PVUSA

PHOTOVOLTAICS for UTILITY SCALE APPLICATIONS

A national cooperative research project for directly harnessing the power of the sun to generate commercial quantities of electricity.

FIRST TECHNICAL REPORT

1995

By
PVUSA Project Staff

Pacific Gas & Electric Company
Research and Development Department
San Ramon, CA 94583

DOE/AL/82993--23
Dist. Category UC-1290

PHASE II -- PHOTOVOLTAICS FOR UTILITY SCALE APPLICATIONS (PVUSA)

FIRST TECHNICAL REPORT 1995

PVUSA Project Staff

Pacific Gas & Electric Company
Research and Development Department
San Ramon, CA 94583

Published -- August 1995

PREPARED UNDER CONTRACT WITH THE UNITED STATES DEPARTMENT OF ENERGY

Under Cooperative Agreement No. DE-FC04-92AL82993

DISCLAIMER

The work disclosed in this report was done with the support of the U. S. Department of Energy, Cooperative Agreement No. DE-FC04-92AL82993. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of PG&E or the U.S. Government, any agency thereof, or any of their contractors or subcontractors.

COPYRIGHT NOTICE

DISCLAIMER

TABLE OF CONTENTS

I. SUMMARY 1

II. PROJECT MANAGEMENT 2

1. Schedule Analysis 2
2. Cost Analysis and Funding Activities 3
3. Principal Activities 3
4. Technology Transfer Activities 5
   a. Publications, Conferences, and Meetings 5
   b. Site Tours 6

III. TECHNICAL ANALYSIS - DAVIS SITE 7

1. System Performance 7
2. Solar/Weather Data 15
3. Operation and Maintenance 16

IV. OTHER PVUSA SITES 18

1. Summary 18
2. Kerman 21
3. Maui 22
4. Austin 23
5. NYSERDA 24
6. NREL/NYPA 25
7. SMUD 26
8. Central and South West Services (CSW) 27

I. SUMMARY

This report summarizes system performance and major project activities over the first four months of 1995. The quarterly technical reports that have been issued for the past several years are being replaced this year by two technical reports covering the January-April and May-August periods, respectively. Performance data for the last four months of the year will be included in the 1995 Progress Report.

Principal activities during the first four months of 1995 included bringing two new systems on line, hosting a two-day Balance of System and Procurement workshop at the Davis site, completing and issuing the EMT Five-Year Assessment Report, and preparing for a management transition in 1996.

PVUSA added two new systems this spring, increasing the project total to 18 systems at nine locations, with a combined capacity of over 1,800 kW. The new systems include CSW's ENTECH US system and VEPCO's AstroPower EMT array. The ENTECH system first paralleled in mid-January and was essentially completed by February, although a variety of subsequent problems with the system's PCU, tracking system, and modules were still being addressed through this report period. At VEPCO, after over a year of start-up activities and contract negotiations with AstroPower, an array acceptance agreement was completed in April. Data collection has not yet begun, though, as PVUSA is awaiting VEPCO approval for telephone access to their data logger.

The Balance-of-System and Procurement workshop at the Davis site drew 17 people from utilities, commissions, consulting, manufacturing and national labs. Based on lessons learned by the project staff, workshop topics included procurement, inadequacies and good innovations in designs, costs, and suggestions for improvements.

At a February stakeholders' video conference meeting, the CEC and SMUD confirmed their interest in assuming joint management of PVUSA beginning in 1996. PVUSA's Steering Committee subsequently requested the CEC and SMUD to proceed with a transition plan and to submit a funding proposal to DOE. It was decided that the CEC/SMUD plan would be re-examined at the SC's June meeting and that if unfavorable indicators emerged, the project would reconsider NREL or possibly another organization to assume management responsibilities.

A final rating of 17.1 kWdc was calculated for the AstroPower EMT-2 array at Davis. The array was installed in November 1994, but the weather was too poor to rate the system accurately until March 1995. The final rating is about 11% less than AstroPower's 1994 contract target. The array has performed reliably, with its only downtime resulting from occasional PCU trips.

Except for VEPCO, data were collected for the other 17 of PVUSA's 18 completed systems. Combined, they have generated over 600,000 kWh since the beginning of the year, about the same energy used by 300 homes over the same period. The project's cumulative generation reached the 5 million kWh mark in March and climbed to nearly 5.5 million kWh by the end of April. Key results for 1994 and the first four months of 1995 are shown in the following table. The locations of systems other than Davis are noted alongside the supplier's name.

Emerging Module Technologies *1994 avg. = [ ]*	Efficiency %	Capacity Factor %	Performance Index[1] %
AstroPower	5.9 [6.1] dc	14 [10]	90
ENTECH	11.3 [10.7] dc	10 [20]	71
Solarex	8.3 [7.8] dc	13 [20]	92
Sovonics	2.2 [2.6] dc	10 [18]	75
Sovonics (Maui, HI)	3.3 [3.4] dc	20 [20]	95
SSI	10.6 [10.0] dc	12 [19]	88
UPG	2.9 [2.8] dc	13 [20]	97
Utility Scale Systems *1994 avg. = [ ]*			
APS	3.3 [3.2] ac	11 [16]	92
ENTECH (Fort Davis, TX)	n/a	n/a	n/a
IPC	7.7 [7.8] ac	12 [10]	64
IPC (Austin, TX)	7.9 [8.2] ac	12 [17]	73
IPC (Farmingdale, NY)	8.6 [8.4] ac	1 [12]	5
IPC (Maspeth, NY)	2.8 [3.3] ac	9 [13]	68
SSI	7.9 [7.5] ac	13 [16]	73
SSI (Kerman, CA)	9.3 [9.0] ac	14 [23]	81
UPG (Fort Davis, TX)	9.0 n/a	21 n/a	74
UPG (Sacramento, CA)	10.8 [9.4] ac	10 [14]	60

II. PROJECT MANAGEMENT

1. Schedule Analysis

Overall, the project continued with plans for a January 1, 1996 transfer of project management duties from PG&E to a joint CEC/SMUD team. The present scheduling emphasis is to complete outstanding PV-related contracts and major technology transfer activities before the end of the year to help the transition go smoothly. The major technology transfer activities remaining for 1995 include: conducting a June workshop at Davis on Power Conversion, Data Acquisition, and System Rating, participating at three more conferences (ASES and two at NREL), issuing the 1994 Progress Report and two Interim 1995 Reports, and issuing five more topical reports (Kerman validation, BOS, DAS, Procurement/Acceptance/Rating, and PCUs/Power Quality).

In January, bids were received for reactivating Golden Photon's, Solar Cells', and Amonix's suspended EMT contracts. In March, the Steering Committee directed that contracts be placed for arrays from Solar Cells and Amonix, and for qualification testing only for Golden Photon. Each of these new procurements is scheduled to be completed by the end of September.

Pending contracts are listed in the following table. At CSW, ENTECH's system is essentially complete, but a variety of start-up difficulties have delayed system acceptance. PSCC was unsuccessful with their proposal to the UPVG for TEAM-UP funding for their planned 50-kW system, and are presently unable to confirm a schedule. VEPCO has rated their AstroPower array at 11.6 kWdc and completed an acceptance agreement, but the array has yet to begin full operation and PVUSA has yet to begin data collection. Bids are presently being reviewed by the Army Corps of Engineers for their 375-kW system to be installed at Yuma, Arizona later this year.

---

1 Defined as the percentage of actual to expected generation. The expected generation adjusts for ordinary differences between actual and rated output caused by variations in insolation and temperature, as well as shortfalls related to scheduled outages, long-term degradation, and BOS limitations. 1994 values are not shown, as the calculation method now includes refinements that result in slightly greater values than previously reported. This report discusses the calculations in detail.

Systems to be installed:	Original Estimated Completion Date	Current Forecast Completion Date
Davis site		
Solar Cells	September, 1995	same
Amonix	September, 1995	same
Host sites		
CSW (ENTECH)	July 1994	February 1995 (contract closure pending)
PSCC (APS)	December 1994	TBD
VEPCO (AstroPower)	August 1993	April 1995 (PV system and DAS inoperative)
DOD (undet. supplier)	October 1995	TBD

2. Cost Analysis and Funding Activities

No new funding was committed this period. However, the EPRI task agreement (companion to the Tailored Collaboration agreement signed in December) was signed at the end of February, allowing PG&E to begin invoicing EPRI. A $2.1M proposal for April 1995 through March 1996 was submitted to DOE in March. The DOE share requested was $1.1M, of which $1M in appropriations are expected. The project did receive $2k in revenue from a workshop held at the Davis site in January.

Expenses for the first three months of 1995 (latest data available) were $625k, lower than the $800k forecast. No significant lump sum payments were made this quarter. EPRI was invoiced for $300k, but only one invoice to DOE for $111k was submitted. (Invoicing fell behind during proposal preparation.)

PG&E submitted to the Defense Contract Audit Agency Incurred Cost Proposals for years 1987 through 1993 as required prior to initiating the audit. These were prepared by Coopers & Lybrand for PG&E.

3. Principal Activities

Principal activities over the January-April 1995 period are detailed below for the Davis, Kerman, and host sites, and for general project activities. The focus for this section is on procurement, engineering, construction, and planning activities. Maintenance activities for operating systems are discussed in Sections III (Davis systems) and IV (Kerman and hosts).

Davis

Three bids for re-activating suspended EMT array contracts were discussed at the February 28 TRC and March 1 Steering Committee (SC) meetings. The SC directed the project to negotiate procurement of two EMT systems (Amonix 19.0 kW high concentration and Solar Cells 10.8 kW cadmium telluride), and to offer one supplier, Golden Photon, a module qualification test only contract. On March 10, Amonix and Solar Cells Inc. were given notice to proceed. Later in March PVUSA staff and Keith Emery of NREL visited Golden Photon's facilities in Golden, Colorado as a precursor to awarding a module qualification contract.

The additional EMT procurements (only one was originally planned) were funded by deferring other activities, such as soiling studies and insolation comparisons. The SC also directed the project team to pursue a US-1 PCU replacement. The PCU replacement discussions were triggered by the fact that one half of the SSI US-1 system's dc capacity remains idle because of an inoperative PCU, and by the recurring failures of the IPC US-1 system's Omnion PCU. PVUSA and Kenetech met at the Davis site on March 31 to discuss system parameters affecting the design of replacement(s). The project subsequently chose to replace the IPC system's 200-kW Omnion PCU with a higher rated Kenetech PCU.

The ENTECH system's tracker roll function failed on Jan. 11. Attempts to reset the tracker were unsuccessful. Field observations indicated travel beyond a limit switch as the problem. ENTECH installed a new roll motor and actuator on January 19, and although its performance was good initially, the system ended up operating sporadically for a few months, particularly under higher wind speeds. As similar poor performance was occurring at the CSW host site, ENTECH proceeded to re-engineer parts of the tracker apparatus. After testing different voltages, motors, and drive configurations at their site, ENTECH replaced the Davis system's entire motor and drive mechanism in May. As of this writing, the new tracker has worked flawlessly.

Kerman

One of the system's two PCUs was down for about six weeks in January and February. After several unsuccessful troubleshooting attempts and component replacements on the inoperative PCU #2 by PG&E Fresno crews and PVUSA staff (with Omnion telephone support), an Omnion technician made a field visit in February and was able to repair the unit by adjusting two pots on a current regulator board. An important programming change was made to enable the PCUs to reset automatically after over/under frequency or voltage disturbances have cleared. This was done because trips requiring manual resets have occurred often, sometimes resulting in a day or more of undetected downtime. The new feature allows one PCU to restart 5 minutes after the line condition returns to normal and the other PCU to restart 30 seconds after the first. Nevertheless, there were several unit trips in March and April that required manual resets. Enhanced irradiance conditions are suspected as the cause of some but not all of these trips, and PVUSA has been supplying Omnion with data to help analyze the problem.

Hosts

Data collection from Central and South West's 100 kW UPG system began in January, although intermittent system operations, phone line interference, incompatible data formats, and an incomplete data summary program have hampered analysis efforts. CSW's 100-kW ENTECH system first paralleled on January 14, but as of the end of April, troubleshooting efforts continued on a variety of start-up problems, including poor tracking, lens cracks, module ground faults, and PCU start-up problems. The UPG system has operated more reliably, but not trouble-free, as discussed in Section IV.

In January, NREL turned over primary maintenance responsibilities for the Maspeth system to the New York Transit Authority and data collection to PVUSA. NREL had been subcontracting maintenance duties and performing data collection, quality checking, and analysis over the system's first 18 months of operation.

At VEPCO, after over a year of start-up activities and contract negotiations with AstroPower, an array acceptance agreement was completed in April. Prior to the agreement, VEPCO conducted field wet resistance testing in January and system rating tests in February-March. The field tests identified two non-contributing source circuit monopoles that contained several wiring, module, and dc collection box failures. Several other unexplained ground faults were identified. VEPCO scaled up SWTDI's 10.2 kWdc rating by 26/24 to estimate the output with all circuits functioning and then added an additional 5% allowance for instrument uncertainty to yield a PTC rating of 11.6 kWdc. Even with the adjustments, the 11.6 kW rating is only 60% of the expected rating. Data collection has not yet begun, as PVUSA is awaiting VEPCO approval for telephone access to their data logger.

Bidding for the DOD's 375-kWac (PTC) Yuma, Arizona system is now closed and the Army Corps of Engineers' bid technical evaluation process is underway. An October 1995 completion date is planned.

The Public Service Company of Colorado's plans for a 50-kW APS system to be installed at Platteville, Colorado were significantly disrupted recently. Cofunding for the system under NREL's a-Si program was lost when the supplier, APS, went out of business this spring. PSCC submitted a proposal to UPVG under its TEAM-UP program but did not receive an award. PSCC is continuing its efforts to proceed and is seeking funding under EPRI's CUE program, but the project's supplier, start date, and even its location are now uncertain.

General

The combined generation from all of PVUSA's operating systems exceeded 0.6 million kWh over the first four months of 1995. The project's cumulative generation reached the 5 million kWh mark in March and climbed to nearly 5.5 million kWh by the end of April.

A second video conference with PVUSA stakeholders was held on February 15 to discuss development of a joint SMUD/CEC project management plan. As presented, SMUD would be responsible for all day-to-day management and operations including all contracting with DOE, utilities, and subcontractors. The CEC would hold title to property and provide guidance in long range planning. Approval by SMUD managers to "enter into negotiations" was received.

The Technical Review Committee met on February 28. Highlights of three topical reports were presented. Reports covered procurement, rating and acceptance; PCUs and power quality; and data acquisition systems. Project management transition and proposed 1995 budget and activities, including EMT procurements, were discussed.

The Steering Committee met the following day. Project management transition and allocation of 1995 funds with regards to EMT and BOS procurements vs. special studies were discussed. The Steering Committee selected CEC/SMUD as the next project manager for PVUSA, assuming that they can meet milestones to ensure management transition on January 1, 1996. The SC requested the CEC and SMUD to proceed with a transition plan and to submit a funding proposal to DOE. It was decided that the CEC/SMUD plan would be re-examined at the SC's June meeting and that if unfavorable indicators emerged, the project would reconsider NREL or possibly another organization to assume management responsibilities.

Following the SC decisions, Brian Farmer met with CEC and SMUD representatives in Sacramento on March 22. Project management transition specifics and the mechanics of preparing the DOE proposal were discussed.

4. Technology Transfer Activities

Publications, Conferences, and Meetings

January:

The PVUSA Balance-of-System and Procurement Workshop was held at the Davis site on January 23-24. PVUSA team members, along with: Brian Champion (West Texas Utilities), Dave Collier (SMUD), Mark O'Neill (ENTECH), Mike Stern (UPG), and Raju Yenamandra (Siemens Solar), gave presentations on balance-of-system designs and lessons learned associated with PVUSA Davis and host systems.

Tom Hoff presented a paper titled "Reducing Distribution System Losses" at the IEEE PES Winter Power Meeting in New York.

February:

Section II.3 above discusses the February TRC meeting.

March:

Work continued on several topical reports and the 1994 Progress Report.

Details of the March Steering Committee meeting are discussed above in Section II.3.

April:

PVUSA's second of seven major topical reports, titled "Emerging Photovoltaic Module Technologies at PVUSA - A Five-Year Assessment," was issued.

The PVUSA Fourth Quarter 1994 Technical Report was issued.

A new member campaign began. Invitation letters and information packages were mailed to over 70 utilities.

Project personnel attended Soltech '95 and the UPVG Annual Meeting, held concurrently in San Antonio, Texas. A presentation was given at Soltech on the recent results and future directions of PVUSA. PVUSA sponsored a booth at the exhibit hall to support its new member campaign.

Preparations began for the PCU, Data Collection, and System Rating Workshop on June 14 & 15 to be held at the Davis site.

Brian Farmer presented a paper titled "Performance and Value Analysis of the Kerman 500 kW Photovoltaic Power Plant" at the American Power Conference in Chicago.

Two papers, "PVUSA Experience with Power Conditioning Units" and "Acceptance Testing and Rating Grid-Connected PV Systems: Experience at PVUSA" were submitted to ASES for publication. The papers will be presented at the ASES conference in July.

Site Tours

During the first four months of 1995, PVUSA hosted 25 tours of the Davis site for a total of 145 visitors, including a January visit by a Chinese renewable energy delegation sponsored by the University of Tennessee, and a March visit by two Sandia Lab representatives.

III. TECHNICAL ANALYSIS - DAVIS SITE

1. System Performance

General

Performance data are listed in Table III.1 for nine Davis systems, including six EMT arrays and three US systems. Overall, the PV systems operated under much poorer than normal seasonal conditions, with the site receiving about 21% less global 30° tilt insolation than Davis' past six-year average for Jan-Apr. This is particularly evident on Figure III.1.

The arrays were kept very clean because the site received 19 inches of rain, nearly twice the normal amount for the first four months of the year. Although the prevailing conditions were generally poor, the site experienced some brief periods in April with exceptionally high cloud-enhanced irradiance. On April 18, the site generated a record peak of 781 kW. Two days later, an irradiance of 1,347 W/m^2 was observed momentarily at the IPC US-1 system. The direct normal irradiance peaked with a 10-minute average of 1,007 W/m^2 on April 21, a level rarely met for beam radiation at Davis.

In Table III.1, dc efficiencies are listed for the EMT arrays and ac efficiencies are listed for the US systems. The insolation totals differ in this table, even for arrays of the same orientation. They differ primarily because this quantity is integrated only when the PCU is on, and the hours of PCU operation vary between arrays. In addition to the instrument uncertainty (typically ±3%), there are also small differences in the field of view from each array.

New system rated

Table III.1 includes one "nameplate" change. A final rating of 17.1 kWdc (16.1 kWac) for the AstroPower EMT-2 array was calculated using March data. The array had previously been assigned a preliminary rating of 18.0 kWdc using Nov-Dec '94 data, but the prevailing conditions at that time of year were not adequate for rating the array. Last year's performance index and capacity factor results have been adjusted to reflect the final rating.

The 5% difference between the preliminary and final ratings is not believed to indicate that the array has degraded or become soiled. Rather, the difference has been attributed to the rating model's sensitivity to input data. Last fall's preliminary rating data set had an average irradiance of 847 W/m^2, an average air temperature of 11°C, and no points near PTC. The final rating data set's average irradiance was 976 W/m^2, its average air temperature was 17°C, and it included a large number of points near to and surrounding PTC. The rating model has overpredicted PTC power for other systems, too, when winter data were used to fit regression constants for the rating equation.

Performance index considerations

Last year, PVUSA deleted system availability and added the performance index (P.I.) to the list of routinely calculated PV statistics. As noted in the past few quarterly reports and in the forthcoming 1994 Progress Report, the system availability was dropped because PVUSA's definition (the fraction of daytime hours with net power greater than zero) tended to yield lower than anticipated values—usually, around 80-85%—even for properly operating systems. These results mislead some to believe systems were generally performing poorly, even though much of the "down time" occurred near sunrise, sunset and under heavily overcast skies.

The P.I., defined as the **ratio of actual to expected generation** over any time interval, is a good replacement for system availability, as it normalizes for low irradiance and other effects when calculating the expected generation. A background paper on the P.I. is included as Appendix A. This paper was presented at the December 1994

IEEE/WCPEC conference in Hawaii. A table listing data and supporting assumptions for each PVUSA system is included as Appendix B.

PVUSA's recommended performance index equation is:

P.I. = actual power ÷ expected power

expected power = rated power × adjustment factors

adjustment factors = IA × TA × DA × BOSA × SA

IA = irradiance adjustment (ratio of actual/rated irradiance)
TA = temperature adjustment (to allow for differences between actual and rated operating temperatures)
DA = degradation adjustment (a periodic adjustment to account for long-term reductions in system rating)
BOSA = balance of system adjustment (a lumped term to adjust for lost generation due to a variety of effects such as tracker limitations, geometry-related shading and field of view losses, and PCU standby and low load efficiency losses)
SA = soiling adjustment (to account for reduced generation caused by accumulated dirt)

When integrated over longer intervals, the equation may be simplified by assuming that most of the adjustment factors are constant, or can at least be represented by a single average value. The recommended integrated form of the equation is

$$\text{P.I.} = \frac{\text{actual kWh}}{\text{actual insolation}} \bullet \frac{\text{rating irradiance}}{\text{rated power}} \bullet \frac{1}{[\text{TA}\cdot\text{DA}\cdot\text{BOSA}\cdot\text{SA}]}$$

PVUSA's calculation attempts to balance the competing goals of accuracy and simplicity without altering the P.I. definition. Accurate, detailed techniques that independently account for many effects are not desirable for the utility user because more measurements are required than are ordinarily available. For example, the varying spectral distribution of solar radiation is often cited as an explanation for seasonal performance fluctuations for some cell types, but quantifying spectral effects is difficult and expensive. The fact that the P.I. is dependent on solar radiation measurements ultimately limits its accuracy to ±3%. Therefore, it is probably not worth the effort to measure effects that are much smaller than the dominant pyranometer/pyrheliometer uncertainty.

On the other hand, oversimplified expressions may yield results of little diagnostic value. This opposite case can be illustrated by including only one adjustment factor in the P.I. calculation, such as irradiance. By ignoring temperature and other effects, the seasonal variations in the P.I. will still be fairly large, and many partial system failures can easily go unnoticed.

Rather than limit the usefulness of the new term by defining rigid calculation rules, the P.I. may find more applications if its calculation procedure remains moderately flexible (but within the guidelines of a few well-defined adjustment factors). Separate values to account for the listed adjustment factors should be "plugged in" when possible, or the factor may be ignored (set to 1.0) if unknown. For example, PVUSA does not regularly monitor the effect of soiling. Reductions in generation caused by dirt buildup directly reduce the P.I.

In practice, the information required by system operators for normal monitoring has differed from that used to describe long-term performance, yet the basic P.I. equation can be adapted for either case. For real-time system monitoring, operators at the Davis site have found the irradiance, temperature, and degradation adjustments to be helpful, but have ignored any balance of system or the aforementioned soiling adjustments. For longer-term analyses such as presented in Table III.1 the balance of system adjustment factor has been included.

The balance of system adjustment factor is difficult to quantify dynamically and does not seem to be as necessary for midday monitoring as it is for longer-term analyses. This is because BOS effects like shading, field of view, tracker error, and PCU low-load losses are generally significant only during the earlier and later hours of the day. The current practice is to consider real-time P.I.'s of 90% or greater as normal, with a green indicator light providing a visual confirmation that system performance is OK. Heavy soiling or failed components that reduce the P.I. to below 90% result in a yellow display, triggering further inspection. One unique implementation of the real-time P.I. is that at low irradiance (<250 W/m^2), the threshold for switching between yellow and green lights has been set at a 50% P.I. rather than 90%. This was done to reduce false yellow alarms by approximating a dynamic balance of system adjustment during hours when shading, PCU losses, etc. tend to be high.

The flexible approach toward applying a mix of adjustment factors has the obvious drawback of inconsistent reporting, depending on which measurements have been included (however, note that other "common" terms such as efficiency, capacity factor, and availability suffer from the same problem). However, as long as the applied adjustment factors are noted when reported (perhaps with subscripts), consistent evaluations are possible.

Four-month performance indices for 1995 for the nine Davis systems ranged from 64% to 97%, with four systems operating at levels of 90% or better. In the case of the better-performing systems, the "lost" generation is attributed to brief and minor failure-related losses, and also to the combined effects of unmeasured quantities such as instrument error, recent degradation, and seasonal spectral effects. Three poor-performing systems experienced significant shortfalls caused by PCU trips and/or poor tracking. The arrays were kept clean by frequent rains throughout the period, and the soiling adjustment factor for each system has been assumed to be 1.0. See Appendix B for a further description of each system's P.I. calculation.

A 5% change to the BOSA factor has increased the index compared to results shown in past quarterly reports and in the 1994 Progress Report (in publication). To avoid conflict with data to be shown in the 1994 Progress Report, the 5% increase has not been applied to the 1994 values listed in Table III.1. If the same 5% adjustment is factored into last year's overall values, then this year's performance has been similar to last year's for six of the systems, distinctly better for two systems (IPC and SSI US-1), and distinctly lower for one system (Sovonics).

The BOSA factor is designed to quantify the uncontrollable losses resulting from a given system's layout, tracking scheme, and PCU characteristics, and can vary somewhat depending on system type. Previously, PVUSA has not accounted for the fact that PCU efficiency decreases with decreasing input power. The effect is significant, as monthly-average PCU efficiencies are about 5% less (relative) than at a system's rated power (data for the SSI EMT array in April '95 verifies this). A 0.95 adjustment is now included within each system's BOSA factor. For a sample single-axis tracking system such as SSI's US-1 system at Davis, the BOSA now consists of a 5% allowance for tracker limitations, field-of-view, and shading losses, in addition to the 5% PCU low-load adjustment, for an overall BOSA of (0.95)(0.95) = 0.90. Although the BOSA is actually a dynamic quantity, the factor may be adequately represented as a constant over longer periods.

Energy

Figure III.1 tracks the monthly energy supplied by the Davis site EMT systems over the past 16 months. Figure III.2 shows the same information for the US-1 systems, including start-up and testing energy delivered prior to system completion. The right scales refer to insolation measured at the site weather station (integrated over all hours). On both plots, the 30° tilt insolation is shown as a reference trend for the fixed tilt systems. On Figure III.1, the 1989-94 monthly average 30° tilt insolation is also included, and on Figure III.2, the horizontal N-S 1-axis insolation is included as a reference trend for the IPC and SSI 1-axis tracking systems.

The monthly energy production patterns generally follow the insolation trends, except that the array energy production also reflects outages, limited operation during installation and startup, and seasonal efficiency variations. The most notable departures from the expected trends on Figure III.1 are the Sovonics array's low output in January and February and the ENTECH array's low output in January. The Sovonics array has operated disproportionately poorly each winter, probably due to a combination of unfavorable spectral conditions and light-induced degradation. The ENTECH array's output was extremely low in January because its tracker was inoperative for about a week and because the site averaged less than 1 hour per day of clear sky direct beam radiation over the month.

The Utility Scale systems' generation trends on Figure III.2 are generally less distinct than those of the EMT arrays, partly because these systems use different orientations and their capacities differ widely, and also because their performance has been interrupted often from various outages. One significant result this year is the relatively low output from the APS array in April compared to last year. Even after adjusting for differences in insolation, this year's output was about 15% less than last year's. The reason is that this year the system experienced about four days of downtime from three morning PCU trips of unknown cause and one scheduled outage for meter calibration.

Table III.1
PVUSA Davis Systems: Performance Summary

Characteristics	SSI EMT-1	Sovonics	UPG	Solarex	ENTECH	AstroPower	APS	IPC	SSI US-1
Orientation (fixed flat plate, tracking)	30° ffp	30° ffp	30° ffp	30° ffp	2-ax trk.	30° ffp	30° ffp	1-ax trk.	1-ax trk.
Initial rating, kW	18.7 dc	17.3 dc	15.7 dc	15.7 dc	16.5 dc	17.1 dc	479 ac	196 ac	67 ac
Installation date	1/89	6/89	12/89	10/90	3/91	11/94	9/92	6/93	5/94
Module area, m^2	169	497	477	182	172	292	11520	2443	845

System	Quantity	1992	1993	1994	Jan-Apr '95
SSI	AC kWh	29261	29891	30141	6420
	Performance Index %	not calc.	not calc.	88	88
EMT-1	DC eff. %	10.1	10.2	10.0	10.6
	AC cap.fac. %	18.5	18.9	19.1	12.4
	Insol. kWh/m^2	1978	1962	2016	416
Sovonics	AC kWh	12181	22758	24350	4366
	Performance Index %	not calc.	not calc.	88	75
EMT-1	DC eff. %	2.8	2.6	2.6	2.2
	AC cap.fac. %	8.7	16.3	17.7	9.5
	Insol. kWh/m^2	1000	1970	2076	426
UPG	AC kWh	25407	25479	26537	5520
	Performance Index %	not calc.	not calc.	95	97
EMT-1	DC eff. %	3.0	2.9	2.8	2.9
	AC cap.fac. %	19.2	19.3	20.1	12.7
	Insol. kWh/m^2	1917	1963	2083	430
Solarex	AC kWh	22767	23572	25915	5609
	Performance Index %	not calc.	not calc.	90	92
EMT-1	DC eff. %	7.3	7.4	7.8	8.3
	AC cap.fac. %	17.2	17.8	19.6	12.9
	Insol. kWh/m^2	1936	1968	2055	430
ENTECH	AC kWh	21117	20032	27258	4554
	Performance Index %	not calc.	not calc.	67	71
EMT-1	DC eff. %	10.7	11.1	10.7	11.3
	AC cap.fac. %	15.4	14.7	19.9	10.1
	Insol. kWh/m^2	1228	1123	1523	250
AstroPower	AC kWh	n/a	n/a	1803	6513
	Performance Index %	n/a	n/a	81	90
EMT-2	DC eff. %	n/a	n/a	6.0	5.9
(start 11/18/94)	AC cap.fac. %	n/a	n/a	10.6	14.0
	Insol. kWh/m^2	n/a	n/a	112	408
APS	AC kWh	214508	530047	650555	149839
	Performance Index %	not calc.	not calc.	83	92
US-1	**AC eff. %**	3.8	3.2	3.2	3.3
('92 data based	AC cap.fac. %	15.3	12.6	15.5	10.9
on 3½ mos.)	Insol. kWh/m^2	494	1396	1757	394
IPC	AC kWh	15600	188541	168742	65117
	Performance Index %	--	not calc.	31	64
US-1	**AC eff. %**	--	8.1	7.8	7.7
('93 data based	AC cap.fac. %	--	12.6	9.8	11.5
on June start)	Insol. kWh/m^2	--	974	843	346
SSI	AC kWh	47012	75658	98995	24870
	Performance Index %	--	--	60	73
US-1	**AC eff. %**	--	--	7.5	7.9
(Quantities reflect intermittent	AC cap.fac. %	--	--	16.3	12.9
pre-June -94 start-up power)	Insol. kWh/m^2	--	--	1022	373

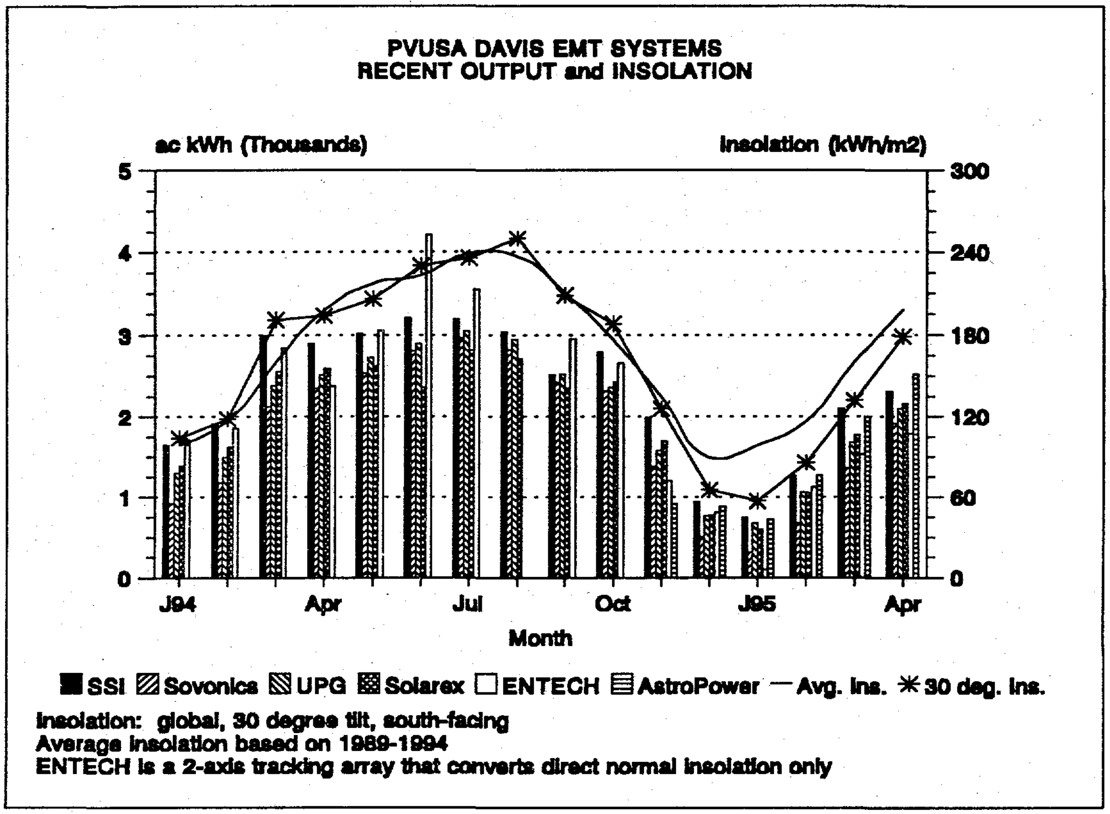


Figure III.1

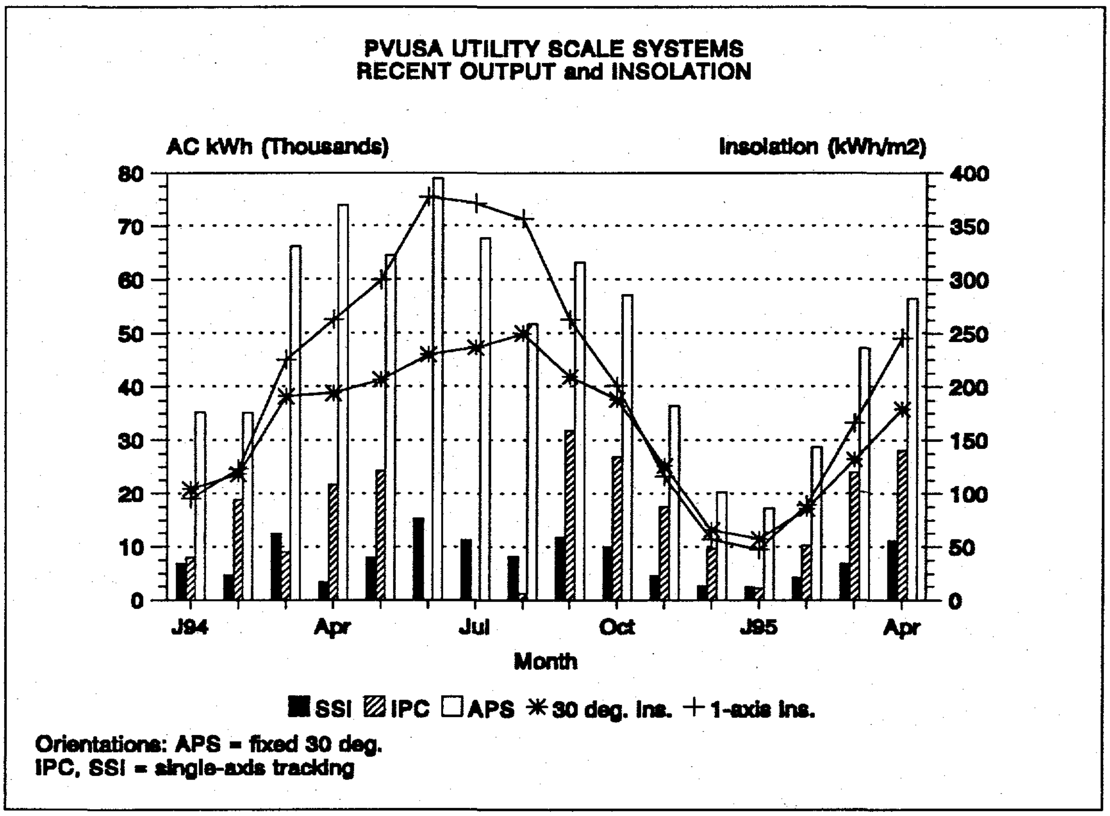


Figure III.2

Efficiency

Figures III.3 and III.4 show monthly average efficiency histories for the EMT arrays and US systems, respectively. DC efficiencies are reported for the six EMT arrays, and ac efficiencies are reported for the three US systems. Except for the ENTECH array, the efficiencies are calculated as the ratio of monthly energy produced to monthly plane-of-array insolation during hours when the PCU was operating. The ENTECH array, which uses a 22X concentrating lens and two-axis tracking structure, shades portions of itself and its pyrheliometer during the early and late hours of the day. Therefore, its efficiency calculations are based on the hours between 9 a.m. and 3 p.m. PST, when shading does not occur at any time of the year.

The EMT arrays' efficiency trends generally remained consistent with their past performance. The single-crystal Si SSI and poly-Si Solarex arrays both dropped in efficiency between January and April as their average operating temperatures rose from the mid-20 °C range to the mid-30 °C range. The SSI array also seemed to maintain a slow overall decrease in efficiency compared to its initial values—note that both its annual summertime low and wintertime high keep dropping slightly each year.

ENTECH's c-Si concentrator array had an erratic efficiency pattern because there were few clear days this winter and also because its recently installed dc tracker tended to operate poorly under windy conditions (the tracker motor was replaced once in January and the complete motor/drive mechanism was eventually redesigned and replaced under warranty in May). AstroPower's poly-Si array has not operated long enough to confirm a seasonal trend similar to the other crystalline arrays. Over its first few months, its efficiency has been unexpectedly steady at slightly under 6%.

The Sovonics and UPG tandem junction a-Si arrays both followed their own established patterns. Both appear to experiencing a slow degradation of about 2% to 4% (relative rate) per year, but the UPG array has exhibited a steady seasonal efficiency (absolute) of around 3% while the Sovonics array has varied smoothly between its wintertime *low* (now under 2%) and its summertime *high* (now under 3%). The Sovonics array's efficiency also dropped somewhat because of what now appears to be a recurring wintertime problem: the PCU tends to remain "ON" on some nights, possibly because of a false positive ac power signal from the unit's drifting power transducer. One result was that the PCU's nighttime station loads slightly reduced the system's total generation and overall efficiency. Neither field adjustments nor a factory inspection of the suspect circuit board have been successful at diagnosing the cause, but a board swapped from an idle PCU in May has operated properly.

Figure III.4 indicates that the US systems' long-term ac efficiency trends have tended to be less regular than the EMT dc trends. This has primarily been a result of partial system outages from PCU limitations and failures. Recently, however, the APS system's efficiency trend has been fairly steady at greater than 3%. The poly-Si IPC/Mobil Solar system efficiency decreased more than normal between January and April. This happened because there were a significant number of hours in March and April when, due to cloud-enhanced high irradiance, the system's Omnion PCU would automatically shed 2 of its 11 source circuits. At times, a third source circuit was manually switched out in an attempt to avoid triggering complete PCU shutdown.

SSI's US-1 system efficiency remained considerably lower than expected, and its seasonal variation has oddly resembled that of the Sovonics a-Si array, with its poorest annual efficiency during the winter. The poor overall efficiency stems largely from unexplainedly degraded dc source circuits, as I-V curves taken in 1994 showed a general efficiency decline of about 15% compared to initial curves taken four years earlier. The winter '94-'95 minimum may just be an aberration resulting from extremely poor insolation and spotty passive tracker performance. There were many hours when the system barely produced enough power to overcome its Bluepoint PCU and 12 kV transformer tare losses, and often, the periods of clear skies were too brief for the system's passive trackers to rotate near to their optimum position.

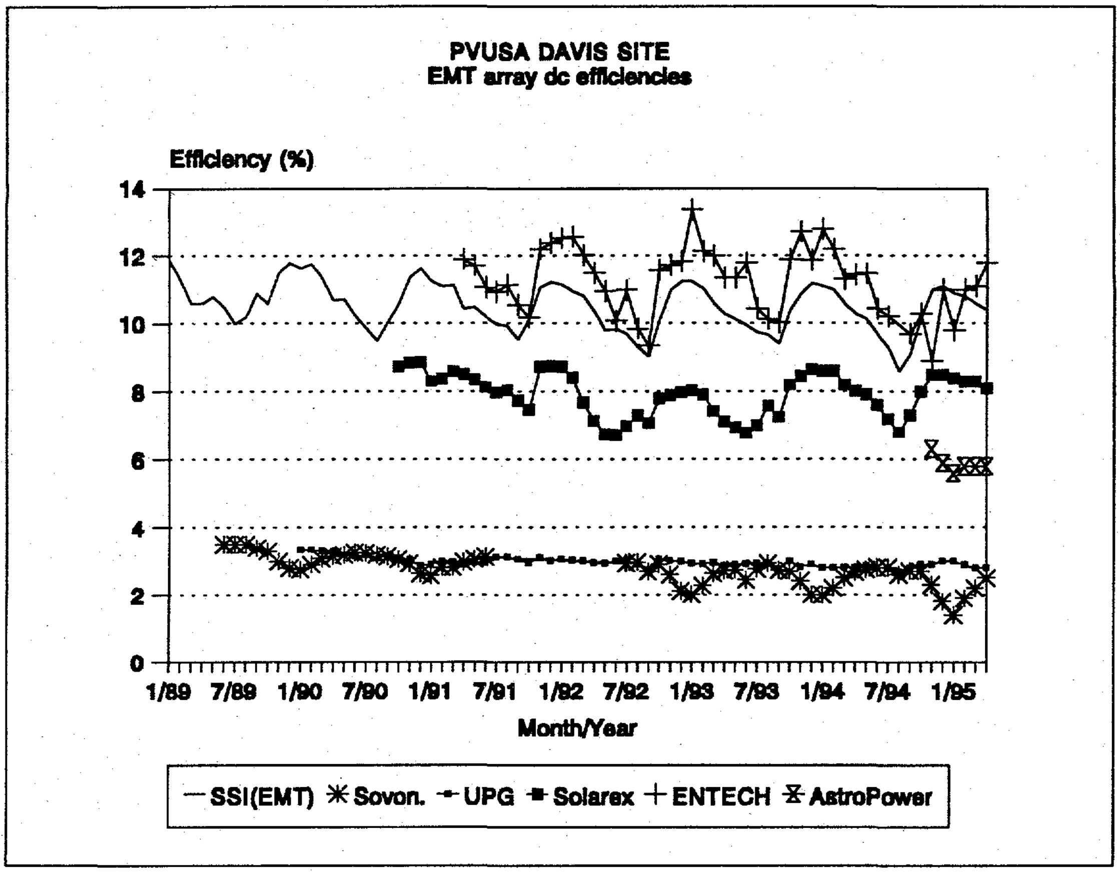


Figure III.3

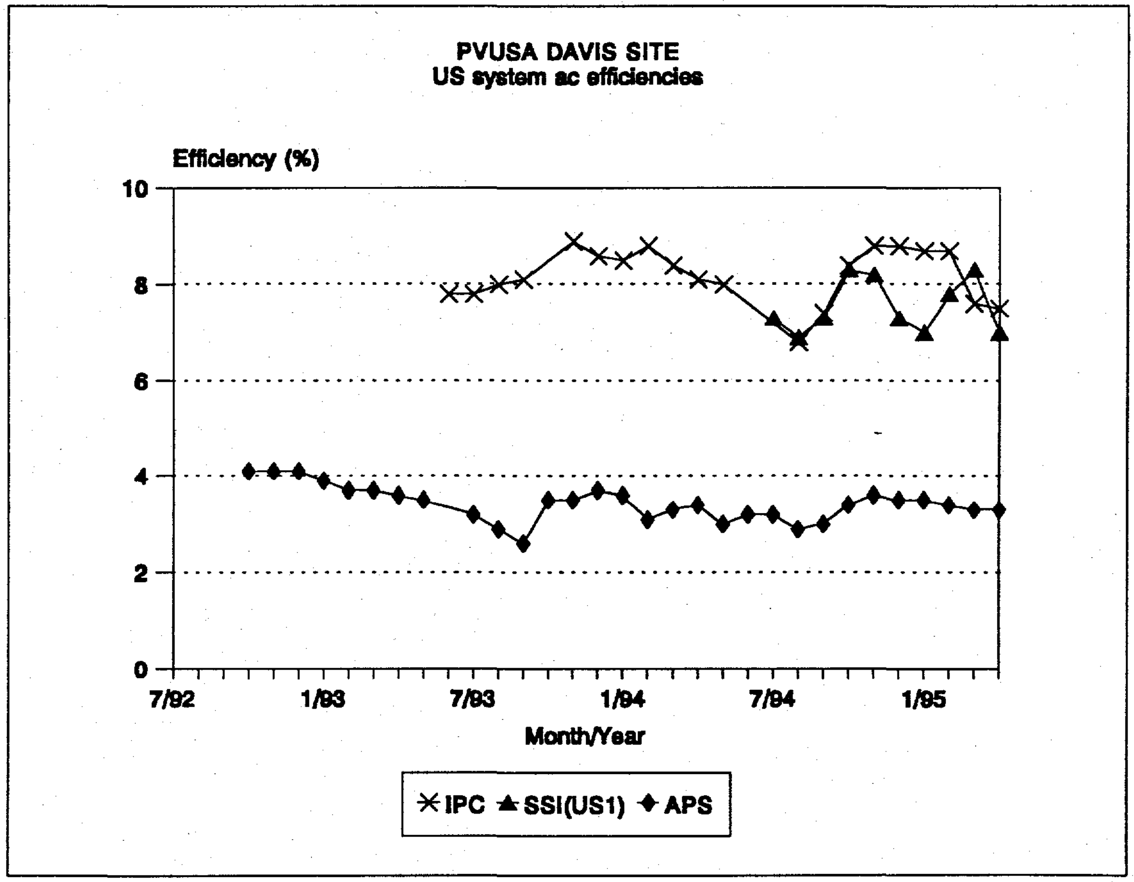


Figure III.4

2. Solar/Weather Data

Table III.2 lists several solar radiation, temperature, and wind speed statistics for 1992-94 and January-April 1995. The global horizontal insolation over the first four months was about 16% below the long-term average. The average ambient temperature was about 1.5 °C greater than normal and the 19" of rain was nearly twice the normal amount for the same period. The average wind speed of 3.7 m/s was notably higher than the site's six-year average of 3.1 ±0.4 m/s.

Table III.2
Solar/Weather Summary

Insolation, kWh/m^2; Peak Irradiance, W/m^2	1992	1993	1994	Jan-Apr '95
LT-Avg. global horizontal insolation	1838	1838	1838	469
Global horizontal insolation	1827	1801	1872	393
Peak 10-min. avg. irradiance	1142	1198	1156	1079
Global 30° tilt insolation	2038	2036	2122	454
Peak 10-min. avg. irradiance	1192	1232	1297	1185
Global normal insolation	2819	2900	3052	559
Peak 10-min. avg. irradiance	1214	1268	1321	1187
Horizontal 1-axis tracking insolation	2498	2593	2748	549
Peak 10-min. avg. irradiance	1124	1230	1233	1149
Direct normal insolation	1839	2064	2289	381
Peak 10-min. avg. irradiance	946	1022	983	1007
Minimum $T_{ambient}$, °C	-2.9	-4.8	-2.5	-1.3
LT-Avg. $T_{ambient}$, °C	15	15	15	10
Avg. $T_{ambient}$, °C	16.3	15.7	15.1	11.5
Maximum $T_{ambient}$, °C	41.7	42.4	40.5	28.9
Avg. wind speed, m/s	3.0	2.9	2.9	3.7
Max. wind speed, m/s (sustained 10-min.)	15.1	13.6	14.2	17.8

3. Operation and Maintenance

Table III.3 summarizes PVUSA's Davis O&M activities. The activities are identified as either preventive maintenance (including planned outages), failure-related (including forced outages), or research activities. This summary does not include Data Acquisition System (DAS) O&M activities. Host system activities are described along with host system performance in the following section of the report.

Table III.3
January - April 1995 O&M Summary

O&M Type	Event	Date; Force x Time, and Expenses (default force is 1 person)
Preventive	Site-BOS:	
	Read meters and report to PG&E Power Control Dept.	Monthly; 0.5 hr
	Check fire extinguishers, emergency lights, security system, site vehicle maintenance, lubricate sump pumps.	Monthly; 5.25 hrs + $68.00
	Conduct weed control.	Quarterly; 2.5 hrs + $20.00
	Calibrate protective relays in I&C building.	4/19; 5.5 hrs
	Calibrate 480 V EMT breakers in I&C building.	4/20, 4/21; 20.2 hrs total
	APS:	
	Clean PCU filters, test emergency lights.	Monthly; 1.25 hrs
	Inspect and lubricate dc switches.	3/16; 2 hrs
	Calibrate protective relays.	4/12; 2.5 hrs
	IPC:	
	Check PCU filters, tracker clock, MOV fuses, startup voltage.	Monthly; 1 hr
	Inspect and lubricate dc switches.	3/16: 2 hrs
	Calibrate protective relays.	4/19; 6 hrs
	Inspect modules and source circuits.	4/20; 2 hrs
	Manual disconnecting of source circuits.	3 occurrences; 0.25 hrs total
	SSI:	
	Inspect and lubricate dc switches.	3/16; 2 hrs
	Calibrate protective relays.	4/12; 7 hrs
	Lubricate tracker bearings and inspect array.	3 occurr.; 8.25 hrs total + $20.00
	ENTECH:	
	Lube and calibrate tracking system, check battery.	Monthly; 2.8 hrs
	EMT-1 & EMT-2:	
	Inspect arrays and adjust PCU operating limits.	Quarterly; 8.8 hrs

Table III.3 (Continued)
January - April 1995 O&M Summary

O&M Type	Event	Date; Force x Time, and Expenses (default force is 1 person)
Failure-related	Site-BOS: (1.75 hrs total)	
	Replaced fuse in sump pump control cabinet.	1/6; 0.5 hrs
	Reset plant after loss of site power.	3/11; 1.25 hrs
	APS: (1.3 hrs total)	
	Reset PCU after misc. shutdowns.	6 occurrences; 1.3 hrs total
	IPC: (26.1 hrs total)	
	Replace repaired bridge board.	1/19; 1.5 hrs
	Troubleshoot Omnion PCU via telecon.	2/9; 8 hrs
	Omnion site visit to repair PCU.	2/13, 2/14; 8 hrs total
	Troubleshoot tracker problem.	4/18; 0.5 hr
	Replace I/O modules in tracker controller.	4/20; 4/27; 2 hrs total
	Reset PCU after misc. shutdowns.	29 occurrences; 5.1 hrs total
	Reset tracker.	3 occurrences; 1 hr total
	SSI: (9.7 hrs total)	
	Replace 4 burned modules and bypass diode.	3/30, 4/4; 6.6 hrs total
	Reset PCU after misc. shutdowns.	16 occurrences; 3.1 hrs total
	EMT-1 ENTECH: (3.4 hrs total)	
	Reset tracker.	6 occurrences; 2.33 hrs total
	Reset PCU due to sync error shutdown.	6 occurrences; 1.05 hrs total
	EMT-1 SSI: (1.1 hrs total)	
	Reset PCU due to synch error.	5 occurrences; 1.1 hrs total
	EMT-1 Sovonics: (0.8 hrs total)	
	Applied insulating compound to burned Tefzel spot.	4/6; 0.25 hrs
	Reset PCU due to dc overvoltage.	4 occurrences; 0.55 hrs total
	EMT-2 AstroPower: (2.4 hrs. total)	
	Replace 3 ac fuses in PCU.	3/6; 1.0 hrs + $15.00
	Reset PCU due to synch error shutdown.	8 occurrences; 1.4 hrs total
Research Activities	Verified thickness of Amonix pedestal.	1/13; 0.25 hrs
	Exchanged logic control cards on DECC PCUs.	6 occurrences; 3 hrs total
	APS array I-V curve tests.	every 6 wks; 1 hr
	Monitor site power quality, process data.	ongoing; 2 hrs/wk

IV. OTHER PVUSA SITES

1. Summary

Figure IV.1.a shows the location and lists basic information about PVUSA's various sites. In addition to the Davis and Kerman sites within PG&E's service territory, host systems are operating in Kihei, HI, Austin, TX, Farmingdale, NY, Maspeth, NY, Sacramento, CA, and Fort Davis, TX. In January, Central & South West Services began start-up activities on a 100-kW ENTECH system at their Fort Davis Solar Park, and Virginia Power began acceptance testing on a 20-kW AstroPower array at their Lake Anna, VA site. Neither system was fully commissioned by the end of April, but both were achieving limited operation while various de-bugging activities continued, and each had been assigned ratings: 88 kWac for the CSW ENTECH system, and 11.6 kWdc for VEPCO's AstroPower array. With these two new additions, the total number of PVUSA systems increased to 18, with a combined capacity of 1,818 kWac. The Public Service Co. of Colorado and the U.S. Department of Defense plan to install 50-kW and 375-kW Utility Scale systems in 1995.

At a glance, Figure IV.1.b compares how much insolation the various sites have been receiving—and how well their systems have been using it. Two key statistics are presented: this year's cumulative global horizontal insolation, expressed as an average daily quantity; and this year's cumulative performance index (see earlier P.I. discussion in Sec. III.1 and supplementary information in Appendices A and B).

Through April, the Maui and Fort Davis sites have received the most insolation, averaging about 50% more than each of the other six sites for which data are available. At Maui, where the monthly insolation is fairly uniform, the insolation over the first third of the year was only slightly less than one-third of the annual average. At Fort Davis, the insolation over the first third of the year was about 29% of the expected annual total. At the other sites, seasonally cloudy and rainy conditions have limited the cumulative yearly insolation to as little as 1/5 of their expected annual totals.

Five of PVUSA's 16 systems with data available operated at a 90% or higher P.I. Only one of these was at a site other than Davis. Seven of the remaining eleven systems achieved P.I.'s ranging from 70% to 90%, three operated in the range of 50% to 70%, and only one system, at Farmingdale (IPC), was down for most of the period. Performance data were not yet available for the CSW ENTECH or VEPCO AstroPower systems.

The following subsections include detailed performance information for operating sites.

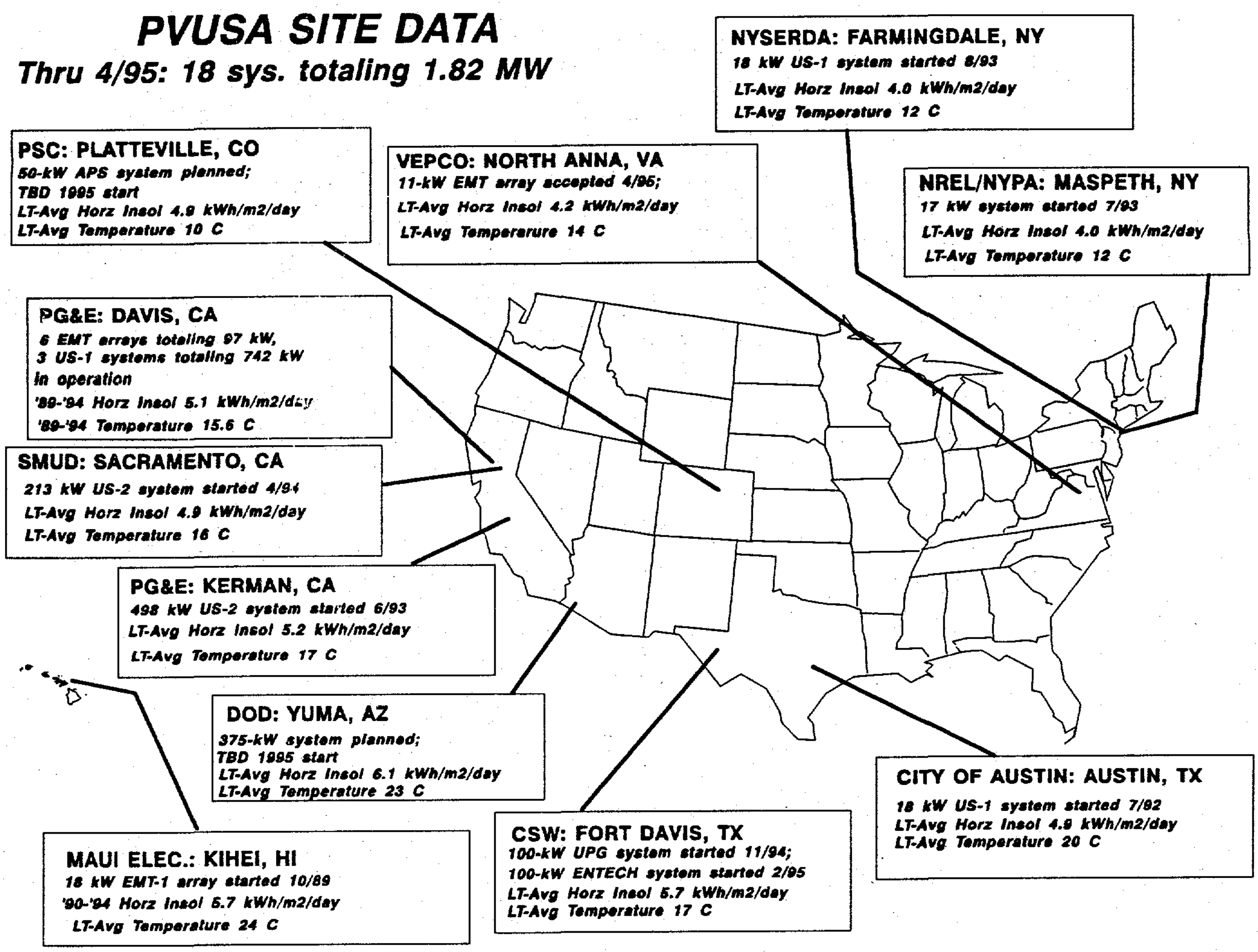
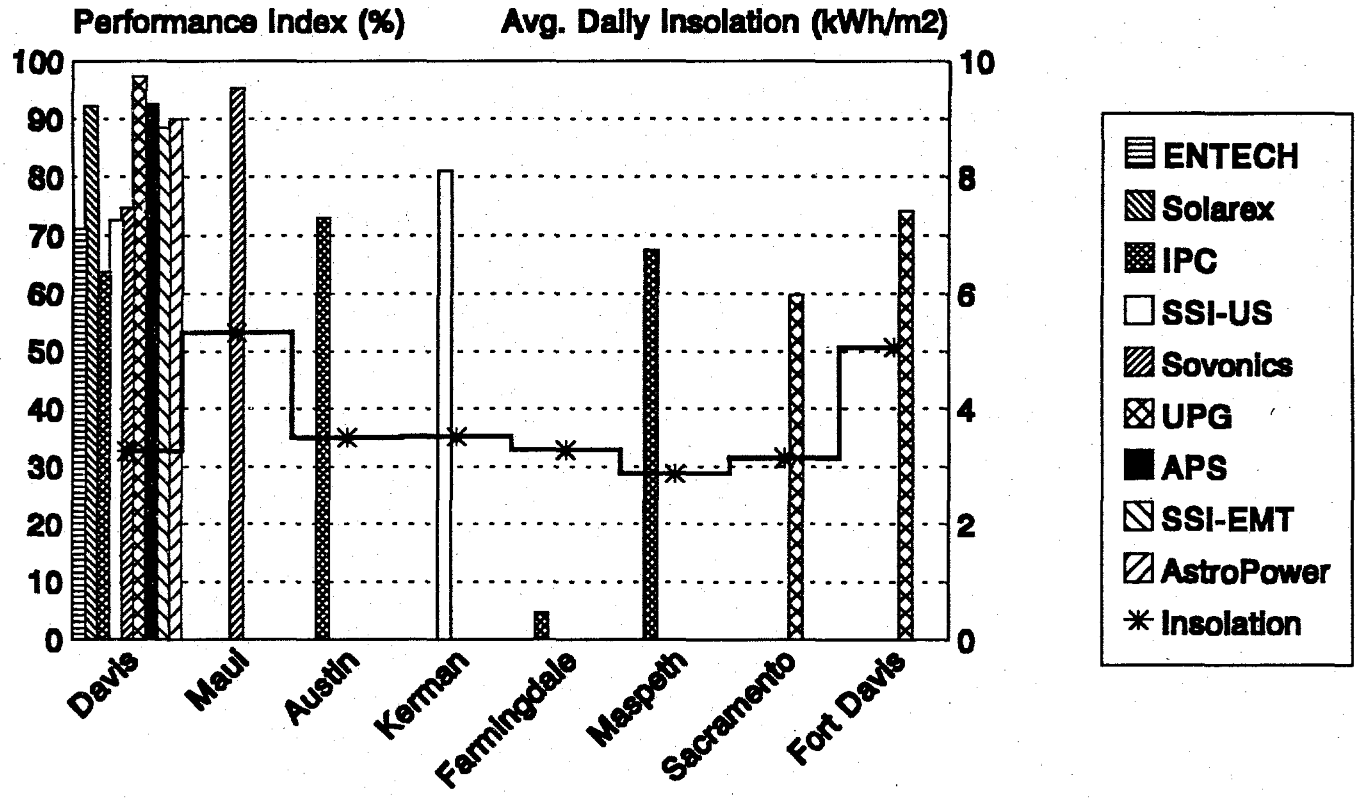

PVUSA SITE DATA
Thru 4/95: 18 sys. totaling 1.82 MW
NYSERDA: FARMINGDALE, NY
18 kW US-1 system started 8/93
LT-Avg Horz Insol 4.0 kWh/m2/day
LT-Avg Temperature 12 C
PSC: PLATTEVILLE, CO
50-kW APS system planned;
TBD 1995 start
LT-Avg Horz Insol 4.9 kWh/m2/day
LT-Avg Temperature 10 C
VEPCO: NORTH ANNA, VA
11-kW EMT array accepted 4/95;
LT-Avg Horz Insol 4.2 kWh/m2/day
LT-Avg Temperarure 14 C
NREL/NYPA: MASPETH, NY
17 kW system started 7/93
LT-Avg Horz Insol 4.0 kWh/m2/day
LT-Avg Temperature 12 C
PG&E: DAVIS, CA
6 EMT arrays totaling 97 kW,
3 US-1 systems totaling 742 kW
in operation
'89-'94 Horz Insol 5.1 kWh/m2/day
'89-'94 Temperature 15.6 C
SMUD: SACRAMENTO, CA
213 kW US-2 system started 4/94
LT-Avg Horz Insol 4.9 kWh/m2/day
LT-Avg Temperature 16 C
PG&E: KERMAN, CA
498 kW US-2 system started 6/93
LT-Avg Horz Insol 5.2 kWh/m2/day
LT-Avg Temperature 17 C
DOD: YUMA, AZ
375-kW system planned;
TBD 1995 start
LT-Avg Horz Insol 6.1 kWh/m2/day
LT-Avg Temperature 23 C
CITY OF AUSTIN: AUSTIN, TX
18 kW US-1 system started 7/92
LT-Avg Horz Insol 4.9 kWh/m2/day
LT-Avg Temperature 20 C
CSW: FORT DAVIS, TX
100-kW UPG system started 11/94;
100-kW ENTECH system started 2/95
LT-Avg Horz Insol 5.7 kWh/m2/day
LT-Avg Temperature 17 C
MAUI ELEC.: KIHEI, HI
18 kW EMT-1 array started 10/89
'90-'94 Horz Insol 5.7 kWh/m2/day
LT-Avg Temperature 24 C

Figure IV.1.a

PERFORMANCE INDEX and INSOLATION
January - April 1995



Insolation: global horizontal
Performance Index: actual/expected generation (exp. gen. considers actual insol., scheduled outages, temperature, BOS losses, and degradation)

Figure IV.1.b

2. Kerman

Tables IV.2.a and IV.2.b summarize 1993, 1994, and January-April 1995 PV system, solar insolation, and weather data for the Kerman site. The Kerman plant's performance index of 81% was somewhat poorer than its adjusted value of 89% for last year (note the earlier reported 1994 P.I. value of 85%, which did not include a more recent 5% allowance for normal PCU low-load losses). This year's performance has been limited by recurring PCU problems. There were 13 occasions when either or both PCUs tripped off line. One was attributed to a grid disturbance and several others were believed to occur as a result of enhanced irradiance, but most occurred for unknown reasons. PVUSA staff met with PG&E Fresno maintenance personnel in January to discuss plant maintenance responsibilities and budget. PVUSA will continue to monitor plant performance and provide technical support, and PG&E will assume principal maintenance responsibilities.

Four days' data were lost in March after the Kerman DAS computer's disk drive became full. The plant operated normally and its accumulated generation data, which is stored independently via a JEM revenue meter, was intact. Key performance data for the missing days have been estimated using the JEM meter readings. The computer was rebooted and files were archived to free up storage capacity. The site's 1-axis reference tracker was repaired in February after being out of service for several months. As with previous months, January and February reference 1-axis insolation was estimated as 5% more than the 24-hr.-based plane of array insolation.

Table IV.2.a
Kerman Performance Summary

SSI system characteristics	
Rating:	498 kW ac
Installation date:	6/93
Total module area:	5210 m^2
Orientation:	Horiz. N-S single axis trkr.

Quantity	1993 (Jul-Dec)	1994	Jan-Apr '95
Performance Index %	n/a	85 (89*)	81
AC kWh (incl. '93 start-up)	647626	1016118	207240
AC eff. %	8.9	9.0	9.3
Cap. fac. %	23.3	23.3	14.4
Max. ac kW	518	533	493
Wtd. avg. T_{module} °C	42	43	35
POA insol. (PCU on) kWh/m^2	1107	2162	519

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.2.b
Kerman Solar/Weather Summary

Quantity	1993 (Jul-Dec)	1994	Jan-Apr '95
1-axis insol. kWh/m^2	1317	est. 2534	est. 549
Horiz. insol. kWh/m^2	895	1835	423
LT-Avg. horiz. insol. kWh/m^2	967 (Jul-Dec)	1899	490
Peak 1-axis irrad. W/m^2	1177	1221	1125
Peak horiz. insol. W/m^2	1223	1205	1048
Min. T_{amb} °C	-2.7	-2	2
Avg. T_{amb} °C	19.5	18	15
LT-Avg. T_{amb} °C	19 (Jul-Dec)	17	12
Max. T_{amb} °C	42.5	42	31
Avg. wind speed m/s	2.4	2.6	2.7
Max. wind speed m/s	10.6	11.4	12.4

3. Maui

Table IV.3.a summarizes 1992, 1993, 1994, and January-April 1995 performance for the Maui Sovonics array. Table IV.3.b summarizes solar/weather data. The system's performance index over the first four months of 1995 was 95%, consistent with its characteristically steady and high performance over the past few years. The principal shortcoming of this system has been that several modules per year have either been damaged or ruined as a result of failed junction box connections. Between January and April, Maui Electric made two trips to repair a total of five open-circuited modules whose junction boxes and associated wiring had melted or burned. This brought the total number of module/junction-box failures to 49 out of 1200 modules (5 in 1995, 9 in 1994, 6 in 1993, 5 in 1992, 11 in 1991, and 13 in 1990).

An outstanding item, resolving the cause of seemingly high ambient temperature measurements, has not yet been addressed. However, some new information is now available that suggests the existing measurements may be too high. NREL included a new site at Kahului, Maui, in its 1994 Solar Radiation Data Manual, and it lists an annual average of 24 °C. The PV site has averaged at least 3 °C higher than that for several years. There may be real and steady differences between the Kahului and Kihei sites' temperatures, but spot checks by PVUSA and Maui Electric personnel and data from a recently installed weather station have also been consistent with NREL's values. (Similarly unexplained slightly high ambient temperatures are also being recorded at PVUSA's Austin and Farmingdale sites, although perhaps for other reasons.)

Table IV.3.a
Maui Performance Summary

Sovonics array characteristics	
Rating:	18.5 kW dc, 17.6 kW ac
Installation date:	10/89
Total module area:	497 m^2
Orientation:	22° tilt, south facing

Quantity	1992	1993	1994	Jan-Apr '95
Performance Index %	n/a	n/a	92 (97*)	95
AC kWh	28085	32405	30760	10100
DC eff. %	3.4	3.3	3.3	3.3
Cap. fac. %	18.2	21.0	20.0	19.9
Max. ac kW	18.7	18.5	18.9	18.9
Wtd. avg. T_{module} °C	44	44	45	41
POA insol.(PCU on) kWh/m^2	1812	2131	2008	655

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.3.b
Maui Solar/Weather Summary

Quantity	1992	1993	1994	Jan-Apr '95
POA insol. kWh/m^2	2148	2180	2146	705
Horiz. insol. kWh/m^2	2070	2098	2065	639
LT-Avg. horiz. insol. kWh/m^2	2008	2008	2008	600
Peak POA irrad. W/m^2	1238	1250	1226	1218
Peak horiz. irrad. W/m^2	1281	1252	1257	1169
Min. T_{amb} °C (Jun-Jul '93 n/a)	16	15	13	15
Avg. T_{amb} °C (Jun-Jul '93 n/a)	28	27	27	26
LT-Avg. T_{amb} °C	24	24	24	23
Max. T_{amb} °C (Jun-Jul '93 n/a)	43	40	43	40
Avg. wind speed m/s	3.7	3.7	3.2	4.0
Max. wind speed m/s	13.3	13.1	14.4	11.3

4. Austin

Table IV.4.a summarizes 1993, 1994, and January-April 1995 performance for the Austin IPC system. Table IV.4.b summarizes solar/weather data. The Austin site's performance index over the first third of the year was 73%, substantially below last year's adjusted annual P.I. of 88%. The system's performance was especially poor during the first three months of the year, operating during less than 60% of the daytime hours during that period. Similar to the experiences at other sites, the Austin system has suffered from recurring trips of its Omnion PCU, with the unit unavailable for about 30 days over the past six months. Some of the PCU problems have required new components and field repairs by Omnion technicians. The system's modules, tracker, and wiring were reported to be in good operating condition.

Table IV.4.a
Austin Performance Summary

IPC system characteristics	
Rating:	17.9 kW ac
Installation date:	7/92
Total module area:	212 m^2
Orientation:	Horiz. N-S single axis trkr.

Quantity	1993	1994	Jan-Apr '95
Performance Index %	n/a	84 (88*)	73
AC kWh	27790	26209	6365
AC eff. %	8.1	8.2	7.9
Cap. fac. %	17.7	16.7	12.4
Max. ac kW	20.0	19.8	17.6
Wtd. avg. T_{module} °C	41.0	40	38
POA insol. (PCU on) kWh/m^2	1617	1522	386

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.4.b
Austin Solar/Weather Summary

Quantity	1993	1994	Jan-Apr '95
POA insol. kWh/m^2	1955	1847	521
Horiz. insol. kWh/m^2	1615	1525	420
LT-Avg. horiz. insol. kWh/m^2	1790	1790	507
Peak POA irrad. W/m^2	1187	1171	1069
Peak horiz. irrad. W/m^2	1193	1181	1041
Min. T_{amb} °C	-1	-2	1
Avg. T_{amb} °C	23	21	18
LT-Avg. T_{amb} °C	20	20	15
Max. T_{amb} °C	42	43	37
Avg. wind speed m/s	1.8	1.8	1.8
Max. wind speed m/s	7.7	9.2	7.1

5. NYSERDA

Table IV.5.a summarizes the system's 1994 and January-April 1995 performance. Table IV.5.b summarizes solar/weather data. The system was down for all but the last five days of the report period due to a PCU failure. The system's 1-axis tracker has not functioned prior to, during, or since the PCU-related outage. The site's ambient temperature measurements have been erratic and generally higher than expected. As the cause is unknown, these data have been excluded from the table. PVUSA has yet to rate the system, and NYSERDA has yet to accept the system from IPC. Until the system is fully operational, PVUSA will continue to use the identical Austin, TX IPC host system's rating of 17.9 kW as a temporary rating. The only reported maintenance activity concerned the warranty repair of the system's Omnion PCU in April.

Table IV.5.a
NYSERDA Performance Summary

IPC system characteristics	
Temporary rating:	17.9 kW ac
Installation date:	8/93
Total module area:	212 m^2
Orientation:	Horiz. N-S single axis trkr.

Quantity	1994	Jan-Apr '95
Performance Index %	66 (69*)	5
AC kWh	19270	426
AC eff. %	8.4	8.6
Cap. fac. %	12.3	0.8
Max. ac kW	23.4	18.2
Wtd. avg. T_{module} °C	30	28
POA insol. (PCU on) kWh/m^2	1079	24

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.5.b
NYSERDA Solar/Weather Summary

Quantity	1994	Jan-Apr '95
POA insol. kWh/m^2	1505	394
Horiz. insol. kWh/m^2	1366	390
LT-Avg. horiz. insol. kWh/m^2	1460	399
Peak POA irrad. W/m^2	1310	988
Peak horiz. irrad. W/m^2	1246	1170
Min. T_{amb} °C	n/a	n/a
Avg. T_{amb} °C	n/a	n/a
LT-Avg. T_{amb} °C	13	4
Max. T_{amb} °C	n/a	n/a
Avg. wind speed m/s	1.6	1.8
Max. wind speed m/s	12.4	10.4

6. NREL/NYPA

Table IV.6.a summarizes the system's 1994 and January-April 1995 performance. Table IV.6.b summarizes solar/weather data. The system's performance index over the first third of 1995 was 68%, somewhat below the system's fourth quarter 1994 adjusted P.I. of 76% and considerably below the system's overall 1994 adjusted P.I. of 87%. Like its predecessor Sovonics EMT array at Davis, this system tends to operate at its lowest efficiency during the winter, an effect attributed to either less favorable spectral conditions, an absence of (summertime) thermal annealing, or both.

NREL provided PVUSA with the NYPA system's DAS phone number and turned over direct data collection authority to PVUSA in January. Previously, NREL had sole access to the site DAS and had been performing data quality checking and analyses. NREL also turned over maintenance responsibility to the New York Transit Authority. No maintenance activities were reported by NYPA or the New York Transit Authority. The only significant outage that was reported was in February, when the system was covered with snow for two days after a storm and registered several false PCU starts. PVUSA will be using spring 1995 data from this system to calculate an updated rating for future reports.

Table IV.6.a
NREL/NYPA Performance Summary

IPC/Uni-Solar system characteristics	
NREL Installed Rating:	17.0 kW ac
Installation date:	7/93
Total module area:	413 m^2
Orientation:	Fixed 10° tilt, south-facing

Quantity	1994	Jan-Apr '95
Performance Index %	83 (87*)	68
AC kWh	19478	4241
AC eff. %	3.3	2.8
Cap. fac. %	13.1	8.7
Max. ac kW	17.7	14.5
Wtd. avg. T_{module} °C	35	28
POA insol. (PCU on) kWh/m^2	1420	367

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.6.b
NREL/NYPA Solar/Weather Summary

Quantity	1994	Jan-Apr '95
POA insol. kWh/m^2	1448	407
Horiz. insol. kWh/m^2	1298	347
LT-Avg. horiz. insol. kWh/m^2	1460	399
Peak POA irrad. W/m^2	1163	1174
Peak horiz. irrad. W/m^2	1050	1064
Min. T_{amb} °C	-17	-13
Avg. T_{amb} °C	14	7
LT-Avg. T_{amb} °C	13	4
Max. T_{amb} °C	39	26
Avg. wind speed m/s	3.2	3.4
Max. wind speed m/s	10.9	10.5

7. SMUD

Table IV.7a summarizes the system's 1994 and January-April 1995 performance. Table IV.7.b summarizes solar/weather data. The 1994 totals are based on a partial year of data collection beginning in mid-August. An interim rating of 213 kW was calculated in October 1994 under conditions that weren't quite satisfactory for assigning a final rating. A final rating based on April or May 1995 data will be used in future reports.

The system's performance index over the first third of 1995 was only 60%, due to a combination of faulty 1-axis tracker operation and intermittent PCU trips. With PVUSA assistance, UPG began troubleshooting the system's tracker this spring. UPG identified errors in the tracker control program on two occasions and was working on the second program modification in late April. PVUSA will provide feedback to UPG on the effect of the tracker program changes.

The SMUD site does not have a reference 1-axis insolation device installed. As its array tracking has not worked properly, the plane of array insolation measurements are not believed to adequately represent the available 1-axis insolation. Therefore, the 24-hr. based insolation listed at the top of Table IV.7.b is labeled as POA rather than reference 1-axis insolation. The nearby Davis site's global horizontal insolation over this period was 4% greater than at the SMUD site, but the Davis reference 1-axis insolation was 15% greater than the SMUD site's. For the P.I. calculations, the SMUD site's available 1-axis insolation was estimated by multiplying the Davis site's 1-axis insolation by the ratio of the global horizontal insolation at SMUD relative to Davis. As with PVUSA's other 1-axis tracking systems, an allowance of 5% has been included elsewhere (in the index BOSA factor) to account for expected non-ideal tracking.

The system was down for the first two weeks of the year, continuing an outage that began in November. The system's Omnion PCU was modified in November to enable it to restart automatically after minor grid-induced trips. Once enabled, however, the auto restart feature triggered other control errors that prevented the PCU from operating normally. In mid-January, Omnion replaced a circuit board to correct the problem. No other maintenance activities were reported, but there were subsequent PCU trips of unknown cause(s) that required manual resets, including several in February, and one in March that resulted in two weeks of down time.

Table IV.7.a
SMUD Performance Summary

UPG/SSI system characteristics	
Interim Rating:	213 kW ac
Installation date:	4/94
Total module area:	2043 m^2
Orientation:	Horiz. N-S single axis trkr.

Quantity	8/16-12/31 94	Jan-Apr '95
Performance Index %	64 (67*)	60
AC kWh	99399	64306
AC eff. %	9.4	10.8
Cap. fac. %	14.1	10.5
Max. ac kW	196	233
Wtd. avg. T_{module} °C	40	31
POA insol. (PCU on) kWh/m²	515	286

* updated 1994 value, consistent with 1995 calculation that now includes a 5% PCU low-load loss allowance.

Table IV.7.b
SMUD Solar/Weather Summary

Quantity	8/16-12/31 94	Jan-Apr '95
POA insol. kWh/m^2 [1-axis insol. est. from Davis]	657	477 [528]
Horiz. insol. kWh/m^2	513	378
LT-Avg. horiz. insol. kWh/m^2	532	453
Peak POA irrad. W/m^2	1048	1072
Peak horiz. irrad. W/m^2	1018	1001
Min. T_{amb} °C	-1	1
Avg. T_{amb} °C	16	13
LT-Avg. T_{amb} °C	16	11
Max. T_{amb} °C	41	29
Avg. wind speed m/s	2.0	3.0
Max. wind speed m/s	12.7	18.3

8. Central and South West Services (CSW)

CSW has recently installed two 100-kW Utility Scale host systems at their Solar Park site near Fort Davis in west Texas. One, from UPG, uses SSI modules, an Omnion PCU, and a UPG 1-axis tracking structure similar to the SMUD host system. This system has been fully operational since November 1994, although some DAS signals were not completed until this January.

As with SMUD's system, some modifications will need to be made to correct errors in the tracker control program, but the system is presently operating with the original control scheme in place. Performance data for the UPG system are listed in Table IV.8.a. A nominal rating of 100 kW is being used to describe this system until a final PTC rating is established using this spring's data. For the P.I. calculations, the 1-axis insolation has been estimated by multiplying the measured global horizontal insolation by the ratio of the El Paso global 1-axis insolation over the El Paso global horizontal insolation, using long-term average data from NREL's Solar Radiation Data Manual. CSW reported having to reattach one module that had fallen from the array because of loose fastening hardware. A subsequent inspection identified 22 other fasteners that were less than hand tight.

CSW's other system, from ENTECH, is a 2-axis tracking concentrator array coupled to an Omnion PCU. The ENTECH system was first grid-tested in January and was essentially completed and rated at 88 kW in February (by SWTDI), but its operation to date has been limited. A number of start-up problems have been encountered, including 8 modules with cracked lenses, 5 modules with electrical failures, a number of unresolved ground faults, wind-related tracker drive problems, and unexplained PCU trips. Some of these issues have yet to be resolved. Table IV.8.b will be filled in more completely when the system is fully operational.

Table IV.8.c lists solar/weather data for the Solar Park. In general, the site DAS system has been difficult to connect to because of chronic poor telephone line quality, and some signals have not been verified. The agreement between the site's Eppley PSP and rotating shadowband global horizontal measurements has been poor, with the shadowband device tending to read about 7% higher. PVUSA plans to use the PSP readings until the differences are explained or corrected.

Table IV.8.a
CSW UPG Performance Summary

UPG/SSI system characteristics	
Nominal Rating:	100 kW ac
Installation date:	11/94
Total module area:	1021.5 m^2
Orientation:	Horiz. N-S single axis trkr.

Quantity	Dec 94	Jan-Apr '95
Performance Index %	n/a	74
AC kWh	12071	61344
AC eff. %	n/a	8.9
Cap. fac. %	n/a	21.3
Max. ac kW	93	105
Wtd. avg. T_{module} °C	n/a	31
POA insol. (PCU on) kWh/m^2	n/a	674

Table IV.8.b
CSW ENTECH Performance Summary

ENTECH system characteristics	
Interim Rating:	88 kW ac
Installation date:	2/95
Total module area:	907 m^2
Orientation:	2-axis trk. concentrator

Quantity	Jan-Apr '95
Performance Index %	n/a
AC kWh	13235
AC eff. %	n/a
Cap. fac. %	n/a
Max. ac kW	97
Wtd. avg. T_{module} °C	n/a
POA insol. (PCU on) kWh/m^2	n/a

Table IV.8.c
Fort Davis Solar/Weather Summary

Quantity	Jan-Apr '95
POA insol. kWh/m^2 [1-axis insol. est. from El Paso]	801 [867]
Horiz. insol. kWh/m^2	609
LT-Avg. horiz. insol. kWh/m^2	631
Peak POA irrad. W/m^2	1288
Peak horiz. irrad. W/m^2	1093
Min. T_{amb} °C	-8
Avg. T_{amb} °C	11
El Paso LT-Avg. T_{amb} °C	11
Max. T_{amb} °C	28
Avg. wind speed m/s	3.4
Max. wind speed m/s	17.1

Presented at the
First World Conference on Photovoltaic Energy Conversion
Waikoloa, HI, December 1994

A NEW PERFORMANCE INDEX FOR PV SYSTEM ANALYSIS

T. Townsend and C. Whitaker
Endecon Engineering
3160 Crow Canyon Rd., Suite 240
San Ramon, CA 94583

B. Farmer
Pacific Gas and Electric Co.
3400 Crow Canyon Rd.
San Ramon, CA 94583

H. Wenger
Pacific Energy Group
32 Valla Court
Walnut Creek, CA 94596

ABSTRACT

This paper describes a term called the Performance Index (P.I.) for analyzing photovoltaic (PV) system performance. The P.I. is the dimensionless ratio of actual to expected generation over any time interval.

PV system performance is often described by applying terms widely used for conventional power plants. However, there are drawbacks to using some of the most common quantities, such as capacity factor, efficiency, and availability. For PV systems, these quantities exhibit wider seasonal variations and smaller magnitudes than for conventional power plants. Consequently, PV systems are often judged to be operating poorly, even in the absence of failures.

At PVUSA, the P.I. is now being used for both real-time power plant monitoring and for longer-term analyses. A description of the calculation procedure and sample results are included.

INTRODUCTION

Answering a simple question regarding PV system performance such as "How well is it working?" proves to be more difficult than it appears. The capacity factor is probably the most useful statistic to answer such a question for many types of power plants, but not for PV. Because of the time-dependent nature of the fuel (solar) resource, normal daily and seasonal variations in solar radiation result in low capacity factors and can mask losses due to component failures or soiling.

Other common performance measures can be calculated, such as energy, average and peak power as a percentage of rated power,[1] efficiency, availability, and equivalent forced outage rate, but with similar drawbacks. Taken together, the additional measures can yield fairly comprehensive assessments, but they also make for cumbersome and potentially misleading interpretations of PV system performance.

For example, a PV system with a wintertime peak equal to 60% of its rated output, operating at 8% efficiency, 15% capacity factor, and 35% availability may have nothing wrong with it, while similar values in the summer would suggest problems exist. Those familiar with conventional plants might mistakenly conclude the PV system had been operating poorly during the winter and might also correctly conclude the summertime performance was poor, but possibly for the wrong reasons.

This confusion prompts another extreme to occur - a tendency to report oversimplified on/off status answers that say little or nothing about how well the system is operating. Both the detailed and oversimplified approaches are inadequate, suggesting the need for a capacity factor-like statistic that doesn't penalize a PV system for externally driven departures from its rated power.

The PVUSA project is now monitoring fourteen PV systems installed at seven sites around the U.S. over the past six years. The installed systems range from 15 kW to 500 kW, with a combined capacity of 1,600 kW. A mix of amorphous, polycrystalline, and single-crystal silicon flat-plate and concentrator technologies are in place, mounted on various fixed tilt and tracking structures [1]. The diversity of locations, sizes, and technology types at PVUSA reinforces the need for a statistic that permits meaningful comparisons by normalizing for weather and plant size/type differences. The P.I. incorporates several desirable characteristics: It is dimensionless, ranges from 0 to 100%, relies on commonly measured quantities for PV systems, applies to real-time and longer-term analyses, normalizes for rated capacity, and independently adjusts for irradiance, temperature, and as many other power loss or gain mechanisms as the user can quantify.

PERFORMANCE INDEX DERIVATION

The P.I. shown in Eqn. (1) is defined as the ratio of actual to expected generation over any time interval [2]. (The following discussion will center on instantaneous power-based P.I. calculations, but an energy P.I. may be calculated by integrating over time.) The actual

[1] Rated power under a set of reference test conditions. Manufacturers' standard test conditions (STC) of 1,000 W/m^2 plane of array irradiance, air mass 1.5, and 25 or 28 C cell temperature have been widely used. As these conditions rarely occur outdoors, PVUSA has developed a more representative set of test conditions (PTC), defined as 1,000 W/m^2 plane of array irrad. (850 W/m^2 direct normal irrad. for concentrators), 20 C air temperature, and 1 m/s wind speed at 10 m height. PTC ratings tend to be about 10% lower than STC ratings.

generation is easily measured with a revenue meter or power transducer, but the expected generation is more difficult to calculate.

$$\text{P.I.} = \frac{\text{Actual Generation}}{\text{Expected Generation}} \qquad (1)$$

Calculating expected generation requires adjusting for effects that drive power up or down from its rated value.

$$\text{Exp. Gen.} = \text{Rated Power} \times \text{Adjustments} \qquad (2)$$

Although a proposed calculation procedure will be derived from Eqn. (2) with recommended adjustments for several key effects, rigid criteria for adjusting the rated power are not defined here. As a general guideline, adjustments should be made for those effects considered uncontrollable (weather-related) or irreversible (design or material-related). While there may be some value in defining a uniform calculation procedure, the statistic may be more useful if the calculation is flexible enough to permit some effects to be adjusted for on an application-specific basis.

Power and energy losses or gains may be attributed to the following effects.

- Irradiance (greater or less than reference)
- Module temperature (greater or less than rated)
- Degradation (long-term rating declines)
- Soiling (dirt, bird droppings, snow)
- Balance of system (BOS) losses, such as:
  - Tracker physical limits (reduced irrad.)
  - Tracker non-ideal performance (reduced irrad.)
  - Shading (mismatch, reduced irrad.)
  - Field of view (reduced irrad.)
  - PCU (standby loads, off-peak power tracking, and low-load reduced efficiency)
  - Transformer (no-load losses)
- Reflection (add'l loss at high incidence angles)
- Solar spectrum (some PVs are sensitive to changes)
- Annealing (degradation can be partly reversed for some PVs under sustained elevated temperatures)
- Outages (full, partial; scheduled, unscheduled)

For effects such as unplanned partial or full outages, the P.I. is useful for determining their impact on actual generation (no adjustment to the expected generation). Allowing for other effects becomes more discretionary. For example, it is debatable whether reduced actual generation due to long-term degradation, soiling, and tracker losses should be accompanied by corresponding reductions in expected generation. Allowing for such effects increases the P.I.

Some effects are difficult or impractical to quantify, like spectral or annealing effects. Only a few effects tend to be at least as significant as the principal uncertainty of at least ±3% associated with most irradiance measurements. The minor effects can therefore be neglected or considered as being lumped with other effects.

As a practical expression, the performance index may be defined as:

$$\text{P.I.} = \frac{\text{Actual Power}}{\text{Rated Power} \bullet \text{IA} \bullet \text{TA} \bullet \text{DA} \bullet \text{SA} \bullet \text{BOSA}} \qquad (3)$$

where adjustment factors are:

IA = Irradiance Adjustment = actual / rated irrad. (integrated, this can be considered an "insolation factor," analogous to the traditional capacity factor)
TA = Temperature Adjustment = $(1 + \beta \cdot (T_{mod} - T_{mod,PTC}))$
β = temperature coefficient, 1/C
T_{mod}, $T_{mod,PTC}$ = actual and rated module temperatures, C
DA = Degradation Adjustment = Present rating / Initial rating
SA = Soiling Adjustment = actual (soiled) power / rated (cleaned) power
BOSA = 1 - (fraction BOS losses)

A term for scheduled outages is not shown here. For real-time monitoring, the P.I. is undefined (and unnecessary) when a system is down for a scheduled outage. When used for longer-term analyses (e.g., monthly), scheduled outages are accounted for by subtracting the insolation received during the outage from the IA term's integrated actual insolation. Integrated, the equation becomes:

$$\text{P.I.} = \frac{\text{Actual Energy} \bullet \text{Rating Irrad}}{\text{Rat. Pwr.} \bullet \text{Act. Ins.} \bullet \text{TA} \bullet \text{DA} \bullet \text{SA} \bullet \text{BOSA}} \qquad (4)$$

Regarding the IA and TA terms: the irradiance and temperature effects are essentially uncontrollable, and the expected power should be adjusted so that the P.I. does not penalize or reward a system as a result of variations in irradiance or temperature. For the integrated Eqn. (4), the correct term to use for the module temperature is the power-weighted-average module temperature. Power-weighting minimizes the effect of cooler temperatures that tend to occur at low power and properly weights the warmer module temperatures characteristic of midday periods.

$$\overline{T_{mod}} = \frac{\sum (\text{Power} \bullet T_{mod})}{\text{Energy}} \qquad (5)$$

Regarding the DA term: At PVUSA, many of the systems have degraded (some by 20%) after several years to the point that their performance looks poor relative to their initial rating. While mindful of the change, PVUSA's operators have found it more useful to adjust the rated power by the ratio of the present/initial rating so that the real-time P.I. can readily identify new system problems.

Regarding the SA term: Due to surrounding agriculture and dry summers, soiling losses can be significant at PVUSA's Davis site. Power losses as high as 20% have been measured on systems that have gone unwashed for several months. Losses resulting from electing not to wash an array should reduce the P.I. Conversely, by including soiling losses the P.I. can be used to identify the degree to which system performance has changed due to other mechanisms.

Regarding the BOSA term: There are a number of losses lumped together in this term. Most are small, dynamic, and difficult to quantify independently. (Doing so generally requires special lab and field tests and additional uncommon measurements.) As they tend to be proportionately more important early and late in the day at low irradiance levels, the effects are often neglected, particularly for real-time diagnostics that focus on midday performance. Combined, however, their effects can be significant: Two of PVUSA's single-axis tracking systems lose 5% to 15% of their annual generation, largely due to non-ideal tracking, and another two-axis tracking system's annual energy is reduced by 10% due to shading losses (note that shading and other BOS-related losses aren't represented in the system's rated power; one reason why actual long-term energy production tends to fall short of expectations).

The reflective losses at high incidence angles, solar spectrum, and annealing effects are generally ignored, although with additional instruments (such as spectroradiometers) and special tests (such as flash tests to plot incidence angle effects and study annealing) their effects could be estimated.

Calculations similar to the P.I. have been proposed. Roy [3] proposed the Operating Reliability Factor, where the capacity factor is divided by an "insolation coefficient;" with the insolation coefficient calculated in a manner analogous to the capacity factor. By dropping the temperature, degradation, soiling, and BOS terms, the P.I. equation reduces to the Operating Reliability Factor. By ignoring the temperature effect, though, the Operating Reliability Factor is subject to significant temperature-related seasonal variations of ±15%, large enough to mask many failure-related reductions in power.

Independent of Roy's work, PVUSA has been using the same calculation for the past few years, with various labels: PV effectiveness, energy-weighted availability, and insolation-weighted capacity factor [1,4].

PERFORMANCE INDEX APPLICATIONS

PVUSA began using the P.I. in 1994 for two applications: real-time monitoring and longer-term performance analyses.

At its Davis site, PVUSA uses a computer display screen to show real-time values for numerous weather quantities, utility and PV system status signals, and PV system electrical parameters. Even with a day-to-day familiarity with the generation patterns exhibited by eight systems ranging from 15 to over 400 kW, the plant's operators have always found it cumbersome to verify correct system performance under prevailing weather conditions. Smaller failures have sometimes gone unnoticed for days because of the overwhelming number of measurements.

A P.I. software calculation was added earlier this year for each PV system, along with a color-coded P.I. display and an audible alarm to alert operators in the event of a system shutdown. At a glance, operators can now see whether each system is operating properly.

The P.I. calculation includes adjustments for irradiance, module temperature, and degradation, but does not adjust for soiling, BOS, or other losses. A green indicator is displayed as long as the P.I. is above 90%. Below 90%, a yellow indicator is used, which generally points to a component failure or heavy soiling. At irradiances below 250 W/m^2, a more generous P.I. threshold of 50% is used to indicate satisfactory (green) performance; without a dynamic BOS loss adjustment included in the P.I. calculation, systems would rarely meet the 90% threshold at low irradiance. A red indicator and accompanying alarm are used to indicate abnormal system shutdowns, while a dark blue indicator is used at night to indicate a normal shutdown.

The other principal use of the P.I. has been for longer-term analyses. Figure 1 illustrates the 500-kW single-axis tracking Kerman PV plant's P.I. for June 1994. Although the system's capacity factor was just 40.5%, its P.I. was 92%. Most of the "lost" generation was simply a result of the sun being unavailable at the rating irradiance of 1,000 W/m^2 for 24 hours each day. In this example, the degree to which soiling reduced the overall generation was unknown and so it was lumped with the failure-related reductions in generation. A BOS loss of 5% was included based on comparisons between the insolation measured on the actual tracking structure compared to that available on an optimally-tracked structure [5].

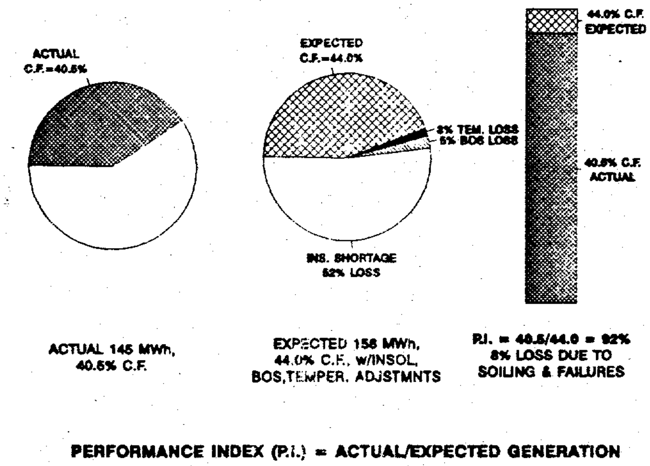


Fig. 1. June 1994 500-kW Kerman PV Plant Performance Index

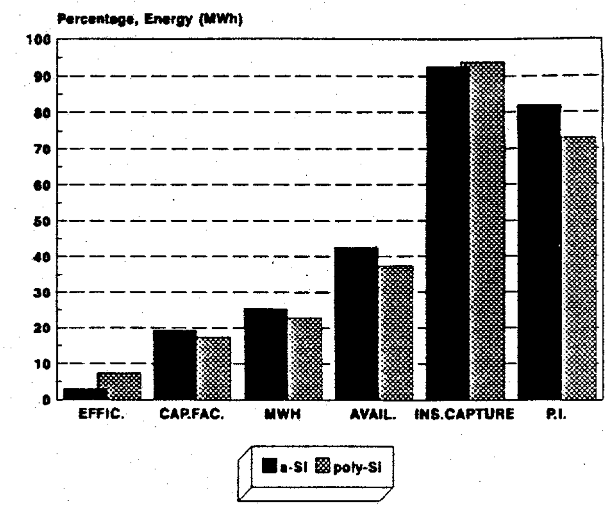


Fig. 2. Annual performance for two 15-kW systems

Figure 2 uses the P.I. and several other quantities to compare the annual performance of two systems with 15 kW ratings. One system consists of amorphous silicon modules and the other consists of polycrystalline silicon modules. The annual efficiency and insolation capture[2] were higher for the poly-Si system, yet the a-Si system produced more energy (therefore, its capacity factor was correspondingly higher) and it was available during a greater percentage of the year. The availability is calculated as the percentage of hours (24-hr. basis) during which net power was supplied to the utility by the PV system. The P.I. shows the a-Si system had the better year, a conclusion that, in this special case of identically sized systems, could have also been reached by comparing the energy produced. Note that while the capacity factor comparison illustrates the same conclusion as the P.I., the capacity factor does not distinguish between changes in weather or system performance.

Figure 3 uses the P.I. to compare the cumulative 1994 performance of 14 systems ranging from 15 kW to 500 kW at 7 sites around the U.S. The average global horizontal insolation is also shown for each site. In this case, the P.I. provides a readily interpreted comparison among systems of vastly different sizes, orientations, and locations. The only adjustment factors used here were for insolation, temperature, and degradation. Through September, only two of the systems have maintained a P.I. of 90% or better. Six others have produced at least 80% of their expected generation, while the remaining six systems have suffered more extensive downtime due to various failures and operated at about 20% to 80% P.I.'s.

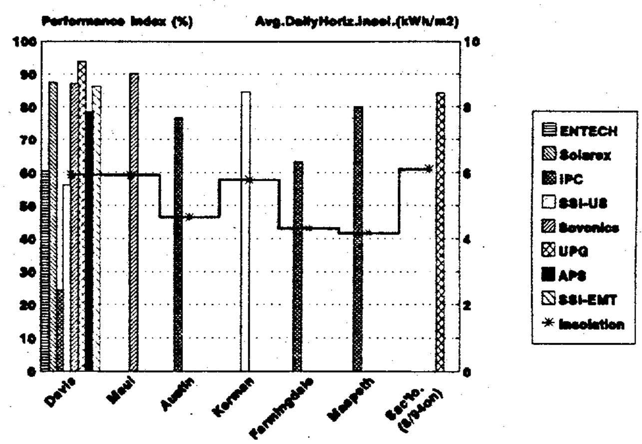


Fig. 3. 1994 P.I., insolation at PVUSA sites

[2] Insolation capture is the % of insolation received during hours when the system was operating, compared to the total insolation received over a given time interval.

REFERENCES

[1] PVUSA Project Team, "1993 PVUSA Progress Report," PG&E R&D Report 007.5-93.8, 1994.
[2] Townsend, T.U., "Performance Index Applications at PVUSA," NREL PV Performance and Reliability Workshop, Lakewood, CO, September 1994.
[3] Roy, A.S., "Comparative Performance of Various Solar-Electric Facilities," *Proc. of the 1989 Annual Conference*, ASES, Lakewood, CO, June 1989.
[4] Townsend, T.U., "Emerging Photovoltaic Module Technologies at PVUSA: A Five-Year Performance Assessment," *Proc. of the 1994 Annual Conference*, ASES, San Jose, CA, June 1994.
[5] Hoff, T., and Wenger, H.J., "The Value of Distributed Generation: The PVUSA Grid-Support Project Serving Kerman Substation," PG&E R&D Report 007.5-94.5, January 1994.

APPENDIX B

1995 Performance Index Worksheet

PERIOD	SYSTEM	KWH	TOTAL INSOL	SCH.OUTG INSOL	Tmod pwr-wtd-av	Tmod PTC	Beta	ORIGINAL AC RATING	RATING IRR kW/m2	DA	TA	BOSA	SA	P.I.
Jan-Apr	SSI-	6420	456.4	5.9	32	47	-0.0045	18.1	1.000	0.898	1.0675	0.93	1.00	88.5
May-Aug	Davis EMT					47	-0.0045	18.1	1.000	0.898	1.0675	0.93	1.00	0.0
Sep-Dec						47	-0.0045	18.1	1.000	0.898	1.0675	0.93	1.00	0.0
Annual		6420	456.4	5.9	32	47	-0.0045	18.1	1.000	0.898	1.0675	0.93	1.00	88.5
Jan-Apr	Sovonics-	4366	462.2	5.9	32	44	-0.0027	15.9	1.000	0.836	1.0324	0.93	1.00	74.8
May-Aug	Davis					44	-0.0027	15.9	1.000	0.836	1.0324	0.93	1.00	0.0
Sep-Dec						44	-0.0027	15.9	1.000	0.836	1.0324	0.93	1.00	0.0
Annual		4366	462.2	5.9	32	44	-0.0027	15.9	1.000	0.836	1.0324	0.93	1.00	74.8
Jan-Apr	UPG-	5520	455.0	5.9	31	51	-0.0010	15.1	1.000	0.881	1.0200	0.93	1.00	97.3
May-Aug	Davis EMT					51	-0.0010	15.1	1.000	0.881	1.0200	0.93	1.00	0.0
Sep-Dec						51	-0.0010	15.1	1.000	0.881	1.0200	0.93	1.00	0.0
Annual		5520	455.0	5.9	31	51	-0.0010	15.1	1.000	0.881	1.0200	0.93	1.00	97.3
Jan-Apr	Solarex	5609	458.2	5.9	31	43	-0.0045	15.1	1.000	0.907	1.0540	0.93	1.00	92.2
May-Aug						43	-0.0045	15.1	1.000	0.907	1.0540	0.93	1.00	0.0
Sep-Dec						43	-0.0045	15.1	1.000	0.907	1.0540	0.93	1.00	0.0
Annual		5609	458.2	5.9	31	43	-0.0045	15.1	1.000	0.907	1.0540	0.93	1.00	92.2
Jan-Apr	ENTECH-	4554	380.9	6.0	42	61	-0.0045	15.6	0.850	1.000	1.0855	0.86	1.00	71.3
May-Aug	Davis EMT					61	-0.0045	15.6	0.850	1.000	1.0855	0.86	1.00	0.0
Sep-Dec						61	-0.0045	15.6	0.850	1.000	1.0855	0.86	1.00	0.0
Annual		4554	380.9	6.0	42	61	-0.0045	15.6	0.850	1.000	1.0855	0.86	1.00	71.3
Jan-Apr	AstroPower-	6513	459.7	5.9	30	44	-0.0045	16.1	1.000	1.000	1.0630	0.93	1.00	90.1
May-Aug	Davis					44	-0.0045	16.1	1.000	1.000	1.0630	0.93	1.00	0.0
Sep-Dec						44	-0.0045	16.1	1.000	1.000	1.0630	0.93	1.00	0.0
Annual		6513	459.7	5.9	30	44	-0.0045	16.1	1.000	1.000	1.0630	0.93	1.00	90.1
Jan-Apr	APS	149839	425.4	9.5	32	49	-0.0027	479.0	1.000	0.835	1.0459	0.93	1.00	92.5
May-Aug						49	-0.0027	479.0	1.000	0.835	1.0459	0.93	1.00	0.0
Sep-Dec						49	-0.0027	479.0	1.000	0.835	1.0459	0.93	1.00	0.0
Annual		149839	425.4	9.5	32	49	-0.0027	479.0	1.000	0.835	1.0459	0.93	1.00	92.5
Jan-Apr	IPC-	65117	548.6	10.6	32	48	-0.0045	196.0	1.000	1.000	1.0720	0.90	1.00	63.8
May-Aug	Davis US					48	-0.0045	196.0	1.000	1.000	1.0720	0.90	1.00	0.0
Sep-Dec						48	-0.0045	196.0	1.000	1.000	1.0720	0.90	1.00	0.0
Annual		65117	548.6	10.6	32	48	-0.0045	196.0	1.000	1.000	1.0720	0.90	1.00	63.8
Jan-Apr	SSI-	24870	548.6	14.0	31	44	-0.0045	67.0	1.000	1.000	1.0585	0.90	1.00	72.7
May-Aug	Davis US					44	-0.0045	67.0	1.000	1.000	1.0585	0.90	1.00	0.0
Sep-Dec						44	-0.0045	67.0	1.000	1.000	1.0585	0.90	1.00	0.0
Annual		24870	548.6	14.0	31	44	-0.0045	67.0	1.000	1.000	1.0585	0.90	1.00	72.7
Jan-Apr	Sovonics-	10100	704.6	0.0	41	44	-0.0027	17.6	1.000	0.892	1.0081	0.95	1.00	95.3
May-Aug	Maui					44	-0.0027	17.6	1.000	0.892	1.0081	0.95	1.00	0.0
Sep-Dec						44	-0.0027	17.6	1.000	0.892	1.0081	0.95	1.00	0.0
Annual		10100	704.6	0.0	41	44	-0.0027	17.6	1.000	0.892	1.0081	0.95	1.00	95.3
Jan-Apr	IPC-	6365	521.3	0.0	38	46	-0.0045	17.9	1.000	1.000	1.0360	0.90	1.00	73.0
May-Aug	Austin					46	-0.0045	17.9	1.000	1.000	1.0360	0.90	1.00	0.0
Sep-Dec						46	-0.0045	17.9	1.000	1.000	1.0360	0.90	1.00	0.0
Annual		6365	521.3	0.0	38	46	-0.0045	17.9	1.000	1.000	1.0360	0.90	1.00	73.0
Jan-Apr	SSI-	207240	546.7	0.0	35	44	-0.0045	498.0	1.000	1.000	1.0405	0.90	1.00	81.1
May-Aug	Kerman US					44	-0.0045	498.0	1.000	1.000	1.0405	0.90	1.00	0.0
Sep-Dec						44	-0.0045	498.0	1.000	1.000	1.0405	0.90	1.00	0.0
Annual		207240	546.7	0.0	35	44	-0.0045	498.0	1.000	1.000	1.0405	0.90	1.00	81.1
Jan-Apr	IPC-	426	522.0	0.0	27	48	-0.0045	17.9	1.000	1.000	1.0945	0.90	1.00	4.6
May-Aug	Farmingdale					48	-0.0045	17.9	1.000	1.000	1.0945	0.90	1.00	0.0
Sep-Dec						48	-0.0045	17.9	1.000	1.000	1.0945	0.90	1.00	0.0
Annual		426	522.0	0.0	27	48	-0.0045	17.9	1.000	1.000	1.0945	0.90	1.00	4.6
Jan-Apr	IPC-	4241	405.5	0.0	28	46	-0.0010	17.0	1.000	0.941	1.0180	0.95	1.00	67.6
May-Aug	Maspeth					46	-0.0010	17.0	1.000	0.941	1.0180	0.95	1.00	0.0
Sep-Dec						46	-0.0010	17.0	1.000	0.941	1.0180	0.95	1.00	0.0
Annual		4241	405.5	0.0	28	46	-0.0010	17.0	1.000	0.941	1.0180	0.95	1.00	67.6
Jan-Apr	UPG-	64306	528.5	0.0	31	44	-0.0045	213.0	1.000	1.000	1.0585	0.90	1.00	59.8
May-Aug	Sacramento US					44	-0.0045	213.0	1.000	1.000	1.0585	0.90	1.00	0.0
Sep-Dec						44	-0.0045	213.0	1.000	1.000	1.0585	0.90	1.00	0.0
Annual		64306	528.5	0.0	31	44	-0.0045	213.0	1.000	1.000	1.0585	0.90	1.00	59.8
Jan-Apr	UPG-	61344	867.0	0.0	31	44	-0.0045	100.0	1.000	1.000	1.0585	0.90	1.00	74.1
May-Aug	Ft. Davis US					44	-0.0045	100.0	1.000	1.000	1.0585	0.90	1.00	0.0
Sep-Dec						44	-0.0045	100.0	1.000	1.000	1.0585	0.90	1.00	0.0
Annual		61344	867.0	0.0	31	44	-0.0045	100.0	1.000	1.000	1.0585	0.90	1.00	74.1
Jan-Apr	ENTECH-	26133	632.0	0.0	0	61	-0.0045	88.0	0.850	1.000	1.2745	0.86	1.00	36.7
May-Aug	Ft. Davis US					61	-0.0045	88.0	0.850	1.000	1.2745	0.86	1.00	0.0
Sep-Dec						61	-0.0045	88.0	0.850	1.000	1.2745	0.86	1.00	0.0
Annual		26133	632.0	0.0	0	61	-0.0045	88.0	0.850	1.000	1.2745	0.86	1.00	36.7
Jan-Apr	AstroPower-	0	0.0	0.0	0	47	-0.0045	11.0	1.000	1.000	1.2115	0.93	1.00	0.0
May-Aug	VEPCO					47	-0.0045	11.0	1.000	1.000	1.2115	0.93	1.00	0.0
Sep-Dec						47	-0.0045	11.0	1.000	1.000	1.2115	0.93	1.00	0.0
Annual		0	0.0	0.0	#DIV/0!	47	-0.0045	11.0	1.000	1.000	1.2115	0.93	1.00	0.0

P.I. = [kWh x Rating Irrad.] / [(Total Insol. - Sched. Outage Insol.) x Orig. Rating x TA x DA x BOSA x SA]

note: Total Insol. based on appropriate reference for each system's fixed or tracking orientation.

TA = (1 + Beta x (Tmod - Tmod,rated))

DA = Present / Original ratings

BOSA = 0.86 (concentrator), 0.90 (1-axis tracking), 0.93 (fixed tilt arrays at ≥30°), 0.95 (other fixed arrays)

Note: BOSA includes effects of non-ideal tracking, reduced PCU efficiency at low loads, and shading.