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**Emerging Photovoltaic
Module Technologies at PVUSA
A Five-Year Assessment**

April 1995

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EMERGING PHOTOVOLTAIC MODULE TECHNOLOGIES AT PVUSA A FIVE-YEAR ASSESSMENT

April 1995

Tim Townsend and PVUSA Project Team

for

Pacific Gas and Electric Company
Research and Development
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ABSTRACT

The Photovoltaics for Utility Scale Applications (PVUSA) project tests two types of photovoltaic systems: new modules fielded as 20-kW Emerging Module Technology (EMT) arrays, and more mature technologies fielded as 20- to 500-kW turnkey Utility Scale (US) systems. This report summarizes experiences of the PVUSA project in operating the first six 20-kW EMT photovoltaic systems. Five systems are installed at Davis, California, and one at Kihei, Hawaii.

Products selected for testing and demonstration were judged to have potential for significant technical advancement or reduction in manufacturing cost. Features leading to selection of each system and findings over the average 5 years of operation are compared in the report. Factory product qualification test experiences along with field acceptance test results are documented. Evaluation includes a broad range of performance parameters, including long-term efficiency, seasonal generation patterns, and maintenance. While some of the arrays have operated as well as any commercial system, others have fared poorly.

Throughout the procurement and operation of these precommercial PV modules, PVUSA has provided feedback to vendors, critical for product improvement. The data and evaluations in this report will be of further benefit to manufacturers and provide general comparative information on a variety of technologies to researchers in utilities, government, and industry alike.

This report is one in a series by PVUSA on experiences and lessons learned through fielding PV systems at the Davis and Kerman, California, sites and at participating "host" utilities. Other topical reports address:

- Construction and safety experience in procuring, installing, and operating PV systems
- Validation of the benefits of the grid-support 500-kW Kerman plant
- Balance-of-system designs and costs
- Power conditioning units, utility interface, and power quality
- Procurement, rating, and acceptance practices
- Data acquisition and analysis

EXECUTIVE SUMMARY

The Photovoltaics for Utility Scale Applications (PVUSA) project, a national public-private partnership established to demonstrate grid-connected photovoltaic systems for utility applications, evaluates PV systems at several locations around the United States. Two types of PV systems are evaluated: new modules fielded as nominal 20-kW Emerging Module Technology (EMT) arrays and more mature technologies fielded as 20- to 500-kW turnkey Utility Scale (US) systems.

PVUSA chose to field EMT arrays to fulfill several project objectives, including performance and reliability evaluation of promising new technologies both side by side and in diverse geographic areas. EMT-1 procurement included five systems installed in Davis, California, from 1989 to 1991 and one system installed in Kihei (Maui), Hawaii, in 1989. This report summarizes PVUSA's experiences in procuring, installing, and operating the six arrays. PV system performance is evaluated in terms of energy generated, efficiency, capacity factor, and maintenance experience—measures typically used for conventional power plants.

Through 1994, the five 20-kW EMT-1 arrays at the Davis site had generated 650,000 kWh for PG&E's grid, and the 20-kW EMT-1 array at the Maui site had contributed 150,000 kWh to Maui Electric's grid. The combined output equals the one-year electric demand of about 130 average U.S. homes.

Overall performance of the EMT arrays has been mixed. Some arrays performed well in terms of reliability and efficiency, comparing favorably with commercial PV systems. However, several arrays had significant schedule delays due to developmental hurdles, initial efficiencies were lower than expected (on a relative basis, 3% to 25% short of their design targets), and all but one have slowly degraded at rates ranging from 1% to 4% (relative) per year. Two arrays experienced a high percentage of module defects and failures, and half of the arrays required significant maintenance efforts to repair or replace failed components, such as tracker controllers and source circuit junction boxes.

Some EMT module features have been incorporated into today's commercial products. For example, the polymer TEFZEL is often used in place of glass or Tedlar as a module cover material. Equally important, EMT features that have proven ineffective are no longer being developed, such as bifacial cells for cast polycrystalline flat-plate modules.

While none of the EMT-1 modules are commercially available, results from these arrays provide valuable information for both utilities and manufacturers. PVUSA members gain first-hand experience in procuring and operating modestly scaled, grid-connected systems. Manufacturers receive important feedback to help develop improved products. Moreover, factory and field testing provide many lessons that will help the PV industry develop products to meet stringent utility requirements.

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GLOSSARY

a-Si	Amorphous silicon
Array	An assembly of modules and panels integrated to form a dc power-producing unit. Includes the support structure, foundations, tracking system, and other components as required.
BOS	Balance-of-system. All equipment and labor, excluding modules, associated with the PV system, such as the support structure, power conditioning unit, and utility grid interconnection equipment.
Capacity Factor	Ratio of actual ac energy production (kWh) in any time interval divided by the product of the ac rating (kW) and the number of hours in the time interval.
DAS	Data acquisition system
DECC	Delta Electronic Control Corporation
DOE	U.S. Department of Energy
Direct Normal Irradiance	The irradiance measured perpendicular to the sun, including only direct beam and circumsolar components.
EMT	Emerging module technology
FWRT	Field wet resistance test
Fixed Flat Plate	Nonconcentrating solar array on a fixed structure
I-V	Current-voltage
Inverter	Equipment that converts dc electricity to ac electricity using power semiconductor components.
Insolation	Sunlight energy received over a period of time, commonly expressed in kilowatthours per square meter.
Irradiance	Sunlight power measured in watts per square meter. An irradiance of approximately 1,000 W/m ² is typical near noon on a clear day.
Module	The smallest complete, environmentally protected assembly of PV cells, optics, and other components, exclusive of tracking, designed to generate dc power when exposed to sunlight.
Module Back Temperature	The temperature of the back of the module.
Monopole	Conductors between modules and from modules to the common neutral connection point of a three-wire source circuit. Essentially one half (positive to neutral or negative to neutral) of a three-wire source circuit.
NREL	U.S. National Renewable Energy Laboratory (formerly Solar Energy Research Institute)
O&M	Operation and maintenance

GLOSSARY (cont.)

PCU	Power conditioning unit. A PCU typically contains a dc-to-ac inverter, as well as system protection and control, maximum power-tracking circuits, and a transformer.
POA	Plane of array
PSP	Precision Spectral Pyranometer
PTC	PVUSA test conditions. Defined as 1,000 W/m ² POA irradiance for flat-plate modules, 850 W/m ² direct normal irradiance for concentrators, 20°C ambient temperature, and 1 m/s wind speed.
PV	Photovoltaic. The direct conversion of sunlight into dc electricity.
PV Cell	The basic device that converts sunlight directly into dc electricity.
Panel	A collection of modules mechanically connected, wired, and designed to provide a field-installable unit.
POA Irradiance	The global irradiance measured on a surface of any orientation.
Pyranometer, Pyrheliometer	Instruments that provide a dc signal voltage proportional to the irradiance they are exposed to. Pyranometers respond to global irradiance, and pyrheliometers respond to direct normal irradiance only.
Si	Silicon
SSI	Siemens Solar Industries, Inc. (formerly ARCO Solar, Inc.)
STC	Standard test conditions. Defined as 1,000 W/m ² POA irradiance for flat-plate modules, 850 W/m ² direct normal irradiance for concentrators, 25°C or 28°C cell temperature, and air mass 1.5 spectrum.
UPG	Utility Power Group
US	Utility Scale

Section 1

INTRODUCTION

This section provides background information on the Photovoltaics for Utility Scale Applications (PVUSA) project, describes Emerging Module Technology (EMT) procurement, and defines the objectives of this report.

BACKGROUND

Established with the U.S. Department of Energy (DOE), PVUSA is a national public-private partnership that is assessing and demonstrating the viability of utility scale photovoltaic electric-generating systems. PVUSA offers utilities the hands-on experience needed to evaluate maturing PV technology, provides manufacturers with a testbed for their products, and encourages technology improvement and cost reductions in PV modules and balance-of-system (BOS) components. The project also facilitates communication between utilities, government laboratories, and the PV industry, which is vital for developing and commercializing utility PV systems.

The project, managed by PG&E, was first defined in 1985 as an outgrowth of its PV research and development program. In 1986, PG&E proposed the PVUSA concept to DOE, the Electric Power Research Institute (EPRI), and the California Energy Commission (CEC) to establish a demonstration and technology transfer bridge between then-current R&D activities and the anticipated large utility PV power plants of the future. Today, PVUSA's participants include 18 utilities, research institutes, and government agencies.

Three groups manage the project. The Steering Committee coordinates overall project direction and approves the project's scope, schedule, and budget. The Technical Review Committee assesses and reviews technical aspects of the project. The Project Team, led by PG&E and its principal subcontractor, Bechtel, conducts daily operations, manages construction, and facilitates technology transfer.

PVUSA has five principal objectives:

1. To evaluate the performance, reliability, and cost of promising PV modules and BOS components side-by-side at a single location
2. To assess PV system operation and maintenance (O&M) in a utility setting

3. To compare PV technologies in diverse geographic areas
4. To provide U.S. utilities with hands-on experience in designing, procuring, and operating PV systems
5. To document and disseminate knowledge gained from the project

Thorough background information about PVUSA is included in the *1989-1990 PVUSA Progress Report* [1], with updates in subsequent annual progress reports [2,3,4,5]. Interim findings and ongoing results have been documented in monthly newsletters, progress reports, and numerous technical papers and presentations given at conferences and workshops (Appendix A lists PVUSA's EMT-related publications).

Two types of PV systems are being tested: promising new modules fielded in 20-kW EMT systems and more mature technologies fielded in 20- to 500-kW turnkey Utility Scale (US) systems. Procurement contracts have been awarded in stages: five EMT-1 contracts were awarded in 1988, three EMT-2 and three US-1 contracts were awarded in 1989, and one US-2 and three EMT-3 contracts were awarded in 1992. To fulfill the fourth objective, PVUSA's hosts have awarded 10 additional contracts to test EMT and US systems in their service territories. Of these 25 contracts, 16 had been completed by the end of 1994, 5 had been canceled, and 4 were still active.

Site preparation began in late 1987 at the project's principal site in Davis, California. The first EMT-1 array was completed in January 1989. By the end of 1989, three other EMT-1 arrays were completed: two at Davis and one at a Maui Electric site in Kihei, Hawaii. The final two arrays were installed in Davis in 1990 and 1991. (See Section 2, Table 2-1 for system characteristics.) With four to six years of operation, the arrays have been on line long enough to assess performance and maintenance histories and identify longer-term trends. An EMT-2 array was installed at Davis late in 1994, and another is being installed at a Virginia Electric Power Company (VEPCO) site, but detailed reports on these arrays will not be prepared until two or more years of performance data are available. Figure 1-1 is a photograph of the Davis EMT field, which occupies 3.2 acres at the Davis site. Figure 1-2 is a photograph of the Maui EMT array, which occupies about 0.25 acre at a U.S. Air Force research station.

Figure 1-1. Davis EMT array field.

Figure 1-2. Maui EMT array field.

Nine US systems have been installed since 1992. Three US systems have been installed at the Davis site: one each in 1992, 1993, and 1994. One US system was installed by the city of Austin, Texas, in 1992. Three systems based on PVUSA Davis US procurements were installed in 1993: one by PG&E at Kerman (near Fresno), California; one by the New York Power Authority in conjunction with the National Renewable Energy Laboratory (NREL) in Maspeth, New York; and one by the New York State Energy Research and Development Authority (NYSERDA) in Farmingdale, New York. In 1994, the Sacramento Municipal Utility District (SMUD) completed a US system at its Hedge substation site in Sacramento, and Central and South West Services completed a 100-kW system at its Fort Davis site in west Texas. Three other US systems are scheduled to be completed in 1995. Assessment of these systems is outside the scope of this report and will be documented in the future.

The combined capacity of the 16 EMT and US systems installed through 1994 was over 1,700 kW. These systems have generated a cumulative total of nearly 5 million kWh since 1989. Systems planned or under construction include another EMT system and three US systems totaling 545 kW, which will increase the total capacity to about 2,300 kW in 1995.

REPORT OBJECTIVES

This report describes the selection, factory and field tests, and system performance of five EMT systems installed in Davis, California, between 1989 and 1991 and one EMT system installed on Maui in 1989. It details findings first summarized in a paper presented at the 1994 American Solar Energy Society Conference in San Jose, California [6].

Section 1 provides background information on PVUSA. Section 2 describes the EMT-1 procurement and selection process. Section 3 discusses EMT-1 module factory qualification testing, and Section 4 discusses EMT-1 field acceptance testing. Section 5 details system performance, applying conventional utility power plant measures such as energy generation, efficiency, and capacity factor. Section 6 reviews the operation and maintenance histories of the arrays and their BOS components. Section 7 presents conclusions. Section 8 lists references. PVUSA's EMT-related publications are listed in Appendix A, and EMT system performance is summarized in Appendix B.

Section 2

EMT-1 SELECTION

EMT PROCUREMENT

EMT procurement was initiated to encourage manufacturers to develop promising PV technologies. PVUSA asked manufacturers to focus on producing and installing the modules, and PVUSA supplied BOS components such as foundations, structures, power conditioning units (PCUs), grounding, and data acquisition (PV suppliers provided for module installation and dc interconnect/source circuit wiring). A nominal 20-kW array size was selected. This size was considered large enough for manufacturers to demonstrate pilot-scale production capabilities and provide a statistically credible number of modules to evaluate, yet small enough to allow manufacturers to avoid constructing large-scale production facilities and to minimize PVUSA's financial risk in purchasing unproven technologies.

The EMT procurement process involved significant interaction among project staff and management, vendors, and the Steering and Technical Review committees. PVUSA held meetings and conducted surveys to determine the interest and capabilities of the PV industry for supplying EMTs. PVUSA developed bid documents that defined technical specifications, schedules, incentives, and general contract terms, and sent Requests for Proposals to interested vendors. Project staff and management and the Technical Review Committee evaluated the responses and submitted recommendations to the Steering Committee, which then selected vendors based on the recommendations and provided direction to the project team on carrying out contract negotiations. After developing a schedule, the project monitored the contractors' progress through the construction period. Once completed, each system underwent a 30-day performance testing period to establish a rating. Vendor payments were scaled down if the installed system fell short of the contract target rating. A PVUSA report on procurement is scheduled for publication in 1995 [7].

TECHNOLOGY SELECTION

The selected PV arrays represented improvements to established technology types, such as single- and polycrystalline silicon (Si), and new technologies with little or no prior commercial applications, such as concentrator modules and tandem-junction amorphous silicon (a-Si). EMT-1 suppliers (including PCU vendor DECC/Helionetics), technology types, and selection factors are described in this section, and Table 2-1 lists system characteristics.

Table 2-1
EMT-1 System Characteristics

Supplier	SSI (ARCO)	Sovonics Davis	Sovonics Maui	UPG	Solarex	ENTECH
Technology	micro-grid crystal Si	tandem junc. a-Si	tandem junc. a-Si	tandem junc. a-Si	bifacial polycryst. Si	concentrator crystal Si
Construction	framed, glass/Tedlar	framed, Tef- zel/ stainless/ galv. steel	framed, Tef- zel/ stainless/ galv. steel	unframed, glass/glass	unframed, glass/Tefzel	framed, acrylic 22X lens
Orientation (°)	fixed 30	fixed 30	fixed 22	fixed 30	fixed 30	two-axis trk.
Target rating (kW dc)	19.2	20.8	20.8	20.8	20.8	21.5
PTC rating (kW dc) ^a	18.7	17.3	18.5	15.7	15.7	16.5
PTC efficiency (%)	11.1	3.5	3.7	3.3	8.6	11.3
Planned completion date	11/88	9/88	9/89	12/88	12/88	1/90
Actual completion date	1/89	6/89	9/89	12/89	10/90	3/91
# modules	400	1,200	1,200	4,992	336	60
Area/module (m ²)	0.426	0.414	0.414	0.095	0.540	2.87

PCU	DECC/Helionetics
Type	Self-commutated with line-tie inductors; combined pulse-width-modulation and stepped-wave summing using bi-polar transistors
Control	Remote or local; maximum power tracking or fixed voltage operation
Input	Voltage: 240-540 Vdc Rated power: 25 kW
Output	Voltage: 480 Vac, 3-phase Power factor: 0.98-1.0 Efficiency: 90-94%

^aRegression model-based rating under PVUSA test conditions (PTC) of 1,000 W/m² global plane of array irradiance (850 W/m² direct normal irradiance for concentrator systems), 20°C ambient temperature, and 1 m/s wind speed.

Siemens Solar Industries (SSI)

ARCO Solar's proposal was selected for several reasons. The company proposed a laser-grooved, single-crystal Si cell (like those developed by Dr. Martin Green of the University of New South Wales) as a building block for an EMT module. Its product had both the highest efficiency of any of the proposed flat-plate modules and the lowest cost (\$/W). The proposed standard test condition (STC) efficiency for the EMT modules (14.1%) represented a relative improvement of about 10% compared to its standard product.

During the manufacturing phase, however, ARCO Solar discovered that the process for producing the laser-grooved cells was not cost-effective and instead designed an innovative "micro-grid" front contact metallization technique. The micro-gridding used narrower and taller contacts than its standard cells to minimize the proportion of top surface area covered by the conductor and simultaneously minimize resistance losses by retaining a relatively large volume of conductor. The new cells more nearly resemble a square shape than the standard cells, resulting in a 5% overall increase in module power for cells occupying the same gross area.

The modules are framed with aluminum channels and have an anti-reflection (AR) treated glass front cover and a Tedlar back cover. Interestingly, without an AR coating on the cells themselves, ARCO Solar applied another of Dr. Green's techniques to preferentially etch an asymmetrical pyramid texture on the cell surface to improve its absorptance. However, the etched cells were not oriented consistently when the modules were fabricated, and the potential benefit of the asymmetrical etching has therefore not been realized. At high-incidence angles, a checkerboard pattern of the randomly arranged etched cells is obvious.

ARCO Solar's array was completed in January 1989, two months behind the scheduled completion date. In 1990, Siemens purchased ARCO Solar and renamed the successor company Siemens Solar Industries (SSI). Throughout the remainder of this report, the array will be referred to as the SSI array. Figure 2-1 shows the installed array. Photographs of the module front and back are presented in Appendix B.

Figure 2-1. SSI array.

Sovonics (now United Solar Systems Corporation), Davis and Maui

The Sovonics tandem-junction a-Si modules incorporate two large cells layered on top of each other and connected in series. Tandem-junction cells are designed to absorb and convert a greater portion of solar radiation than conventional single-junction thin-film cells, particularly in the longer (infrared) wavelengths of the solar radiation spectrum. As proposed in 1988, the tandem junction cells were believed to be subject to less light-induced degradation (although experience subsequently proved to the contrary). The Sovonics module was selected because its design called for a 2-foot-by-4-foot, low-voltage, high-current module. Difficulties were encountered in applying the new clear-plastic TEFZEL front cover over such large areas, and necessitated using a final design of 1-foot-by-4-foot modules rated at 20 amps and 1 volt in place of the 40-amp, 1-volt modules.

The Sovonics modules were manufactured by vapor-depositing the cell layers onto a substrate of flexible stainless steel in a continuous roll-to-roll process. The cells were then laminated with ethylene vinyl acetate (EVA) and TEFZEL on the front and a layered EVA/nylon/EVA/galvanized steel plate on the back, and the completed laminates were framed with aluminum channels.

Two arrays were installed—one at Davis and one at Maui. The Maui modules were manufactured several months after the Davis modules and incorporated a few small design changes to improve durability and performance (see Section 3 for a discussion of the changes). The Sovonics Davis array was completed in June 1989, nine months behind the scheduled completion date. The Maui array was completed on schedule in September 1989. In 1991, Sovonics and Canon formed a joint venture company to manufacture PV products. The new company, United Solar Systems Corporation (USSC), has continued to provide technical support for the Sovonics arrays, but prefers to distinguish Sovonics products from USSC products. Figure 2-2 is a photograph of the installed array at Davis. Appendix B contains photographs of the front and back of the module for Davis and the back of the array for Maui.

Figure 2-2. Sovonics array at Davis, California.

Utility Power Group (UPG)

UPG uses tandem-junction a-Si modules, although they differ from the Sovonics modules. The UPG module is smaller (1 foot by 1 foot) but its voltage is higher (12 volts), and it is constructed with a frameless glass superstrate and glass rear cover. An inexpensive sheet metal section is attached to the back side of a series of 12 modules with a structural adhesive to make one rigid panel. This module was selected because its innovative and durable design yielded favorable prototype test results at the then-Solar Energy Research Institute (now National Renewable Energy Laboratory). The advanced thin-film technology was considered promising for an EMT program. UPG's array was completed in December 1989, one year behind the scheduled completion date. Figure 2-3 is a photograph of the installed array. See Appendix B for photographs of the front and back of module.

Figure 2-3. UPG array.

Solarex

Solarex chose to develop an EMT module to experiment with a new design, to gain experience developing a utility-grade system, and to participate in a project where it could demonstrate a high-quality, reliable product. These modules use polycrystalline silicon (poly-Si) cells similar to their existing commercial modules, with the addition of a clear back cover and a contact grid on both sides of each cell to create a “bifacial” module. The front cover is glass and the back cover is TEFZEL. Like the UPG module, this module is frameless, with added stiffness provided by aluminum channels that link six modules to form one panel. This module was selected because of the higher efficiency expected of the bifacial design. The Solarex array was completed in October 1990, 22 months behind the scheduled completion date. Figure 2-4 is a photograph of the installed array, and photographs in Appendix B show the module front and back.

Figure 2-4. Solarex array.

ENTECH

The ENTECH module uses a curved, line focus Fresnel lens to concentrate direct normal sunlight by a factor of 22 times onto a narrow strip of high-efficiency, single-crystal Si cells. A patented prism lens cell cover is used to further direct the concentrated light away from the extensive high-current cell gridlines that cover 50% of the cell and onto the remaining active cell area. The cells are cooled by aluminum fins attached to the back of the module. A central tracker controller and two drive mechanisms simultaneously adjust the tilt and roll position of a single row of 60 modules. This module was selected for several reasons. Its advanced concentrator cell technology offered an efficiency improvement over the prior generation product (a 300-kW system atop a 3M Company parking structure in Austin, Texas). It had the highest proposed array efficiency (15%) of all bids, and it was deemed the most viable concentrator technology available. ENTECH's array was completed in March 1991, 14 months behind the scheduled date. Figure 2-5 is a photograph of the installed array, and photographs in Appendix B show the front and back of the module. The back-of-module photograph also shows the central tracking mechanism, which was upgraded in 1994.

Figure 2-5. ENTECH array.

DECC/Helionetics

Each of the six EMT-1 arrays, including the Maui array, feeds dc power to an identical DECC PCU custom-designed to accept a wide range of dc input voltages (240-540 Vdc) and dc power up to 25 kW, with 3-phase ac output at 480 volts (see Figure 2-6). The units are self-contained in NEMA-4 outdoor enclosures and mounted in the shade of the arrays. PCU characteristics are listed in Table 2-1. Overall efficiency (90%-94%) is a little lower than that achievable in PCUs designed to operate over a narrow range of input voltages. However, the flexible design permits a fair performance comparison among side-by-side arrays with widely varying current-voltage characteristics.

Figure 2-6. DECC/Helionetics power conditioning unit.

Structures/Foundations

PVUSA supplied the south-facing fixed 30° tilt support structures and foundations for four of the six EMT arrays. This orientation provides the maximum annual generation for a fixed tilt array at the Davis site. ENTECH supplied its own two-axis tracking structure because its design was integrated with the module design. PVUSA placed the ENTECH array foundations in accordance with ENTECH's design. For the Maui array, Sovonics supplied an innovative ballasted, fixed tilt structure at an angle of 22° (to maximize annual energy generation at that site). The structure consists of a combination of steel unistrut channels mounted to massive concrete blocks sitting on a lava rock surface. The shallower tilt angle prevented the PCU from being installed within the shade of the array, and a simple fiberglass-roofed sunshade was consequently erected to shade it.

Section 3

FACTORY TESTING

OBJECTIVE

To ensure the safe, reliable operation of the EMT modules, PVUSA requires the manufacturers to pass a set of factory qualification tests on production-line modules. The factory tests, based on existing and proposed industry standards developed principally by NREL, Sandia National Laboratory, and the Jet Propulsion Laboratory (JPL), are designed to demonstrate durability and sustained performance under demanding utility conditions. The scope of the tests enables PVUSA and the manufacturers to determine acceptability of design, materials, and manufacturing processes. After successfully completing the tests, manufacturers are not permitted to make changes unless PVUSA agrees. In some cases, retesting has been required as a result of module changes.

Areas addressed by the qualification tests include:

- Reliability and durability
- Electrical performance
- Mechanical strength
- Safety
- Corrosion resistance

TEST SEQUENCE

PVUSA uses two test sequences—one for flat-plate modules and one for concentrator modules. A diagram of the PVUSA factory module qualification test sequence for flat-plate modules is shown in Figure 3-1. This six-module test sequence draws from NREL's "Interim Qualification Tests [IQT] and Procedures for Terrestrial Photovoltaic Thin-film Flat-plate Modules," with a few modifications to accommodate module types not covered by the procedure [8]. The IQT was based largely on the JPL Block V qualification tests developed in the early 1980s. PVUSA's 1993 progress report discusses the test sequence and modifications to the procedure in more detail [4]. The test sequence used for ENTECH's concentrator modules is shown in Figure 3-2. It was a modified version of Sandia's 1988 qualification test sequence, and was subsequently published by Sandia in its 1992 updated "Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules" [9].

Figure 3-1. Flat-plate module qualification test sequence.

Figure 3-2. Concentrator module qualification test sequence. Vertical lines indicate how many modules undergo each test. Numbers in parentheses refer to the approximate number of days needed to perform the test. Visual inspections are performed after each test.

RESULTS

Most manufacturers had difficulty conducting the factory qualification tests. A few lack sufficient equipment to perform in-house testing; moreover, some outside laboratories were unable to carry out all of the test steps, particularly the wet insulation-resistance and wet hi-potential (hi-pot) tests. Despite the difficulties encountered in running the tests, PVUSA found good agreement within the industry that these rigorous steps were necessary to ensure adequate quality products for the future utility market. After several years of operation, the reliability of most of the EMT modules has been as good or better than more mature commercial modules. Factory qualification test experiences for the EMT-1 suppliers are summarized in this section.

SSI (400 modules)

SSI successfully conducted all factory tests in-house. Only minor problems were encountered, and the final design passed qualification. This result was not unexpected since a majority of qualification test problems are related to the encapsulation system. SSI's encapsulation for the EMT module was identical to that used in its commercial modules.

Sovonics (1,200 modules each at Davis and Maui)

The original shipment of 600 modules (2 feet by 4 feet) for the Davis site passed Sovonics' in-house tests. During initial field tests, however, PVUSA identified numerous pinholes with solder bumps protruding from the modules' TEFZEL covers, and the entire defected shipment was rejected. A new design, using smaller modules (1 foot by 4 feet) with improved soldering and thicker TEFZEL/EVA lamination, passed the qualification test. A second shipment of 1,200 modules was successfully installed.

Before the Maui array's modules were fabricated a few months later, it was noticed that some of the Davis array's module covers were beginning to delaminate, typically with dime-sized bubbles. Sovonics resolved the problem by texturing the front surface with a pattern similar to window screening, which relieved surface stresses on the cover, and by modifying an assembly step to avoid cutting through the cover material when applying the frame. The Maui modules passed the qualification tests and show no signs of delamination after five years of operation. Eighty-one bubbled Davis modules have been replaced under warranty, although only two failed electrically by shorting to the frame (most of the bubbles were cosmetic defects, but the delaminations may progress to more serious electrical failures).

UPG (4,992 modules)

Initially, the hail and wet hi-pot tests caused minor problems. However, the final module design passed all tests. As a new and very small manufacturer making its first product, UPG found the EMT program beneficial to product development efforts. The module qualification process resulted in several module improvements, and the EMT testbed provided independent verification of its PV technology. UPG has branched out its operations and installed over 350 kW through 1994 using commercially proven single crystal Si-based modules, but the design of each system contains elements first deployed and tested on its EMT-1 array.

Solarex (336 modules)

After several iterations, Solarex indicated that its frameless bifacial modules passed its in-house qualification testing, and the shipment was installed at Davis. As with Sovonics' first modules, however, PVUSA identified numerous pinhole failures, where solder bumps pierced the TEFZEL cover. The entire shipment was disassembled, returned to the factory, and refabricated with dressed solder connections, a thicker EVA layer, and a thicker TEFZEL rear cover. The second shipment passed all factory tests satisfactorily.

Solarex found the wet high-pot test to be an important albeit difficult step and has modified its current module design and material to improve wet high-pot performance (especially after the humidity freeze test). The manufacturer also concluded that the frameless module concept worked fine (and has since developed frameless commercial modules), but the bifacial cell did not work satisfactorily (performance details are discussed in Section 5), and TEFZEL was not a good choice as a back sheet.

ENTECH (60 modules)

ENTECH's concentrator modules successfully passed qualification tests conducted by Sandia National Laboratory. The PVUSA modules were actually a next-generation improvement over the design used for a 300-kW system (3M parking garage) installed in Austin, Texas, which experienced intermittent ground faults after rainstorms. PVUSA's EMT modules incorporated better sealed cable lead-ins, nylon thrust washers, additional internal cell sealing, and improved mechanical fasteners.

PCU FACTORY TESTS

The PCUs were custom-designed for PVUSA by DECC/Helionetics. Nine units have been purchased: Six are being powered by the EMT-1 arrays, and three are reserved for later EMT arrays at the Davis site. The units are designed to accept a wide range of input voltages (240-540 Vdc) and produce 3-phase, 480 Vac output power. The units are rated at 25 kW dc input power.

DECC's factory testing included system protection functional tests for ground fault, over/under frequency, and over/under voltage. Factory measurements were also taken to verify performance specifications for efficiency, power factor, and harmonic distortion. DECC reported conversion efficiencies of 90% at one-fourth power and 94% above half power; power factor > 0.99 ; and current distortion of 2% typical, 5% maximum, and 3% maximum for any single harmonic.

Section 4

FIELD TESTING

OBJECTIVES

Field tests are performed to verify proper module shipping and installation, to assess safety and power quality, and to facilitate contract payment by establishing a system rating under PVUSA test conditions.

TESTING

Field tests include the following reviews, inspections, and measurements:

- Engineering review of system drawings
- As-built inspection of modules
- Wet megger, or Field Wet Resistance Test
- Current-voltage (I-V) curves
- System protection preparallel inspection and functional tests
- Power quality tests
- System conditioning and performance rating periods

Field West Resistance Test (FWRT)

The FWRT was adapted by PVUSA from a similar indoor test developed by JPL. At PVUSA, the leakage current resistance is measured to determine the integrity of environmental seals among modules and their interconnecting wiring/components before the system is accepted. After being open-circuited and wetted with an aqueous surfactant, an array segment is subjected to 500 or 1,000 volts, and the leakage resistance to ground is measured with a megaohmmeter. Excessive leakage current indicates potential for corrosion and shock hazards.

The test has proven to be highly effective in detecting quality control problems in manufacturing, shipping, and installation processes and identifying a wide range of defects undetectable by simple inspection or power measurement. Defects detected by the test include hairline cracks, pinholes, poorly sealed connections, and even scratches from slipped tools. The test is easy to run when spot-checking

repairs, and is periodically rerun to ensure safe array operation and to detect component deterioration. No PVUSA system, EMT or otherwise, has passed the FWRT on the first trial.

I-V Curves

I-V curves are measured with a special capacitive charge device called an I-V curve tracer. The curve tracer records rapidly changing array current and voltage while an initially short-circuited array (actually, the array is initially slightly reverse-biased) charges a large capacitor up to the open-circuit voltage of the array. Ordinarily, a plot of the paired I-V points yields a smoothly varying exponential curve, but in the presence of failures, irregularities will appear. The I-V curves are also used to verify proper PCU operating voltages for maximum power operation and to periodically gauge degradation and the before/after effects of dirt accumulation.

Preparallel and Functional Tests

Utility preparallel and functional tests are performed to verify the proper operation of system protection equipment, such as relays, breakers, and switches.

System Conditioning and Performance Rating Periods

These tests are run consecutively to verify proper operation and establish a basis for contract payment. The conditioning period runs for 30 days after the completed system has been offered to PVUSA. Early “infant mortality” failures or obvious problems are addressed at that time, and systems subject to light-induced degradation can move toward more stable power levels. During this period, PVUSA calibrates its various instruments because some calibrations are best performed with an actual PV array as a dc source.

A 30-day performance rating period follows the conditioning period. Coincident measurements of dc power, irradiance, ambient temperature, and wind speed are used in a regression analysis to calculate coefficients A, B, C, and D to fit Equation 4-1. The regression equation and its fitted coefficients are then used to predict system power at PTC (or any other conditions within the model’s useful range).

$$\text{dc power} = A * \text{Irradiance} + B * \text{Irrad.}^2 + C * \text{Irrad.} * T_{\text{ambient}} + D * \text{Irrad.} * \text{wind speed} \quad (4-1)$$

Ordinarily, the uncertainty of power estimates made with this model is within $\pm 4\%$. For contract *payments* only, a 4% allowance is applied to those ratings which fall short of their target capacity, and the performance-based portion of the total contract value (40%) is then scaled down to reflect the adjusted rating's shortfall. The useful range of the model depends on the linearity of the PV system with respect to changes in irradiance, ambient temperature, and wind speed, as well as the distribution of conditions in the rating data set. Normally, a concentration of irradiance observations between 750 and 1,000 W/m² tends to make the model most accurate in that region.

Applying this model to the EMT systems, PVUSA has found that except for winter months, a sufficient number of irradiance observations usually occurs in any 30-day period near 1,000 W/m² (for the fixed flat-plate arrays) and near 850 W/m² (for the concentrator array) to reliably estimate PTC power. (The temperature and wind speed terms, although usually significant, are less important than the irradiance terms.) It has been more difficult to obtain satisfactory correlations for a-Si arrays than for poly- and single-crystal Si arrays: a-Si technologies seem to be less sensitive to temperature and more sensitive to other factors, such as solar spectral composition, incidence angle, light-induced degradation, and thermal annealing. The 1989-90 progress report discusses the rating model in more detail [1].

FIELD TEST RESULTS

Table 4-1 reviews the EMT array proposed and actual ratings. Table 4-2 lists the coefficients used with Equation 4-1 to obtain the actual PTC ratings and to predict array power under other conditions.

SSI

During the initial December 1988 FWRT, the following items failed: six inadequately sealed module junction boxes, three modules with back surface cuts, and two faulty bypass diodes. These items were easily repaired or replaced. The other tests and inspections were satisfactory, and the system was rated at 18.7 kW dc at PTC, 3% less than the contract target rating. The system was completed in January 1989, within one month of its scheduled start date.

Table 4-1
EMT Array Ratings

Supplier	Proposed PTC (kW dc)	Actual PTC ¹ (kW dc)	difference actual vs. proposed (%)
SSI	19.2	18.7	-3
Sovonics-Davis	20.8	17.3	-17
Sovonics-Maui	20.8	18.5	-11
UPG	20.8	15.7	-25
Solarex	20.8	15.7	-25
ENTECH	21.5	16.5	-23

¹The uncertainty of each rating is estimated to be $\pm 4\%$.

Table 4-2
EMT Array Regression Rating Coefficients

Supplier	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>r</i> ^{2*}
SSI	21.68	-1.212	-0.09400	0.1670	0.99
Sovonics-Davis	17.26	-0.3350	0.01274	-0.01309	0.99
Sovonics-Maui	19.96	-2.642	0.05740	0.07890	0.99
UPG	15.71	-1.545	0.08080	-0.04520	0.98
Solarex	17.07	-0.5476	-0.04450	0.1088	0.99
ENTECH	25.60	-5.651	-0.08656	0.3277	0.92

Note: Coefficients for Equation 4-1: $dc\ kW = A \times Irr. + B \times Irr.^2 + C \times Irr. \times T_{amb.} + D \times Irr. \times Wind\ speed.$

**r*² is a quantity called the coefficient of determination. It is a dimensionless measure of how well the correlation fits the observed data (1.0 = perfect fit, 0.9 or greater is satisfactory), and should not be confused with the coefficients A, B, C, and D.

Sovonics

The first Davis array was rejected in January 1989 (see Section 3 for details). Except for an initial ground fault that was traced to a poor connection, installation of the second shipment went smoothly, and the system was completed in June 1989, about six months behind the scheduled start date. The system was rated at 17.3 kW dc, 17% short of Sovonics' 20.8-kW target.

Sovonics' Maui array was installed on schedule in September 1989. Delaminations occurring on the Davis array necessitated changing a few fabrication steps to correct the problem. Sovonics also incorporated a higher reflectivity back surface to increase efficiency. This array was installed by Sovonics and Maui Electric. An FWRT was not performed because Maui Electric did not require it. The system was rated at 18.5 kW dc, almost 7% more than the Davis array, but still 11% short of the contract capacity. Payment for this array was handled by Maui Electric.

UPG

As a very small company making its first product, UPG's production capacity was limited. Consequently, production was almost one year later than planned, taking nine months (April to December 1989) to fabricate and install the array's 4,992 one-square-foot modules. Seven module failures were identified during the initial FWRT: four due to cracked glass and three of undetermined cause. After these were replaced, start-up problems were minor (a loose junction box connection that caused a voltage imbalance was repaired by simply tightening the connection; and an underground cable was replaced after it was found to be causing an intermittent ground fault). The system was rated at 15.7 kW dc, 25% short of its contract 20.8-kW target.

Solarex

Solarex refabricated its bifacial modules after the first shipment failed the FWRT in April 1990. The refabricated modules passed the second FWRT, and the array was completed in October 1990, 22 months behind schedule. Like UPG, this system was rated at 15.7 kW dc, 25% short of its contract 20.8-kW target. The bifacial design was expected to boost efficiency relative to conventional poly-Si cells, but the improvement appears to have been minor. Module I-V curve tests conducted by PG&E showed that the back surface of nameplate 60-watt modules generated just 2 watts, even at 1 sun intensity. It is believed that few of the charge carriers generated by stray light absorbed on the modules' back surface actually migrate far enough to be separated by the cell's p-n junction. Most recombine within the cell's

comparatively thick lower "p" layer and simply heat up the cell. Under normal field conditions, the additional power contributed by the rear surface is far less than measured in PG&E's tests because of the low irradiance received on the array's back surface. From this experience, Solarex concluded the bifacial design did not merit the extra manufacturing cost.

ENTECH

The ENTECH array began operating in March 1991, about two years behind its originally planned start date. The FWRT identified two minor module connector failures that were easily repaired. The system was rated at 16.5 kW dc, 23% short of its contract 21.5-kW target. ENTECH attributed the shortfall to three factors: (1) the most significant factor, accounting for over half of the shortfall, was that cell temperatures under the nearly still PVUSA test condition wind speed (1 m/s at 10 m) soared about 24°C higher than anticipated; (2) the cells manufactured for ENTECH by Solarex measured about 5% lower than expected; (3) the cell efficiency measurements were found to be about 5% too high because of a calibration change in Sandia's concentrator reference cell.

PCU FIELD TESTS

The DECC/Helionetics PCUs passed PG&E's preparallel tests satisfactorily. The power quality field test results were consistent with DECC's factory measurements. The field-measured current distortion ranged from 4% to 7%, which translated to 2% to 4% at full load, within DECC's factory specification. Power factors ranged from 0.98 to 1.0, close to DECC's specified > 0.99 and well within the project's specified 0.8 lagging and 0.9 leading power factor at full power. The only significant problem encountered in field testing the PCUs was that none of the units could be installed, connected to an array, and started successfully without factory assistance. Each unit required field servicing by DECC's technician to fine-tune the PCU to match the individual array I-V characteristics before it would match with the grid. After the initial service, each PCU operated properly.

SYSTEM PERFORMANCE

Sunlight is an intermittent and relatively dispersed energy source, which makes it difficult to apply conventional measures of utility power plant performance to PV systems. PV system output is both time-dependent and non-dispatchable. Even in the absence of failures, PV systems can often appear to be operating poorly [10]. Widely used utility performance measures such as capacity factor, efficiency, or availability are ordinarily smaller for PV than for conventional forms of generation, and exhibit wide seasonal fluctuations that can mask reductions in output due to such factors as soiling or failed components. Despite these limitations, meaningful comparisons among PV systems can still be accomplished using common measurements, sometimes with modified definitions (e.g., nighttime hours may be excluded from some calculations). In this section we analyze performance by comparing each system in terms of energy generated, efficiency, and capacity factor. Reliability issues are addressed in Section 6, and a summary of annual performance is in Appendix C.

ELECTRICAL ENERGY GENERATION

Through 1994, the six EMT arrays generated 803,412 kWh (17% of the generation from all of the PVUSA systems), enough to offset 1,300 barrels of oil burned using conventional electric generation. With a combined rated ac capacity of 97 kW and an average output of 4.6 kWh per day per kilowatt, the EMT systems are presently generating enough electricity to meet the average annual demand of about 27 homes (based on a residential load of 500 kWh/month per home).

Figure 5-1 shows the annual generation for each system (left scale) and its corresponding unit output (right scale). The average unit output of 4.6 kWh/day/kW is a key statistic, representing the combined effects of climate, orientation (structural mounting), and system reliability. This result should be a useful guideline for system sizing and sensitivity studies because PVUSA's climate(s), orientations, and reliabilities are typical of well-designed, well-sited, and well-operated systems, as described in the following sections.

Figure 5-1. Annual EMT electric generation.

Climate

Although the climates in Davis and Maui differ, the average fixed tilt global insolation at both sites has been nearly the same: 5.9 and 5.8 kWh/m²/day at Maui and Davis, respectively—a difference of 1.7%. The best sites in the southwest desert regions receive about 15% more annual insolation than the Davis or Maui sites, whereas a typical midwest location such as St. Louis, Missouri, receives about 15% less annual insolation than the Davis site.

Orientation

All but one EMT array is oriented due south on a fixed tilt structure. Although this orientation is typical of most PV systems, it does not demonstrate the generation characteristics for various tracking systems or fixed tilt systems of different orientation. In general, tracking systems can boost annual unit output by 20% or more. For the two-axis tracking ENTECH array, the average output has not been greater than the fixed tilt systems. The expected boost due to tracking has not been realized for this system. Even though there are normally about 15% more peak hours of direct normal irradiance per year at Davis than peak

hours of global fixed tilt irradiance, the concentrator modules' tracking system is mechanically limited and arranged closely so that it converts only about 90% of the annual direct normal insolation.

Reliability

With just a few exceptions, PVUSA's systems have experienced little downtime, and so the average unit output for other well-designed systems should not vary much from PVUSA's results. One exception was the ENTECH array, which experienced numerous tracker controller failures and resulted in several months of lost generation. The ac controller and drive mechanisms were eventually redesigned and replaced in late 1994 with dc-based components to decouple tracker operation from utility power. Additionally, the Sovonics Davis array was out of service for one year due to failure of a source circuit junction box. This downtime was excluded from the analysis because of PVUSA's decision to reevaluate and eventually redesign the junction box.

EFFICIENCY

EMT array efficiency is defined as dc electric energy output divided by solar energy input. Solar energy input is the insolation measured with a wide-spectrum pyranometer, multiplied by the total framed module area. Although principally a function of technology type, efficiency is also sensitive to ambient conditions, such as temperature, wind speed, dust, and solar spectral characteristics. Assuming proper maximum power point operation, dc quantities permit fairer comparisons among module types by removing any potential differences in ac performance caused by differences among PCUs.

Figure 5-2 tracks monthly average dc efficiencies. Three distinct groupings correspond to, from highest to lowest, single-crystal Si, poly-Si, and a-Si technologies. ENTECH and SSI arrays have the highest efficiency, typically 10% to 12% for summer-to-winter efficiencies. ENTECH's relative advantage is evident in all but peak summer months. PV cells designed for concentrated light (here, 22X) can achieve higher efficiencies than comparable cells under normal sunlight, although this advantage is somewhat negated if the concentrator cell operates at an elevated temperature.

Figure 5-2. EMT array monthly dc efficiencies.

The ENTECH array is not actively cooled. In the absence of wind for forced cooling, cell temperatures soar, operating at 25°C greater than its neighboring flat-plate arrays on a summer day. This higher operating temperature causes an efficiency loss (about 10% relative) because the tracking array's shallow tilt angles in summer inhibit natural convection. At other times of the year, steeper tracker tilt angles enhance cooling from natural convection. (ENTECH has since designed an array for cooler temperatures, with longer heat sink fins to dissipate heat more effectively and a narrower and longer module shape. The area is the same, but the narrower configuration has a smaller, 17X concentration ratio.)

Along with normal seasonal variation, the arrays seem to be experiencing slow annual degradation. It is difficult to make an accurate estimate because important factors such as temperature and soiling are not static, and the measurement uncertainty is generally greater than the degradation rate. However, long-term relative degradation (1%-2% per year) has been estimated by two methods, as follows, and the long-term relative efficiency change rates for the arrays are shown in Table 5-1:

- Method 1: A relative degradation rate is calculated as the slope of a best-fit line through a history of temperature-adjusted efficiency data for April and October of each year. April and October were chosen because conditions at those times of the year tend to be close to PTC¹ and the arrays are generally very clean. Small adjustments to a common 45°C *module* back temperature were made using temperature coefficients of -0.45% per centigrade for the single-crystal Si and poly-Si arrays, and -0.25% per centigrade for the a-Si arrays.
- Method 2: An updated PTC rating is calculated using October 1993 data. The percentage change in the PTC rating was divided by the number of years between the ratings to obtain a simple average annual degradation rate.

Table 5-1
EMT Array Long-Term Annual Relative Degradation Rates

Array	Years of operation through 1994 and (years spanned by Method 1 - semi-annual efficiency trend)	Relative rate by Method 1 ^a	Relative rate by Method 2 ^b
SSI (crystal-Si)	6.0 (5.6)	-1 ± 1%	-2 ± 1%
Sovonics Davis (a-Si)	5.6 (5.1)	-4 ± 1%	-4 ± 1%
Sovonics Maui (a-Si)	5.2 (4.6)	-2 ± 1%	-3 ± 1%
UPG (a-Si)	5.1 (4.6)	-2 ± 2%	-3 ± 1%
Solarex (poly-Si)	4.2 (4.1)	-2 ± 1%	-3 ± 2%
ENTECH (conc. crystal-Si)	3.8 (3.6)	0 ± 2%	+1 ± 2%

Note: Uncertainty expressed as ± two standard deviations, or approx. 95% confidence interval.

^aEstimate basis: Quality-checked efficiency trend for each April and October, temperature-adjusted to 45°C.

^bEstimate basis: Initial vs. October 1993 recalculated PTC ratings.

Because crystal Si cells such as those used in the SSI array are believed to have consistent lifetime performance, other causes have been suggested for the apparent drop in efficiency, such as breakdown of the EVA encapsulant. In 1993, Springborn Laboratories tested a sampling (about two dozen) of the SSI EMT array's 400 modules with a geologist's blacklight to look for fluorescent patterns as evidence of EVA breakdown. Distinct fluorescent patterns were seen above each cell. However, no visible

¹ At PTC, flat-plate module back temperatures are about 45°C.

discoloration of the EVA was apparent, and there is an ongoing debate as to the extent of transmissivity loss in EVA, even in severely discolored modules.

Recent studies² have shown that glass with cerium compounds exhibits fluorescent behavior and, fortunately, also inhibits breakdown of the EVA encapsulant. However, cerium was not used as a glass ingredient in 1988 when these modules were fabricated. Recent studies have also reported that the method used to cure the EVA influences its long-term stability. Although slow-cure EVA (SSI modules) is typically used, fast-cure EVA may be preferred for PV applications.² Other factors suggested as potential causes for overall system degradation include increasing resistive losses due to corrosion, or failed components such as internal connections or bypass diodes.

The poly-Si Solarex array has shown the same type of seasonal variation as the SSI array. It also appears to be degrading, although from February 1992 to July 1993, partial failures affecting one and sometimes two of the array's 14 source circuits were responsible for much of the drop (Figure 5-2). After adjusting for the failures, an annual degradation of 2%-3% was calculated by the same methods used to estimate the SSI array's long-term degradation (Table 5-1). This array did not show widespread evidence of EVA breakdown, except on two modules, where a minor fluorescent pattern was evident around overheated and corroded internal busbar connections.

The three tandem-junction a-Si arrays have averaged around 3% efficiency, and a long-term degradation trend also appears to be emerging. Although difficult to distinguish when plotted on the same scale as the other arrays, the efficiency of the Davis Sovonics array has varied considerably compared to the Maui Sovonics or Davis UPG arrays. Figure 5-3 illustrates the monthly efficiency trend of the Davis Sovonics array. The monthly ambient temperature and the monthly ratio of non-infrared (ultraviolet and visible wavelengths < 780 nm, labeled "UV" on the plot) solar insolation are plotted along with the efficiency trend. These quantities may significantly influence the efficiency of the Sovonics array. Ordinarily, efficiency decreases with increasing temperature, but the opposite trend is apparent with this array.

² Presented by Springborn Laboratories and NREL researchers at the September 1994 PV Performance and Reliability Workshop in Lakewood, Colorado.

Figure 5-3. Sovonics array efficiency, “UV” insolation, and ambient temperature at the Davis site.

The exact cause for this behavior has not been isolated. One explanation is that thermal annealing is (partly) reversing light-induced Staebler-Wronski degradation, predominating over the usual immediate effects of high temperature during the warmer summer months. Some report that under actual field conditions, temperatures are not hot for long enough periods for the annealing to have but a minor effect on long-term efficiency [11], whereas ongoing NREL tests suggest that the annealing effect may be significant.³

The UV ratio also seems to correlate reasonably well with the efficiency trend, especially in the first few years (a filtered pyranometer used to measure infrared insolation could not be calibrated after its initial installation, and its readings appear to have drifted noticeably over time). Sovonics’ technology does not

³ Presented by Springborn Laboratories and NREL researchers at the September 1994 PV Performance and Reliability Workshop in Lakewood, Colorado.

respond to radiation of wavelengths greater than about 750 nm (infrared and longer wavelengths). Consequently, its efficiency should be greater when the infrared proportion of total radiation is low, an effect noted by the PVUSA Project Team [1] and by Gonzalez and Carroll [12].

The a-Si arrays have shown seasonal variations in efficiency that are either very flat or opposite the poly- and single-crystal Si arrays. This does not imply that the temperature sensitivity of a-Si is opposite the poly- and single-crystal Si arrays, but it is less—about -0.25% per centigrade for a-Si, and -0.45% per centigrade for the other types. Factors such as spectral changes, light-induced Staebler-Wronski degradation, and thermal annealing are thought to influence the seasonal performance of some a-Si technologies, whereas other technologies are relatively insensitive to these effects. The seasonal efficiency variation of the UPG array has been fairly subtle, but the Sovonics array has shown wide seasonal swings ($\pm 18\%$). Possibly owing to a near-uniform climate, the Sovonics array at Maui has not varied seasonally, although its efficiency has dipped temporarily on several occasions due to module failures.

Efficiency of the Maui Sovonics array has not only been steadier, but steadily higher than its Davis counterpart by about 20%. We can attribute this to a post-Davis module design change incorporating a better back-surface reflector on the Maui modules, as well as to warmer temperatures and more favorable solar spectral conditions on Maui. The Maui site has a warmer and more humid climate than Davis; consequently, the proportion of infrared insolation is, on average, about 10% lower than at Davis.⁴

Like the SSI single-crystal Si and Solarex poly-Si EMT arrays, PVUSA's three a-Si EMT arrays have also degraded since start-up in 1989. The two Davis a-Si arrays had been exposed for six months before their PTC ratings were established, so most of their initial Staebler-Wronski degradation was believed to have passed. The initial rating for the Maui array was performed after about two months of exposure. The a-Si arrays seem to be degrading at a rate of 2% to 4% per year, using the same methods of estimating long-term degradation as for the single- and poly-Si arrays (see Table 5-1). However, because the study period is short compared to the uncertainty in the estimates, it is too soon to determine if these trends are significant. The observed degradation rates will be significant if they persist over the next few years.

⁴ Based on preliminary data collected at the Maui site for two years with a factory-calibrated filtered (780 nm) Eppley PSP.

CAPACITY FACTOR

The capacity factor is calculated as the dimensionless ratio of energy produced over a given time, divided by the product of the system rating and the time interval. Monthly or annual time intervals are commonly used, although other time intervals, such as peak load periods only, may be specified as well. The capacity factor helps utility planners and operators understand characteristic daily output patterns of PV systems and their match with demand patterns. As with conventional plants, the capacity factor is influenced by system reliability, but it is also a function of the rating basis and sunlight (fuel) availability. Sunlight availability varies widely and is, in turn, dependent on the time period, local climate, and system orientation. Capacity factors are higher for systems rated under PTC than for systems rated under STC. In general, capacity factors are higher for tracking systems than for fixed tilt systems. Capacity factors during midday periods on clear days are higher than capacity factors over longer time intervals.

Based on the normal annual insolation for Davis and Maui, the maximum annual capacity factor for the EMT arrays should be about 24%, but actual values have been around 20%, attributed to downtime for repairs or maintenance and reduced output from dust. For comparison, *tracking* systems in the best U.S. southwest locations might approach 35%, whereas a fixed system in a location such as Washington, D.C., is typically 15% to 17% [13].

Figure 5-4 shows the monthly capacity factors for the EMT arrays, averaged over several years. For the fixed tilt Davis systems, the capacity factors normally range from 10% (winter) to over 25% (summer), with an annual average of about 20% for arrays in good operating condition. For the ENTECH concentrator array, the seasonal swing is more pronounced. Davis is often cloudy in the winter, and under cloudy skies, power produced by the concentrator system is minimal. In the summer, the two-axis tracking system takes advantage of the long, clear days to achieve high capacity factors. The irregularities in ENTECH's trend are a result of downtime from tracker controller failures. The seasonal variations in daylight hours at the Maui site are smaller and the weather patterns are more uniform, so the monthly capacity factor pattern is smoother than the Davis site. The Maui capacity factor tends to dip lower in the summer because its 22° fixed tilt orientation results in higher incidence angles and lower insolation in the summer compared to the spring or fall. (Note: The Maui system is located at a latitude of 21°, while the Davis arrays are at 39°).

Averages range from 4 to 6 years, depending on the system.

Figure 5-4. EMT array average monthly capacity factors.

Even if a power plant's 24-hour-based capacity factor is low, its capacity value may be high if its output corresponds well with a utility's peak demand periods. For PG&E, most of the capacity value accrues between noon and 6 p.m. on weekdays from May through October. Over this peak period, PV capacity factors are typically much higher than their monthly average. The two-axis tracking ENTECH system has demonstrated a peak period capacity factor of 75%, and the other south-facing fixed tilt systems have averaged about 60%. System simulations performed for Davis with the PV f-Chart program show that 40° fixed tilt systems oriented 65° west of south to increase their capacity value could attain peak period capacity factors of 70%, although the higher peak period generation would sacrifice about 10% of the annual energy production. Figure 5-5 shows the peak period capacity factors for the Davis EMT arrays. Modeled estimates of possible peak period capacity factors for three different orientations shown on the right side of the plot.

Figure 5-5. Peak period capacity factors for Davis EMT arrays.

Section 6

MAINTENANCE

Maintenance costs for PV systems are expected to be low because most PV systems lack the rotating or moving mechanical systems, process systems, and fluid flows characteristic of conventional generation. Experience at PVUSA and other locations suggests that the O&M cost for mature PV power plants should be on the order of \$0.005/kWh [13]. However, because of their small size, experimental nature, and the R&D environment in which they are operated, EMT systems were expected to have higher maintenance costs than larger, mature systems.

EMT maintenance costs have varied considerably among technologies and from year to year, with a substantial portion of failure-related maintenance attributed to BOS components, not modules. Annual maintenance costs have generally been higher than \$0.01/kWh, and have ranged as high as \$1.00/kWh.

Only the 2 Sovonics EMT arrays have had a significant number of module defects. About 85 of its 1,200 Davis modules (1.2% per year) have been replaced due to cosmetic delaminations or blisters on the TEFZEL cover (79 modules) and complete failures (6 modules). Additionally, PVUSA found a bullet hole in another module (it was still operating) and used a non-conductive silicone compound to seal the hole. Of the 1,200 Maui modules, 43 (0.7% per year) had failed junction boxes. Most were replaced, but a few were repaired by cleaning and rewiring the connections. None of the Maui modules have experienced cover delaminations.

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

Figure 6-1 shows the labor and material maintenance costs not covered under warranty for the five Davis EMT arrays and their PCUs (comparable records were not available for the Maui site). Figure 6-2 shows the cumulative module replacement histories. The good reliability demonstrated by most of the EMT arrays has been a welcome result, attributable to initial factory qualification tests that were as rigorous as those used to develop today's more established products.

Figure 6-1. EMT non-warranty maintenance costs by year of operation, Davis site.

Modules: SSI-400, Sovonics-1200, UPG-4992, Solarex-336, ENTECH-60
 ENTECH: No failures after 3.8 years

Figure 6-2. Module replacement histories through 1994.

Most failures have been BOS-related. Although few components aside from a few fuses have failed, the EMT-1 DECC PCUs have tripped off line about 400 times over their first 10,400 unit-days of operation, or slightly over one trip per unit per month. In each case, a manual reset was required, which restarted the units; on a number of occasions, the trips resulted in several days of downtime (e.g., weekends). Nearly half of the total PCU trips occurred on the Maui array during its first three years of operation, but these practically ceased after Maui Electric widened the PCU's allowable frequency window from 60 Hz ± 0.3 Hz to 60 Hz ± 1.5 Hz in fall 1992 [14]. PVUSA and DECC have been successful in troubleshooting attempts to reduce (but not eliminate) intermittent morning start-up synchronization errors, the most frequent type of trips on the Davis units.

After the PCUs, the most significant failures involved source circuit junction boxes on the Solarex and Sovonics arrays and tracker controller failures on the ENTECH array. Problems with the intermediate junction box were traced to water intrusion and poorly located and sealed penetrations. They were remedied by redesigning the components to prevent similar failures. For the ENTECH array, the tracker controller was replaced, poor connections were secured, and harmonic filtering was added to better protect the controller from line distortion and transients. During fall 1994, a newly designed tracker controller was installed in place of the original. The new system is dc-based and uses ac power to charge a battery at night, then uncouples the tracker drive from the grid by day, drawing on stored dc power from the battery to run the system.

Section 7

CONCLUSIONS

Five advanced PV technologies have been fielded as 20-kW arrays at Davis, California, and one at Kihei (Maui), Hawaii. These EMT arrays continue to operate successfully after installation. They have operated for four to six years, depending on installation date.

The six EMT systems have features such as higher efficiency, better reliability, or lower-cost manufacturing processes that distinguish them from commercial modules of the same vintage. During the evolution from laboratory to pilot production, manufacturers can determine whether their manufacturing processes merit further development or scale-up. A few EMT contracts were canceled due to difficulties in trying to achieve satisfactory pilot production. For those products which have been fielded at PVUSA, lessons learned by the manufacturers influenced their subsequent commercialization strategies.

PVUSA did not intentionally impose unjust requirements. Understandably, the first-time costs of developing the EMT modules were high for most, if not all, manufacturers, and economic comparisons were therefore excluded from the EMT evaluations. It was anticipated that the EMT testbed would be an avenue for manufacturers to field test new products by providing funding for experimental modules and technical evaluation services.

EMTs allow PVUSA to establish baseline information for the components of an array (e.g., junction boxes and interarray wiring). This information is valuable even if the module technology is not commercialized. The EMT installations have also provided PVUSA with an opportunity to establish procedures for performing O&M and tracking costs. Although the O&M costs for these new technologies are expected to be higher than larger commercial systems, EMT maintenance procedures have proven useful in developing corresponding procedures for US systems.

Performance of the EMT arrays has ranged from very good to very poor in terms of efficiency, reliability, and overall generation. Some arrays have operated as well as any commercial system— noteworthy for products with no prior field test experience. The arrays that performed poorly have provided valuable lessons learned in this research arena that will guide development of future, improved

products. In particular, module failures have occurred less frequent than BOS components. System dc efficiencies have ranged from as low as 2% for a-Si to as high as 13% for concentrator crystal-Si systems. Regardless of technology type, the installed array efficiencies fell below the manufacturers' targets. The shortfalls ranged from 3% to 25%. Capacity factors followed expected seasonal trends, averaging about 20% annually and 60% to 75% during PG&E's peak demand periods. Annual maintenance costs varied from less than \$0.01/kWh to over \$1.00/kWh. EMT maintenance costs have generally been higher than the projected target for larger, mature systems (\$0.005/kWh), but it should be noted that these costs reflect PVUSA's priority as a research facility, not as a revenue venture.

Some of the new design features in the EMT modules have proven to work well and are being used in commercial products. The EMT testbed has also served as an appropriate arena to identify less successful features; manufacturers find the feedback useful for improving products.

The following manufacturer-specific results are being used by utilities to increase their understanding of PV as an electricity supply option, and by PV manufacturers to refine product designs and gauge commercialization plans. It is likely that future commercial PV technologies will differ from their predecessors at PVUSA as improvements in efficiency, reliability, and module cost are realized. Several favorable features of the EMTs have already been incorporated into PV manufacturers' current products. The EMT testbed has also proven valuable for identifying likely failure mechanisms and developing improved components.

Until higher needs for the modules or structures are identified, PVUSA plans to continue operating these systems and to supplement them with new EMTs as they become available to increase the statistical base for evaluation, to gain additional operating experience, and to showcase improvements in PV technologies with time.

SSI MICRO-GRID MODULES

Through a combination of changes (larger cells, micro-gridding, cell etching, and an anti-reflective treatment on the top glass cover), SSI's micro-grid modules achieved a relative efficiency increase of about 10% compared to its standard product; this was, however, about 3% short of the expected goal. The changes may not have been economic for the manufacturer: Five years later, SSI has not incorporated any of these features into its standard product line. Module reliability has been excellent,

but array output has been dropping at a rate of 1% to 2% per year after five years. Although this decline in performance does not appear to be significant, it has focused renewed attention on the value of long-term monitoring to determine at what rate crystal silicon-based modules degrade with time.

SOVONICS TANDEM-JUNCTION, SAME-BANDGAP, AMORPHOUS SILICON MODULES

Sovonics pioneered the use of TEFZEL as a cover material. Despite initial difficulties, the material has held up well, and Sovonics' successor company, United Solar Systems Corporation, is using it in lightweight, flexible modules. The efficiency of this module, which uses same-bandgap cells, has been low (~3%), although the Maui version has generally operated about 15% better relative to the Davis version. The fielded tandem design did not seem to lessen the effects of initial or longer-term degradation. Sovonics' product appears to be sensitive to additional factors not explainable with commonly used models: Solar spectral content and thermal annealing, for example, tend to make summer efficiency greater than winter efficiency, a pattern different from crystalline silicon modules. Moreover, there is an apparent overall degradation of 2% to 4% per year. Module reliability has been fair—a significant number of failures were caused by overheated, loose junction box connections at Maui (0.7% per year) and blistering/delamination of the untextured TEFZEL cover at Davis (1.4% per year).

SOLAREX BIFACIAL POLYCRYSTALLINE SILICON MODULES

Despite an expected improvement in efficiency over its standard polycrystalline silicon module, the Solarex bifacial module has operated at about the same efficiency (7.5%) as its standard module. The bifacial design does not seem to be beneficial for the thicker-cast cells, especially when mounted in a fixed tilt array with little stray light absorbed on the back of the module. The TEFZEL back cover has held up very well. Although numerous initial failures occurred due to pinholes, these problems were resolved. Only one of the array's 336 modules has failed after over four years of operation.

Solarex concluded that the EMT program was a costly and ineffective avenue for product development. The company felt obligated to use one module design to meet a schedule, even though the final design did not fit well with its long-term planning. Solarex would probably not participate in another EMT program, citing high product costs due to qualification testing and pilot-scale manufacturing.

UPG TANDEM-JUNCTION, SAME-BANDGAP, AMORPHOUS SILICON MODULES

The UPG modules have operated reliably and at a steady albeit low efficiency. As with other manufacturers' arrays, the UPG array appeared to have a slow annual decline in efficiency (2% to 3% relative decrease). The module's design is low cost and durable, although its sheet metal "chimney" makes it more difficult to service than conventional modules. The UPG module operates about 3°C -5°C higher than the other flat-plate modules, which has not appeared to be a drawback: Array efficiency has been much less sensitive to temperature (-0.1% per centigrade) than the other technologies (-0.25% to -0.5% per centigrade). It has been speculated that its higher operating temperatures have helped lessen the effects of light-induced degradation through thermal annealing.

ENTECH CONCENTRATOR ARRAY

Since installation three years ago, ENTECH's 60-module concentrator array has operated without any module failures. Its average efficiency (11%) has been the highest of PVUSA's arrays, although its relative performance was expected to be about 20% higher. The shortfall was attributed to lower-than-expected cell efficiencies and an inadequate thermal design during the summer months at low wind speeds. Lessons learned at PVUSA have enabled ENTECH's new design to achieve lower temperatures and higher efficiency. The system's tracker controller has not operated reliably and was finally replaced with a dc-based system.

Section 8

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Appendix A

EMT-RELATED PVUSA PUBLICATIONS

EMT-RELATED PVUSA PUBLICATIONS

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Appendix B

MODULE PHOTOGRAPHS

Photograph B-1. SSI front of module.

Photograph B-2. SSI back of module.

Photograph B-3. Sovonics front of module, Davis site.

Photograph B-4. Sovonics back of module, Davis site.

Photograph B-5. Sovonics back of array, Maui site.

Photograph B-6. UPG front of module.

Photograph B-7. UPG back of module (rotated + 90°).

Photograph B-8. Solarex front of module.

Photograph B-9. Solarex back of module.

Photograph B-10. ENTECH front of module.

Photograph B-11. ENTECH back of module and central tracking mechanism.

Appendix C

1989 - 1994 PERFORMANCE SUMMARY

1989 - 1994 PERFORMANCE SUMMARY

Performance Category	System	1989	1990	1991	1992	1993	1994
ac Energy (kWh)	SSI Davis	33,391	34,243	31,133	29,261	29,891	30,141
	Sovonics Davis	25,034	29,037	12,087	12,181	22,758	24,350
	Sovonics Maui	5,713	29,518	27,319	28,085	32,045	30,760
	UPG	4,559	29,349	25,823	25,407	25,479	26,537
	Solarex	n/i	4,715	26,016	22,767	23,572	25,915
	ENTECH	n/i	n/i	27,558	21,117	20,032	27,258
dc Efficiency (%)	SSI Davis	10.7	10.6	10.4	10.1	10.2	10.0
	Sovonics Davis	3.3	3.1	2.9	2.8	2.6	2.6
	Sovonics Maui	3.7	3.7	3.4	3.4	3.3	3.4
	UPG	n/i	3.2	3.0	3.0	2.9	2.8
	Solarex	n/i	8.8	8.2	7.3	7.4	7.8
	ENTECH	n/i	n/i	11.2	10.7	11.1	10.7
ac Capacity Factor (%)	SSI Davis	21.4	21.7	19.7	18.5	18.9	19.1
	Sovonics Davis	21.8	20.9	8.7	8.7	16.3	17.7
	Sovonics Maui	21.4	19.1	17.7	18.2	21.0	20.0
	UPG	n/i	22.3	19.5	19.2	19.3	20.1
	Solarex	n/i	17.8	19.7	17.2	17.8	19.6
	ENTECH	n/i	n/i	26.8	15.4	14.7	19.9

Note: Start dates are staggered; therefore, some quantities are based on a partial year's performance. See Table 2-1 for installation dates.
n/i = not installed, n/r = not recorded