CONF-970953--

SAN097-2450C
SAND--97-2450C

RECEIVED
OCT 15 1997
OSTI

PHOTOVOLTAIC SYSTEM RELIABILITY

Alexander B. Maish
Sandia National Laboratories
Albuquerque, NM 87185-0753

Christopher Atcitty
Sandia National Laboratories
Albuquerque, NM

Steve Hester
Utility PhotoVoltaic Group
Washington, DC

Daniel Greenberg
Ascension Technology, Inc.
Lincoln Center, MA

Don Osborn, David Collier
Malissa Brine
Sacramento Municipal Utility District
Sacramento, CA

ABSTRACT

This paper discusses the reliability of several photovoltaic projects including SMUD's PV Pioneer project, various projects monitored by Ascension Technology, and the Colorado Parks project. System times-to-failure range from 1 to 16 years, and maintenance costs range from 1 to 16 cents per kilowatt-hour. Factors contributing to the reliability of these systems are discussed, and practices are recommended that can be applied to future projects. This paper also discusses the methodology used to collect and analyze PV system reliability data.

INTRODUCTION

Photovoltaic (PV) systems are being installed in great numbers throughout the U.S, and the world. Although PV modules now enjoy high reliability due to a significant multi-year effort by both the U.S. Department of Energy (DOE) and industry, the same is not always true of PV systems. The long-term health of the photovoltaic (PV) industry requires that PV systems work as expected. Anecdotal reports of inverter, battery, and other component failures give an impression of high maintenance costs, low availability, and poor system reliability. Presently many systems are sold only on the basis of initial cost, but purchasers of these systems must consider, in their purchase decision, the full system life-cycle cost (LCC) including first cost, operation and maintenance (O&M) cost, and cost of non-availability. At present the latter two costs are not well known.

Even for systems that do operate reliably, customers, suppliers, and manufacturers can benefit from knowing what O&M expenses to expect. This knowledge will reduce technology risk to the customer and improve likelihood of commitment to PV projects. System integrators and utilities may benefit from O&M cost information to improve system designs, to properly price service agreements and warranties, and to optimize maintenance strategies. The DOE and component manufacturers may benefit from identifying cost drivers to optimally focus research and quality assurance resources to improve product reliability.

This paper not only discusses the reliability of several current PV systems, but it also investigates the factors that contribute to their reliability and recommends practices that can be applied to future projects. In the process this paper also discusses the methodology used to collect and analyze PV system reliability data, and what measures are used to characterize reliability.

A RELIABILITY SUCCESS STORY

Flat plate silicon PV modules had dismal reliability in the early years of development when several companies first tried to design and manufacture them. In the late 70's and early 80's the Jet Propulsion Laboratory (JPL) conducted an extensive program to improve the reliability of flat plate silicon PV modules.[1] JPL developed 5 sequential specifications known as Blocks I-V addressing a stream of failure mechanisms identified by module testing, field exposure, and failure analysis. It identified 13 major failure mechanisms and developed allowable failure rates for each limiting the increase in system energy cost to 20% over 30 years. JPL then conducted research to achieve a basic understanding of each failure mechanism, and developed design solutions. It also developed tests to fail deficient modules and pass ones known to survive in the field. This program was extremely successful. The Southwest Technology Development Institute measured 5-year failure rates of pre-Block IV modules at 50%, while post-Block III module 5-year failure rates were only 1.5 per 10,000 per year.[2] The lesson of this effort is that high reliability is achieved by an iterative process to design reliability into the product. The same is needed for PV systems. Although system reliability is sometimes quite good, in order to improve system reliability we need to identify the causes of failure, apply good research and design practices towards reducing failures, and learn from the successes of the past.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Dept. of Energy under Contract DE-AC04-94AL85000.

DEFINING AND QUANTIFYING RELIABILITY

Most PV system operators are interested in quantifying the reliability of their systems especially if they are already collecting performance data. However, many don't know the best way to go about it. How does one define reliability? What information does one need to collect and how does one analyze it? How does one use the results to improve the reliability of a system? Answers to these questions have been extensively investigated by Sandia National Laboratories' Systems Reliability Department and applied to many industries. The primary tool used by this group is a state-of-the-art software package called WinR™ developed for the semiconductor industry. It runs on a Windows® based PC platform and is available for license by interested companies. The code generates a statistical model of the failure mechanisms of a system which, in addition to characterizing a system's reliability, can be used to extrapolate system reliability performance over periods longer than those monitored or to investigate the effects of alternate components or maintenance strategies.

The WinR software generates four measures of system reliability; time-to-failure, time-to-repair, availability, and maintenance cost. Although each of these provides insight into system performance, the maintenance cost, stated in terms of cents per kilowatt-hour, has the most relevance to system life-cycle cost. Life-cycle costing enables one to find the appropriate tradeoff between investment in a more reliable design (or one with a warranty) that has a higher initial cost and paying higher maintenance and downtime costs over the system's life resulting from a lower-reliability design. Because maintenance and downtime costs vary from project to project, the optimum tradeoff will vary as well. Life-cycle costing also gives the full system cost which must be compared with the value of energy or the avoided cost to determine the project's economic viability.

Before running an analysis with WinR, the user must define the failure modes and organize them into a hierarchical structure by component and subcomponent. Then (s)he must define the logical relationship between the failure modes and the system failure by developing a fault tree. Generally in the PV systems observed, the fault tree is very "flat" because each failure mode leads immediately to a system failure without requiring another failure mode event to occur. Each failure mode needs a time-to-failure and a time-to-repair which can be better expressed as a distribution rather than as a single value. If empirical data is available, WinR can create the distribution function automatically. Alternatively, the user can provide a distribution. WinR allows one to enter a cost-to-repair for each failure mode.

Once the analysis is run, WinR enables a user to plot the four measures of reliability as distributions rather than as single values. It also enables the user to view the sensitivities of the system reliability measures to the individual failure mode time-to-failure and time-to-repair values, which can be indispensable in identifying the main contributors to system unreliability and maintenance cost.

DATA COLLECTION

Due to its independent, non-commercial status and present involvement in a wide range of PV activities, Sandia is in a unique position in the PV community to work with a wide range of PV projects to characterize the reliability status of PV systems. This past year Sandia has provided support for the collection of reliability data at a wide range of PV systems including grid-tied and grid-independent, small and large. Not all of these have yet produced sufficient data for meaningful results, but the scope should identify the major issues and reliability status for different application categories.

Not every PV project meets the criteria to provide valuable reliability data. A project should ideally include enough similar components to provide a statistically valid measure of reliability. This can be in the form of many similar PV systems, or a large system with many similar components. Crucial to the effort is a mechanism and commitment by the PV project to collect data in a thorough and consistent manner. Ideally data would flow through one person who would ensure consistency in the recording of failure events. Although WinR can handle some lapses in data, the more thorough the data is, the better the results. Finally, a site should provide data relevant to future PV systems.

Support of these projects included, almost universally, help in identifying appropriate data to collect. In some cases projects already had computer-based failure event forms tied directly to a database. In other cases no reporting mechanism existed. Some projects record all phases of a failure event (notification or identification, inspection, repair, and follow-up) on one form, and some record each activity as a separate record linked by an event number. Sandia worked with each PV project to ensure necessary data was collected in the manner most convenient to that project. Where a project was starting from scratch, a generic form developed by Sandia was used as a starting point.

Although more data was generally collected for use by the project, the core data items needed for a reliability analysis is fairly minimal. For each failure one needs to record (or estimate) the system identification, the date of failure, the date of repair, the failure type, and the repair cost. The data analyst also needs to know the system design and number and type of components so (s)he can develop the fault tree. Monitoring start and end dates are also needed.

PRESENT STATUS OF PV SYSTEM RELIABILITY

The most extensive reliability data exists for grid-tied residential projects. Grid-tied residential systems are currently receiving significant visibility with the announcement of the U.S. Department of Energy's (DOE) Million Solar Roofs Initiative. The Sacramento Municipal Utility District (SMUD) installed over 400 2-kW to 4-kW grid-tied residential systems as part of its PV Pioneer Program. This paper used data from four project phases installed between 1993 and 1995 including one each by RMI and Placer in 1995. (Table 1, Figure 1). These systems include inverters from Omnion, Trace, and Pacific, and panels from Siemens, Solec, and Solarex. Data collected over the past year by SMUD is providing the best insight into the operating costs of this type of utility-owned and operated residential PV program.

Table 1 - SMUD's PV Pioneer Program Description

PV Pioneer Phase	Panel Mfct	Inverter Mfct	# Syst	# kW	# modules
1993	Siemens	Omnion	108	400	8288
1994	Solec	Omnion	119	400	4928
1995/RMI	Solarex	Pacific	25	87	1872
1995/Placer	Solarex	Trace	80	329	6216
Total			332	1216	21,304

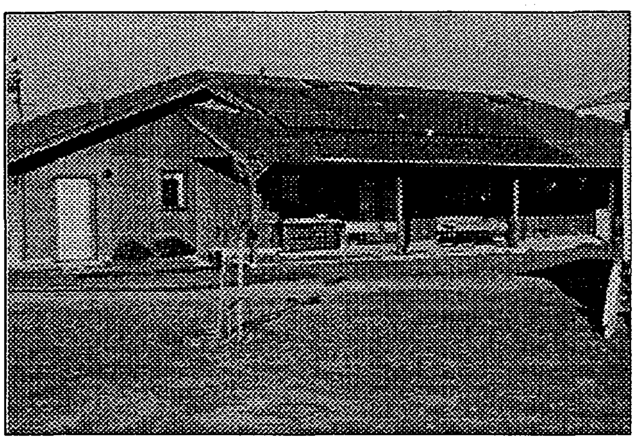

Figure 1 - SMUD 4-kW Residential System

Another smaller PV program installed and monitored by Ascension Technology for the Environmental Protection Administration (EPA) in 1993 has provided additional data analyzed by Sandia. The EPA1 project includes nine 4-kW and six 12-kW grid-tied residential and commercial systems. The Utility PhotoVoltaic Group (UPVG) has also funded Ascension to monitor the performance and reliability of 110 small, medium, and large grid-connected systems being installed as part of UPVG's Round 1 and Round 2 TEAM-UP program. Ascension is currently monitoring 21 systems ranging from 2-kW residential to 35-kW utility systems as part of this program. Ascension has also reported on the failures observed in 126 PV systems it has been monitoring since 1994.[3] Results from this study are included here. Other monitoring efforts are underway for grid-independent systems. The Colorado Energy Office has installed over 50 PV lighting systems throughout its state parks which are installed and maintained by one individual. Sandia is providing support to collect maintenance data on these systems which are analyzed in this paper. The PV Services Network (PSN) is collecting data on water pumping systems from its member utilities which have over 100 systems installed. Other monitoring efforts in the works include the Florida Solar Energy Center's (FSEC) monitoring of the Martin Luther King Blvd. lighting system in Atlanta, and the Bureau of Land Management's (BLM) monitoring of its "host" sites which are sub-kilowatt systems to provide power to the recreation vehicles of its volunteer site hosts.

Reliability of Grid-Tied Systems

The PV Pioneer program instituted by SMUD is a model utility-run program for grid-tied residential systems. One of its beneficial aspects for reliability purposes is that the program is autonomous, so a dedicated service technician is available rather that having to rely on existing utility technicians unfamiliar with PV. This also improves reliability reporting. SMUD logs failures in a computer database which is updated to reflect service calls reported on a one-page paper form.

Table 2 shows the number of failure events reported between 8/1/96 and 7/1/97 in the SMUD systems. These were analyzed by Sandia using WinR to characterize observed system reliability and to model reliability under different assumptions. The majority of the failures involved the inverters. Inverters are undergoing intense efforts by inverter manufacturers and DOE to improve their reliability, and many of the failures analyzed here have led to design changes by the manufacturers so that these failures will not recur. Failures resulting from installation errors were not modeled by WinR as they are non-recurring beginning-of-life failures which the software does not handle. The installation failures listed are ones identified during the 1996 to 1997 monitoring period.

In all the cases analyzed using WinR, failure rates were computed using 200 Monte-Carlo trials and a failure rate distribution based on observed failures. The first case analyzed for each SMUD project phase assumed one year of operation and used the observed mean-times-to-repair (MTTR). These actual times-to-repair were skewed due to not having a service technician for several months after reliability monitoring began on 8/1/96. For this case, no downtime cost was included. A second case was run which included the cost of lost electrical power to show the impact of downtime on maintenance costs. Value of the lost power was computed assuming generated electricity had a value of 10¢ per kilowatt-hour and each system produced the average 4 MWh of electricity per year. During this period the inverters were under warranty, so the cost included only administrative labor, service technician travel and repair time, shipping when necessary, and parts when the repair was performed in the field. The loaded cost of the repair administrative support was assumed to be $20/hour, and that of the technical support was assumed to be $60/hour.

Table 2 - SMUD's PV Pioneer Program Failures

PV Pioneer Phase	# Failures Modeled	Inverter Failures	Installation Errors (not modeled)
1993	27	24	0
1994	8	8	1
1995R	18	18	3
1995P	15	15	2
Total	68	65	6

To eliminate the impact of the skewed time-to-repair, a third case was run using a more realistic MTTR. Failure identification, which impacts time-to-repair, is an important issue in system reliability. In grid-tied systems, failure identification is hampered by the lack of impact on the homeowner caused by an outage and the lack of any run-light on the inverters. SMUD relies on homeowner reports that the inverter is silent, and on monthly readings of the separate PV electric meter installed on each system. Currently, however, SMUD's billing database requires manually entering each system identification to check for lack of output. On the other extreme, Ascension monitors its systems' performance using a sophisticated instrument package that reports daily to a central computer that compares actual to predicted output. Discrepancies are flagged and a call is made to the site operator the next day to investigate. An intermediate alternative which is receiving development support by Sandia is a relatively inexpensive (few $100) monitoring system which can also phone-in diagnostic data on a periodic basis to a central computer. The economic viability of such monitoring systems for non-research use will depend on the application.

The third case was run with a time-to-repair of 40 days, which reflects current response time. This includes a nominal 30 day failure identification period (using meter results) and 10 day repair response. An important part of minimizing downtime is that spare inverters are kept on hand to exchange with failed units so the system is not down while the failed unit is repaired. This is possible with larger projects such as SMUD's.

Analyses for periods longer than a few years need to include the impact of expired warranties. During the warranty period, the inverter manufacturer bears the cost of inverter repair parts and labor, but after the expiration of the warranty SMUD bears those costs. Repair costs for each failure mode were estimated in conjunction with the inverter manufacturers. In actuality, SMUD plans to use a local university to repair inverters at a significant savings over these costs now that inverter warranties are ending. The fourth and fifth cases were run for a period of 10 years. The fourth case assumed the inverter warranty period is 2 years, which is the case for existing PV Pioneer systems. Another advantage of SMUD's large PV project size is its ability to win concessions from suppliers. SMUD was recently able to get the warranty on inverters raised to 5 years for its next project phase. The fifth case investigates the impact on maintenance cost of this increase.

Tables 3 through 6 show the results of the SMUD analyses for each phase of the PV Pioneer program. These results do not include the costs of installation failures, potential failures which were not observed during the monitoring period, or preventive maintenance, which should probably be performed every few years to avoid problems known to occur on other similar systems. Mean-time-between-failures (MTBFs) varied from 7 to 16 years, which is an improvement over inverter performance of a few years ago. Actual mean-time-to-repair (MTTR) varied from 2-1/2 to 7 months reflecting the delay in hiring a service technician at the beginning of the analysis period. Actual system availability, which ranged from 83 to 98%, reflects these long MTTRs. For the analyses using a shorter 40-day mean-time-to-repair, availability increased significantly to between 93.5% and 99%.

Table 3 - 1993 PV Pioneer Project Reliability
Performance monitored 8/96 - 7/97

1993	1 Year			2yr/8yr	5yr/5yr
	Actual MTTR		40 day MTTR	40 day MTTR	40 day MTTR
	No Down Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost
MTBF	6.95 yr	6.95 yr	6.95 yr	6.95 yr	6.95 yr
MTTR	216 days	216 days	40 days	40 days	40 days
Avail.	86.4%	86.4%	96.2%	96.2%	96.2%
Maint $	2.1¢ per kWh	4.6¢ per kWh	2.6¢ per kWh	5.2¢ per kWh	4.2¢ per kWh

Maintenance costs varied significantly between the project phases, but the trends between case studies was similar. The lowest cost 0.4¢ to 4.2¢ per kilowatt-hour) was observed for the first case representing actual costs observed to date. When the cost of lost energy is included, these costs rise 50-100% due to the long response times. Assuming a 40-day response time drops the maintenance cost back to only 15-30% above the base case. A longer analysis period to include the effects of an expired service warranty raised costs by 5-200%, with smaller rises (0-120%) observed for the longer warranty period. It is important to note that all these maintenance and downtime costs are significantly below retail values of electricity, demonstrating that even with all the failures being observed with inverters, maintenance cost is significantly below electricity value. To determine overall project economic viability it is still necessary to include a levelized installation cost when comparing costs to electricity value.

Table 4 - 1994 PV Pioneer Project Reliability
Performance monitored 8/96 - 7/97

1994	1 Year			2yr/8yr	5yr/5yr
	Actual MTTR		40 day MTTR	40 day MTTR	40 day MTTR
	No Down Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost
MTBF	15.8 yr	15.8 yr	15.8 yr	15.8 yr	15.8 yr
MTTR	78 days	78 days	40 days	40 days	40 days
Avail.	98.3%	98.3%	99.0%	99.0%	99.0%
Maint $	0.40¢ per kWh	0.57¢ per kWh	0.50¢ per kWh	1.5¢ per kWh	1.1¢ per kWh

Table 5 - 1995/Placer PV Pioneer Project Reliability
Performance monitored 8/96 - 7/97

1995 Placer	1 Year			2yr/8yr	5yr/5yr
	Actual MTTR		40 day MTTR	40 day MTTR	40 day MTTR
	No Down Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost
MTBF	11.2 yr	11.2 yr	11.2 yr	11.2 yr	11.2 yr
MTTR	108 days	108 days	40 days	40 days	40 days
Avail.	88.8%	88.8%	95.4%	95.4%	95.4%
Maint $	4.2¢ per kWh	6.0¢ per kWh	4.7¢ per kWh	7.6¢ per kWh	6.5¢ per kWh

Table 6 - 1995/RMI PV Pioneer Project Reliability
Performance monitored 8/96 - 7/97

1995 RMI	1 Year			2yr/8yr	5yr/5yr
	Actual MTTR		40 day MTTR	40 day MTTR	40 day MTTR
	No Down Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost	10¢/kWh Dn Cost
MTBF	16.2 yr	16.2 yr	16.2 yr	16.2 yr	16.2 yr
MTTR	173 days	173 days	40 days	40 days	40 days
Avail.	83.5%	83.5%	93.5%	93.5%	93.5%
Maint $	3.5¢ per kWh	6.6¢ per kWh	4.3¢ per kWh	4.5¢ per kWh	4.5¢ per kWh

One would normally expect maintenance cost to be inversely proportional to system MTBF. Surprisingly, in these studies maintenance costs correlate only weakly with MTBF. This is due to the wide variation in repair costs for the different types of failures observed in the different SMUD project phases. Some inverter failures required simple component replacements and some required more extensive repairs. Using an analogy to the JPL module Block V program, with the MTBFs observed here, inverters installed between 1993 and 1995 fall somewhere between Block III and Block IV in maturity. The design of inverters installed since then have benefited immensely from analyzing these failures, and an analysis of the 1996 and subsequent SMUD PV Pioneer phases should show noticable improvement in reliability. If one can eliminate the failures requiring extensive repairs and increase the MTBFs to the 20+ year range, residential grid-tied systems run in a large well-managed project similar to SMUD's should have maintenance costs well below 1¢ per kilowatt hour.

Table 7 gives the results of a WinR analysis of the Ascension/EPA systems which were monitored during its initial years of operation from 1993 to June 1996. The effect of the daily monitoring of system performance by Ascension is evident in the rapid repair response (19 days). System failures were much more frequent than those in the SMUD project even though the inverters were Omnion 2200's, the same as those used in the 1993 Phase of the SMUD project. The differences in failure rates may be due to catching high beginning-of-life failures rates in the EPA1 data and catching just lower middle-of-life failure rates in the SMUD systems which were not monitored until several years after installation. In fact, the EPA1 project did have beginning-of-life failures (software-induced inverter shutdowns and incorrect fuses in the dc disconnects) which have been corrected. The bottom line of Table 7 reflects the analysis re-run without these failures.

Table 7 - Ascension/EPA Project Reliability
Performance monitored 1993 to 6/96

EPA	2 Year Warranty 8 Year Non-Warranty		5 Year Warranty 5 Year Non-Warranty	
	Actual MTTR		Actual MTTR	
	No Down Cost	10¢/kWh Dn Cost	No Down Cost	10¢/kWh Dn Cost
MTBF	1.2 yr	1.2 yr	1.2 yr	1.2 yr
MTTR	19 days	19 days	19 days	19 days
Avail.	91.9%	91.9%	91.9%	91.9%
Maint $	15.3 ¢/kWh	16.3 ¢/kWh	12.5 ¢kWh	13.4 ¢/kWh
Adjusted Maint $	9.5 ¢/kWh	10.1 ¢/kWh	7.5 ¢/kWh	8.2 ¢/kWh

Ascension recently reported that its monitoring of 126 systems since July 1994 provided data on 190 failure events.[3] As in the other projects analyzed here, the bulk of these failures (76%) were inverter problems. With 237 inverter-years in its database, Ascension found there was an inverter failure on the average of every 1.65 years. Other problems included disconnect switch problems (20, due to blown fuses), source-circuit protector failures (5, due to blocking diode and fuse failures), module problems (12, due to ground faults, dead or shattered modules giving an average module problem of once per 552 years) and 9 array wiring problems.

Reliability of Grid-Independent Systems

Detailed maintenance data has also been collected on grid independent systems that do not include an inverter. The Colorado Parks systems are small (sub kilowatt) lighting systems installed throughout Colorado. Results of a WinR analysis of the reliability of these systems is given in Table 8. Vandalism is a major problem with these systems, accounting for 60% of the maintenance costs. Without including vandalism, system reliability is excellent, with 96% availability, over 13 year MTBF, and a maintenance cost of $25 per system per year. Chris Dunn, who designs, installs, and maintains these systems, recommends designing a standard system with as few components as possible which is easy to maintain and replace. The control board he developed for the Colorado Parks project has four components. He minimizes field assembly by putting the control board in a weatherproof box so that after mounting he only needs to connect the panel and loads to it. Even so, installation by local maintenance personnel has not worked for him.

Table 8 - Colorado Parks Project Reliability
Performance monitored 1/97-7/97

	Actual Cost (No Downtime Cost)	No Vandalism (No Downtime Cost)
MTBF	7.9 yr	13.5 yr
MTTR	63 days	66 days
Avail.	94.6%	96.5%
Maint $	$58 per system per year	$25 per system per year

WHAT CONTRIBUTES TO HIGH SYSTEM RELIABILITY?

In this paper several PV projects have been evaluated to determine their system reliabilities. Without knowing the value of energy in each project and the levelized initial cost of the systems it is beyond the capability of this study to determine whether the measured reliability allows for an economically viable project or not. However, it is possible to identify several factors contributing to high observed system reliabilities.

Just as reliability has been designed into PV modules it must also be designed into PV systems. This means not only using reliable components, but also using them together correctly in a well-designed system. And it means providing the proper infrastructure to minimize failures and to respond to them in a manner that maximizes reliability when failures do occur. The existing experience with PV components and systems must be incorporated into future systems or the process of iterating to more reliable designs will be slowed.

There is clearly a large opportunity to increase the reliability of inverters. Significant efforts are focused on improving the MTBF of inverters, and, like the program for PV modules, it will take an iterative program of failure identification, engineering redesign, and further testing. By taking advantage of lessons learned with other similar components it may be possible to shortcut some iterations and speed the process of developing a highly reliable product.

System design also requires good engineering practice including complying with standards, using components appropriately, and using experienced PV designers. Infrastructure support is critical. Using service technicians experienced with PV to install and repair PV systems provides a major boost in system reliability. The systems examined in this paper have incorporated these elements and represent some of the more reliable systems of their type in existence.

Beyond these recommendations, however, it is also clear that project size has a big impact on system reliability. The size of the SMUD PV Pioneer project gives it several advantages in system reliability, as have become evident in the course of this paper. Having numerous identical systems takes advantage of design standardization. Not only is the service technician better able to repair a few standardized designs, but it is easier to maintain an inventory of spares to minimize system downtime and number of service trips. Additionally, once a design or installation problem is identified it can be corrected on all the systems in the project preventing numerous failures. A larger project permits having a trained PV service technician and administrative support dedicated to the project rather than using whomever is available. Having a large number of systems in a small area minimizes service travel time. Finally, a large project can command lower initial system prices and longer component warranties.

Awareness of the importance of PV system reliability to the viability of such systems is the first step towards its improvement. The tools and methods exist to identify and improve system reliability. Accomplishing this task opens the door to even greater use of photovoltaics in the domestic and international markets.

REFERENCES

[1] Elmer Christensen, Flat-Plate Solar Array Project – Ten Years of Progress, JPL 400-279, October 1985.

[2] Southwest Technology Development Institute, Field Experience with Photovoltaic Systems: Ten-Year Assessment, EPRI TR-102138, March 1993.

[3] Miles Russell, Frequency of Problems in Over 100 Grid-Tied PV Systems, 1997 PV Systems Performance and Reliability Conf., Las Cruces NM, August 5-6, 1997.