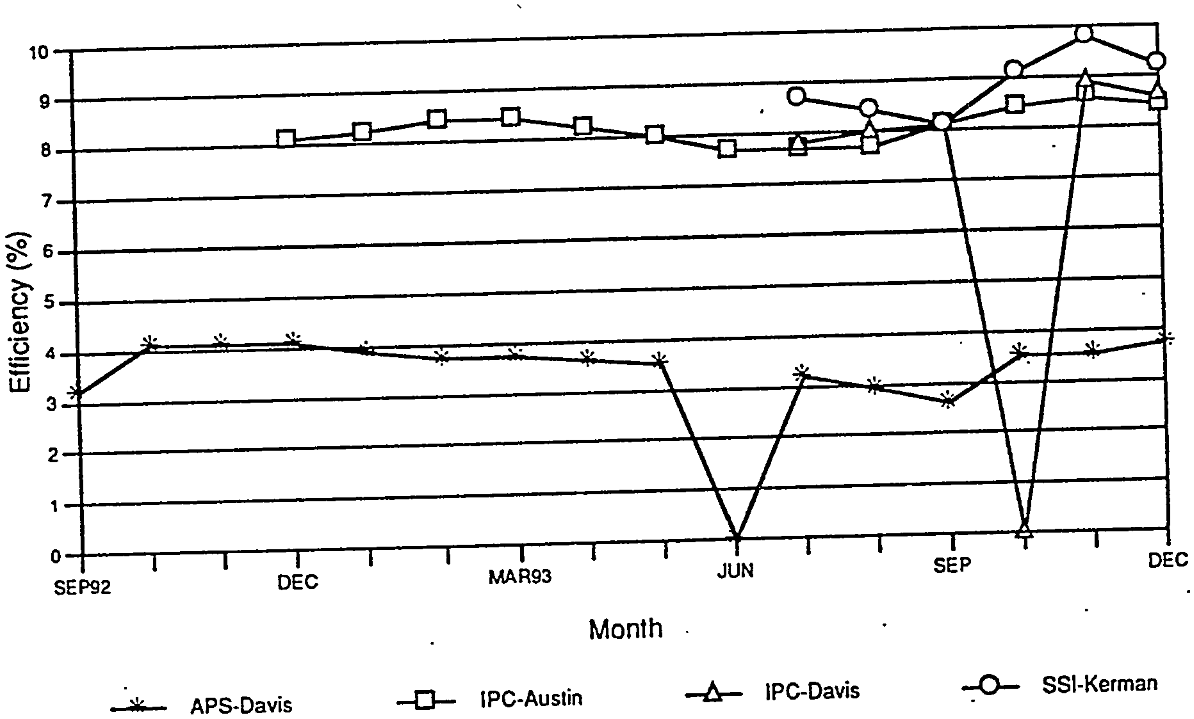


Figure 5-9
PVUSA US System ac Efficiencies

CAPACITY FACTOR

The capacity factor is calculated as the dimensionless ratio of ac energy (kWh) produced during a given time, divided by the product of PVUSA's ac rating (kW) 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.

Monthly capacity factors during 1993 for the six EMT arrays at Davis and Maui are shown in **Figure 5-10**. Monthly capacity factors during 1993 for the four US systems at Davis, Austin, and Kerman are shown in **Figure 5-11**. The trends are the same as observed for monthly generation, but are normalized to a dimensionless 0 to 1 scale. The capacity factor is a function of system availability, 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.

Four of the six EMT arrays shown in **Figure 5-10** exhibit similar monthly capacity factor trends, varying smoothly from about 8 to 10 percent in the winter to more than 25 percent in the summer. These arrays—from SSI, Sovonics, UPG, and Solarex—are identically oriented at a fixed 30° tilt, and each demonstrated good reliability throughout the year. The 1993 annual capacity factor for these arrays ranged from 18 to 20 percent, consistent with results dating from 1989 (see **Table 5-3**).

The ENTECH concentrator array uses a two-axis tracking system to capture direct normal insolation only. In the absence of failures this type of system will exhibit a wider seasonal swing but similar annual capacity factor. In 1993, however, the ENTECH array's tracker controller failed repeatedly, resulting in an uneven capacity factor pattern and an annual capacity factor of just 15 percent.

The Maui array performed reliably in 1993, and its fairly flat monthly capacity factor pattern reflects its consistent monthly insolation pattern. Its annual capacity factor was 21 percent.

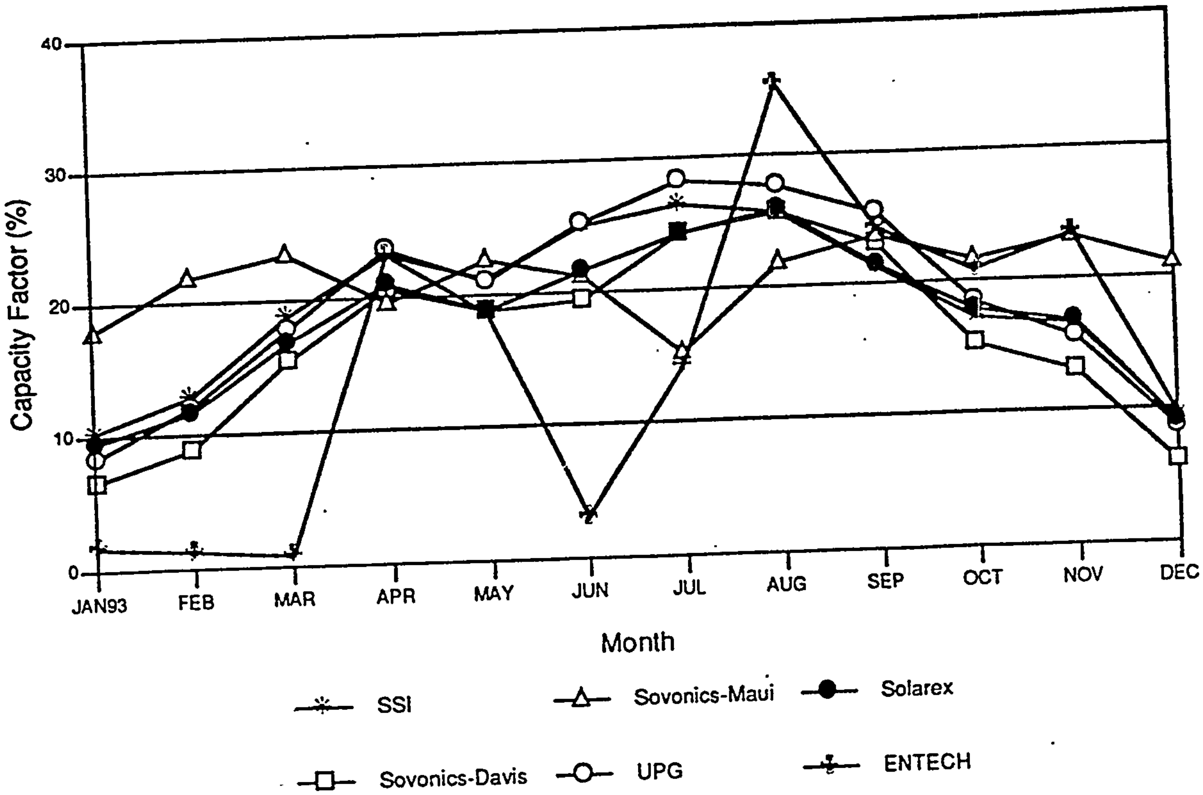


Figure 5-10
1993 PVUSA Capacity Factors
EMT Arrays

Figure 5-11 illustrates 1993 monthly capacity factors for the US systems. The Davis APS system shows significant dips in April, May, June, July, and September, resulting in an annual capacity factor of 13 percent. Had it operated more reliably, its annual capacity factor could have exceeded 20 percent. The IPC Austin system also experienced a number of partial and full outages, especially between April and July, resulting in an annual capacity factor of 18 percent. Owing to its one-axis tracking orientation, its annual capacity factor may reach 26 percent if it operates reliably in the future. Partial year data are shown for the Kerman SSI and Davis IPC one-axis tracking systems. The Kerman system operated reliably, achieving a capacity factor for July through December of 23 percent. The IPC system's PCU incurred problems shortly after it began full operation. Its capacity factor for June through December was just 13 percent. Based on one-axis insolation data recorded at Davis over the past 3 years, these two systems may be able to achieve annual capacity factors as high as 28 percent.

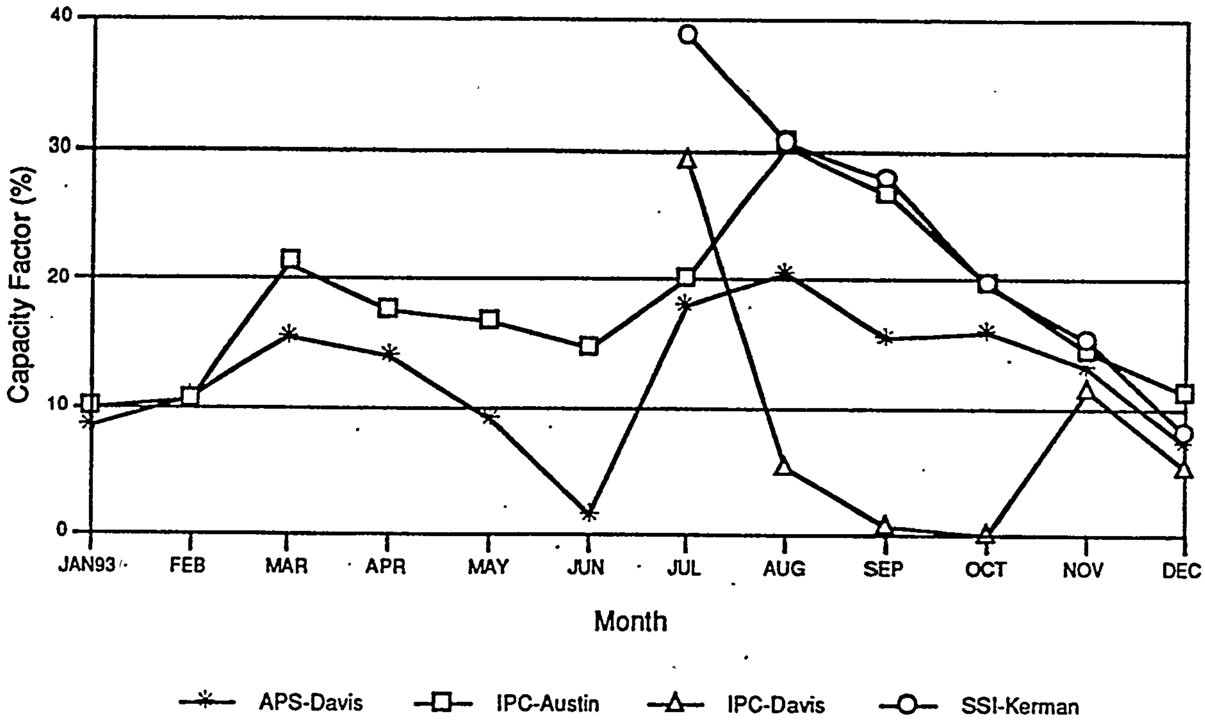
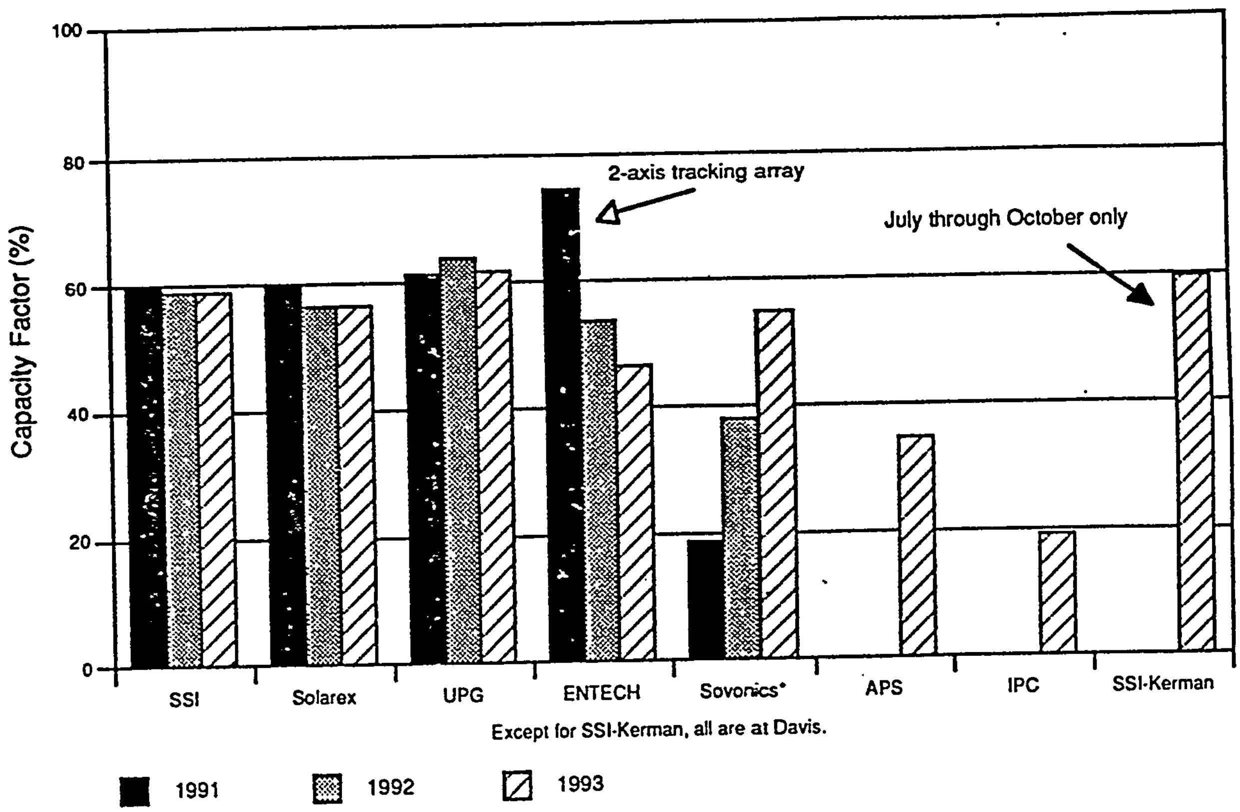


Figure 5-11
1993 PVUSA Capacity Factors
US Systems

Capacity factors over shorter time intervals can be much higher than the monthly capacity factors shown above. **Figure 5-12** illustrates the capacity factors for each array during PG&E's 1991, 1992, and 1993 peak periods (weekdays in May through October, 12 p.m. to 6 p.m.). Peak-period capacity factors of 60 percent are typical for fixed arrays that face south, and capacity factors as high as 75 percent have been demonstrated for the two-axis tracking array. Significant downtime limited the 1993 peak-period capacity factors for the ENTECH, APS, and IPC systems. The Kerman SSI system's 1993 peak-period capacity factor of 60 percent is somewhat low because the peak-period calculation is based only on data from July through October; the peak-period capacity factor in July alone was 78 percent. Had the plant been on-line in May, the estimated peak-period capacity factor for May through October would have been about 66 percent.



On-peak hours include 786 to 792 hours on weekdays in May through October, from noon to 6 pm.

Figure 5-12
Summer Peak-Period Capacity Factors for PVUSA Systems in PG&E Territory

*Out of service from late June 1991 until July 1992

Several drawbacks arise from using the capacity factor to gauge system performance. One is that the capacity factor is sensitive to the chosen time interval and, on an annual basis, cannot exceed 50 percent if nighttime hours are included. Another drawback is that significant reductions in output due to partial outages, soiling, and other causes may be obscured by much larger normal variations in insolation. **Figure 5-13** introduces a variant of the capacity factor, called the "insolation-weighted capacity factor," which factors out sunlight intensity. With this measure, system performance is no longer penalized as a result of darkness, and performance is not obscured by high or low insolation.

Like the capacity factor, the insolation-weighted capacity factor is dimensionless, and can be calculated over any time interval. It is obtained by dividing the capacity factor by a similarly-defined "insolation factor." Following the definition of capacity factor described earlier, the insolation factor is calculated as the ratio of actual insolation divided by the product of the rating irradiance and the time interval. (For flat-plate systems, PVUSA uses a rating irradiance of 1000 W/m^2; for concentrator systems using only direct normal insolation, the rating irradiance is 850 W/m^2.)

The insolation-weighted capacity factor can be a useful diagnostic to identify reduced output due to high temperatures, degradation, soiling, spectral variations, and partial and full outages. It can be interpreted as the ratio of how efficiently a system operated over the chosen period compared with how efficiently it operated when it was first rated. Although it rarely happens, the magnitude of the insolation-weighted capacity factor can exceed 1.0 if the system operated more efficiently than it did under PTC (e.g., on a cool, windy, and clear day with a clean array surface and no component failures over a short time interval).

Figure 5-13 indicates that the best annual results for PVUSA's ten systems have averaged around 80 percent. This result implies that on average, the systems operate at 80 percent of their rated efficiency. Sub-par performance is easy to identify. For example, in 1991 and 1992, the Davis Sovonics array generated less than 40 percent of what it would have generated when it was first rated. (The array's poor performance was the result of a year-long outage caused by a failure in the main dc collection junction box.)

Other types of failures that show up on this plot are the numerous PCU trips and module junction-box failures on the Maui Sovonics array in 1991 and 1992, junction-box failures on the Solarex array in 1992 and 1993, and tracker controller-related downtime on the ENTECH array in 1992 and 1993. Extensive downtime during 1993 on the APS and Davis IPC systems is also apparent.

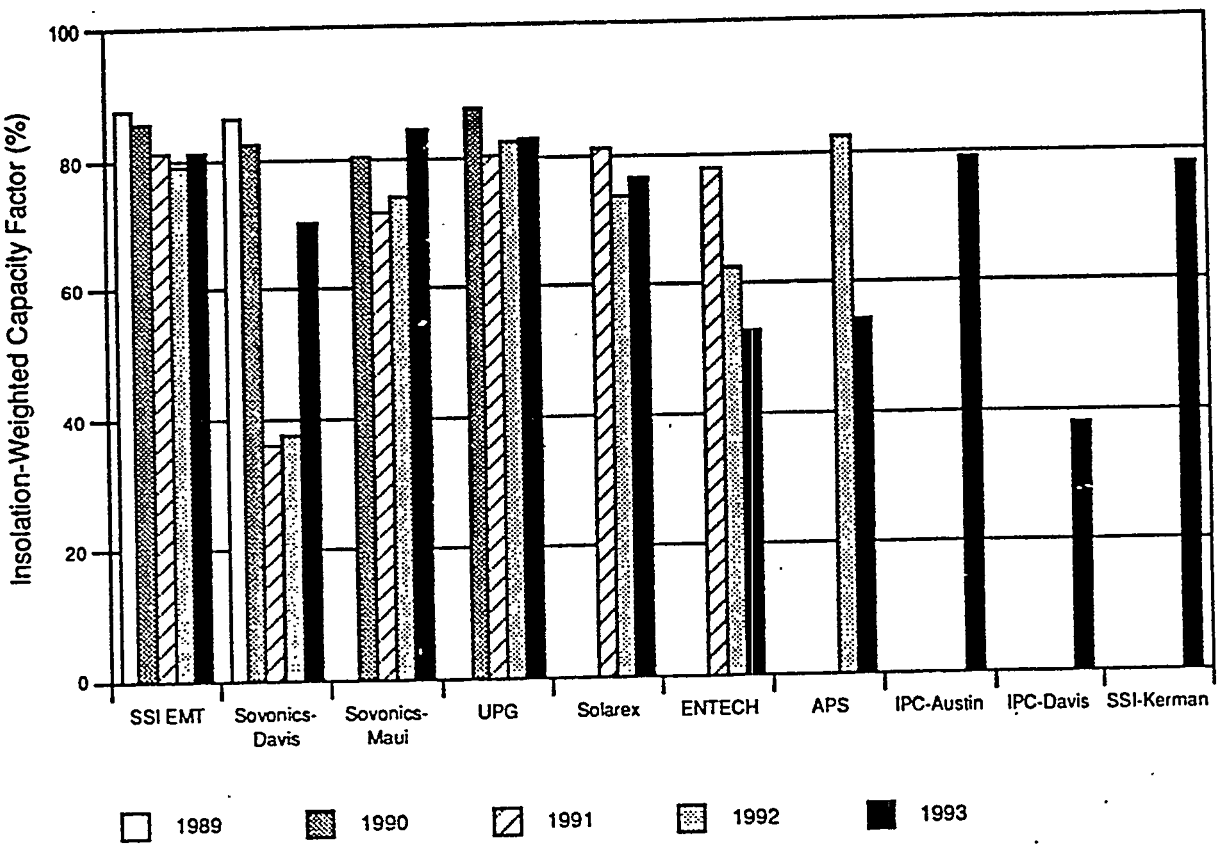


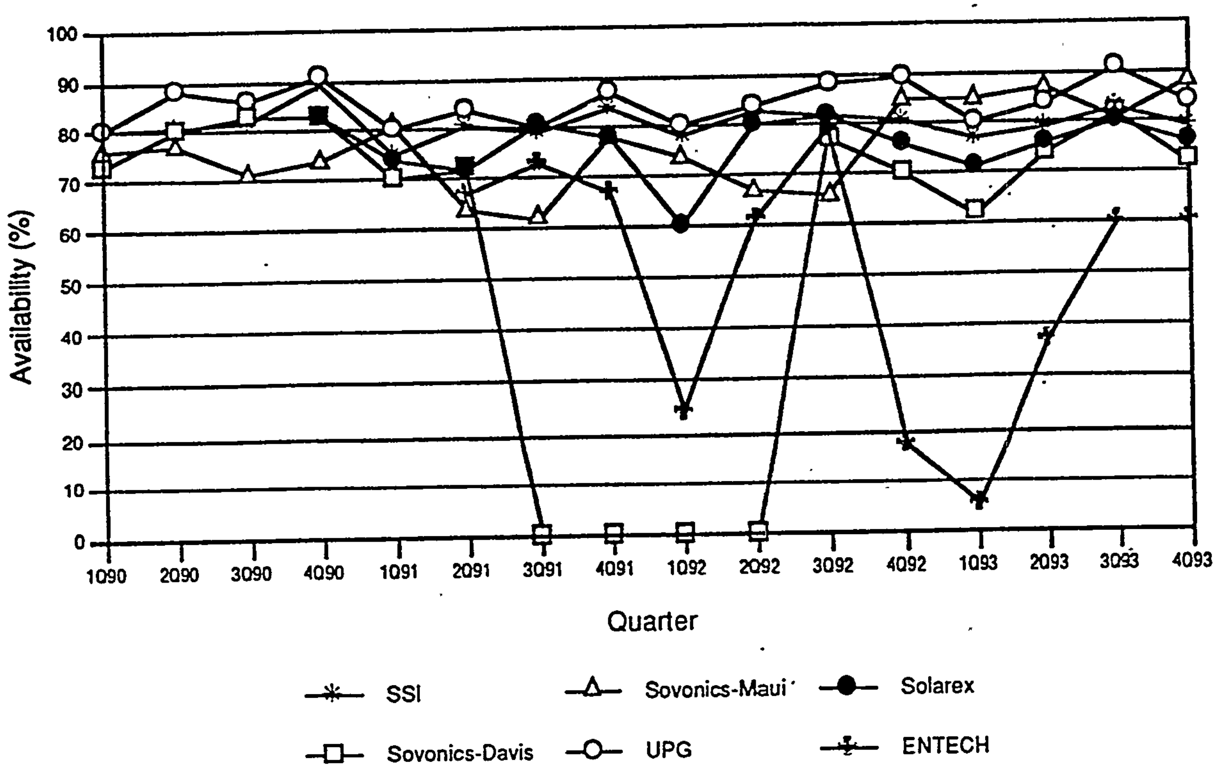
Figure 5-13
Annual Insolation-Weighted Capacity Factors

SYSTEM AVAILABILITY

System availability is defined by PVUSA as the percentage of daylight hours during which a system supplies net power to the utility grid. System-based availabilities are affected by the array orientation and system operating characteristics and reliability. Availability is also affected by poor weather, because at very low irradiance during cloudy daytime hours, power output may drop below zero due to internal system power requirements.

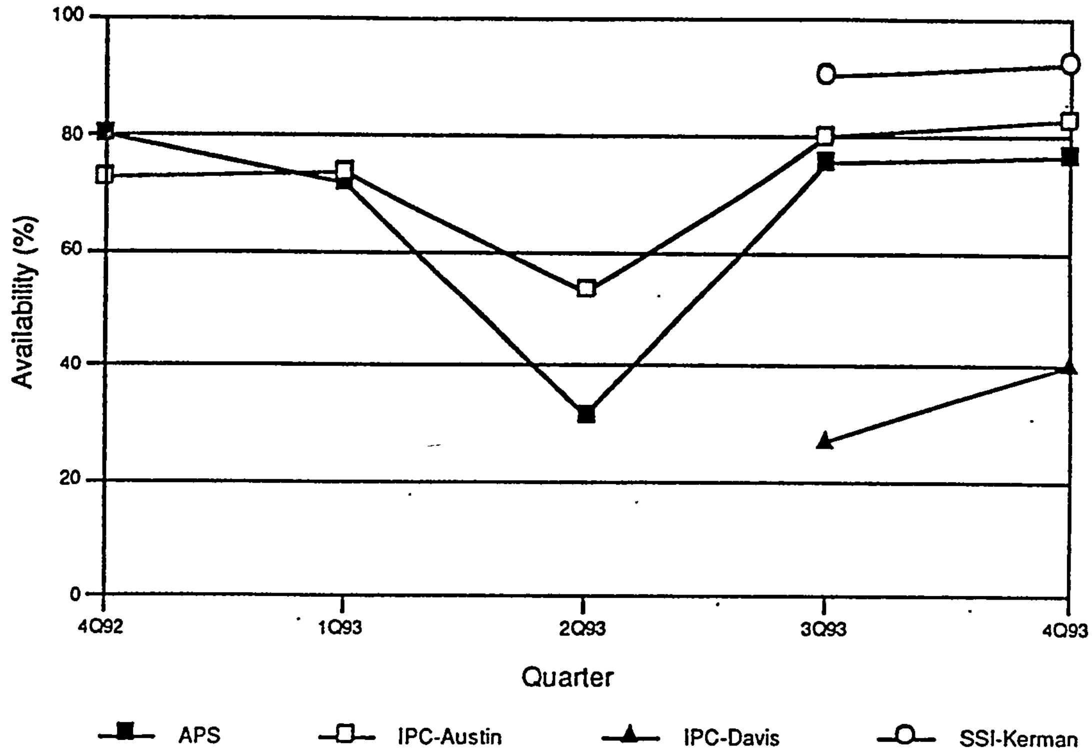
System availability calculations are sensitive to the amount of time during which array power is not high enough to overcome the PCU's internal load (about 0.4 kW for the EMT DECC PCU). During the hours near sunrise and sunset, the irradiance and PCU efficiency are often too low to produce net power output. Also, EMT arrays with higher ratings can be expected to exceed the PCU's minimum requirements at lower irradiance levels than arrays with low ratings. However, the amount of unused potential energy during the sunrise and sunset hours is small—typically, less than 2 percent of the total daily insolation. Therefore, availability as defined here is a conservative number.

Figure 5-14 charts system availabilities for the six EMT arrays during 1990 through 1993. (No data are available for 1989.) **Figure 5-15** shows corresponding information for the four US systems. System availability has typically ranged between 60 and 90 percent, except for the Sovonics and ENTECH systems at Davis. The Sovonics system was out of operation from late June 1991 until July 1992. In 1993, the ENTECH array continued to experience the same tracker controller problems that sharply reduced the system's availability during the early and late months of 1992. **Figure 5-15** highlights very high availability during the latter half of 1993 for the Kerman SSI system, low second quarter 1993 availability for the Austin IPC and Davis APS systems, and very poor availability for the Davis IPC system. A detailed description of the causes for the various systems' downtime is included in Section 6.



Availability is defined as percent of daylight hours during which a system supplies net power to the grid.

Figure 5-14
EMT Array Daylight System Availabilities



Availability is defined as percent of daylight hours during which a system supplies net power to the grid.

Figure 5-15
US Systems Daylight System Availabilities

Section 6
OPERATION AND MAINTENANCE

This section describes major operation and maintenance (O&M) activities during 1993 at the Davis, Kerman, and project participants' sites. It also discusses improvements to the PVUSA O&M database and estimates maintenance costs at the Davis site.

MAJOR O&M ACTIVITIES DURING 1993

One of PVUSA's objectives is to assess the O&M requirements of PV systems within an electric utility setting. Summarized below are failure-related O&M activities during 1993 for the five EMT-1 arrays at Davis, the EMT-1 array in Maui, the Davis US-1 systems, the Kerman US-2 system, the City of Austin IPC system, and the PCUs. A chronological list of all O&M activities during 1993 is listed by system in Appendix C.

EMT-1

SSI

- A module thermocouple was reattached.

Sovonics Davis

- The array operated on three of four circuits from May 27 to July 15 due to a junction-box failure on one module. A replacement module was installed on July 15, and the system was returned to normal. Repairs were delayed until other site activities with higher priorities were completed. A second module was found with a similar failure on November 16 and replaced on November 18.

Sovonics Maui

- Six modules with failed junction boxes were replaced, bringing the cumulative total to 35 out of 1200 (5 were replaced in 1992, 11 in 1991, and 13 in 1990). This corresponds to an annual failure rate of about 0.8 percent.
- Four modules that were open-circuited were repaired; three by cleaning the connections at the junction box and one by replacing a charred interconnecting wire.
- There was a span of several days in July and one earlier occurrence when the PCU shut down for unknown causes. However, overall system availability for 1993 remained above 84 percent.
- The ambient temperature data problem of unbelievably high temperatures that was first addressed in 1992 continued. In April 1992, the data logger was replaced and in June 1993, the data logger battery was replaced. Maui Electric has checked the instruments; however, the persistent problem prompted PVUSA to temporarily suspend reporting

ambient temperature data in June and July. Maui Electric is working with a contractor to identify and resolve the problem.

UPG

- No failure-related O&M.

Solarex

- A voltage imbalance and decrease in power output led to the discovery of a miswired switch (resulting from an upgrade) and two blown fuses in the junction box of one source circuit. The switch was repaired and the fuses were replaced, restoring the circuit to normal.
- During an inspection of the array to troubleshoot the problem noted above, two modules were identified with browned busbars. Both modules are still able to carry full power because of a redundant cell-level current path.
- On February 20, water intruding into an intermediate source circuit junction box shorted several connections and burned wires, diodes, and terminal strips. The problem—a failed penetration seal in the junction box—was identified in March. Initial repair in April was unsuccessful because of a wiring error that damaged three blocking diodes. Final repairs were completed on July 20, restoring the circuit to full power.

ENTECH

- The ENTECH system experienced 19 failures of its tracking system. Thirteen of the failures were related to the tracker controller board, three were due to controller wiring and limit switch problems, and three failures occurred as the result of loose connections. ENTECH has changed to a dc-powered tracker control system for its new systems. PVUSA is reviewing the benefits of retrofitting the Davis system.
- An ENTECH technician was on site for nine days in March and early April to troubleshoot the array tracking problems.

EMT PCUs

- The PCU connected to the SSI array experienced six synchronization errors. The Davis Sovonics PCU required one reset for a synchronization error. The PCU connected to the UPG array experienced 11 synchronization errors. The PCU connected to the Solarex array experienced one error, and the PCU connected to the ENTECH array experienced eight errors. In each case a manual reset was needed to restore operation.
- The PCUs connected to the SSI, Sovonics, and Solarex arrays each experienced one door interlock error, all on the same day that a brief storm carrying 100-mph winds hit the Davis area.
- As a result of the continuing synchronization errors, the start-up voltages on UPG and SSI were increased in August, delaying morning start-up for approximately one-half hour. This adjustment has reduced the number of errors.

- A problem with the Sovonics PCU shutdown scheme is under review.

US-1 (Davis)

SSI

- Siemens installed their repackaged inverter 'A' in January, and received permission from PG&E to operate it and the previously installed repackaged inverter 'B' unattended. SSI was unable to achieve reliable PCU operation and encountered other problems associated with ground fault protection, bypass diodes, tracking accuracy, and transducers. **Figure 6-1** shows a burnt module due to bypass diode failure. Some improved PCU reliability was achieved during October. The final PCU test started on December 17 and is scheduled to be completed by January 28, 1994.

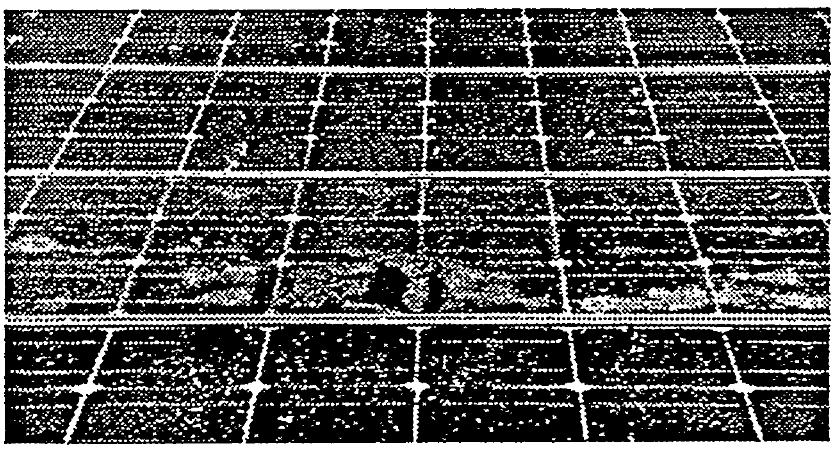


Figure 6-1
Burnt Module Due to Bypass Diode Failure
on Davis SSI US-1 System

APS

- Line disturbances continue to be problematic for the PCU. Eight incidents of PCU failures linked to line disturbances resulted in cleared ac fuses.
- On three occasions the PCUs failed to start up in the morning, and manual resets were performed.
- Warranty repair to 960 panel parallel connectors was performed in June. All the repaired connectors were accepted following field wet resistance testing.

- Following one particular ac fuse replacement resulting from a 12-kV line transient, APS technicians attempted to restart the PCU. Initiating the reset energized a solid ground fault through two failed movistors inside the dc disconnect switches. This resulted in arcing damage to both dc enclosures and destroyed movistors. A root-cause analysis concluded that the ground fault protection wiring should be revised, and after a 9-day repair outage the PCUs were successfully restarted.

- Failed connections on a DAS metering terminal board were identified and repaired. This failure resulted in a temporary loss of one phase of the ac voltage signal and an apparent drop of one-third in ac power.

- Warranty replacement of a failed dc contactor was performed by APS technicians on two occasions. APS technicians also repaired a ribbon cable connector.

IPC

- IPC completed contractual field rewiring of 1100 modules during the first quarter of 1993. Subsequently, the system was restarted and successfully completed the acceptance and performance tests.

- The PCU required manual resetting 23 times due to line disturbances, overpower, overtemperature, and bridge fault trips. Two bridge failures resulted in about six weeks of downtime. The underlying cause of PCU trips due to dc overvoltage is under investigation.

US-2 (Kerman)

- The Kerman system began its performance rating period on June 15. During the rating period (June 15–August 1) a source circuit fuse cleared, reducing the system output for 4 days. SSI replaced the fuses, and the system returned to normal.

- Warranty repairs following the performance period included module replacement, bypass diode replacement, actuator replacements, and panel realignment and tightening of loose hardware. **Figure 6-2** shows an unusual tracking system failure where one evaporator tube dropped to the ground due to loose hardware and jammed the array. Notwithstanding the summer and fall warranty repairs, the facility maintained an average availability of 91 percent.

IPC (Austin Host System)

- During the first quarter of 1993, the City of Austin reported 7 days of downtime resulting from a loose ac disconnect switch termination.

- Additionally, Austin reported the tracker was stuck facing east for 4 days, lowering energy production for this period.

- The system experienced 8–10 days of downtime each month during the second quarter due to a faulty PCU circuit board. Subsequently the circuit board was replaced.

- Redundant limit switches were added, and hardware for existing switches was replaced due to corrosion.

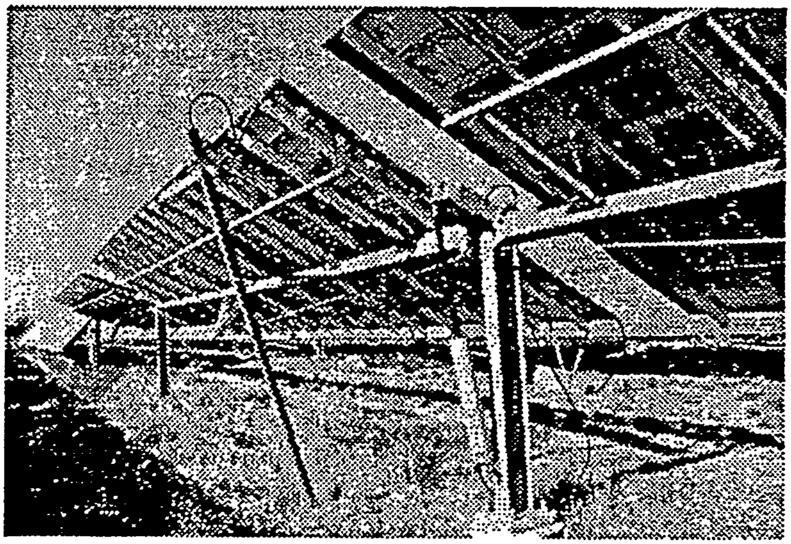


Figure 6-2
Tracking System Failure Due to Loose Hardware,
Kerman US-2 System

OPERATION AND MAINTENANCE DATABASE

Work continued in 1993 to refine the O&M database and to input archived O&M logs from the Davis site. Improvements to the database enhanced the ability to input standardized events and execute specific maintenance queries. The database includes maintenance records from Davis EMT-1, US-1, and Kerman US-2 systems. **Figure 6-3** illustrates the current O&M report and inspection sheet.

The database operates within a Windows™ environment and minimizes the necessity to insert individualized terminology. Through normal commands, queries of any subsection may be accomplished. The template does provide for case-specific notes to supplement data input.

PVUSA O&M REPORT AND INSPECTION SHEET

Log #	Date:	Start Time:	Stop Time:

Site:

- ☐ EMT-1 ENT
- ☐ EMT-1 SOV
- ☐ EMT-1 SSI
- ☐ EMT-1 SX
- ☐ EMT-1 UPG
- ☐ EMT-1 EPRI
- ☐ EMT-2 EPRI
- ☐ I.C BLDG
- ☐ US1-APS
- ☐ MAUI
- ☐ US1-IPC
- ☐ US1-SSI
- ☐ US2-KERMAN
- ☐ Other________

Type of Maintenance:

- ☐ Planned-Preventive
- ☐ Unplanned-Failure Related
- ☐ Research Related

Description of Event:

- ☐ BOS Failure
- ☐ Clearance
- ☐ DAS Problem
- ☐ DAS Upgrade
- ☐ Erosion Problem
- ☐ Exchange Equip.
- ☐ Facility Improvement
- ☐ FWRT
- ☐ Inverter Failure
- ☐ Line Disturbance
- ☐ Module Failure
- ☐ Non-Routine Maint.
- ☐ Pump Failure
- ☐ PV Sys.Problem
- ☐ PV Workshop
- ☐ Read Meters
- ☐ Routine Inpect.
- ☐ Routine Maint.
- ☐ Security Problem
- ☐ Safety Problem
- ☐ Vegetation Problem
- ☐ Other:____________________________

ActionTaken:

- ☐ Adjust
- ☐ Calibrate
- ☐ Clean / Wash
- ☐ Connect
- ☐ Disconnect
- ☐ Inspect
- ☐ Install
- ☐ Load
- ☐ Modify
- ☐ Repair
- ☐ Replace
- ☐ Reset
- ☐ Procurement
- ☐ Supervise/Buddy
- ☐ Test
- ☐ Warranty
- ☐ Other:________________

System Involved / Subsystem(s) Involved

System:	AC Electrical:	DC Electrical:	Tracker:	Site:	Site DAS:
☐ DAS	☐ Circuit Brkr.	☐ Blocking Diode	☐ Actuator/Seal	☐ Buildings	☐ Computer
☐ PCU	☐ Fuse	☐ Bypass Diode	☐ Bearings	☐ Drainage	☐ Datalogger
☐ PV Module	☐ Inverter	☐ Bypass Diode	☐ Clock	☐ Fences	☐ MD9
☐ Support Structure	☐ Relaying	☐ Combiner Box	☐ Controller	☐ Erosion Ctrl.	☐ Pyranometer
☐ Other:______	☐ 12kV Transf.	☐ Fuse	☐ Lubricate	☐ Pest Ctrl.	☐ Sensor
	☐ Other:______	☐ Interconnect	☐ Motor Drive	☐ Pumps	☐ Software
		☐ Movistor	☐ Receiver	☐ Roads	☐ Thermocouple
		☐ Switch	☐ Sensor	☐ Security	☐ Tranducer
		☐ Other:______	☐ Stow	☐ Veggie Ctrl.	☐ Weather Sta.
			☐ Wake-up	☐ Other:______	☐ Wiring
			☐ Winch		☐ Other:______
			☐ Other:______		

Downtime

Problem Occurred:	Downtime Hours:		Present Status:
Date:	Partial System:	Whole System:	☐ Whole system On
Time:			☐ Partial system Off
			☐ Whole system Off

Materials and Labor

PVUSA WBS:		Work Done by:	Materials/Parts Used:	Materials Cost:
☐ BSD	☐ KEY-2	☐ BEV		
☐ BSK	☐ KEY-2K	☐ DJS		
☐ DAS	☐ MTN	☐ DLM		
☐ DASK	☐ SAF	☐ KOB	**Major Equipment Used:**	**Equipment Cost:**
☐ EMT-2	☐ SAFK	☐ PAH		
☐ EMT-3	☐ SPD	☐ RSR		
☐ EVA	☐ SPK	☐ TUT		
☐ KEY-1	☐ ____	☐ ____		

Total Force:	Hours per Person:	Work Complete: ☐ Yes ☐ No	Labor Cost:	Total Cost:

Figure 6-3
O&M Worksheet

MAINTENANCE COSTS

With the refinement of the O&M database, PVUSA is better equipped to track maintenance costs. Maintenance costs at Davis are being logged for both the EMT-1 and US-1 systems. However, because Davis is an R&D site with additional staffing, research, and technology transfer activities, maintenance costs tend to be higher than the costs anticipated for mature utility-scale systems. A brief review of failure-related maintenance costs for the APS US-1 system is shown in **Table 6-1** and for the IPC US-1 system in **Table 6-2**. Due to the developmental nature and small size of EMT systems, maintenance costs are not considered indicative of larger, more proven systems and therefore are not reported. PVUSA described O&M at Davis in a technical paper entitled "Operations and Maintenance at PVUSA: Utility Perspective on the Operation of PV Systems," which was presented at the IEEE PVSC conference in May 1993.

Table 6-1
1993 Davis Failure-Related Maintenance Costs for APS US-1 System

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Monthly Labor (mh)	Monthly Material ($)[a]	Cumulative Labor Cost (cents/kWh)	Cumulative Mat'l Cost (cents/kWh)[a]	Cumulative Total Cost (cents/kWh)
January	30012	30012	1.25	0	0.21	0.00	0.21
February	34908	64920	1	86	0.17	0.13	0.31
March	54648	119568	1	0	0.14	0.07	0.21
April	47867	167435	3.5	0	0.20	0.05	0.25
May	40250	207685	54.5	358	1.47	0.21	1.69
June	5323	213008	8	0	1.63	0.21	1.83
July	63616	276624	6	0	1.36	0.16	1.52
August	73217	349841	5	86	1.15	0.15	1.30
September	52900	402741	5.1	458	1.06	0.25	1.30
October	56658	459399	7	175	1.01	0.25	1.26
November	45308	504707	0	0	0.91	0.23	1.15
December	25341	530048	8	200	0.95	0.26	1.20

[a] Material costs listed are for reference only. Most materials were provided by vendors under warranty.

Table 6-2
1993 Davis Failure-Related Maintenance Costs for IPC US-1 System

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Monthly Labor (mh)	Monthly Material ($)[a]	Cumulative Labor Cost (cents/kWh)	Cumulative Mat'l Cost (cents/kWh)[a]	Cumulative Total Cost (cents/kWh)
April	20500	20500	0	0	0	0	0
May	41003	61503	0	0	0	0	0
June	52289	113792	0	0	0	0	0
July	42838	156630	4	0	0.13	0	0.13
August	7560	164190	4.2	0	0.25	0	0.25
September	639	164829	2.7	0	0.33	0	0.33
October	0	164829	28	0	1.18	0	1.18
November	16036	180865	28.5	425	1.86	0.23	2.10
December	7676	188541	5.5	625	1.93	0.56	2.49

[a] Material costs listed are for reference only. Most materials were provided by vendors under warranty.

The Kerman US-2 system, which began commercial operation on June 15, 1993, is providing a test bed for predicting realistic maintenance costs. Kerman is an unstaffed facility that is remotely monitored and operated. A brief review of failure-related maintenance costs at the Kerman PV plant from June 15 through December 31, 1993 is shown in **Table 6-3**.

Table 6-3
1993 Kerman Failure-Related Maintenance Costs

Month	Monthly Energy (kWh)	Cumulative Energy (kWh)	Monthly Labor (mh)[a]	Monthly Material ($)[b]	Cumulative Labor Cost (cents/kWh)[a]	Cumulative Mat'l Cost (cents/kWh)[b]	Cumulative Total Cost (cents/kWh)
June	67323	67323	9.5	0	0.71	0.00	0.71
July	143043	210366	28	500	0.89	0.24	1.13
August	113542	323908	13.5	23	0.79	0.16	0.95
September	100005	423913	18	0	0.81	0.12	0.94
October	72146	496059	22	1250	0.92	0.36	1.27
November	54164	550223	7.5	23	0.90	0.33	1.22
December	29493	579716	6.5	23	0.91	0.31	1.22

[a] Travel costs incurred to support activities are not included.
[b] Material costs listed for reference only. Most materials were provided by vendors under warranty.

Tables 6-1, 6-2, and **6-3** include both project and vendor labor hours, which were assigned a cost of $50/mh. Most materials were supplied under warranty, but were allocated at replacement cost value.

Figure 6-4 depicts the cumulative energy produced in relationship to consumed materials and labor costs at the Kerman facility. System repair costs may have been reduced below the levels indicated if the system had not been undergoing contractual acceptance repairs by the PV contractor.

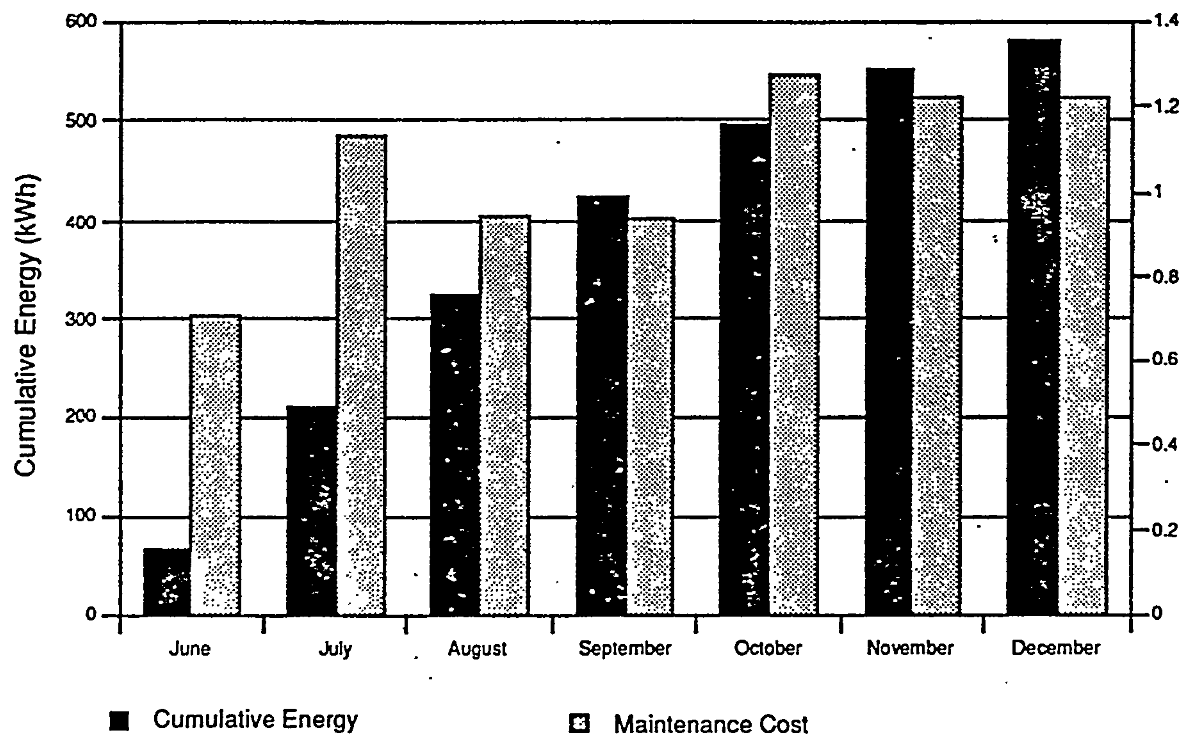


Figure 6-4
Kerman Maintenance Cost per kWh

Section 7
SPECIAL TESTS

This section summarizes special tests, including current-voltage curve traces, electric and magnetic field tests, infrared camera scans, and power quality measurements.

I-V CURVES

Current-voltage (I-V) curve tests are conducted on completed dc arrays to obtain "snapshot" data for diagnostics and baseline rating estimates. I-V curves 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.

I-V curves for the US-2 system at Kerman were taken on February 15 and April 13; sample curves are shown in **Figure 7-1**. A second set of I-V curves were taken on September 22, 1993, as a complement to the infrared camera scan test of the array.

ELECTRIC AND MAGNETIC FIELDS

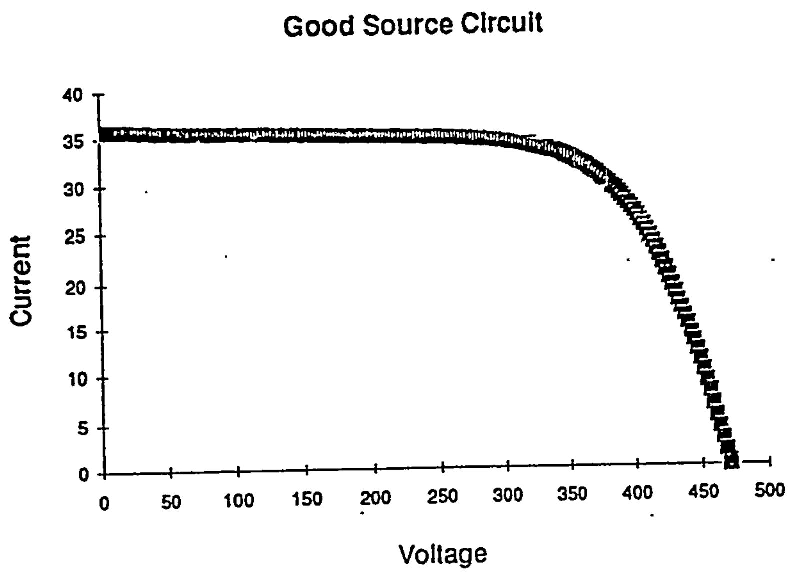
Electric and magnetic fields (EMFs) are energy fields associated with the existence and movement of electric charges. Electric fields are present wherever electric charges exist; magnetic fields are present wherever electric current exists.

EMF data were collected at the PVUSA sites in Davis and Kerman in March and April 1993, respectively. Readings were taken at midday, as quickly as possible to minimize the effect of changing environmental conditions. Although not comprehensive, EMF data taken at PVUSA indicate that 60 Hz magnetic fields (the EMF type of greatest public concern) are significantly less for PV arrays than for household appliances.[1]

INFRARED CAMERA SCAN

An infrared (I/R) camera scan of a PV array attempts to locate hot spots that may reveal problems. Such hot spots may indicate loose terminations for array wiring or modules carrying more current than normal, possibly because of nonconducting modules in the same parallel string. The I/R camera is aimed at the array, and data are recorded on videotape, which can be viewed and analyzed later.

[1] C. Jennings, G. Chang, and K. Bell, "PV EMF," IEEE Photovoltaic Specialist Conference, May 1993.



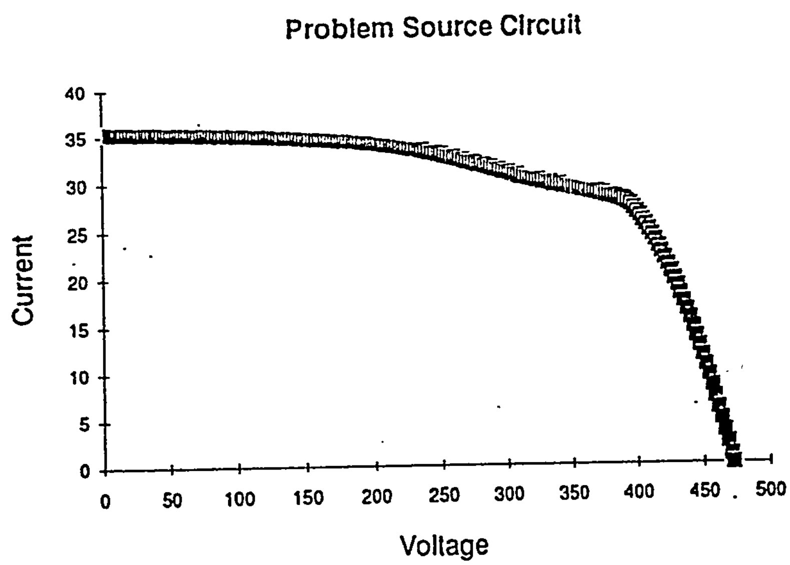


Figure 7-1
Sample I-V Curve Trace, Kerman

On September 22 and October 18, 1993, a comprehensive I/R scan of the Kerman PV plant was conducted by technicians from PG&E's Technical and Ecological Services. About 80 module-related hot spots were identified. Five modules were identified as having burned terminals of varying degrees and were replaced. Six other modules were not damaged, but had loose wire terminations and were properly retorqued. All other modules exhibiting hot spots were operable and revealed no deficiencies upon further inspection. The I/R scan test equipment was set to detect small variations in temperature (1° to 3°). This setting may have been too sensitive given the normal temperature variations seen on arrays. Further development of testing techniques are required, but initial indications are that I/R camera scans represent a valuable test for early identification of array problems. With refinement, I/R scans may be a useful alternative for pinpointing module problems that are indicated (although not precisely) in I-V curve tests. Currently, clamp-on ammeters (current guns) are used to identify the precise location of wiring and module deficiencies detected by I-V curves.

POWER QUALITY

Power quality (PQ) measurements for PV plant output are of interest to utilities. PQ data at Davis and Kerman are being collected using Basic Measurement Instruments' (BMI) "PQNode." PV output at the utility distribution voltage, 12.47 kV, is being monitored, and data are archived in permanent electronic storage. **Figure 7-2** shows a power quality wave fault recorded at the Davis site.

To date the data have been valuable diagnostic tools for identifying variations in utility voltages (such as transients). In some cases, utility transients have been correlated with PV plant outages.

Harmonic content for PV systems at the Davis and Kerman sites was found to be within limits recommended by IEEE 519. However, high-frequency noise at Kerman, generally at the PCU switching frequency, had elicited complaints from two utility customers. The high-frequency noise was eliminated by adding filter capacitors at the PCU output. **Figure 7-3** displays the waveform, and **Figure 7-4** displays the voltage spectral plot for phase A to neutral of the 12-kV bus at 410-kW ac at the Kerman plant after filter capacitors were added on July 21, 1993. The high-frequency components between 6000 and 8000 Hz displayed on the voltage spectral plot now seem to be within acceptable levels as no additional problems have been identified. Previously, high-frequency components above this level were found to cause interference with sensitive electronic equipment (e.g., digital clocks and smoke detectors).

PASS Disturbance

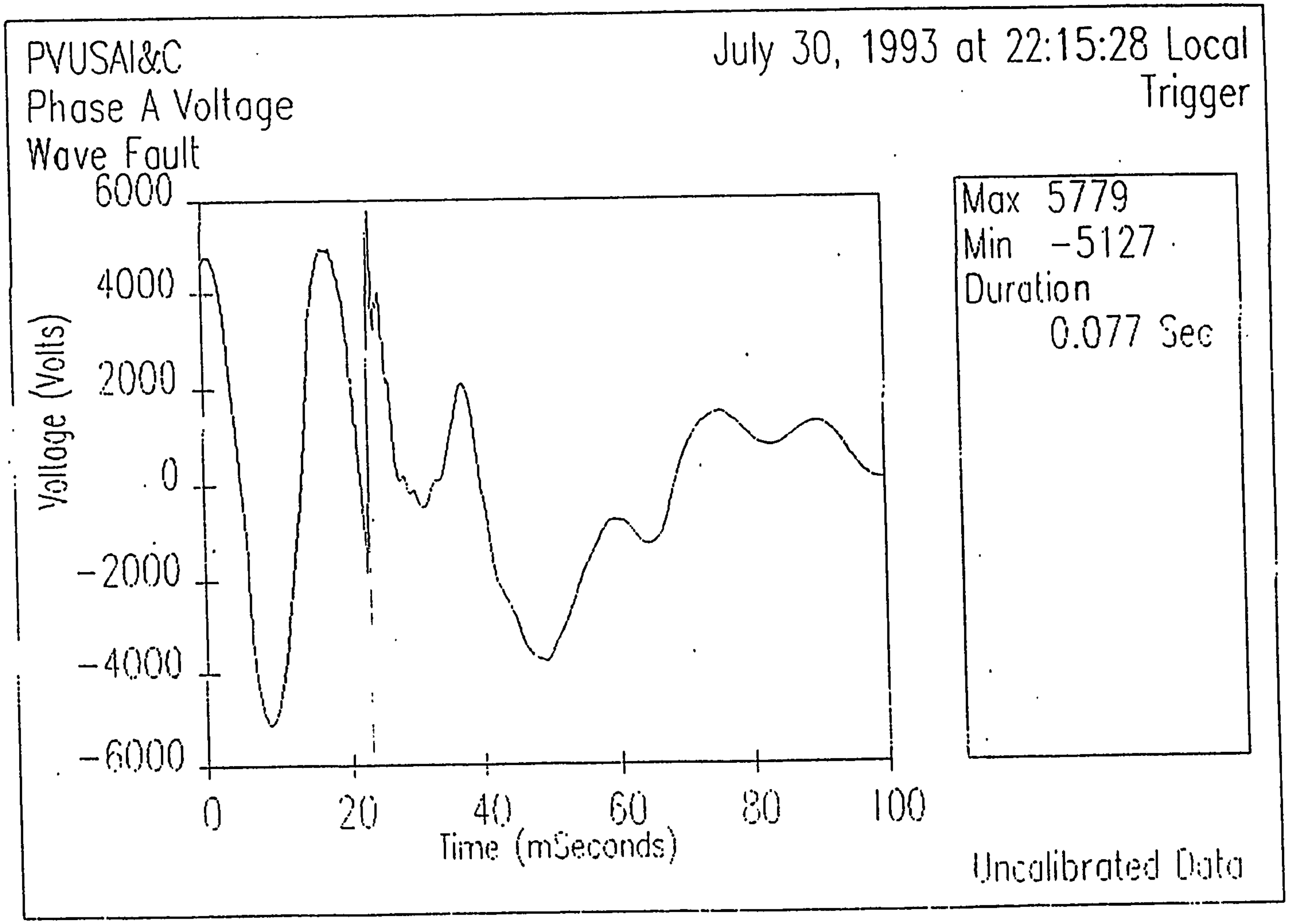


Figure 7-2
Power Quality Wave Fault

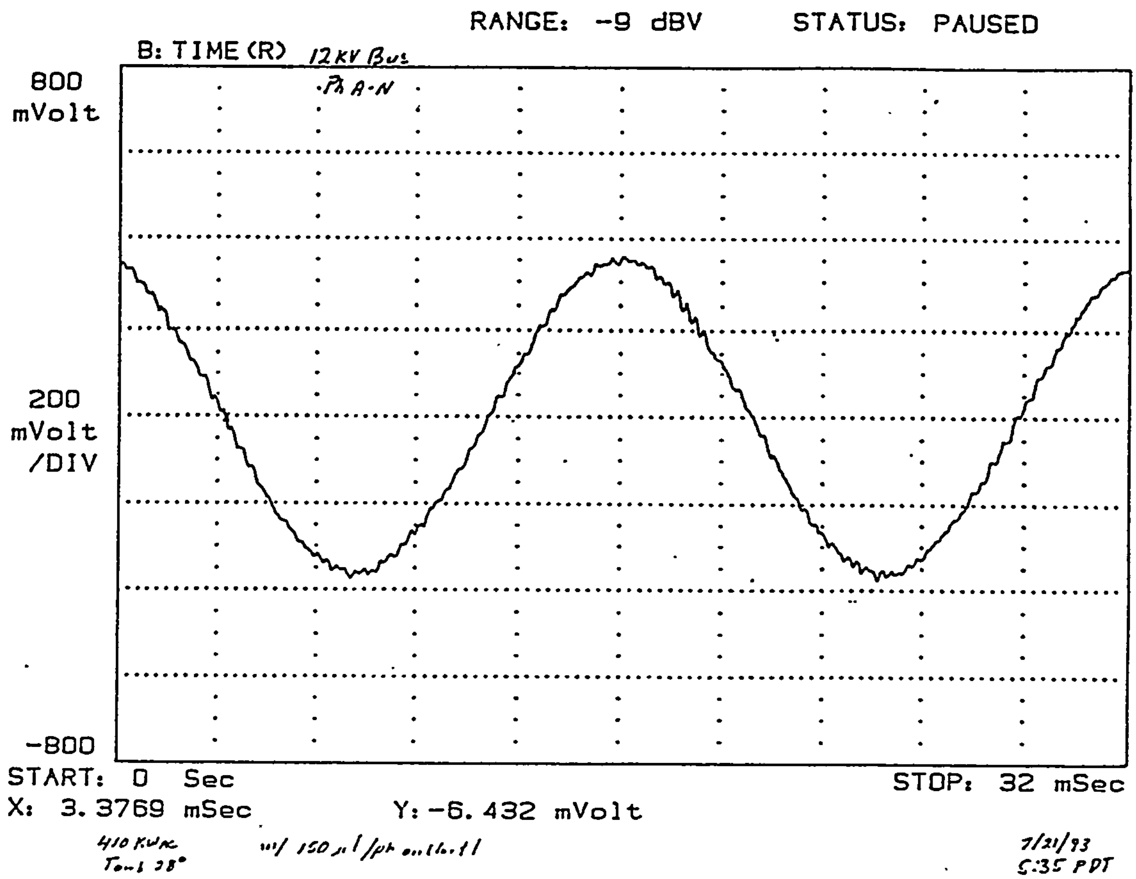


Figure 7-3
Kerman 12-kV Voltage Waveform

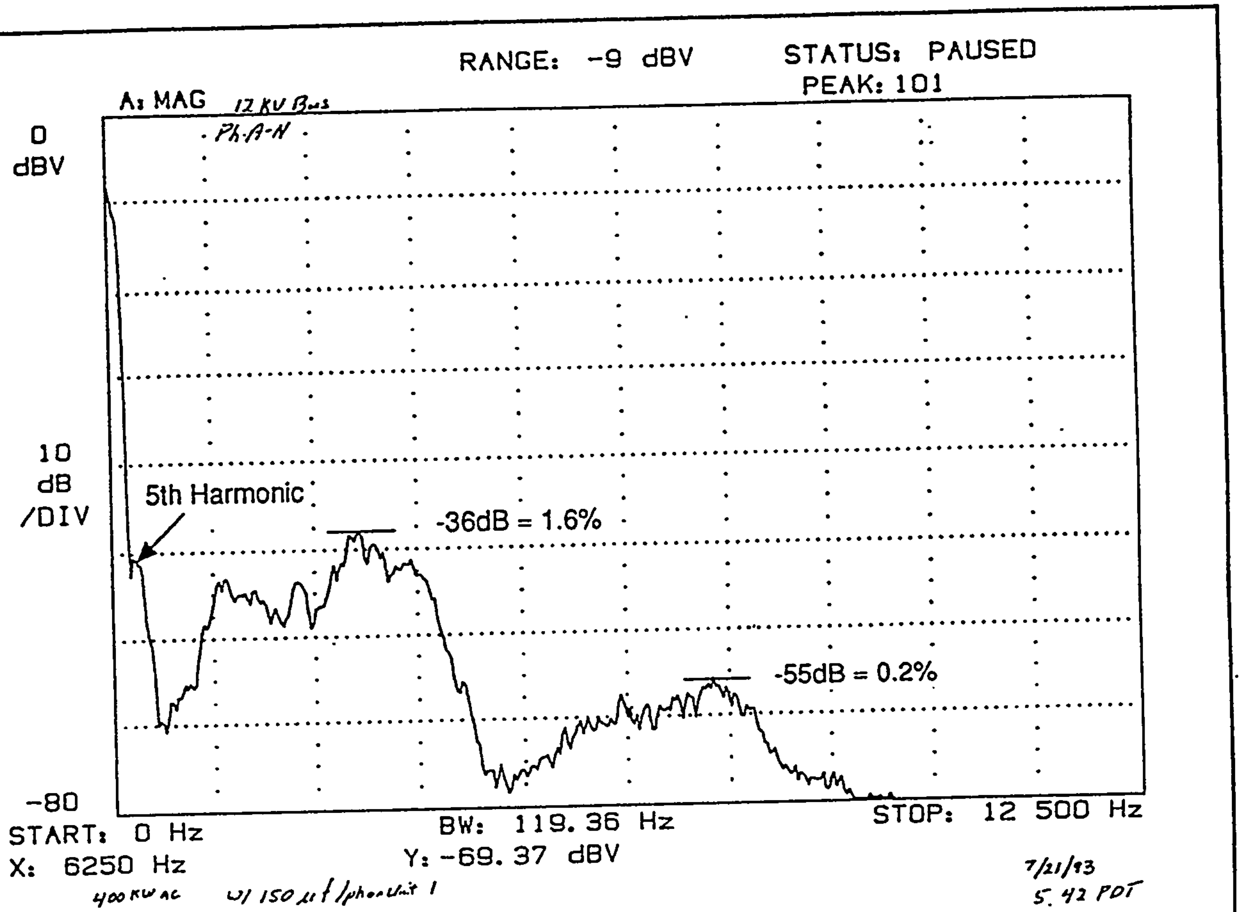


Figure 7-4
Kerman 12-kV Voltage Spectral Plot

Section 8
OTHER ACTIVITIES

This section describes 1993 activities in the areas of project planning, technology transfer, and safety.

PVUSA PROJECT PLAN

Following initial efforts to develop an overall project plan, and a strategy planning meeting, efforts began to develop a strategic plan that will maximize the value and benefits of PVUSA to its cosponsors. A key factor in this planning was the funding available from the principal funding organizations. At the planning meeting held in Washington, D.C., on April 24, 1993, a consensus was reached that PVUSA is a valuable resource that should yield two years of operating experience on installed systems and various educational benefits. A key need was identified for near-term documentation and widespread dissemination of PVUSA experience. Strategic planning will continue into 1994 with input from PVUSA members, government agencies, and related interest groups.

PVUSA activities in 1994 will reflect the initial concerns raised during the April 1993 meeting, with an emphasis on technology transfer through workshops, topical reports, and further development of methodologies for assessing grid-support PV.

KERMAN PROJECT PLAN

The Kerman Project Plan was completed in December 1992, and is available upon request from the PG&E-PVUSA Project Manager. Implementation of the plan began in 1993.

As a targeted grid-support system the Kerman PV installation has three objectives: (1) to quantify the distributed and system benefits based on measured performance data for an actual T&D application; (2) to physically demonstrate a utility's ability to locate modular generation within its T&D system; and (3) to confirm actual operation and maintenance costs and requirements for a large-scale PV plant operated by utility T&D personnel.

Analysis began in 1993 and will continue into 1994. A presentation of preliminary results is planned for a workshop in early 1994.

TECHNOLOGY TRANSFER ACTIVITIES

1993 technology transfer activities continued with ten PVUSA technical papers and presentations, two workshops, four quarterly reports, and 169 tours of the Davis site. PVUSA personnel also attended industry working groups. These activities are described in detail in Appendix F. In October 1993, the *1992 PVUSA Progress Report* was issued.

SAFETY

The Safety Committee met three times during 1993. The Illness and Injury Prevention Program (IIPP) and Safety and Health Action Plans (SHAP) were updated. The final SHAP was issued to the Project Team in October. Work continues on PV-specific safety guidelines. Safety audits were conducted at both Davis and Kerman. Safety training of site personnel for CPR and fire extinguishers took place in 1993. Weekly site safety meetings were held, and site technical staff attended two-day seminars on OSHA safety practice. Specific training requirements for site individuals are reviewed and updated annually.

Following a minor grass fire in Davis, fire breaks were disked to prevent a repetition. Site personnel continue to evacuate the Davis site while shooting practice is in progress at the Davis police firing range.

No lost time or OSHA-reportable incidents occurred at Davis or Kerman in 1992 and 1993.

OPERATION AND MAINTENANCE WORKSHOP

In April, PVUSA hosted a three-day workshop on PV power plant design, operation, and maintenance at the Davis site. The workshop, which was cosponsored by EPRI, was attended by 15 personnel from eight utilities, including three from PG&E Fresno. Topics included PV safety, fundamentals, and design criteria, and hands-on exercises on PV and BOS troubleshooting.

In August, PVUSA hosted a two-day O&M workshop at Kerman (see **Figure 8-1**). The workshop was led by three PVUSA personnel and attended by 11 PG&E Fresno substation maintenance personnel. The Kerman workshop, which was an abbreviated version of an O&M workshop held earlier at Davis, was targeted specifically for Kerman activities. Its purpose was to introduce Fresno substation maintenance personnel to the PV technology at Kerman because the Fresno staff eventually will service the PV installation.

Figure 8-1
Kerman O & M Workshop, August 1993

OPERATION AND MAINTENANCE MANUALS

Two O&M manuals were under preparation in 1993 for Davis and Kerman. The Davis manual covers safety, site facilities, technology types, and includes information on off-site contacts. The manual will be a "living" document with its first issue scheduled for early 1994.

The Kerman O&M manual (completed in late 1993) is intended to serve as a model for similar grid-support PV systems. It includes a schedule for routine maintenance and information to provide guidance to PG&E substation maintenance personnel regarding suppliers' detailed O&M reference materials.

PVUSA SITE TOURS

Tours of the PVUSA 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 facsimile (916) 753-8469. Tours range in duration from 30 to 60 minutes, and large groups (20 or more) can be accommodated with adequate notice.

Section 9

KEY FINDINGS AND CONCLUSIONS

PROCUREMENT AND CONSTRUCTION

EMT Systems

Since its inception PVUSA has contracted for five EMT-1, three EMT-2, and three EMT-3 PV systems, each consisting of 20-kW (nominal) arrays. EMT-2 and EMT-3 technologies have tended to be less mature than EMT-1 technologies, indicating the need for additional development before most of these products can be fielded.

Due to a combination of factors (including lack of financing, inability to pass qualification tests, and module performance instability), only one EMT-2 contract (AstroPower) was still active at the end of 1993; four EMT-2 contracts became inactive in 1993.

The EMT procurements have demonstrated the value of establishing milestones and schedule dates with options if difficulties arise. PVUSA's experience with its 1-kW demonstration requirement is limited to the EMT-3 Amonix and Solar Cells, Inc., contracts. Nonetheless, indications are that this requirement is valuable for the EMT procurement process, even though Amonix was the only supplier to certify completion in 1993.

PVUSA's experience with EMT-2 and EMT-3 suppliers indicates some PV research laboratories can have difficulty in making the transition from cell production to assembly-line manufacturing of PV modules. Developing and implementing an effective quality assurance and control plan is difficult for some suppliers, but improves product consistency and alleviates many concerns on behalf of the purchaser.

Utility-Scale Systems

The PVUSA project has installed three utility-scale turnkey PV systems at Davis and one 500-kW ac system at Kerman. Lessons learned at Davis were applied at Kerman, and the following conclusions are drawn from the four installations:

- Turnkey, grid-support PV plants (200–500 kW) that are designed to utility standards can be completely installed (from award to commercial operation) in 9 months or less. With standardization a 6-month period should be achievable. Commercial incentives for meeting schedule and output targets are advisable.

- Design and construction of the Kerman plant showed that to obtain a quality installation, utilities must be knowledgeable about PV and directly involved with PV projects or hire experienced system integrators and architect engineers. Adequate design reviews, safety reviews, quality control/inspection, scheduling, testing, and contract management are vitally important for achieving a quality installation.

- Based on Kerman data, first costs for a utility-standard (non-research) balance of plant are expected to be about $2.20/W. First cost for a utility-standard turnkey PV array will be $9.00/W or less depending on the technology selected.

- Availability of commercial PCUs for PV applications is limited. A major industry initiative to encourage the development of PCU technology is advisable. PCU cost, reliability, and power quality need to be addressed.

ENGINEERING

No industry standards exist for inverters or PCUs designed for PV application. Until standards exist, PVUSA recommends PCU designs be subjected to design safety review by a competent engineer or laboratory to validate acceptability in terms of NEC 90-6 "Examination of Equipment for Safety." PVUSA technical specifications now require safety reviews of both PCU designs and the overall system.

Grid-support applications of PV generating systems such as Kerman require consideration of the PCU/grid interface. To the extent possible, the utility feeder should be tested and characterized for the PCU supplier in terms of impedance, available fault current, anticipated line transients (frequency, duration, etc.), range of voltage and frequency, size and switching patterns for capacitor banks on adjacent feeders, and potential noise contributions from other utility customers on the same feeder.

PERFORMANCE

In 1993, the project added two US systems totaling 700 kW of new capacity. These additions increased the project's total operating capacity to 1300 kW, with 12 EMT and US systems in operation at six sites in California, Hawaii, Texas, and New York. At year's end, four additional systems totaling 250 kW were being completed in Virginia, California, and New York.

Knowledge gained on a broad range of technical issues regarding utility PV systems continues to be a principal benefit of PVUSA's efforts, but the energy generated is becoming a significant product, too. Electricity generated in 1993 was 1624 MWh—a PVUSA record and enough to satisfy the annual demand of about 270 homes. Since 1989, PVUSA's systems have cumulatively generated more than 2500 MWh, an offset of more than 4000 barrels of oil through conventional generation.

With exceptions for outage time, the output profile for PV systems corresponds almost directly with the solar radiation profile. Seasonal variation in PV system output is dependent on both orientation and location. For the fixed 22° tilt array in Maui, the monthly generation fluctuates very little. For the fixed arrays in Davis, the summertime output has been about three times greater than the wintertime output, and for single-axis arrays, the seasonal variation can be as high as 5:1.

PV systems' good summertime performance correlates well with utility loads. Capacity factor, a widely used performance measure for conventional utility plants, also applies to PV systems and helps illustrate the favorable match between PV output and utility loads. During peak load hours in July (PG&E's overall peak period includes weekdays from noon to 6 p.m., May through October), the newly installed Kerman PV plant operated at a capacity factor of 78 percent, even though its annual capacity factor is expected to be about 29 percent. From May through October, PVUSA's systems demonstrated peak-period capacity factors ranging from 60 to 75 percent, with the lower range represented by fixed tilt systems that are not oriented to maximize afternoon output. Corresponding annual capacity factors for PVUSA's systems have ranged from 20 to 27 percent.

Annual efficiencies of silicon-based PV technologies being evaluated at PVUSA range from about 3 to 3.5 percent for amorphous silicon arrays, about 8 percent for polycrystalline arrays, and 10 to 11 percent for single-crystal arrays.

In the case of the APS fixed-tilt array, the improvement in efficiency and power output after cleaning was calculated to be 19 percent. After 4 months of dirt accumulation the array was cleaned well by an October rain. The annual effect of soiling losses is commonly estimated to be 5-10 percent. PVUSA's results suggest cleaning arrays during the summer months, which are typically dry, may significantly improve system performance during utilities' peak load hours.

After its first year of operation, the APS system's rated power degraded by about 11 percent. This is substantially less than the first-year degradation of 20 percent often seen in a-Si systems. Most of the APS panels, however, were exposed for about 4 months in a short-circuited condition before power measurements were recorded, and any degradation that may have occurred during the initial exposure period has not been determined. Even with the first-year degradation, the system's present rated power is about 7 percent above its 400-kW design rating.

PVUSA has investigated the effect of long-term system degradation for PVUSA's EMT arrays with 3–5 years of operation. Three a-Si systems have been degrading at rates of 2–4 percent per year, with a standard error of about ±1 percent. The Siemens microgridded single-crystal silicon system has degraded at an average rate of 1 percent per year (±0.3 percent) in 5 years. The Solarex bi-facial polycrystalline silicon system has degraded at a rate of 1.9 percent per year (±0.6 percent) in 3 years. After 3 years, the ENTECH system does not appear to be degrading.

A new measure of system performance, the insolation-weighted capacity factor, has been developed to supplement other common measures of PV system performance. This factor divides the traditional capacity factor by a similarly-defined "insolation factor," resulting in a unit measure of performance independent of the amount of sunlight available. For PVUSA's systems with good operating histories, insolation-weighted capacity factors have averaged about 80 percent. For the system designer this result indicates that even for highly reliable systems, actual long-term generation will be only about 80 percent of the expected generation based on a given system's rated capacity. The shortfall may be attributed to temperature-related efficiency losses, soiling, and maintenance outages.

For PV systems in good operating condition, system availability (the percentage of daytime hours when net power is supplied to the utility) has averaged about 80 percent. (It is only coincidental that the magnitudes of availability and the above-mentioned insolation-weighted capacity factor are the same.) Even without outages, system availability is usually below 100 percent because systems cannot generate sufficient power during the earliest and latest hours each day, or during periods of low fuel (i.e., sun) to overcome PCU and transformer tare losses. Several systems, notably the Sovonics and ENTECH EMT arrays and the APS and IPC US systems, have had lengthy periods of low availability. In each case the low availability resulted from BOS component failures.

OPERATION AND MAINTENANCE

Lessons learned in 1993 include the following:

- Refinements made to PVUSA's O&M database during 1993 will enhance the project's ability to assess O&M requirements of PV systems within an electric utility setting.
- The Kerman US-2 system is providing a realistic test bed for determining utility maintenance costs for a commercial grid-support PV facility. Preliminary data indicate system maintenance costs for the initial 6 months of operation at Kerman are approximately $0.01/kWh.
- Recent experience at Kerman indicates PV systems have matured, and remote operations are a viable alternative. Initial analysis of the Kerman facility indicates an overall availability in excess of 91 percent; this availability includes planned outages.

- EMT-1 flat-plate arrays continue to require moderate maintenance and repairs, and have not exhibited the high frequency of repair as might be expected of research technologies. Maintenance costs for US-1 systems continue to be higher than expected, primarily due to prototype PCUs and a 12.47-kV feeder that experiences periodic line transients.
- The Davis site developed an automated schedule for routine maintenance that will help ensure reliable operations.
- A summary of Davis failure-related maintenance labor indicates 97 percent of staff time was spent on BOS items, only 3 percent on replacing two modules.

SYSTEM TESTING

PVUSA system testing for harmonic levels at Kerman found inverter outputs were within the following specified limits: 5 percent total harmonic current distortion, 3 percent single-frequency current distortion, 3 percent total harmonic voltage distortion, and 1 percent single-frequency voltage distortion.

Following PVUSA testing, customer complaints prompted further tests, which found high-frequency (6000 Hz) harmonics coincident with the inverter switching frequency. Filter capacitors were added to correct the problem. The acceptability of the filter capacitance was determined empirically; that is, customer complaints ceased.

PVUSA has found its power quality specifications do not adequately address all possible harmonic (noise) problems. Unacceptable harmonics can be experienced in a wide range of frequencies. Additionally, national standards (e.g., ANSI/IEEE standard 929-1988, Section 4.4) do not have sufficient data to allow definitive specifications.

TECHNOLOGY TRANSFER

Domestic and international interest in the PVUSA project continued to grow in 1993. The Project Team handled numerous requests for papers, data, and technical guidance. The Davis facility hosted 150 tours for more than 750 visitors from approximately two dozen countries. In addition several tours and a dedication ceremony were held at the Kerman site.

For the first time PVUSA conducted PV workshops. A workshop at Davis, cosponsored by EPRI, addressed PV design, operation, and maintenance; a second workshop at Kerman was held to train PG&E local operators in PV O&M.

PVUSA published several reports and papers, including the *1992 PVUSA Progress Report*, four quarterly technical reports, the monthly "PVUSA Update," and ten other papers and presentations for seven conferences and workshops.

Feedback received from project participants and others throughout the year indicated a desire for increased documentation of lessons learned at PVUSA. The 1994 project plan calls for up to six topical reports relating to various aspects of PVUSA. Several workshops also are planned.

PVUSA also continued its ongoing standards development work with the Institute of Electrical and Electronics Engineers, Inc. (IEEE) and the International Electrotechnical Commission (IEC).

Section 10
FUTURE WORK

1. Technology transfer will be given a high priority in 1994. As part of that effort, PVUSA plans to publish six topical papers in 1994 through early 1995. Topics include the final assessment of EMT-1 systems; PV construction and safety; BOS design and cost; PV power quality issues; PV system procurement, rating, and acceptance testing; and data acquisition.

2. PVUSA will host workshops to present its topical reports.

3. Validation work for the Kerman US-2 installation will continue in 1994. PVUSA will evaluate initial results, test assumptions used to justify the installation, refine methodologies, and draw insights applicable to other T&D systems and PV installations located in those systems. From the data and methodologies, the economic benefits resulting from the operation of Kerman in the distribution system will be determined.

4. Procurement and installation of the remaining EMT-2 are anticipated. Procurement of one additional EMT system is planned pending funding availability.

5. Collecting, monitoring, and analyzing data obtained from existing EMT and US systems are important for long-term evaluation and will continue at the same high level.

6. O&M activities will be closely tracked and added to the growing database. A trend toward truer, more representative O&M cost is expected as the larger database provides statistically better data. Procedures developed during 1993 for performing O&M and tracking O&M costs will be evaluated and updated, as necessary.

7. PVUSA's database will be expanded to incorporate data collected from new host systems.

8. PVUSA will work with the Utility Photovoltaics Group (UPVG) and Photovoltaics for Utilities (PV4U) on commercialization strategies for PV technologies.

Appendix A

WEATHER DATA

Table A-1 compares totals for several weather characteristics at the Davis site from 1989 through 1993. **Table A-2** compares totals for the Maui site from 1990 through 1993. **Table A-3** lists totals for the Austin site through 1993. **Table A-4** lists partial-year data for the Kerman site, beginning in July 1993. Detailed 1993 monthly weather and performance summaries for all four sites are included in Appendix B. Certain quantities are not measured at all the sites; for example, precipitation is measured only at the Davis site. Also, because of the wide variety of fixed and tracking PV systems installed at Davis, a greater number of insolation orientations are measured there.

Table A-1
PVUSA Davis Weather Summary

	1989	1990	1991	1992	1993
Insolation, kWh/m^2					
Global horizontal (long-term = 1838)	1812	1890	1877	1827	1801
Global 30° tilt	2104	2213	2123	2038	2036
1-axis tracking (horiz. N-S axis)	n/a	n/a	2707	2498	2593
Global normal	2982	3185	3044	2819	2900
Direct normal	2189	2509	2260	1839	2064
Average $T_{ambient}$, °C (long-term = 15°C)	14.9	15.7	15.6	16.3	15.7
Minimum $T_{ambient}$, °C	-6.4	-9.7	-6.0	-2.9	-4.8
Maximum $T_{ambient}$, °C	43.7	42.7	43.8	41.7	42.4
Average wind speed, m/s	2.9	3.2	3.2	3.0	2.9
Maximum wind speed, m/s	17.5	13.7	14.1	15.1	13.6
Rainfall, inches (long-term = 18")	11	15	11	20	24

Table A-2
PVUSA Maui Weather Summary

	1990	1991	1992	1993
Insolation, kWh/m^2				
Global horizontal (long-term average n/a)	2122	2075	2070	2098
Global 22° tilt	2078	2158	2148	2180
Average $T_{ambient}$, °C *(June–July 1993 n/a)*	28.0	28.0	28.2	27.0
Minimum $T_{ambient}$, °C *(June–July 1993 n/a)*	15.8	17.0	15.7	14.8
Maximum $T_{ambient}$, °C *(June–July 1993 n/a)*	44.0	42.4	42.7	40.2
Average wind speed, m/s	3.0	3.5	3.7	3.7
Maximum wind speed, m/s	14.7	14.0	13.3	13.1

Table A-3
PVUSA Austin Weather Summary

	1993
Insolation, kWh/m^2	
Global horizontal (long-term average = 1700 kWh/m^2)	1615
1-axis tracking (horiz. N-S axis)	1955
Average $T_{ambient}$, °C (long-term = 20°C)	22.6
Minimum $T_{ambient}$, °C	-1.2
Maximum $T_{ambient}$, °C	41.9
Average wind speed, m/s	1.8
Maximum wind speed, m/s	7.7

Table A-4
PVUSA Kerman Weather Summary

	1993
Insolation, kWh/m^2	*Jul-Dec*
Global horizontal (Fresno long-term averages: Jul–Dec = 967 kWh/m^2, annual = 1973 kWh/m^2)	895
1-axis tracking (horiz. N-S axis)	1317
Average $T_{ambient}$, °C (Fresno long-term averages: Jul–Dec = 19°C, annual = 17°C)	19.5
Minimum $T_{ambient}$, °C	-2.7
Maximum $T_{ambient}$, °C	42.5
Average wind speed, m/s	2.4
Maximum wind speed, m/s	10.6

Figure A-1 shows the monthly insolation during 1993 at the Davis site for five orientations: global horizontal, global 30° tilt, global normal, direct normal, and global north-south single-axis.

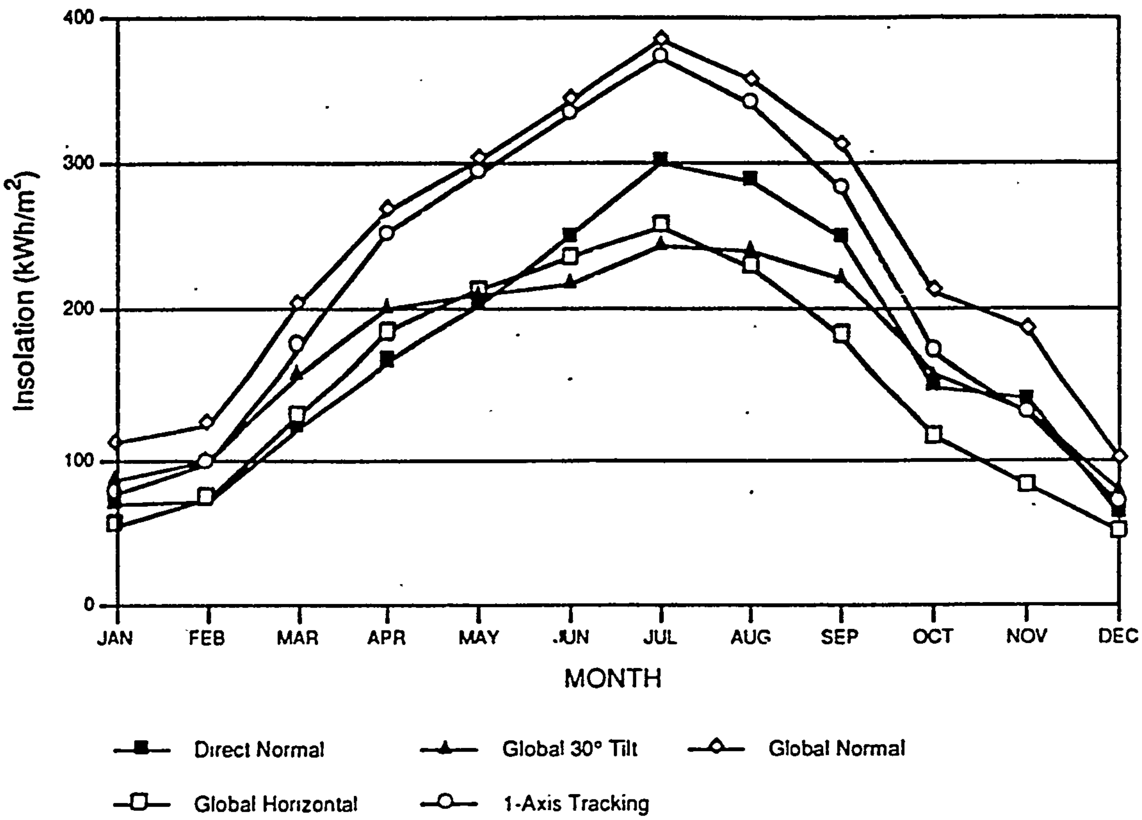


Figure A-1
1993 PVUSA Davis Insolation

Relative to the highest annual quantity, global normal, the next best orientation was the global single-axis, which received 89 percent of the global normal insolation. Direct normal insolation was 71 percent of the global normal, global 30° tilt insolation was 70 percent, and the global horizontal was 62 percent.

Figure A-1 also shows that the largest differences among 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 two 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 among the various orientations become less important because of generally cloudy weather. Much of Davis's rainfall occurs then, and there are often prolonged periods of heavy fog. The amount of insolation on every orientation, especially direct normal, is reduced greatly during overcast periods.

The global 30° 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).

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° tilt orientation. During the summer the solar incidence angles are smaller on the horizontal surface than on the fixed 30° tilt surface. During the winter incidence angles are always large on the horizontal surface (at least 60°). When coupled with short (9.3 hours during winter compared with 14.6 hours in summer) and often cloudy days, the horizontal surface receives considerably less insolation than at other times of the year.

Figures similar to **Figure A-1** are not available for PVUSA's Maui, Austin, and Kerman sites because fewer irradiance measurements are made at these sites. However, figures showing trends in 1993 monthly POA insolation for these sites are included in Section 5 as overlays with the monthly generation trends. The following text refers to those figures in Section 5.

1993 monthly POA insolation data for the Maui site are shown in **Figure 5-4**, along with the Maui site's monthly energy production. Although the annual insolation for the fixed 30° tilt in Davis has been nearly the same as the annual insolation for the 22° tilt or horizontal orientations in Maui, the seasonal variation in insolation (especially for the 22° tilt) has been smaller at Maui, in part because seasonal variations in day length are reduced as latitude approaches the equator. At Maui the ratio of the highest to the lowest monthly POA insolation was only 1.25, compared with a ratio of 3 for the Davis site. Additionally, site weather characteristics at Maui tend to be less seasonally dependent. For the Maui site in 1993, the month with the highest insolation (March) was only 14 percent higher than the average monthly insolation during the past 4 years. The worst month (January) was only 8 percent less than the 4-year average. At Davis the best month in 1993 was 38 percent above the 5-year average, and the worst month was 55 percent lower than its 5-year average.

Monthly POA insolation data for the Austin site in 1993 are shown in **Figure 5-5**. At Austin the POA is a horizontal north-south single-axis orientation. Variation in seasonal insolation at Austin was smaller than at Davis. The peak monthly single-axis insolation was about 3 times greater than the lowest winter insolation; at Davis the comparable ratio was about 5. The smaller seasonal variation at Austin is partly a result of its lower latitude and partly due to its climate. Compared with Davis, Austin tends to have more cloudy days in summer and a few more clear days in winter.

An unusual characteristic of the 1993 Austin insolation trend was a distinct dip in June's insolation compared with surrounding months. There was a corresponding dip in the site's horizontal insolation for that month, too; a detailed inspection of the data did not identify any gaps or anomalous measurements. There were only about five clear days in June; overall the monthly "clearness" index was about 16 percent below normal.

Total 1993 single-axis insolation at Austin was about 25 percent less than for the corresponding orientation at Davis. This result merits some scrutiny, though, as Austin's horizontal insolation was only about 10 percent less than Davis's. Austin's single-axis insolation may have been comparatively lower because

- The actual axis of rotation at Austin is 12° west of south. Although this is a small deviation, annual insolation nevertheless decreases as the orientation of a horizontal 1-axis tracking surface progresses toward an east-west axis.
- Tracker calibration errors have resulted in less than optimum tracking positions.
- The Austin tracker is mechanically limited to about ±40° of rotation, while the Davis instrument is free to rotate a full ±90° between sunrise and sunset. Higher incidence angles on the Austin tracker during the early and late hours of each day result in lower insolation.
- The tracker was stalled at its east limit position for several days in February and March, resulting in incorrectly low single-axis insolation measurements on each occasion.

Figure 5-6 shows monthly POA insolation data for the Kerman site from July through December 1993. At Kerman the POA is a horizontal north-south single-axis orientation. During the second half of 1993, the total single-axis insolation at Kerman was about 4 percent less than Davis, with similar monthly differences between the two locations. (As a cross-check 2 percent more insolation was recorded at Davis during the last half of 1993 for the fixed horizontal orientation.) Long-term data indicate the Kerman site ordinarily receives about 5 percent more annual insolation than Davis. The 1993 results may differ from the long-term trend because of deviations from normal weather at either site. The relatively low Kerman measurement also may be partly due to more dirt accumulation on the pyranometer lenses, although this effect has not been quantified. Because the Kerman site is unstaffed, pyranometer lenses are cleaned less often than the lenses at the Davis site, which are cleaned three times per week. (In a 1993 paper Feuermann and Zemel estimated the reduction in pyranometer responses due to dirt to be about 1 percent per week.[1])

After insolation, ambient temperature and wind speed are the next most important weather-related influences on system power output. Crystal silicon-based PV output drops 0.4–0.5 percent for each degree (°C) the temperature increases, while output for amorphous silicon-based PV modules drops approximately 0.25 percent for each degree the temperature rises. **Figure A-2** compares 1993 average and extreme temperatures at Davis, Maui, Austin, and Kerman.

June and July values have been excluded from the Maui data. Although Maui Electric and PVUSA staff have long believed Maui measurements may be 3–5°C higher than expected, no obvious problems were identified until June 1993, when the data logger battery began to fail, and temperature values rose high above a normal range. With a new battery, readings are again consistent with those of the past several years. As part of a separate project for the State of Hawaii, in late 1993 R. Lynette and Associates installed another solar/weather station adjacent to the Maui PV system. Temperature data from this station will be compared with PVUSA's data, and adjustments will be made if necessary.

1 D. Feuermann and A. Zemel, "Dust-induced Degradation of Pyranometer Sensitivity," *Solar Energy*, vol. 50, no. 6, pp. 483–486.

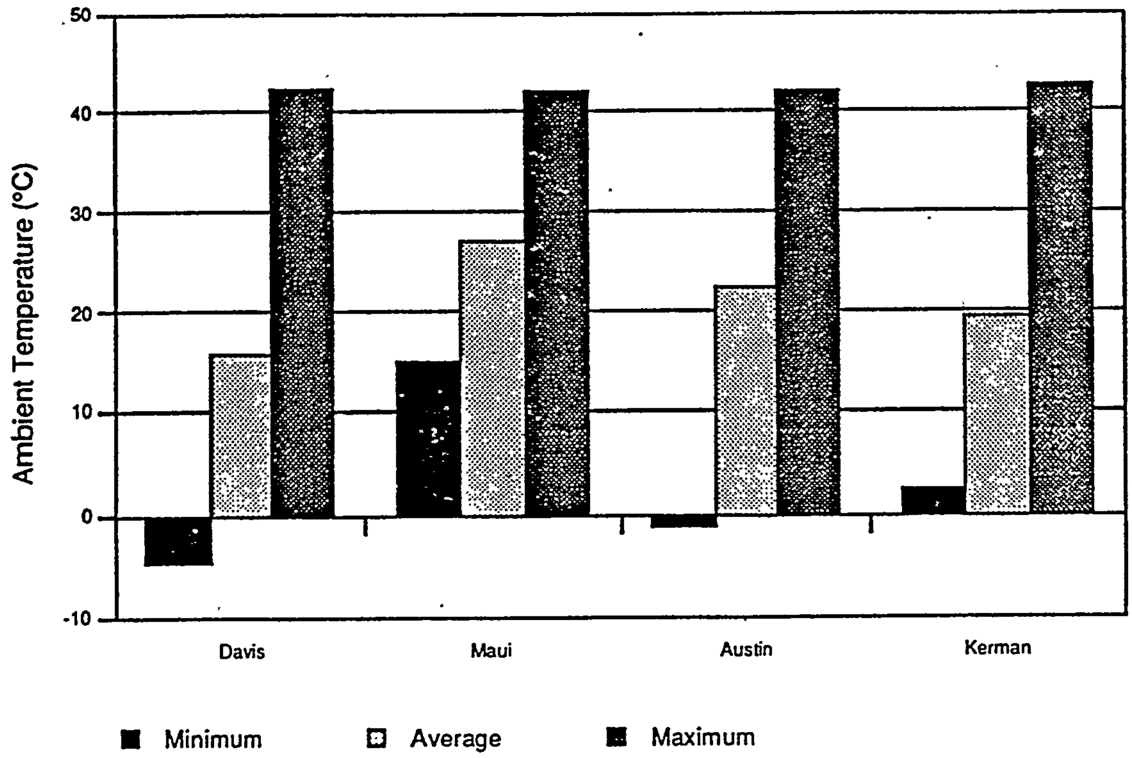


Figure A-2
1993 Temperature Comparisons

Maui: No June, July; Kerman: July through December only

Figure A-3 compares 1993 average and peak wind speeds for the Davis, Maui, Austin, and Kerman sites (only July–December data are included for Kerman). The sensitivity of PV system output to wind speed changes is 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, changing wind speed from zero to 1 m/s at 1000 W/m^2 irradiance can reduce module temperature by 20°C (increasing power by 8–10 percent); increasing wind speed from 4 to 5 m/s at the same irradiance may only reduce module temperature by 2°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.

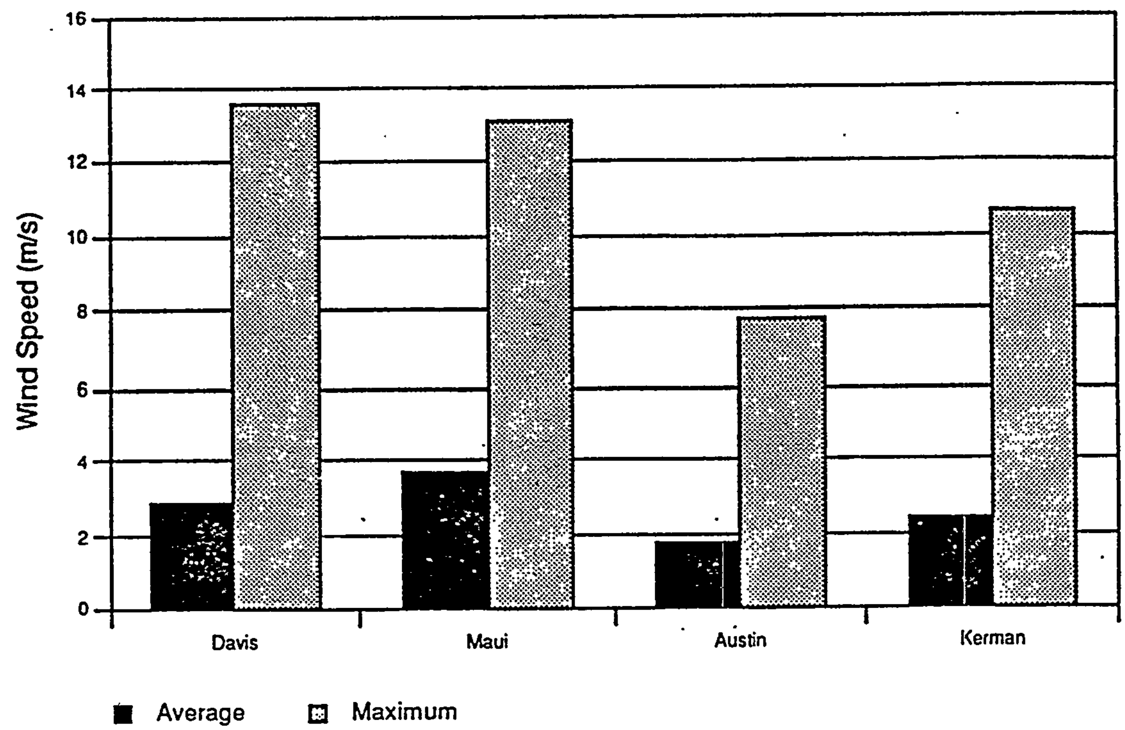


Figure A-3
1993 Wind Speed Comparisons

Kerman: July through December only

Appendix B

DETAILED MONTHLY WEATHER AND PERFORMANCE SUMMARIES

Tables B-1 through **B-3** contain detailed month-by-month data on solar resource, site weather, and system performance for the PVUSA Davis site. **Tables B-4** through **B-6** contain similar data for the PVUSA Maui site. **Tables B-7** through **B-9** and **B-10** through **B-12** list corresponding information for PVUSA's Austin and Kerman sites. (Fewer quantities are measured at the Maui, Austin, and Kerman sites.)

Array and system efficiencies are based on the module area times the number of modules in the system. System availability is defined by PVUSA as the percentage of daylight hours during which the system supplies net power to the utility grid.

In 1992, the Davis resource data were collected and presented as filtered (780–3000 nanometer wavelengths) and unfiltered (300–3000 nanometer wavelengths). In 1993, filtered data were collected but not reported because of uncertainty about the accuracy of data since the instruments were not recalibrated.

Table B-1
1993 PVUSA Davis Solar Resource Data

	Global Normal		Global 30° Tilt		Global Horizontal		Direct Normal		Global 1-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	1096	112	947	86	618	56	867	70	721	77
February	1144	124	1064	99	749	73	884	71	876	98
March	1230	203	1170	159	927	130	917	121	1087	176
April	1240	267	1232	199	1097	184	945	167	1103	250
May	1268	301	1229	208	1198	211	947	201	1230	292
June	1203	343	1123	216	1119	234	958	248	1176	333
July	1163	384	1122	242	1112	255	955	299	1135	372
August	1202	356	1170	237	1091	226	1022	287	1132	340
September	1190	312	1085	218	901	180	946	248	1033	282
October	1205	211	1147	158	859	115	920	149	888	171
November	1085	186	961	133	668	82	936	141	774	131
December	1158	101	899	79	587	51	890	62	664	70

Table B-2
1993 PVUSA Davis Weather Data

	Ambient Temperature (°C)			Wind Speed (m/s)		Precipitation	
Month	**Min.**	**Avg.**	**Max.**	**Avg.**	**Max.**	**Total (in./month)**	**Max. (in./day)**
January	-3.4	6.4	17.3	3.3	12.8	9.92	1.95
February	0.3	8.9	18.5	3.2	13.6	5.88	1.35
March	3.1	13.8	24.4	2.6	11.2	2.48	0.62
April	3.7	14.8	31.4	3.3	13.2	0.60	0.56
May	5.3	18.1	32.3	3.3	12.9	0.62	0.35
June	8.3	22.6	40.0	3.5	13.2	0.48	0.48
July	11.1	24.0	40.0	2.9	9.3	0.00	0.00
August	10.2	23.2	42.4	3.0	9.8	0.00	0.00
September	8.5	21.6	39.3	2.5	11.6	0.00	0.00
October	5.5	17.8	34.6	2.4	10.7	0.31	0.19
November	-4.8	10.4	27.0	2.7	12.2	2.40	1.04
December	-4.1	6.2	18.8	2.5	9.8	1.55	0.46
Annual	-3.4	15.7	42.4	2.9	13.6	24.24	1.95

Table B-3
1993 PVUSA Davis Performance Data

Month	System	T Mod. Wt. Avg.[a] (°C)	POA Insol.[b] (kWh/m²)	Effic.[c] (%)	ac Energy (kWh)	Max. ac Power (kW)	System Avail. (%)
January	SSI EMT-1	n/a[d]	84	11.2	1366	16.6	70
	Sovonics	24.4	82	2.0	746	10.6	52
	UPG	25.5	71	2.9	907	12.0	71
	Solarex	22.6	86	8.0	1058	13.4	61
	ENTECH	30.2	8	13.4	174	17.2	6
	APS	24.6	66	**3.9**	30012	393.4	68
February	SSI EMT-1	27.2	97	11.0	1558	17.9	77
	Sovonics	28.0	92	2.3	936	13.2	59
	UPG	28.2	95	2.9	1215	13.2	83
	Solarex	25.8	96	7.9	1178	13.7	70
	ENTECH	32.6	7	12.1	131	15.9	5
	APS	28.0	81	**3.7**	34908	422.2	74
March	SSI EMT-1	37.2	158	10.6	2505	18.5	84
	Sovonics	37.7	157	2.6	1811	14.9	73
	UPG	38.6	153	3.0	2005	14.7	85
	Solarex	35.2	159	7.4	1873	14.2	80
	ENTECH	41.9	4	12.0	83	13.9	3
	APS	37.9	128	**3.7**	54648	465.5	73
April	SSI EMT-1	37.5	195	10.3	3015	19.7	86
	Sovonics	37.1	196	2.7	2349	15.6	80
	UPG	38.1	198	2.9	2556	15.5	91
	Solarex	35.1	199	7.1	2275	14.7	83
	ENTECH	43.0	142	11.3	2596	18.8	62
	APS	36.8	116	**3.6**	47867	498.4	56
	IPC[e]	n/r	n/r	n/r	20500	n/r	n/r
May	SSI EMT-1	41.7	188	10.1	2852	18.3	73
	Sovonics	41.3	186	2.7	2226	15.2	68
	UPG	40.8	182	2.9	2360	14.4	76
	Solarex	39.7	189	7.0	2095	13.7	70
	ENTECH	46.1	117	11.3	2143	18.4	45
	APS	43.1	99	**3.5**	40250	456.5	40
	IPC[e]	n/r	n/r	n/r	41003	n/r	n/r
June	SSI EMT-1	44.8	217	10.0	3246	17.9	79
	Sovonics	44.5	210	2.4	2214	12.4	73
	UPG	46.0	209	2.9	2735	14.3	85
	Solarex	43.0	215	6.8	2343	13.4	76
	ENTECH	48.7	18	11.8	342	17.2	9
	APS[f]	no data	no data	no data	5323	no data	6
	IPC	49.1	276	**7.8**	52289	205.7	83

n/r = not recorded

a Average module temperature, weighted with respect to system power.
b Does not include insolation received during system outages.
c Dc efficiencies are shown for emerging module technologies (EMTs). For utility-scale (US) systems, ac efficiencies are shown in **boldface** type.
d Module temperature thermocouple readings were out of range in January, July, and August because the thermocouple became detached.
e Only ac kWh are reported for IPC's start-up and testing period in April and May.
f The APS system was out of service for all but the last two days of June, and only ac kWh data are available for those two days.

Table B-3
1993 PVUSA Davis Performance Data
(Cont'd)

Month	System	T Mod. Wt. Avg.[a] (°C)	POA Insol.[b] (kWh/m²)	Effic.[c] (%)	ac Energy (kWh)	Max. ac Power (kW)	System Avail. (%)
July	SSI EMT-1	n/a[d]	240	9.7	3528	17.2	82
	Sovonics	48.3	235	2.8	2848	15.5	78
	UPG	50.1	240	2.9	3166	14.6	89
	Solarex	47.1	238	7.0	2716	13.8	80
	ENTECH	54.6	98	10.4	1651	16.1	32
	APS	49.3	174	**3.2**	63616	416.1	64
	IPC	51.6	223	**7.8**	42838	196.2	63
August	SSI EMT-1	n/a[d]	233	9.7	3422	16.7	85
	Sovonics	48.5	233	2.9	3012	14.8	82
	UPG	49.6	234	2.9	3096	14.2	91
	Solarex	47.1	232	7.6	2902	14.4	83
	ENTECH	53.3	248	10.1	4071	16.2	83
	APS	49.3	222	**2.9**	73217	415.6	88
	IPC	46.9	39	**8.0**	7560	188.6	12
September	SSI EMT-1	44.9	193	9.4	2758	16.2	80
	Sovonics	47.1	218	2.7	2627	14.2	86
	UPG	49.4	220	2.8	2746	13.7	93
	Solarex	45.5	194	7.3	2319	13.9	77
	ENTECH	51.8	168	10.0	2711	16.0	69
	APS	47.4	179	**2.6**	52900	358.5	77
	IPC	47.8	3	**8.1**	639	169.5	1
October	SSI EMT-1	34.2	150	10.4	2312	18.0	83
	Sovonics	39.3	153	2.7	1803	15.3	79
	UPG	41.3	153	3.0	2051	15.2	88
	Solarex	37.5	151	8.2	1985	15.6	82
	ENTECH	47.2	126	11.9	2415	17.8	65
	APS	39.5	139	**3.5**	56658	462.9	82
	IPC	0	0	**0**	0	0	0
November	SSI EMT-1	25.3	131	10.9	2140	16.4	83
	Sovonics	30.6	134	2.4	1489	12.1	79
	UPG	33.0	133	2.8	1690	12.2	89
	Solarex	28.9	132	8.4	1819	14.1	81
	ENTECH	38.1	127	12.7	2615	19.2	76
	APS	31.7	113	**3.5**	45308	373.6	81
	IPC	25.1	74	**8.9**	16036	153.5	64
December	SSI EMT-1	23.3	75	11.2	1190	15.1	72
	Sovonics	25.5	75	2.0	698	11.0	58
	UPG	25.2	75	2.9	953	11.7	76
	Solarex	22.6	77	8.6	1009	13.1	66
	ENTECH	34.3	47	14.5	1104	18.1	41
	APS	24.9	60	**3.7**	25341	332.3	67
	IPC	19.7	37	**8.6**	7676	133.8	58

n/r = not recorded

[a] Average module temperature, weighted with respect to system power.
[b] Does not include insolation received during system outages.
[c] Dc efficiencies are shown for emerging module technologies (EMTs). For utility-scale (US) systems, ac efficiencies are shown in **boldface** type.
[d] Module temperature thermocouple readings were out of range in January, July, and August because the thermocouple became detached.

Table B-4
1993 PVUSA Maui Solar Resource Data

Month	Global 22° Tilt: Peak Irradiance (W/m^2)	Global 22° Tilt: Insolation (kWh/m^2)	Global Horizontal: Peak Irradiance (W/m^2)	Global Horizontal: Insolation (kWh/m^2)
January	1213	164	978	132
February	1157	180	1028	153
March	1250	204	1225	192
April	1220	187	1252	194
May	1156	192	1235	215
June	1109	174	1183	203
July	1109	170	1191	194
August	1156	185	1195	197
September	1184	188	1156	183
October	1208	181	1111	160
November	1160	186	950	148
December	1119	175	916	135

Table B-5
1993 PVUSA Maui Weather Data

Month	Ambient Temperature (°C): Min.	Ambient Temperature (°C): Avg.	Ambient Temperature (°C): Max.	Wind Speed (m/s): Avg.	Wind Speed (m/s): Max.
January	15.5	24.8	35.1	3.8	13.1
February	15.0	24.3	36.4	3.8	9.8
March	14.8	25.4	38.4	4.3	12.2
April	17.7	27.4	40.2	3.5	10.6
May	19.1	27.8	39.2	4.1	11.7
June	n/a	n/a	n/a	3.5	10.1
July	n/a	n/a	n/a	3.5	10.6
August	21.4	30.0	41.8	3.6	12.4
September	20.8	29.6	41.9	3.5	10.6
October	20.9	28.8	41.6	4.0	11.0
November	17.8	27.0	39.2	4.4	12.2
December	16.9	25.6	37.5	3.3	12.1

n/a = not available

Table B-6
1993 PVUSA Maui Sovonics Performance Data

Month	T Mod. Wt. Avg.[a] (°C)	POA Insol.[b] (kWh/m²)	dc Eff. (%)	ac Energy (kWh)	Max. ac Power (kW)	System Avail. (%)
January	42.7	154	3.3	2333	17.7	80
February	42.7	166	3.4	2583	17.7	83
March	41.8	204	3.2	3049	18.0	90
April	45.7	187	2.9	2483	18.5	88
May	42.0	191	3.4	2964	17.2	86
June	n/a[c]	173	3.4	2675	16.3	85
July	n/a[c]	137	3.2	1994	15.2	67
August	45.4	184	3.4	2838	17.3	87
September	44.9	188	3.4	2977	17.4	89
October	43.3	178	3.4	2829	18.1	86
November	42.9	186	3.4	2944	17.5	90
December	44.1	175	3.4	2736	16.6	89

a Average module temperature, weighted with respect to system power.
b Does not include insolation received during system outages.
c Module temperature data were corrupted in June and July as a result of a failing data logger battery.

Table B-7
1993 PVUSA Austin Solar Resource Data

	Global Single-Axis Tracking		Global Horizontal (long-term average in [ ])	
Month	Peak Irradiance (W/m²)	Insolation (kWh/m²)	Peak Irradiance (W/m²)	Insolation (kWh/m²)
January	898	75	707	63 [84]
February	1005	100	831	83 [99]
March	1029	158	953	131 [140]
April	1078	190	1074	157 [152]
May	1150	215	1119	178 [179]
June	1187	186	1193	164 [196]
July	1094	253	1084	210 [206]
August	1125	248	1144	202 [189]
September	1065	200	1038	161 [152]
October	994	147	891	120 [130]
November	864	101	781	80 [93]
December	936	83	690	65 [81]

Table B-8
1993 PVUSA Austin Weather Data

	Ambient Temperature (°C) (long-term average in [ ])			Wind Speed (m/s)	
Month	Min.	Avg.	Max.	Avg.	Max.
January	1.7	11.8 [9.8]	9.8	1.4	6.2
February	1.9	14.6 [11.8]	11.8	1.7	6.4
March	0.3	18.3 [15.3]	15.3	1.9	7.6
April	9.6	21.6 [20.3]	35.2	2.1	6.2
May	12.6	25.9 [24.0]	37.5	1.8	5.6
June	22.0	29.8 [27.6]	37.7	2.2	7.7
July	26.1	32.5 [29.2]	41.9	2.7	6.2
August	25.8	33.6 [29.3]	41.3	1.9	5.7
September	14.5	30.1 [26.0]	41.5	1.6	7.2
October	1.2	23.2 [21.2]	37.9	1.8	6.4
November	-1.2	15.0 [15.0]	30.4	1.6	5.8
December	1.8	14.7 [11.3]	27.5	1.4	6.1

Table B-9
1993 PVUSA Austin IPC Performance Data

Month	T Mod. Wt. Avg.[a] (°C)	POA Insol.[b] (kWh/m^2)	ac Eff. (%)	ac Energy (kWh)	Max. ac Power (kW)	System Avail. (%)
January	26.9	75	8.2	1306	17.5	75
February	30.5	71	8.4	1265	18.8	61
March	36.2	158	8.4	2825	20.0	85
April	38.3	127	8.2	2204	19.5	59
May	46.0	130	8.0	2210	19.0	49
June	43.8	115	7.7	1873	19.2	52
July	49.1	164	7.7	2673	17.6	57
August	50.3	248	7.7	4062	18.1	92
September	48.3	200	8.1	3426	18.2	91
October	38.5	148	8.4	2624	18.0	87
November	28.6	101	8.6	1845	16.7	83
December	27.4	82	8.4	1478	17.5	79

[a] Average module temperature, weighted with respect to system power.
[b] Does not include insolation received during system outages.

Table B-10
1993 PVUSA Kerman Solar Resource Data

Month	Global Single-Axis Tracking (Reference)		Global Single-Axis Tracking (Plane of Array)		Global Horizontal	
	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)
July	1114	358	1076	330	1050	243
August	1177	319	1060	288	1223	217
September	1100	272	1081	243	1102	178
October	896	175	851	160	797	120
November	814	129	710	111	636	86
December	722	64	672	58	596	51

Table B-11
1993 PVUSA Kerman Weather Data

Month	Ambient Temperature (°C)			Wind Speed (m/s)	
	Min.	Avg.	Max.	Avg.	Max.
July	14.8	26.6	39.4	3.1	6.6
August	6.8	26.1	42.5	2.9	6.6
September	9.9	23.6	39.0	2.5	7.4
October	9.0	20.0	35.0	1.9	7.1
November	-2.7	11.9	27.4	2.0	10.6
December	1.0	8.5	21.6	1.9	8.5

Table B-12
1993 PVUSA Kerman SSI Performance Data

Month	T Mod. Wt. Avg.[a] (°C)	POA Insol.[b] (kWh/m^2)	ac Energy (kWh)	ac Eff. (%)	Max. ac Power (kW)	System Avail. (%)
July	51.2	301	143043	8.7	518	90
August	49.8	242	113542	8.4	464	86
September	35.6	242	100005	8.1	436	96
October	40.0	156	72146	9.1	417.8	89
November	29.7	108	54164	9.8	378.6	97
December	21.9	58	29493	9.2	310.1	93

a Average module temperature, weighted with respect to system power.
b Does not include insolation received during system outages.

Appendix C

DETAILED SUMMARIES OF 1993 O&M ACTIVITIES

Tables C-1 through **C-3** summarize major O&M activities in 1993 at the PVUSA site in Davis. **Table C-4** summarizes failure-related O&M activities in 1993 at PVUSA's Austin and Maui sites. **Table C-5** summarizes failure-related O&M activities in 1993 at Kerman. Labor hours include time spent by PVUSA personnel and vendors, with the exception of time spent in travel to and from sites. Major O&M activities are categorized as:

- Preventive maintenance (includes planned outages)
- Failure-related maintenance (includes forced outages)
- Research-related activities

Some activities, such as washing arrays, do not interrupt plant performance.

The last six months of 1993 were the first months of operation for the Kerman plant and the Davis IPC system. Many of the items listed in **Table C-5** and the IPC section of **Table C-2** can be attributed to start-up problems or infant mortality and were corrected under warranty. PVUSA does not believe these costs are indicative of long-term O&M activities for the plant.

Table C-1
O&M Activities in 1993 for PVUSA Davis EMT-1

Event	Date; Number of People x Time (default is 1 person)
ENTECH	
Preventive Maintenance: 20 hr	
Inspect tracker clock and position, NIP alignment, stow battery, array, and wiring.	monthly; 2 hr
Lubricate trackers, bearings, and motors.	quarterly; 2 hr
Failure-Related Maintenance: 112.5 hr	
Repair tracker controller board failures.	16 failures; 32.5 hr total
Inspect tracking system, remove roll motor.	3/4; 4 hr
Troubleshoot tracker limit switch and wiring.	3/16; 2 x 0.75 hr
ENTECH rep on site for service/repair.	3/29-4/9; 72 hr total
Reset PCU due to Sync Error shutdown.	8 occurrences; 2.5 hr total
SSI	
Preventive Maintenance: 2 hr	
Adjust PCU start-up voltage.	8/9; 1 x 2 hr
Failure-Related Maintenance: 5.7 hr	
Reset PCU due to Sync Error shutdown.	6 occurrences; 1.5 hr total
Reattach module thermocouple.	1/15; 2 x 0.75 hr
Reset PCU due to door interlock error.	2/19; 10 mins
Solarex	
Failure-Related Maintenance: 17.25 hr	
Reset PCU due to door interlock error.	2/19; 10 mins
Correct one source circuit out of service due to switch wiring problem and cleared fuses.	3/31; 2 x 1 hr
Identify two modules with browned busbars. Modules OK because of redundant current path.	3/31; 2 x 0.5 hr
Identify voltage imbalance; water pooling in junction box caused shorting and burned connections.	3/31; 2 x 1.5 hr
Repair connections, but imbalance remained. Switched out circuit.	4/19; 2 hr
Inspect bad source circuit. Found failed diodes in intermediate junction box.	6/10; 2 x 0.25 hr
Replace diodes in intermediate junction box.	7/20; 2 x 4 hr
Reset PCU due to Sync Error shutdown.	7/30, 9/6; 0.6 hr total
Sovonics	
Failure-Related Maintenance: 11.65 hr	
Reset PCU due to door interlock and Sync Error shutdowns.	2 occurrences; 0.6 hr total
Junction box failure.	5/27; 3 x 0.25 hr
Test circuit voltage balance and power after junction box failure.	6/14; 2 x 0.1 hr
Replace modules (burned junction box).	2 occurrences; 9 hr total
PCU shutdown circuit intermittently.	3 occurrences; .5 hr total
UPG	
Preventive Maintenance: 2 hr	
Adjust PCU start-up voltage to reduce Sync Errors.	8/9; 1 x 2 hr
Failure-Related Maintenance: 2.75 hr	
Reset PCU due to Sync Error shutdown.	11 occurrences; 2.75 hr total
Other EMT-1	
Preventive Maintenance: 14 hr	
Inspect and wash arrays.	7/8, 7/13; 14 hr total

Table C-2
O&M Activities in 1993 for PVUSA Davis US-1

Event	Date; Number of People x Time (default is 1 person)
APS	
Preventive Maintenance: 44 hr	
Install roll-up access doors on PCU container.	3/19; 20 hr
Conduct field wet resistance tests, routine inspections, and cathodic protection tests.	7/1, 7/6, 7/27, 8/5; 12 hr total
Clean/replace window filters.	monthly; 1 hr
Failure-Related Maintenance: 101.85 hr	
Manually reset inverter; PCU would not start automatically.	1/7; 0.25 hr
Manually reset inverter 3; would not start automatically.	1/22; 2 x 0.5 hr
Troubleshoot PCU, replace fuses, reset breaker.	2/12; 1 hr
Smoke alarm shutdown. Inspect and reset PCU.	3/19; 2 x 0.5 hr
Inspect downed system after 4/21 line disturbance.	4/22; 2.5 hr
Consult with APS on nature of 4/21 failure.	4/26; 2 x 0.5 hr
Check fuses; repair and restart PCU (warranty repairs).	5/3-10; 2 x 25 hr
Diagnose and repair failed metering terminal board.	5/19-20; 2 x 1.5 hr
PCU trip due to line disturbance.	5/21; 0.5 hr
Inspect PCU; identify failed fuses.	5/24; 2 x 0.5 hr
Perform safety clearance for blue connector repairs.	6/15; 2 x 3 hr
Lift clearance for system restart; warranty repairs completed.	6/29; 2 x 1 hr
Electrical clearances.	7/1, 7/7; 3 hr total
Inspect DAS signal problem at PCU.	7/7; 1 hr
Investigate cause of PCU shutdown and reset.	7/12; 2 x 1.25 hr
Troubleshoot PCU failures, replace fuses as required.	8/2, 8/23, 9/13, 9/14; 9.5 hr
Troubleshoot and adjust PCU voltages to increase output.	8/30; 1 x 0.5 hr
Reset PCU due to line disturbance.	9/12; 1 x 0.1 hr
Replace dc contactor.	9/20; 1 hr
Reset PCU due to loss of site power.	10/4; 0.5 hr
Replace four fuses (two each) in Inverters 2 and 4.	10/5; 0.5 hr
Replace Inverter 2 gate driver board diode.	10/6; 2 x 3 hr
Repair ribbon cable connector in Inverter 3.	12/2; 2 x 3.5 hr
Replace dc contactor in Inverter 2.	12/7; 1 hr
Research-Related Maintenance: 84 hr	
Inspect and photograph module defects	3 occurrences; 84 hr total
IPC	
Preventive Maintenance: 10 hr	
Test MOV fuses, replace PCU filters, reset tracker clock.	quarterly; 2.5 hr
Failure-Related Maintenance: 73.65 hr	
Reset PCU due to line disturbances and bridge faults.	22 occurrences; 8.2 hr total
Reset PCU due to "dc overvoltage" shutdowns.	14 occurrences; 3.5 hr total
Remove and ship PCU circuit boards to Omnion.	9/9; 1 hr
Reinstall repaired circuit boards.	9/29; 1.5 hr
Troubleshoot Omnion PCU.	9/21; 0.2 hr
Replace EPROM.	10/4; 0.5 hr
Return master control board to Omnion	10/5; 0.5 hr
Repair failed bridge by Omnion.	10/22–11/5; 54 hr total
Replace three fuses, one IGBT, two Snubber boards.	12/10; 4.25 hr total
Research-Related Maintenance: 12.25 hr	
Check tracking accuracy.	6/18; 2 x 0.25 hr
Measure source circuit currents.	7/21; 1 hr
Take complete set of I-V curves.	7/22; 2 x 4 hr
Update data logger DAS program.	7/27; 1.5 hr
Insulate roof of PCU to lower cabinet temperature.	8/17; 1 hr
Remove one source circuit per IPC's request.	12/22; 0.25 hr

Table C-3
O&M Activities in 1993 for PVUSA Davis BOS Site

Event	Date; Number of People x Time (default is 1 person)
Preventive Maintenance: 240.75 hr	
Read 480-V and 12-kV in/out meters and report readings to PG&E Power Control Department.	monthly; 0.5 hr
Inspect site/arrays.	monthly; 2 hr
Clean PSPs in weather station (3 x/wk.) and in new arrays (daily).	daily; 0.25 hr
Update single-line diagram.	2/10; 2 x 3 hr
Landscape/reinforce APS PCU entryway.	4/2; 0.5 hr
Inventory hazardous materials in I&C bldg. and general cleanup.	5 occurrences; 11.5 hr total
Service water trailer.	4/7; 3 x 20 mins
Drain ditches, general cleanup, and weed control.	4/9, 4/23; 8 hr total
Remove site waste to landfill.	monthly; 1 hr
Test transfer trip.	annually; 1 hr
Clean up site; check fire extinguishers, safety boxes, and site 12 kV clearance.	monthly; 3 hr
Lubricate site pumps during rainy season.	20 occurrences; 10 hr total
Charge site equipment batteries.	monthly; 2 hr
Install tour path signs, clean sump and adjust floats, repair erosion and roads, conduct ground megger tests (subcontract or maintenance).	5 occurrences; $9500 est. cost
Install 12-kV surge arresters (US-1 subcontract).	9/9; 20 hr + $1000 est. cost
Remove and check scissors lift tire.	9/20; 2 hr
Failure-Related Maintenance: 12.75 hr	
Respond to grass fire on 2 acres at SE corner of site; no damage (PVUSA and Davis Fire Dept.).	6/7; 2 x 1 hr
Repair broken door lock, replace site pump fuses.	7/28, 8/31; 2.25 hr total
Replace tour path ropes.	9/28, 9/29; 8 hr total
Replace emergency light lamps.	11/18; 0.5 hr
Research-Related Maintenance: 34 hr	
Install PQNode permanently.	3/26; 2 x 8 hr
Prepare facilities, get materials for EPRI workshop.	4/5; 1 hr
Back up PQNode data.	monthly; 1 hr
Inspect as-built PQNode and uninterruptible power supply wiring diagram updates.	4/21; 3 hr
Troubleshoot BMI software (PQNode didn't react to line disturbances).	9/13; 1 hr
Reset reference pyranometer tracker controllers.	12/23; 2 x 0.5 hr

Table C-4
Failure-Related Activities in 1993 for PVUSA Host Systems[a]

Event	Date; Number of People x Time (default is 1 person)
Austin IPC[b]	
Failure-Related Maintenance	
Inverter tripped.	2/10
Return inverter to service; loose terminal found in ac disconnect switch.	2/17
Adjust west tracker limit from 39° to 41.5°.	2/24
Tracker stalled at east limit switch.	2/25
Reset tracker and adjust east limit from 42° to 45°.	3/2
Tracker hit east limit switch and stalled.	3/3
Reset tracker and change array azimuth from 0° to 5°.	3/4
Perform experiment to determine tracker rotation step set point. Adjust set point from 3.36° to 3.97°.	3/5
Adjust array azimuth set point to 12°.	3/22
Multiple inverter trips due to faulty circuit board caused 8–10 days down time per month through second quarter until corrected in August.	Various; typically 0.5 hr each
Inverter tripped with multiple fault messages.	4/27
Inverter did not start up—power supply LED lit.	5/21
Order new gate driver board.	5/25
Inverter did not start up and was reset.	6/1
Install new gate driver board, but inverter would not start up.	6/11; 1 hr
Adjust set points on crowbar board and start up inverter.	6/16; 2 hr
Disconnect crowbar board from power supply.	6/25
Remove crowbar board and power supply from inverter and return to Omnion.	6/28; 1 hr
Install new power supply and crowbar board and start up inverter.	7/12; 1 hr
Inspect limit switch bolts per IPC request.	9/7
Replace limit switch bolts, install redundant light switches.	9/25; 3 hr
Maui Sovonics	
Failure-Related Maintenance: 23 hr	
Two PCU shutdowns, causes unknown.	2/1, 7/2; 2 x 1 hr
Replace data logger batteries.	7/8; 1 x 1 hr
Six module junction box failures; replace modules in three cases.	Various; typically 2 x 4 hr
Repair three modules by cleaning and tightening connections at junction boxes.	Various; typically 2 x 4 hr
Repair one damaged module interconnect wire by recrimping new lug on damaged end.	1 x 2 hr
Perform weed control (contractor).	1st quarter; time unknown

[a] No preventive maintenance or research activities reported during 1993 for Maui and Austin arrays.
[b] Duration of Austin activities not always reported.

Table C-5
Failure-Related Activities in 1993 for Kerman US-2

Event	Date; Number of People x Time (default is 1 person)
Failure-Related Maintenance: 104.5 hr (Some events were logged but did not require staff time.)	
Inverter 1 shut down with "CABINET OVERTEMPERATURE" fault; HVAC breaker in Inverter 1 found tripped; reset HVAC breaker and started up Inverter 1.	6/20; 0.75 hr
Inverter 2 shut down with "REG or CROWBAR FAULT;" unit reset and started up.	6/21; 0.5 hr
HVAC modifications installed in both inverters.	6/22; 2 x 4 hr
Inverter 2 shut down with "REG or CROWBAR FAULT."	6/26
Inverter 2 reset, and unit started up.	6/29; 0.25 hr
Three failing actuators identified.	7/7
Inverter 2 developed dc voltage offset of 17 Vdc, indicating an array problem.	7/9
Reduced power contactors for Inverter 1 malfunctioned.	7/9
Both inverters shut down.	7/9
Inverter 2 shut down, would not restart. Inverter 1 shut down and restarted with reduced power contactors open.	7/13
Inverter 2 shut down and remotely reset.	7/13; 0.5 hr
Inverter 1 shut down and remotely reset.	7/14; 0.5 hr
Two failed modules found in circuit 16.	7/14; 2 x 6 hr
Two failed modules replaced.	7/21; 3 x 2 hr
Three failed actuators replaced.	7/21; 3 x 3 hr
Inverter 2 developed dc voltage offset of 47 V, indicating an array problem.	7/29
Voltage imbalance in Inverter 2 found to be caused by blown fuse in dc collection box for circuit 17P.	8/4; 2 x 1 hr
Additional capacitors installed in Inverter 1.	8/4; 2 x 4 hr
Fuse replaced in circuit 17P that caused voltage imbalance.	8/4; 2 x 0.5 hr
One circuit added to reduced power contactor in Inverter 1.	8/4; 2 x 1 hr
Both inverters shut down.	8/6
Both inverters started up remotely.	8/8; 0.5 hr
Failed actuator removed and returned to supplier.	9/8; 2 x 3 hr
Loose actuator hardware tightened.	9/16; 2 x 6 hr
Four actuators replaced.	10/26; 2 x 4 hr
Five modules replaced, and seven connections tightened.	10/27; 2 x 7 hr
Inverter 1 developed dc voltage offset of 40 Vdc, indicating an array problem.	11/18
Inverter 1 shut down with "Start-up Sequence Error" message and was reset.	11/23; 2 x 0.5 hr
Circuit 1N fuse replaced to correct dc offset.	11/23; 2 x 3 hr
Inverter 1 shut down and remotely reset.	11/29; 0.5 hr
Inverter 2 developed dc voltage offset of 100 Vdc, indicating an array problem.	12/23
Circuit 13N fuse replaced to correct dc offset.	12/28; 2 x 3 hr

Appendix D

ADDITIONAL PVUSA TEST SITES

Appendix D includes system and site descriptions for each PVUSA site that was completed or under construction by December 1993. It also 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.

City of Austin, Texas

This 17.9-kW grid-interactive system is located at the City of Austin Convention Center. It features one row of Mobil Solar bi-module PV panels, a 25-kW ac Omnion PCU, an IPC horizontal single-axis structure and tracker drive system, 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 as one row of PV panels oriented on a horizontal north-south axis. It contains 96 modules with a total PV aperture area of 212.1 m^2. The array is located on top of the convention center's eastern wall. The tracker drive controller and array monopole disconnects are located at the southern end of the row, and the winch is located in the middle of the row, west of the center pedestals. The PCU, dc disconnect switches, and DAS are located inside the convention center.

Maui Electric, Hawaii

The 17.6-kW array is located just north of Kihei, Maui, in one corner of a U.S. Air Force experimental station. The array consists of 1200 Sovonics EMT modules similar to those in the Sovonics array at Davis. The modules are tilted at 22° on a fixed, south-facing structure designed by Sovonics. The system uses a 25-kW DECC PCU.

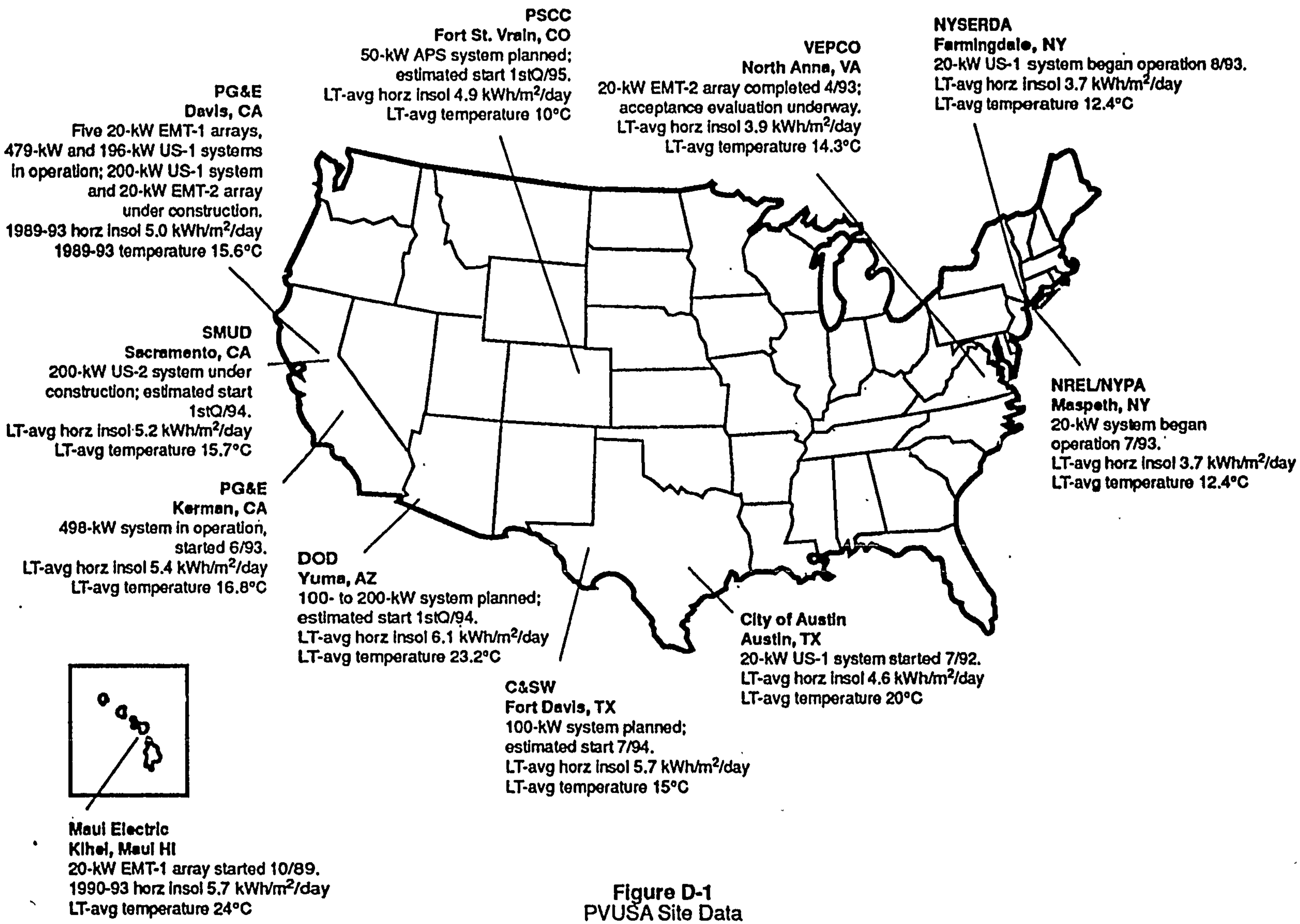


Figure D-1
PVUSA Site Data

Virginia Electric Power Company (VEPCO)

This nominal 19.3-kW grid-interactive system is located at VEPCO's Vista PV site near the North Anna nuclear power plant in Lake Anna, Virginia. It features two rows of AstroPower thin-film polycrystalline modules, an Omnion 25-kW inverter, and a fixed, south-facing flat-plate structure at a 30° tilt. A PVUSA DAS was ordered in 1993. Also in 1993, a contractual dispute concerning acceptance of the completed array arose; VEPCO and AstroPower are negotiating an agreement that will allow system operation. An operational date in early 1994 is anticipated.

New York Power Authority (NYPA)

This 17.0-kW grid-interactive system is part of the National Renewable Energy Laboratory (NREL) amorphous silicon project. Located atop the New York City Transit Authority materials warehouse in Maspeth, New York, the NYPA system is a demand-side management PV application that supplies power to offset the warehouse's daytime electrical needs. The system consists of 14 rows of USSC Model UPM-880 amorphous-silicon modules at a 10° tilt above the horizontal, and a 25-kW Omnion inverter.

An interesting aspect of this system is its nonpenetrative roof installation that uses concrete parking curbs to anchor the array. A standard PVUSA DAS and cellular phone are used to upload data for analysis. The DAS and inverter are located next to the electrical distribution panel in the warehouse. System operation began in July 1993.

New York State Energy Research and Development Authority (NYSERDA)

NYSERDA has installed a host system at the State University of New York's (SUNY's) Farmingdale campus in Long Island. This 20-kW grid-connected system, which was installed by IPC, is one of three similarly-sized arrays operating on the SUNY campus. It has a single-axis tracking system, Mobil Solar modules, and a north-south orientation. Its three inverters and a DAS are located in a modified "Seatainer" trailer approximately 500 ft from the array. The weather station is installed on the roof of an adjacent building approximately 8 m above grade. System operation began in August 1993.

Sacramento Municipal Utility District (SMUD)

SMUD is hosting a 200-kW system, which was installed by Utility Power Group (UPG). The system is located near the Hedge substation on Sacramento's southeast border. **Figure D-2** shows the SMUD site.

The SMUD system has Siemens M55 modules arranged in 20 rows; one-third horsepower motors rotate each row about a north-south axis. A single-tracker controller regulates movement of the motors simultaneously. 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 ft above ground level. The inverter is a 250-kW Omnion series 3200. It has a standard PVUSA DAS and SMUD's SCADA system for remote operations. System operation is expected in the first quarter of 1994.

Kerman, California (PG&E)

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. It features 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 SITES

Other host sites scheduled for future operation are:

Utility	Location	Date
Central and Southwest Services	Fort Davis, TX	1994
DOD Tri-Service Review Panel	Yuma, AZ	1994
Public Service of Colorado	Fort St. Vrain, CO	1995

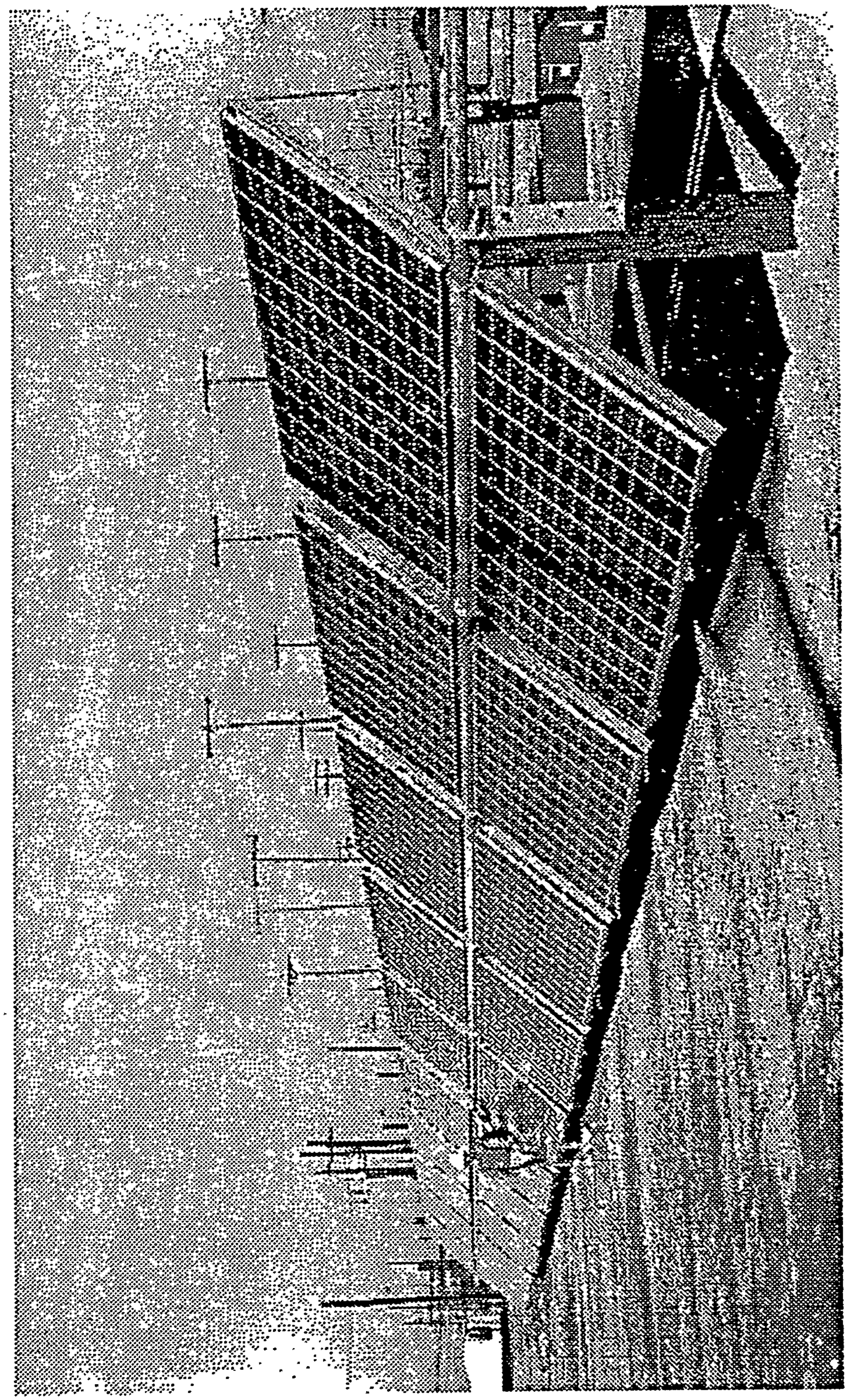


Figure D-2
PVUSA SMUD Host System

Appendix E

PVUSA QUALIFICATION TESTS

This section briefly discusses module qualification tests for acceptance of PV modules by PVUSA, which are based on tests developed by the National Renewable Energy Lab, previously the Solar Energy Research Institute (SERI). It also describes modifications made by PVUSA to the tests to accommodate PV modules not covered by SERI procedures.

MODULE QUALIFICATION TESTS

PVUSA requires that module qualification tests be performed to establish the acceptability of the design, materials, and manufacturing process of PV modules. Tests must be conducted on modules produced from a contractor's production line. After successful completion of the tests no changes in design, materials, or manufacturing process are allowed unless PVUSA agrees to the changes. PVUSA may require that modules be retested after changes are made.

FLAT-PLATE MODULES (THIN-FILM, CRYSTALLINE, OR POLYCRYSTALLINE SILICON)

Flat-plate modules must pass the tests described in "Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-film Flat-Plate Modules" (SERI/TR-213-3624, January 1990, R. DeBlasio, et al.). **Figure E-1** shows the SERI/TR-213-3624 test sequence.

PVUSA MODIFICATIONS TO SERI/TR-213-3624

To accommodate module types not covered by TR-213-3624, PVUSA's TRC has accepted several modifications to SERI/TR-213-3624.

- Visual Inspection (SERI/TR-213-3624, paragraph 4.1) is clarified as follows:

  Photographs are not necessary; complete documentation, however, is necessary.

- Wet Insulation-Resistance Test (SERI/TR-213-3624, paragraph 4.5) is modified as follows:

  "All resistance measurements shall exceed an impedance equivalent to 12.5 μ A/ft^2 at a voltage equal to twice the system's open circuit voltage plus 1000 volts dc."

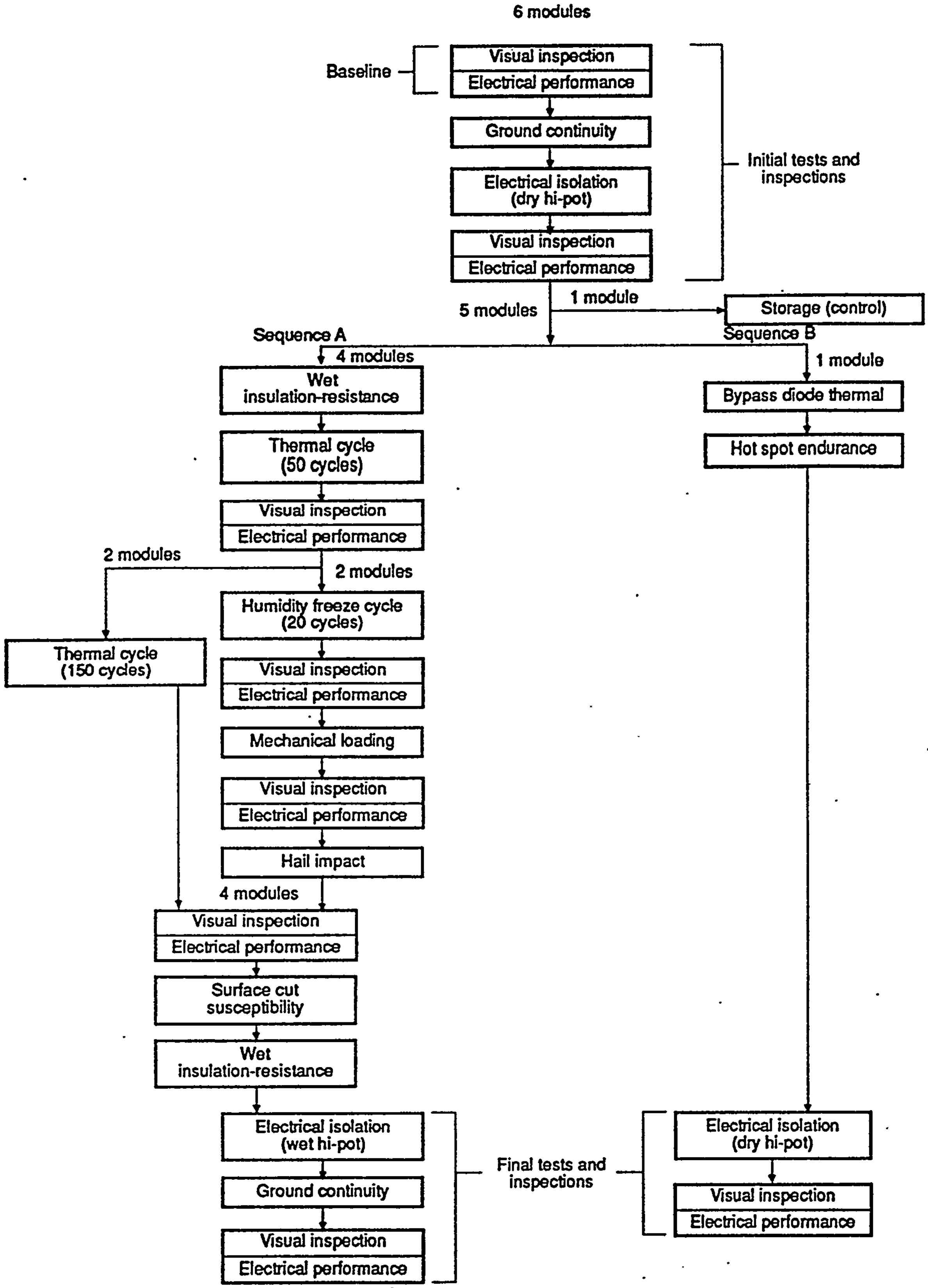


Figure E-1
SERI/TR-213-3624 Qualification Test Sequence

- Mechanical Loading Test (SERI/TR-213-3624, paragraph 4.8) may be replaced by the following test procedure:

  Modules shall be mounted to a rigid test structure by the same means proposed for mounting the contractor's modules to their panel. An essentially uniform load of 30 psf shall be applied to module surfaces and left in place for 30 minutes. The modules shall then be inverted, and the 30 psf load shall be applied to the reverse side for 30 minutes. These two loadings shall be repeated for three cycles. Upon completion of three cycles, the modules should not show evidence of permanent deformation, other mechanical damage, or decreased electrical output.

  The test described above provides some evidence of a module's structural integrity and its ability to survive wind forces in the field. The test is not intended to be elaborate or to test the fatigue endurance of cell interconnects. Loading with sand bags, shot, or similar simple means is deemed adequate. The module may be horizontal and at room temperature for the test.

- Electrical-Isolation Test (Wet Hi-Pot) (SERI/TR-213-3624, paragraph 4.11) is modified to include:

  "The temperature of the module and solution shall be 22°C ± 3°C. Leakage current shall be less than 12.5 μ A per square foot of module aperture area."

- Hot-Spot Endurance Test (SERI/TR-213-3624, paragraph 4.13)

  The SERI/TR-213-3624 tests are for flat-plate, thin-film PV modules. For other types of PV modules (e.g., crystalline or polycrystalline materials), one module shall be subjected to the hot-spot endurance test described in paragraphs 36.1 through 36.29 of Underwriters Laboratories' document UL1703, "Standard for Flat Plate Photovoltaic Modules and Panels," (August 1, 1986).

CONCENTRATOR MODULES

Concentrator modules must pass the tests described in "Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules" (Sandia Report #SAND 92-0958.UC-272, June 1992).

Appendix F

TECHNOLOGY TRANSFER ACTIVITIES

Appendix F includes a list of PVUSA technology transfer activities during 1993, including papers, presentations, workshops, and tours for visitors to the site.

MEETINGS

In January, PVUSA attended an IEEE SCC21 Module Qualification Subcommittee meeting in Dallas, Texas, and a meeting of the California section of the PV4U utility photovoltaic users' group was held at the Davis site.

In March, PVUSA attended an IEEE SCC21/IEC TC 82 meeting in Northbrook, Illinois.

In June, PVUSA attended a joint IEEE/ASTM/IEC PV Codes and Standard Forum at NREL in Golden, Colorado.

In September, a PVUSA representative visited the NREL/NYPA and NYSERDA host sites, and PVUSA representatives visited AstroPower to discuss delivery of their EMT-2 array.

PAPERS AND PRESENTATIONS

In April, PVUSA presented a paper titled "PVUSA—Progress and Plans" and gave a presentation covering the Kerman project plan in grid-support methodology at the Solar '93 Soltech/ASES Conference in Washington, D.C.

In May, PVUSA presented three papers at the 23rd IEEE PV Specialists Conference in Louisville, Kentucky: "Operations and Maintenance at PVUSA: Utility Perspective on the Operation of PV Systems," "PV EMF," and "PVUSA Kerman Costs."

In September, PVUSA attended the NREL PV Performance & Reliability Workshop and presented a paper on "Field Wet Resistance Test Procedure and Results at PVUSA."

In September, PVUSA gave a presentation at the Fifth EPRI/CRIEPI Workshop on Utility Interconnected PV Systems in Carmel, California.

In October, the *1992 PVUSA Progress Report* was issued, and PVUSA presented a paper, "PVUSA Status and 1994 Project Plan," at the 12th NREL PV Program Review Meeting in Denver, Colorado.

In November, PVUSA presented a technical paper, "Construction of the 500-kW ac Kerman Photovoltaic Power Plant," at the Power-Gen '93 conference in Dallas, Texas.

In December, PVUSA gave a presentation at the UPVG Grid Applications Workshop in Detroit, Michigan.

WORKSHOPS

In April, PVUSA hosted a three-day workshop at the Davis site on PV powerplant design, operation, and maintenance. The workshop was cosponsored by EPRI.

In August, PVUSA conducted an operation and maintenance workshop at the Kerman site.

In November, PVUSA participated in a roundtable/workshop held by UPVG on Distributed Generation in Phoenix, Arizona.

SITE TOURS

In 1993, PVUSA hosted 169 tours of the Davis site for a total of 911 visitors.

Appendix G

TERMS AND ABBREVIATIONS

APS	Advanced Photovoltaic Systems, Incorporated.
a-Si	Amorphous silicon.
Availability	Percentage of daylight hours (sunrise to sunset) during which a system supplies net power to the utility grid.
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.
Capacity Factor	Ratio of actual monthly ac energy production (kWh) divided by the product of the ac rating (kW) and the number of hours per month.
CdTe	Cadmium telluride.
CEC	California Energy Commission.
CSI	Campbell Scientific, Incorporated.
CSWS	Central and South West Services, Incorporated.
DAC	Data acquisition computer.
DAS	Data acquisition system.
DECC	Delta Electronic Control Corporation.
DOD	U.S. Department of Defense (Tri-Services Panel).
DOE	U.S. Department of Energy.

Efficiency	Ratio of monthly energy produced to monthly POA insolation during hours when the PCU is operating.
EMF	Electromagnetic field.
EMT	Emerging module technology.
EPRI	Electric Power Research Institute.
FWRT	Field wet resistance test.
GFY	Government fiscal year.
GP	Golden Photon.
HCPV	High-concentration photovoltaic.
Hz	Hertz, unit for frequency, cycles per second.
IEC	International Electrotechnical Commission.
IEEE	Institute of Electrical and Electronics Engineers.
IPC	Integrated Power Corporation.
I/R	Infrared.
I-V	Current-voltage.
JPL	Jet Propulsion Laboratory.
MSEC	Mobil Solar Energy Corporation.
NREL	U.S. National Renewable Energy Laboratory (formerly Solar Energy Research Institute).

NYPA	New York Power Authority.
NYSERDA	New York State Energy Research and Development Authority.
O&M	Operation and maintenance.
PCU	Power conditioning unit. Contains a dc-to-ac inverter, system protection and control, and maximum power tracking circuits.
PG&E	Pacific Gas & Electric.
POA	Plane of array.
PQ	Power quality.
PSCC	Public Service Company of Colorado.
PSP	Precision Spectral Pyranometer.
PTC	PVUSA test conditions. Defined as 1000 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.
QA/QC	Quality assurance/quality control.
SC	PVUSA Steering Committee.
SCADA	Supervisory Control and Data Acquisition.
SCI	Solar Cells, Incorporated.
SI	Silicon.

SMUD	Sacramento Municipal Utility District.
SNL	Sandia National Laboratories.
SQL	Structured Query Language.
SSI	Siemens Solar Industries, Incorporated (formerly Arco Solar, Inc.).
STC	Standard test conditions. Defined as 1000 W/m^2 POA irradiance for flat plate modules, 850 W/m^2 direct normal irradiance for concentrators, 25° 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.
TRC	PVUSA Technical Review Committee.
UPG	Utility Power Group.
US	Utility-scale.
VAR	Volt-Ampere reactive, unit for reactive or apparent power.
VEPCO	Virginia Electric Power Company.