Commonwealth Energy Biogas/PV Mini-Grid Renewable Resources Program

Making Renewables Part of an Affordable and Diverse Electric System in California

Contract No. 500-00-036

Initial Characterization Report for 1st System: PowerLight Sloped PowerGuard 20 kW PV System

Project 3.2 Building Integrated PV Testing and Evaluation Project

Task 3.2.2a (3) Final Report

Prepared For:
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Executive Summary

Introduction

The Building Integrated PV Evaluation Project, under which this work was performed, is one of several projects that make up the Commonwealth Energy Biogas/PV Mini-Grid Renewable Resources RD&D Program (visit www.pierminigrid.org). Commonwealth Energy Corporation and the California Energy Commission Public Interest Energy Research (PIER) program fund the work. The intent of this project is to develop consistent informative reviews of commercially available PV systems, and the tests and procedures for conducting those reviews. These reviews cover system design and documentation, installation, and performance.

This Initial Characterization Report is the first in a series of reports that will describe samples of systems installed on the Headquarters building of the Inland Empire Utility Agency. This Initial Characterization report on a 20kW Sloped PowerGuard system from PowerLight Corporation, addresses the design and documentation, the installation, results from component and commissioning tests, and preliminary system rating. An Interim report, which will follow in the next few months, will provide a more accurate system rating. Six-month and 12-month reports will summarize the performance of the system based on the installed data acquisition systems. These reports will also describe the review process and tests procedures so that they may be offered to standards development bodies such as ASTM and IEEE. Finally, a Consumer Confidence Guideline will summarize all of this information in a format that is hopefully more consumer friendly and less technically daunting.

PowerLight Sloped PowerGuard Initial Characterization Summary

Below is a brief summary of the results detailed in the remainder of this report:

System Description: Major components of the Sloped PowerGuard system include 120 of Sanyo's HIP-190BA2 high-efficiency photovoltaic modules, on PowerLight's unique tilted mounting system, and connected to a Xantrex PV-20208 three-phase inverter.

Design and Documentation: The most unique feature of this system is the mounting system, which is ballasted and orients the modules at a 10^{o} tilt angle. A rear wind deflector/support reduces the uplift forces and, therefore, the requirements for ballast and connections to the building (read: roof penetrations) are also reduced. According to PowerLight, this design has been wind-tunnel tested and this configuration is capable of safely handling a windspeed 99 MPH. The design windspeed for this location is 85 MPH so this design is verified that it exceeds the wind-loading requirements for this site with a building of this height. Design enhancements are used for regions with higher windspeed requirements such as the southeast coastal region of the United States.

Documentation provided with the system was found to be exemplary for a system of this size (20kW being at the small end of the 10 – 225kW range of PowerGuard systems—multiples of these systems are often installed for larger projects). While noting some areas for potential improvement, the documentation proved to be well assembled and straightforward for answering questions during and after array installation and acceptance testing.

Installation: Array installation was performed by a combination of PowerLight personnel and contractors with no previous experience with the Sloped PowerGuard system, putting the mounting system and documentation to the test. The equipment was well-packaged making array assembly quite simple. The installation had to consider the placement of one plumbing vent that could not be relocated. With a small amount of planning in the array layout, this obstacle was easily avoided and the installation progressed without any other difficulties. The array installation took a total of 68 labor hours over the course of less than two days. The manufacturing tolerances of the sheet metal and panels were quite good making field modifications of the panels unnecessary for fitting purposes.

Initial Performance: The Sanyo HIP-190BA2 module was previously characterized by Sandia, information that will be used in subsequent evaluations. The inverter had not been independently characterized, and Endecon worked with Sandia to develop appropriate test procedures and to perform a subset of those procedures on the inverters used at the IEUA facility. From these tests, we expect the inverter to operate at an efficiency of 93.5 to 94 percent at full output power and operate the array within 1-2% of its maximum power point. Based on initial IV curves, we estimate the rating of this system to be 19.8 kWac at PVUSA Test Conditions. However, since the installation and initial characterization were completed in the middle of winter when the sun was at very low angles and since the array was also at a fairly low tilt angle, the peak irradiance on the array was too low to provide an official rating—that will have to wait for the Interim Report.

Conclusions

During initial testing, it was discovered that the inverter maximum power point tracking function (MPPT) was having difficulty with the Sanyo array. After numerous tests and evaluation of the problem by with responsive support from both PowerLight, and Xantrex, an interim solution was developed that seems to have solved the majority of the tracking problems observed. A final solution is due for implementation in April 2004. Other than this array-inverter interrelation issue, the PowerLight Sloped PowerGuard system has met the general expectations of a commercial product in a mature market. A preliminary system rating of 19.6 kWac PTC has been established. This rating is based on I-V curves that may be inaccurate due to the capacitance of the array.

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1 Introduction

This initial characterization report is designed to provide an overview of the documentation, design review, installation review, and initial performance of the PowerLight Sloped PowerGuard System photovoltaic (PV) power system (see Figure 1). At 20kW, the system is at the small end of the range of PowerLight PowerGuard PV systems, but is fully representative, incorporating all components and critical aspects of their larger systems. PowerLight offers the Sloped PowerGuard system in standard sizes ranging from 10 kW to 225 kW.

The system is installed on the roof of the Inland Empire Utilities Agency (IEUA) headquarters building in Chino, California where it is being compared to systems and hardware from a variety of suppliers. This system evaluation and comparison is a principal component of the Building Integrated PV Testing and Evaluation Project, one of several projects undertaken as part of the Commonwealth Biogas/PV Mini-Grid Renewable Resources RD&D Program (visit www.pierminigrid.org). Commonwealth Energy Corporation and the California Energy Commission Public Interest Energy Research (PIER) program fund the work.

Figure 1 PowerLight Sloped PowerGuard 20kW PV System

The evaluation begins with a detailed description of the PV system itself as well as the IEUA facility. The system documentation and the installation process are then reviewed subjectively. Next, the measured performance of the system and key components is presented followed by a discussion of cost. The appendix contains a report provided by Sandia National Laboratories on the characterization of the inverter used in this PV system.

The information and results are intended for a sophisticated reader, one with at least some basic knowledge of solar energy and photovoltaics. A less rigorous report will be prepared at the end of this project. Also, as this report deals with initial characterization, the focus is more on the component level, for which we have measured data; rather than on the system, for which we have little measured data. Future reports will emphasize system performance and will provide comparisons of the various systems located at the IEUA facility.

It should be stressed that subjective reviews represent the opinions of the author(s). While the authors have collectively reviewed hundreds of PV systems ranging in size from a few watts to several megawatts, this report is a first attempt at a more consumer-oriented system analysis with subjective valuations. Evaluating PV systems can be a complex and often bewildering endeavor for those new to the industry. This characterization report is part of a project that attempts to demystify some of the complexity of PV system selection and provide solid information of valuable to anyone implementing a PV system. A summary table is available on the www.pierminigrid.org website to review all of the evaluation criteria. These criteria will likely evolve and be refined as more systems are subjected to this process.

2 System Description

Roof penetrations, whether for attaching the array to the building or for routing electrical conductors from the roof to the inverter or utility connection point, require special flashing and sealing procedures to ensure a tight long-lasting water seal. These procedures can be complex, and expensive, and the resulting penetrations are an on-going maintenance concern, so there is strong incentive to reduce the number of penetrations. A ballasted system is one way to reduce roof penetrations by using mass to hold the array in place rather than physical attachments. The Sloped PowerGuard system is one of two commercial rooftop PV power system designs supplied by PowerLight (www.powerlight.com). The "Sloped" designation refers to the fact that the array is tilted at a 10^o angle to improve annual energy capture (compared to the standard horizontal PowerGuard structure. The array is held in place under its own weight (the ballast) and by the interlocking nature of the individual tiles. The angle of the panel is a compromise between uplifting forces from winds and improved energy production. PowerLight offers the Sloped PowerGuard system in a variety of sizes in segment from 10 to 225 kilowatts in size.

PowerLight's other roof mounting system uses weighted horizontal panels to hold the array on a building roof. The panels use a similar foam base as the Sloped PowerGuard product and are deployed at hundreds of locations throughout the United States. Both systems are designed for ease of installation without roof penetrations and also provide shade and thermal insulation for the roof in addition to the electric power benefits. The relative benefit of the Sloped PowerGuard over the standard product is in three areas: (1) the improved tilt angle of 10^o versus horizontal, (2) the improved thermal performance of the PV module due to the additional air space beneath the module, and (3) possible improved cost due to the potential lower cost of the sheet metal in contrast with the cementitous cover on the standard PowerGuard product.

The first two benefits translate directly to improved performance. The resulting 10-degree improvement in tilt angle corresponds to a 7% improvement in annual performance according to a PVWATTS simulation for the Chino, California area. In discussions with the manufacturer it is estimated that the Sloped PowerGuard design operates approximately 5^oC cooler on average than its horizontal counterpart (using Installed Nominal Operating Cell Temperature as the basis for energy comparison). With a $-0.5\%/^oC$ power-loss due to temperature coefficient module (e.g. crystalline silicon) would see a 2.5% improvement in performance while the Sanyo module with a lower $-0.32/^oC$ coefficient will only see a 1.6% improvement in performance. Overall, the Sanyo module experiences an 8.7% improvement in energy performance of the Sloped versus non-sloped product while a typical crystalline silicon module would experience a 9.7% improvement in energy production.

This 20 kW Sloped PowerGuard system uses 120 of the Sanyo Model HIP-190BA2 high-efficiency photovoltaic modules. The modules are made with HIT process. The 190-Watt Sanyo module is measures 52" x 35.25" (1.32 m x 0.90 m). The manufacturer specifications for the module are shown in Table 1:

Table 1 Manufacturer Specifications for HIP-190BA2

Description	Notation	Value
Power (max.)	Pp (watts)	190 W
Voltage at maximum-power point	Vp (volts)	54.8 V
Current at maximum-power point	Ip (amps)	3.47 A
Open circuit voltage	Voc (volts)	67.5 V
Short circuit current	Isc (amps)	3.75 A
Nominal operating cell temperature	NOCT (Celsius)	44.2 °C
Power temperature coefficient	T_K (Pp)	-0.30 %/°C
Open circuit voltage temperature coefficient	T_K (V_{oc})	-0.169 V/°C (-.25%/°C)
Short circuit current temperature coefficient	T_K (I_{sc})	N/A
Series cells per cell string	Nseries	96
Parallel cell strings per module	Nparallel	1
Maximum System Voltage	Vsys,max	600 V
Operating temperature, minimum	Tambient,min	-20 °C
Operating temperature, maximum	Tambient,max	+40 °C
Connection type	Two 12AWG single conductor USE-2 terminated with Multi-Contact connectors	

Note that these HIP modules are graded into three nominal power ranges during the quality control phase: 175W, 190W, and 205W modules. The modules reviewed in this system are of the 190W grade.

The array is arranged in 15 series strings of 8 modules with a footprint of approximately 33' x 74' or 2,440 square feet. A single Xantrex PV-20208 inverter processes the power and connects to the building 480 Vac power through a step-up 208/480V isolation transformer. The inverter is located in a dedicated, conditioned room within the building.

The array's 10-degree tilt is less than the 30-degrees needed for maximum annual energy at the Chino, California location. It represents a reasonable design compromise between maximizing annual energy, power, and energy density on a rooftop (the lower the tilt, the closer the modules can be placed without shading one-another), wind loading, and mechanical considerations (wind load increases with tilt angle). These tradeoffs are discussed in the next section. Note also that the 10° tilt is relative to the roof surface, which itself has some tilt for drainage purposes (approximately 2° for the IEUA Headquarters Building), and the direction of the roof tilt aligns with the tilt of the array structure, so that the array is actually tilted about 12 degrees from horizontal.

2.1.1 PowerLight Sloped PowerGuard Mounting System

At its factory in Berkeley, CA, PowerLight mounts each solar power module on an extruded polystyrene foam insulating "tile"(See Figure 2). A pallet-full of tiles is shipped to the site, each with a pre-mounted sheet metal cap in place of the traditional cement-covered tile used on previous PowerGuard products. The metallic cover has lower weight and has better tolerances making assembly slightly easier than the standard cement-covered tile. The tiles are fitted together on the roof and held in place with a sheet metal "curb" around the edge of the array that is filled with concrete paving blocks as ballast. The modules are installed flat and then tilted into final position after the array is in place. The metal covered panels provide some ballast and distribute the weight of the modules, which provides the majority of the ballast, over a relative wide area to reduce contact pressure on the roof and distribute the overall weight of the array evenly.

Figure 2: A PowerGuard Tile

A key concern for a PV mounting system is wind loading. The large surface area of the PV array acts like a sail, especially when the wind comes from the north. To reduce the impact of the wind, a wind deflector is located on the north side of the module. The combination of the wind deflection and the weight of the ballast are used to keep the array in place during the highest design winds. This design has been wind-tunnel tested and this configuration is capable of handling a windspeed 99 MPH, which exceeds the wind-loading requirements for this site.

The slightly tilted plane-of-array orientation is a compromise between the low wind load of a horizontal orientation and the improved performance and drainage (to prevent dirt buildup at the lower edge of the module frame) of a higher tilt orientation.

2.1.2 Test Facility

The Sloped PowerGuard system is installed at the IEUA headquarters building in Chico, CA, which hosts the evaluation of several similarly sized PV systems (see Figure 3). The roof of the building is roughly 245 ft by 160 ft (74.7 m x 48.8 m). The vertical, or north-south axes of the PV arrays are parallel with the short dimension of the roof area, which is oriented 23.5° east of north.

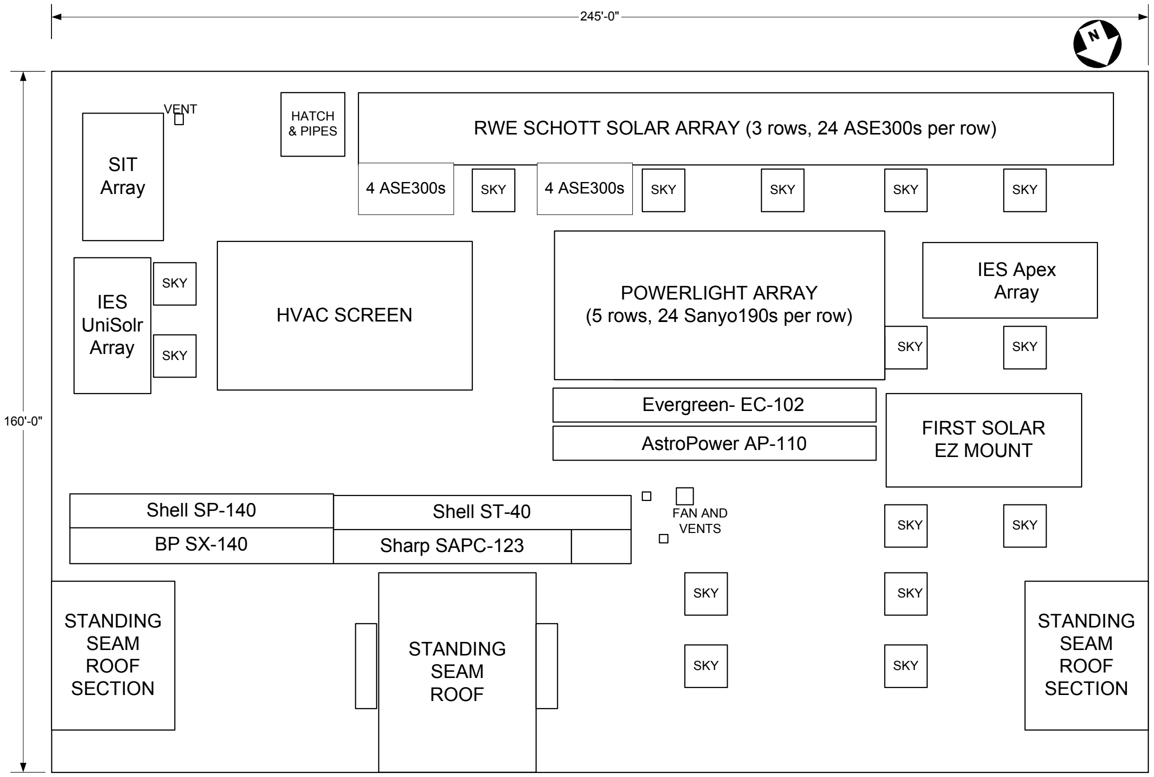

Figure 3 Layout of PV Systems on IEUA Headquarters Rooftop

Figure 4 shows that Chino is located approximately 50 miles east of Los Angeles in the San Bernardino valley. This region has had a history of livestock ranching since the mid-nineteenth century, which remains a significant land use industry in spite of widespread suburban encroachment. Inland Empire Utilities Agency (IEUA) was formed in 1950 as the Chino Basin Municipal Water District (CBMWD) for the purpose of delivering supplemental water to the region. The mission of the IEUA has expanded since then to include water treatment, recycled water delivery, biosolids/fertilizer treatment provider, and, more recently, biogas electric energy generation. The IEUA administration complex is located adjacent to the Regional Plant 5 (RP5) that is currently under construction with a planned eventual electric power generation capacity of 5 MW or more.

Figure 4 Regional map showing location of Chino, California

The average annual air temperature in Chino is about 16 °C (61 °F), with typical range of -2 to 40 °C (29-103 °F). Average wind speed is 1.5 m/s (3.4 mph), with a sustained peak of 6.7 m/s (15 mph)[1]. Annual average daily peak hours of sunlight on a horizontal surface is 5.4 hrs, with monthly average range about 2.7 hrs in December to 7.6 hrs in June.[2] The Chino area has an extensive dairy and other livestock industry producing more airborne soil contaminants than most urban and suburban sites. This airborne soil collects on PV modules and reduces photovoltaic output.

2.1.3 Other Systems

The PowerLight system is one of several that have been installed on the IEUA facility comprising the Large System Evaluation portion of the Commonwealth Energy PIER project. While this report focuses solely on the initial characterization of the PowerLight system, some initial comparisons are made and future reports will provide more thorough comparison. The other systems installed on the IEUA facility are briefly described on the project web site (http://www.pierminigrid.org/pubproject32.html)

In addition, a Small System Evaluation for this PIER project is being established at a separate facility (the PVUSA site in Davis, CA) to compare systems for residential roof-top application.

2.1.4 Procurement and Review Process

The PowerLight Sloped PowerGuard 20 kW PV System was selected by the Technical Advisory Committee (TAC) based on the criteria set forth by the PIER PV System Evaluation Plan approved by the California Energy Commission. Once the TAC selected the systems, a budget was developed and approved by the system owner, Commonwealth Energy. Inland Empire Utilities Agency then contracted with Commonwealth, to lease the PV system for five years and buy the system at the end of the lease.

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[1] Basic weather data derived from four years of Pomona weather data commencing in January 2000, obtained from http://www.cimis.water.ca.gov.

[2] Solar resource data provided by the NASA (National Atmospheric and Space Administration) Surface meteorology data site on the web at http://eosweb.larc.nasa.gov/sse/ .

As part of PIER PV System Evaluation plan, assurances were made to reduce the probability that suppliers would “cherry-pick” the best modules for the evaluation. Because demand for PV modules is very high for every manufacturer, including Sanyo, suppliers simply do not have the luxury of selecting only the best for a particular project. In general, modules are shipped soon after they are manufactured, which was the case with the PowerLight Sanyo array.

The Sloped PowerGuard modules shipped from the module manufacturer to the PowerLight facility where, as previously noted, they were assembled into the roof panels and shipped to the Chino site on one delivery truck. The arrays were installed by a combination of PowerLight personnel, Commonwealth contractors and IEUA personnel under the direction of Endecon Engineering, who supervised the construction. This arrangement enabled Endecon to closely evaluate the installation of each system separate system, and compile a more meaningful comparative analysis.

3 Documentation Review

The availability of a complete system documentation package is a key requirement for achieving reproducible success in system installations. This review takes a close look at the following items for completeness and value to the installer and customer.

☒ System description and specifications
☒ Parts and source lists for equipment supplied and not supplied with package
☒ Electrical diagrams and schematics
☒ Mechanical drawings
☒ Installation and checkout procedures
☒ Operation, maintenance and troubleshooting instructions
☒ Owners manuals for individual major components
☒ Information on how system performance monitoring is accomplished
☒ Warranty information on components and complete system

Each of these items is evaluated separately and a rating is provided on the documentation as a whole.

3.1 Contents of the System Documentation

PowerLight provided a total of three documents for their Sloped PowerGuard system: a Design Submittal, the Installation Manual, and the system Operation and Maintenance Manual. The 31-page Design Submittal included a brief system description, the scope of PowerLight's involvement in providing equipment and training, the warranty on the system components, component specifications, wind design calculations, wire and conduit specifications, basic systems drawings, a Gantt chart outlining the project schedule, and a materials list specifying everything provided with the system. According to the Design Submittal document, this design has been wind-tunnel tested and this configuration is capable of handling a windspeed 99 MPH. This maximum windspeed includes a safety factor of 1.4 and an importance factor of 1.15. Importance factor is a multiplier used by civil engineers when describing the relative importance of a particular installation from the standpoint of life safety. For instance, an installation suspended over a crowded courtyard would have a much higher importance factor than an installation behind a fence in a remote field. The failure calculations are performed in the same manner for the two installations, but an added safety margin is applied to the installation that has a higher consequence of failure. The design windspeed for this location is 85 MPH so this design is verified that it exceeds the wind-loading requirements for this site with a building of this height.

The Installation Manual, at 51-pages, describes the installation procedure including, safety concerns, site preparation, unpacking the shipped materials, assembling the array, installing combiner box and inverter, system start-up and commissioning, repair and replacement of any each major system component, and troubleshooting the system. The manual is filled with color photos and diagrams that provide important detail to augment the text. Helpful comments accompany most steps to ensure that each step is done properly. Safety warnings are routinely mentioned at the appropriate stages of the manual in red lettering for emphasis. The system startup and commissioning section is quite succinct and straightforward providing solid advice on how to make sure that each part of the system is working properly. A dry megohmmeter test is included in the commissioning section to help ensure that the system has no obvious ground-faults prior to startup. The trouble-shooting section is also helpful to resolve problems that arise during installation or after the system has been operating for some time.

The Operation and Maintenance Manual is the main document provided for the system after installation. It includes much of the same basic information found in the Design Submittal, but, as the name suggests, it includes the important O&M information needed to keep the system in good operating form throughout the life of the system. Other important information included in this document includes as-built drawings of the array, showing the location of each numbered source circuit. The appendices include a performance simulation showing the estimated monthly kWh performance with a max/min band for each month. This guidance is quite helpful for verifying that the system was working properly in the previous month, or suggesting further investigation may be needed to determine why the output is low. Also included in the appendices is an array test form to be filled out at installation and each time the array is fully tested, and a maintenance log format to provide a means of consistently reporting any unexpected or scheduled maintenance.

3.2 Evaluation of the System Documentation

The Sloped PowerGuard system is a new product so the documentation is still under development. However, the documentation was found to be exemplary for a system of this size (20 kW). The level of detail would be adequate for a system of over one hundred kilowatts. The manual was not referenced as often as that of the RWE system since PowerLight representatives were on hand to assist with the installation. The project manager read through the installation document in the days before the installation so most of the process was familiar when it came time to do the work.

The product preparation by PowerLight at their factory ensures that field installation is quite simple and straightforward. Once the edges of the array are marked out on the roof surface, it is a matter of putting together a puzzle where every piece is identical. The installation document strongly focuses on acceptance testing and troubleshooting since the installation is so straightforward.

In general, the information was well laid out and showed that the company had experience supplying information needed by system owners and installers. PowerLight generally sells their systems to customers as turnkey systems. Since PowerLight personnel are involved with each installation, the detail in the documentation is not as important as it would be if they sold equipment for third-party contractors to install.

The PowerLight documents did clearly feature safety warnings in strategic locations through each document informing all readers of the dangers of working with high voltage dc electrical systems on top of commercial rooftops. These warnings not only included issues related to shock and electrocution hazards, but it also included warnings and instructions related to fall protection and other key occupational safety issues not often addressed in solar system documentation.

Procedures for system commissioning were above average for PV system documentation. Good detail is given on how to calculate and anticipate what the open-circuit voltage of each string should be under typical testing conditions. The procedures instruct the installer to measure the dc current from each string with a clamp-on ammeter while the system is operating to make sure that all strings are producing similar current under similar conditions. There is not a lot of guidance on how to determine an actual system rating or whether the overall ac output is performing as expected (other than the monthly performance comparison discussed above). Since PowerLight monitors each of their installations, it is likely that they take this data over time and produce a system rating from a series of date over a period of time. While this may explain the lack of focus on this issue in the acceptance testing section of the manual, addition of this material would make for a more complete manual.

Given their focus on providing turnkey projects, PowerLight's documentation is somewhat different from other manufacturers that focus on system packaging for installation by independent contractors.

3.2.1 Documentation Strong Points:

1. Safety information is prominent and includes areas such a fall protection that are often overlooked in system documentation.
2. Installation manual is thorough and has good pictures, diagrams, and text to explain the installation process.
3. Acceptance testing procedures are quite good.
4. For the novice system owner, the manual's dearth of detailed information may be a welcome relief from the volumes.

3.2.2 Documentation Weak Points:

1. On the other hand, the manual's information may appear a tad thin to the seasoned PV engineering professional who would prefer a preponderance of information to sort through and decide which is most important. An example is the brief documentation that is provided for the module.
2. Because the system is not sold to contractors, detailed drawings of the individual components are not as necessary. PowerLight may have plagiarism concerns about distributing detailed proprietary drawings.
3. The system acceptance test does not sufficiently address expected ac performance.

4 Installation Review

4.1 Shipping

The Sloped PowerGuard 20 kW system was delivered to the site in a single delivery truck. The array was shipped on 12 larger pallets, each with a footprint of approximately 4'x 6'. The module panels were stacked 13 high measuring about 5½ feet high. Additional hardware, sheetmetal, paverbricks, and electrical equipment were shipped on an additional five standard pallets. The fragile modules were well protected in the stacked arrangement with additional extruded polystyrene "blue board" on top of each pallet, corner protection, and plastic wrapping to hold the pallet together.

Lifting to the roof was accomplished with a truck-mounted crane owned and operated by the Inland Empire Utility Agency (IEUA) (see Figure 5).

Figure 5: Shipping container being lifted by truck crane

There was no breakage caused by the shipping, handling, or lifting of the equipment. The extra blue board was laid under each pallet to spread the load of the pallet evenly on the roof and to prevent protrusions from damaging the roof membrane (see Figure 6). This technique worked extremely well and the blue board was re-used throughout the project to provide a cushion for abrasive or sharp objects that could possibly damage the roof. Excess shipping material consisted of wrapping plastic, cardboard, pallet bands, blue board, and pallets. Some of this material was kept on the roof to assist with the future installations and most of the remainder was acceptable for placement in the miscellaneous recycling bin at the IEUA Headquarters building.

The PowerLight system was the first PV system to be installed on the IEUA Headquarters roof. With no other systems in place, it enjoyed the greatest flexibility in the staging process, which turned out to be an overall advantage since the large number of pallets that made up the system required the largest staging area. Because of the weight of the modules pallets, these pallets were placed at the very edge of the roof directly over the roof trusses to minimize the structural stress of the pallets on the roof.

Figure 6: Setting panel pallet on polystyrene board to protect roof

4.2 Array Installation

Personnel with no previous experience with the PowerLight system assisted in the array installation. PowerLight provided oversight and guidance for the installation with two PowerLight personnel who guided an additional 2-4 workers throughout the installation. The array installation took place over a two-day period. On the first day, the array location was finalized, the panels installed, and the array assembled.

The layout for the array is critical to the overall ease of installation. Since the array is made up of 15 eight-module series strings, the best layout called for 5 rows of 3 series strings each (24 module panels per row). This necessitated a footprint of approximately 75 feet wide by 35 feet deep. In order to keep clear of all shading obstructions (in particular the HVAC screen in Figure 3) and large obstacles (e.g., skylights), the center of the roof was chosen for the array. This location was ideal with the exception of a single plumbing vent that could not be relocated. This vent was used as the key location around which the rest of the array was located. Figure 7 shows how the vent fit neatly behind a panel in the second row of modules. Once this location was identified relative to the panel spacing, the rest of the array layout was very straightforward (see Figure 8, Figure 9, and Figure 10). The entire layout process and setting of all 120 panels took about half a day.

Figure 7 Array layout placing vent between module and wind shroud

By the end of the first day, most of the wiring within the array was complete and the entire array grounding installed (see Figure 11, Figure 12, and Figure 13). On the second day, the array wiring was completed and several miscellaneous projects were accomplished such as placing signs, running the array wires to the rooftop junction box, and final cleanup. Six workers providing an average of 8 hours of labor each accomplished the first day's work. The second day was a partial day with 4 workers providing an average of 5 hours of labor each.

Figure 8 (above) Carrying panel

Figure 9 (far right) Carrying panel to set in place

Figure 10 Interlocking panels with tongue-and-groove assembly

Table 2 Installation Labor Summary

Day	# of workers	Total Labor Hours	Activity
1	6	48	Roof Prep, install array and most wiring
2	4	20	Complete circuit wiring to junction box, finish misc. items
TOTAL		68	

This totaled 68 labor hours to install the entire 20 kW array as summarized in Table 1. It should be noted that this was only the third installation of this particular product and 4 of the 6 workers had never worked on this system previously. Southern California Roofing, the company that installed the membrane roof, provided most of the installation labor. A trained, experienced crew could probably complete the array installation 50 labor-hours.

Figure 11: Installing grounding straps after all panels are placed on roof

Concrete pavers
for perimeter ballast

Figure 12: Installing perimeter ballasted curb

Figure 13 Lifting module-shroud assembly and snapping shroud into slots
(home run wire for series strings already in place)

4.3 Electrical Balance of Systems (BOS) Installation

The electrical balance of system installation consisted of running 10 AWG wire from the rooftop junction box to the combiner box that was located on the roof. Since the array has 15 independent series strings, 15 pairs of wires were run to the combiner box where each circuit was terminated on a fuse block and combined into a single array circuit. This array circuit was connected to a rooftop disconnect (added by the project to facilitate testing—see Figure 14) before running through conduit to the PV room set aside within the IEUA headquarters building. The dc disconnect, inverter, isolation transformer, and ac disconnect were installed in the PV room. Standard utility pulse-initiating kWh meters were installed to monitor system output power and energy.

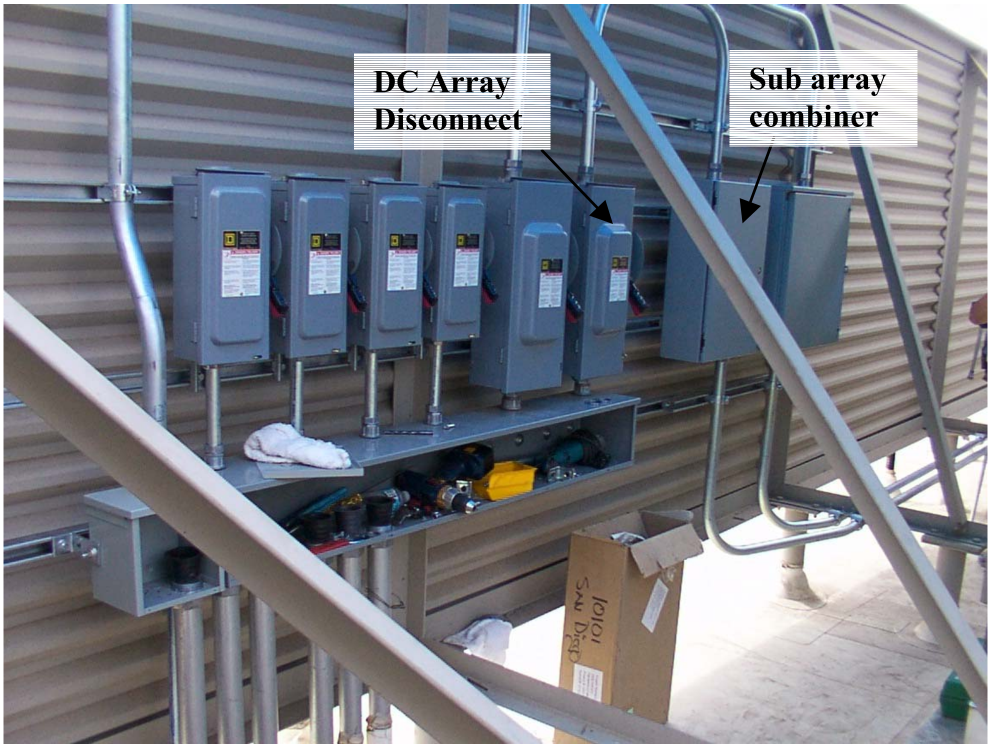

Figure 14: Disconnects for all 12 rooftop systems

Power was routed from the PV room to the building’s main electrical room about 20 feet away, and fed through a dedicated circuit breaker to a 480Vac service panel. A 12 kV transformer at the adjacent building 100 yards away energized this panel.

The electrical maintenance personnel of the Inland Empire Utilities Agency (IEUA) provided the labor for the electrical balance of system installation. All the wiring from the rooftop array thru the inverter room to the service panel inside the building was run by IEUA. It took a total of approximately 60 labor hours to install all the electrical related to this system. It is difficult to develop and exact number for this project since all three 20 kW segments were under construction at the same time. Much of the labor was shared among the various installations.

5 PV System Initial Performance Review

5.1 Module Characterization

The Sanyo Model HIP-190BA2 modules have been characterized by the PV module testing laboratory at Sandia National Laboratories. This laboratory has tested more than 130 PV modules, establishing a database of operational information for commercial PV modules. A detailed description of module characterization process is available at http://www.sandia.gov/pv/docs/PDF/viennaking1.pdf. The Sanyo Model HIP-190BA2 is currently among the most efficient modules on the market. The 190-Watt Sanyo module measures 52" x 35.25" (1.32 m x 0.90 m) for an area of 12.7 ft^2 or 1.18 m^2. Its STC rated power-to-area ratio is 160.7 W/m^2 (16.1% efficient) making it the most efficient module tested in this project.

The module's high efficiency is claimed to be due to the Sanyo HIT (Heterojunction with Intrisic Thin-Layer) technology, which consists of a thin layer of amorphous silicon on the front and back of a single-crystal silicon cell. Although various PV experts have theories as to why this cell is more efficient than a standard crystalline silicon cell, the nature of the Sanyo process is highly proprietary. The resulting performance, however, is significantly better than other commercially available flat-plate (i.e., non-concentrating) products.

Manufacturer's specifications are shown in Table 3 and measured performance from the Sandia database is shown in Table 4.

Table 3: Manufacturer Specifications for HIP-190BA2

Description	Notation	Value
Power (max.)	Pp (watts)	190 W
Voltage at maximum-power point	Vp (volts)	54.8 V
Current at maximum-power point	Ip (amps)	3.47 A
Open circuit voltage	Voc (volts)	67.5 V
Short circuit current	Isc (amps)	3.75 A
Nominal operating cell temperature	NOCT (Celsius)	44.2 °C
Power temperature coefficient	T_K (Pp)	-0.30 %/°C
Open circuit voltage temperature coefficient	T_K (V_{oc})	-0.169 V/°C (-.25%/°C)
Short circuit current temperature coefficient	T_K (I_{sc})	N/A
Series cells per cell string	Nseries	96
Parallel cell strings per module	Nparallel	1
Maximum System Voltage	Vsys,max	600 V
Operating temperature, minimum	Tambient,min	-20 °C
Operating temperature, maximum	Tambient,max	+40 °C
Connection type	Two 12AWG single conductor USE-2 terminated with Multi-Contact connectors	

Table 4: Sandia Measured Performance Data for HIP-190BA2

Description	Notation	Value
Module model number	Model	HIP-190BA2
Vintage of tested sample	Vintage	2003 (E)
Area of module	Area	1.151 m^2
Cell technology	Material	HIT-Si
Series cells per cell string	Series_Cells	96
Parallel cell strings per module	Parallel_C-S	1
Short circuit current at reference conditions	Isco	3.708 A
Open circuit voltage at reference conditions	Voco	69.339 V
Current at maximum power point under reference conditions	Impo	3.424 A
Voltage at maximum power point under reference conditions	Vmpo	56.710 V
Nominal operating cell temperature	NOCT (Celsius)	49 °C (+/- 4°C)
PVUSA PTC Temperature	PTC (Celsius)	56 °C (+/- 4°C)
Isc temperature coefficient	αIsc	0.001329 A/°C
Imp temperature coefficient	αImp	-0.000391 A/°C
Voc temperature coefficient	βVoco	-0.1888 V/°C
Vmp temperature coefficient	βVmpo	-0.1751 V/°C
Maximum power temperature coefficient as a function of effective irradiance, Ee	Pmp Temp Coefficient	-0.3202%/°C

Performance Data Translation

$E_e = (E/E_0)\, f_1(AMa-1.5)\, f_2(AOI)$ = Effective Irradiance Ratio (Eqn. 1)

$Isc(E_e, T_C) = nmp^* E_e[Isc_0 + \alpha_{Isc}(T_C-T_0)]$; T_C = Measured cell temp, °C (Eqn. 2)

$Imp(E_e, T_C) = nmp^*\{C_1 + E_e[C_2 + \alpha_{Isc}(T_C-T_0)]\}$ (Eqn. 3)

$Voc(E_e, T_C) = nms^*[Voc_0 + C_4 \ln(E_e) + \beta_{Voc}(T_C-T_0)]$ (Eqn. 4)

$Vmp(E_e, T_C) = nms^*\{Vmp_0 + C_6 \ln(E_e) + C_7 [\ln(E_e)]^2 + \beta_{Vmp}(T_C-T_0)\}$ (Eqn. 5)

Location:		
Site	IEUA Headquarters Building	
Lat	33.97	Site latitude, °
Long	117.675	Site longitude, °
Alt	100	Site altitude, m
STM	120	Local Std Time Meridian

Reference Conditions:		
E_0	1000	Reference irradiance, W/m^2
T_0	50	Reference module temp, °C
AMa_0	1.5	Reference air mass
AOI_0	0	Reference AOI, °

Module Characteristics			
Mfg.	Sanyo	Model	HIP-190BA2
ns	# of cells in series	np	# of cells in parallel
Isc_0	Isc @ reference conditions, A	Imp_0	Imp @ reference conditions = $C_1 + C_2$, A
Voc0	Voc @ reference conditions, V	Vmp0	Vmp @ reference conditions, V
α_{Isc}	Isc temperature coefficient, A/°C	α_{Imp}	Imp temperature coefficient, A/°C
β_{Voc}	Voc temperature coefficient, V/°C	β_{Vmp}	Vmp temperature coefficient, V/°C
C_1	Imp regression coefficient, A	C_6	Vmp regression coefficient, V
C2	Imp regression coefficient, A	C_7	Vmp regression coefficient, V
C_4	Voc regression coefficient, V		

The above equations and coefficients describe the changes in the IV performance curve of the PV module under various sunlight and temperature conditions. Using these equations, an accurate performance model can be developed for the PV array to input into an overall system performance model. Currently a few commercially available computer simulation programs use this method as the array model in their simulation. Sandia has written several papers comparing the output of this model with real system performance showing close agreement between the two.

5.2 Inverter Characterization

Sandia National Laboratories has been extremely supportive of this evaluation project. Under a separate contract, Endecon Engineering has been working with Sandia to develop standardized performance test procedures for grid-connected PV inverters. That document is intended to provide a comprehensive performance test regimen and the Commonwealth BIPV project provided the perfect opportunity to begin evaluating the test procedure[3]. Samples of the two inverter models (Xantrex PV20208 and SMA SB2500U) used in the Large System Evaluation at

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[3] At the time of this writing, the latest draft of the inverter performance test procedure is available on the Endecon Engineering web site (www.endecon.com). It will eventually become a Sandia Report and will be offered to IEEE and IEC for review as a potential standard.

the IEUA headquarters were sent to Sandia and were subjected to a series of tests to evaluate their performance. It is important to note that all tests done on the Xantrex PV20208 include the 208/480 step-up isolation transformer in the evaluation.

Some of the procedures, as currently envisioned in the document, were beyond the capabilities of Sandia. For example, the procedures assume the use of a sophisticated programmable DC source (simulated PV array) to provide the wide range of array power and voltage levels and IV curve characteristics called out in the document. Sandia uses a reconfigurable PV array and available sunlight to power their inverter tests. Also, delays in purchase approval and desire to meet an installation schedule resulted in a relatively short window of opportunity for testing. Despite these restrictions, Sigifredo Gonzales of Sandia was able to obtain data for a majority of the key operating conditions. The test results are presented in the letter report in Annex A. The results from the Sandia Tests are summarized below.

5.2.1 Efficiency

Figure 15 and Figure 16 show the measured conversion efficiency relative to three important parameters. Each of the curves is plotted against the output power level, shown as a percentage of rated output power level (20 kW for this unit).

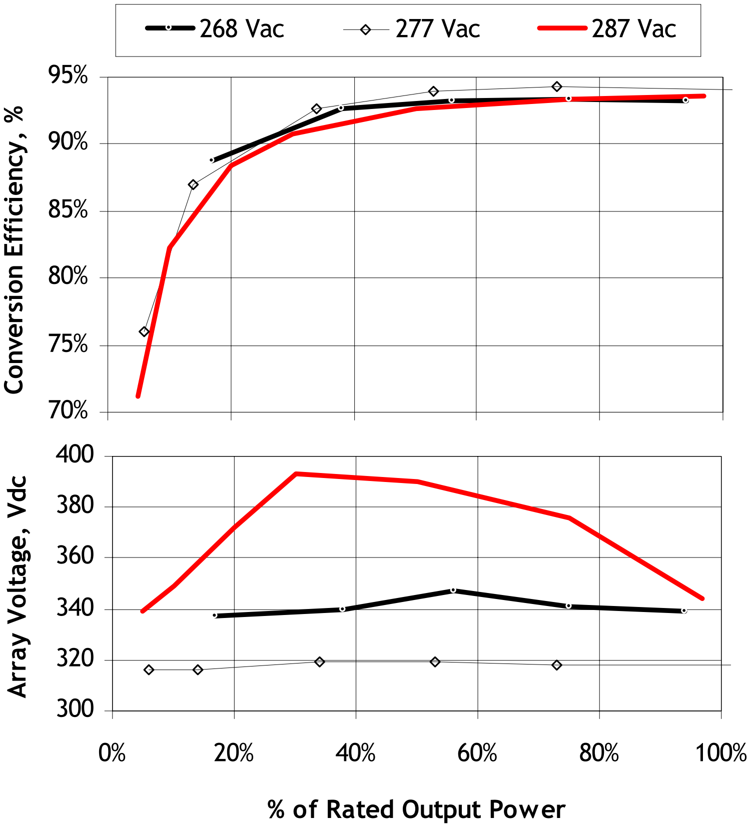

Figure 15 Xantrex PV20208 Efficiency at 25°C Ambient

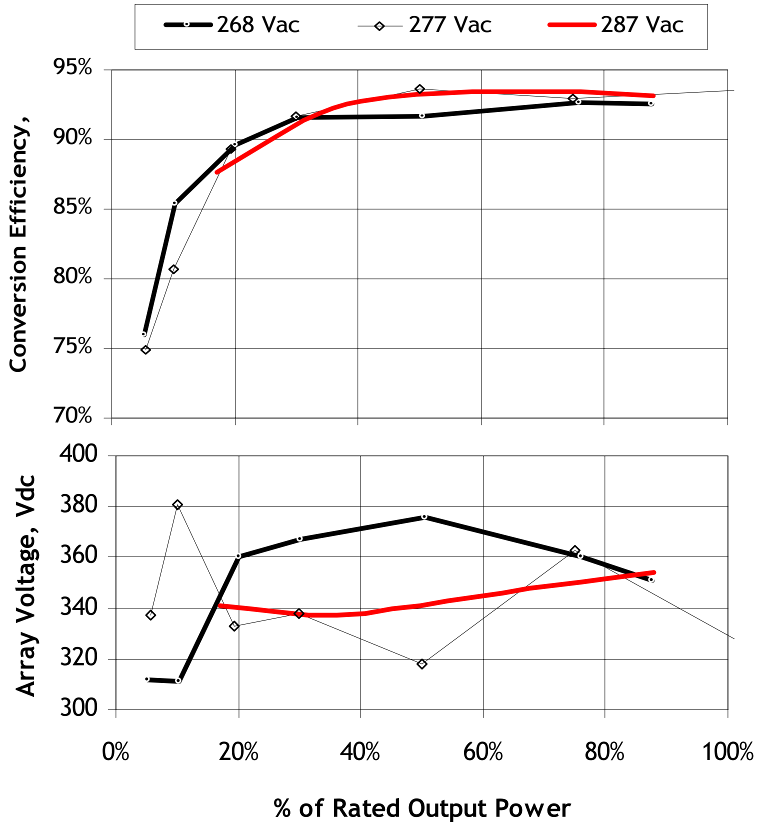

Figure 16 Xantrex PV20208 Efficiency at 45°C Ambient

The unit was tested at two different ambient temperatures: 25°C shown in Figure 15 and 45°C in Figure 16. These two temperatures were used since 25°C is often used by the manufacturer for the nominal ratings of an inverter and 45°C represents a typical maximum ambient temperature for an inverter in many parts of the United States. These tests were done in a thermal test chamber to control the operating temperature. The three curves in each plot represent ac line voltages near the minimum, nominal, and maximum operating points. Finally, the lower plot in each Figure shows the Array operating voltage for each of the data points[4] While the test operator could control ac voltage (using a programmable ac power supply) and, to a lesser extent, array output (by adding or removing one of the array's six strings or simply waiting for the irradiance level to drop), the facility had little control over array voltage, which is a function of the PV array characteristics (configuration and technology), the ambient conditions (irradiance level and array temperature), and the inverter's maximum power point tracking routine. The PV20208 has a specified dc operating range of 300 to 600 Vdc.

In general, the efficiency performance, which includes the isolation transformer, is consistent with highly efficient inverters, with a measured maximum efficiency of over 94%. Coupled with an inverse relationship to array voltage, efficiency for the most part exceeds 92% above the 40% of rated output level. There is a slight decrease in efficiency at the higher ambient temperature,

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[4] Each of the data points in these plots are themselves averages of time-series data

but since the inverters for the IEUA system are mounted within a conditioned space, they are unlikely to see temperature extremes. Low-power performance is especially important for low tilt angle arrays, since the clear-sky irradiance level does not exceed 650 W/m^2 for several months the winter. The efficiency of the PV20208 below 50% or rated power is also quite high, exceeding 80% at or above the 10% power level.

It would have been preferable to have performed these tests at a series of fixed dc voltages and determined both the overall effect of dc voltage on inverter efficiency and the expected efficiency for the actual array and site conditions. The plots suggest a small decrease in efficiency with increasing dc voltage and that the differences between the three ac voltage plots probably has more to do with dc voltage than ac voltage. Under PVUSA Test Conditions (PTC), the RWE Schott array is expected to operate at around 350 Volts and close to 100% of rated output. From Figure 15, the 267Vac and 287Vac plots are both in the range of 350V at the upper end of the power range. From these, we would expect an efficiency of about 93.5-94% at full output power.

As noted in the Sandia report, there was insufficient time to perform the fold-back tests on the inverter. ”Fold back” is the action performed by the inverter to handle high ambient temperatures and high array output both of which can cause excessive inverter temperatures. Many inverters sense when the power electronics reach their upper temperature limit and reduce or fold back power output to prevent overheating. The ambient temperature and power level at which this occurs is of importance to the system installer. If the desired installation location for the inverter often sees high ambient temperatures, it may be necessary to reduce the size of the PV array or provide some additional means to cool the inverter. High irradiance conditions, such as can occur with cloud enhancement, and the resulting high current flowing through the power electronics can also cause high inverter temperatures and result in fold back.

Though specific tests were not performed on the Xantrex 20208 inverter, anecdotal evidence gathered during the testing some provides some insight. When the inverter was initially set up in the environmental chamber for testing, the cooling fan was not operating due to some damage during shipping. This went unnoticed because the fans within the chamber are much louder than the inverter fan. An operating temperature problem became apparent during the first high power tests. The inverter shut down and locked itself off requiring the power to be cycled off to clear the temperature fault.

Once it was soon discovered that the inverter fan was not working (the fan is supposed to operate whenever the inverter is running—i.e. it is not thermostatically controlled), the fan was reconnected and the inverter was able to run at 110% of full output (22 kWac) at an ambient temperature of 45^{o}C without reaching the shutdown temperature. This data suggests that the inverter can handle relatively high ambient temperatures and power levels simultaneously. It also helps to confirm that the IEUA facility is unlikely to experience a thermal shutdown since the array is properly sized for the inverter and the inverter is installed in an interior conditioned space.

5.2.2 MPPT Effectiveness and Tare Loss

Two other important characteristics that were evaluated by Sandia are MPPT effectiveness and Tare losses. MPPT effectiveness (or array utilization, MPPT accuracy, etc.) is a measure of how well the inverter operates the array at the maximum power point on its IV curve. The maximum power point changes as a function of both irradiance level and array temperature, so it is important that the inverter adjust the operating point regularly to maintain peak output. Evaluating MPPT effectiveness is rather tricky and remains a topic of some debate. The Sandia results show that the inverter operates the array within 1-2% of the expected maximum power point, for the few points at which it was evaluated. This is a reasonable result and one should expect an inverter to maintain this effectiveness over a wide range of conditions. Since the uncertainty associated with this measurement is in the same 1-2% range, these results are useful only to say that the unit does not exhibit gross MPPT error. However, MPPT problems continue to crop up in new inverter designs so it is at least somewhat reassuring that none were seen in the PV20208.

Tare Loss is a measure of the power drawn by the inverter from the utility when there is no inverter output. The Sandia results show that the inverter (primarily the transformer) draws 180 to 230 W, depending on the utility ac voltage. Tare loss is one of the factors contributing to inverter efficiency, and a key reason for the exponential drop-off in efficiency at low power levels—by definition, tare losses are constant with respect to output power thus constitute a greater percentage loss at low power. However, unless the inverter is designed to mitigate tare loads at night, by disconnecting the isolation transformer, for example, tare losses will reduce the daily energy production from the system.

For example, take a 20 kW inverter with 200 Watts of tare loss operating an average of 12 hours per day at a capacity factor of 20% (over a period of time period it produces energy equivalent to rated output for 20% of that period of time). For this example, the system produces 20 kW*0.20 *24 hrs = 96 kWh per day (on average). That production value includes the tare losses during the 12 hours of operation but ignores the energy drawn from the utility at night (200 W*12 hours = 2.4 kWh per day or about 2.5% of the system production). Assuming a utility electricity cost to the system owner of $0.10 per kWh, that comes out to about $88 per year in additional operating cost. An inverter with a 15 year life and that does not switch out its tare load at night would need to cost $1,320 (or 6.6 ¢/Watt) less than one that does switch out the tare loads to break even. Conversely, if the manufacturer were to offer a tare load disconnect feature, the end-use price of the feature would have to be less than $1,320 to make economic sense.

Note that this is a very simple analysis that does not take into account the time value of money, the wide range of utility electricity costs, variations in inverter life etc. Tare losses do not usually make or break system performance, but they can be on par with other typically considered system losses, such as wiring and module mismatch, and can cause annoying discrepancies in expected versus measured performance if not accounted for. Many installations with this type of inverter have implemented a field-retrofitted contactor to mitigate this tare loss. Although these contactors have been successful in removing the tare losses, in some cases these contactors have caused other problems such as tripping the serving breaker in the morning because of the inrush current on the transformer. A manufacturer-supplied option or feature would be much more attractive than an aftermarket retrofit from another supplier.

5.2.3 Reliability Estimate

Inverters tend to be the weak link in the PV system reliability chain. Very few applications require high power electronic equipment to operate essentially 24 hours a day 7 days a week with little or no maintenance or operator intervention—such is the lot of the PV inverter. Reliability can be expressed in a number of ways, including Mean Time to First Failure (MTFF)[5], Mean Time Between Failures (MTBF), availability, unscheduled down time, etc. These parameters are statistical measures of some facet of reliability and are preferably based on large samples of unit performance. Depending on the age and popularity of the design, PV inverter manufacturers are getting to the sales volumes necessary to determine these parameters accurately. Very little reliability information is currently available for PV inverters.

In the mid to late 1970's, when PV module manufacturers were experimenting with materials and processes to package silicon PV cells, and again in the mid 1980's when they began manufacturing thin film products, PV module reliability was a major issue. At that time, the Jet Propulsion Laboratory began its "Block" program and developed the initial module qualification tests intended to force manufacturers towards more reliable materials and processes. NREL expanded and codified those tests and the result—with a few, not unexpected exceptions—has been an industry segment with almost unquestioned reliability. Modules with 20-year warranties are common, and there is good reason to believe that in 20 years, modules installed today will still be putting out a reasonable percentage of their initial rating.

These days, more than by the PV modules, system reliability is generally affected by BOS component (wiring, connectors, disconnects, fuses, j-boxes, etc) selection and installation and especially by the inverter. Inverters in particular have gotten a reputation as a reliability concern. It is generally agreed that this reputation is due, at least in part, to the regular changes manufacturer's were making to their designs, materials, component selections, etc. Manufacturers never made enough of one design to work out all of the reliability bugs. Anecdotally, the situation has improved markedly over the past three to five years, especially with those models that count hundreds to tens of thousands of samples in the field.

Sandia National Laboratories' Reliability project is currently undertaking the task of identifying the most important aspects of inverter reliability for the U.S. Department of Energy. As part of this effort, they are forming a baseline understanding of the reliability of existing inverters with actual field data. This effort also includes performing laboratory reliability evaluations on various products to see how these methods correlate with one another. The data from the Sandia project will not be available during the course of this project, so the manufacturer was contacted directly for a response on the issue.

A goal of the high-reliability inverter program and Sandia National Laboratories is a Mean Time to First Failure (MTFF) of greater than 10 years. Whether this is a good or bad number, it is at least an objective goal that can be measured and evaluated. According to Xantrex Vice President of Advanced Technology, Raymond Hudson, Xantrex has approached reliability evaluation in two ways: statistical analysis of historical "returns" data (when and why a product was returned for repairs) and modeling based on component failure data. Details of both analyses are

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[5] MTFF is defined as the time it takes for 50% of the production of an inverter model to experience a first failure.

Figure 17: Final Inverter Installation

proprietary; however, Mr. Hudson did share the following results. First, a Telcordia Technologies SR-332 model component failure analysis performed on a product that is similar to the PV20208 yielded an MTFF of 11.1 years using what he felt were conservative estimates. Secondly, Xantrex returned unit data showed that once a product has matured—that is after initial design flaws are found and corrected, and after the product quality program has been fully established, an MTFF of much greater than 10 years is readily achievable.

Since there are few inverters that have been manufactured relatively unchanged for 10 years, these are obviously extrapolations of available data. It is also important to note that a unit failing within the first year or two after installation—even a "mature" model—is not necessarily an indication that the reliability figures are bogus. It may mean that a customer got a unit in the wrong half of the reliability curve. Without being able to independently verify Xantrex results, the information from the inverter manufacturer helps add to the understanding of inverter reliability, particularly the Xantrex PV20208. However, future results from the Sandia Reliability project should continue to help shed light on where we stand and where we are headed with inverter reliability.

There is one last observation the authors would like to make related to the Xantrex PV-series inverter. This observation is based on first-hand experience and our discussions with engineers involved in the system design and performance evaluation at both RWE Schott Solar and PowerLight Corporation over the past several years. The field experience with the reliability of the PV-series inverter has been significantly better than many other grid-connected inverters over the past 20-25 years. This is a qualitative evaluation and somewhat difficult to quantify, however, given the dozen or so grid-connected PV inverter models that have been fielded in the U.S. over the past 20-25 years, the PV-series inverters are among the most reliable and are currently the most common 3-phase PV inverters in U.S.

5.3 Array Mounting Effects on Performance

The array is mounted at a 10° angle to PowerGuard panel platform. A deflector shield supports the backside of the module with venting at the top and bottom to promote convective airflow while still deflecting a majority of the wind coming from the north side of the array. Although there is a significant amount of room for the heated air behind the module to escape, it is by no means a free air location. It is anticipated that the module will run slightly hotter than a module on an open rack. The difference in height between the front and back edge at a total of 10° angle from the roof surface should provide better year-round performance than the horizontal orientation typical of PowerLight's other PowerGuard product. This is a compromise between a higher tilt angle intended to maximize annual energy, and mounting the modules horizontally to maximize the number of modules on a roof.

As noted previously, there is also a wind loading consideration. The greater the tilt angle, the more the modules are affected by high winds, with uplift from northerly winds hitting the backs of the modules is the greater structural concern. The slight tilt angle provided in the Sloped PowerGuard product also improves the thermal efficiency of the modules allowing them to operate at a cooler temperature than horizontal. In addition to the shading provided by the tilted module, the metal-covered extruded foam base provides an excellent thermal barrier for heat attempting to enter or leave the building. The actual operating temperature of the module and the roof will be measured as part of the ongoing performance evaluation.

5.4 Field Wet Resistance Test

5.4.1 Background

The Field Wet Resistance Test (FWRT) was pioneered at PVUSA[6] where it was used to find failures in the module, array wiring, and junction box insulation systems. As depicted in Figure 18 below, a megohmmeter (often referred to by the trade name "megger"; the test is thus sometimes called, "wet-megger") is used to measure the leakage impedance of an electrically isolated PV array segment that has been sprayed with a weak aqueous surfactant (soapy water).

The array segment is isolated by disconnecting the plus and minus leads from the rest of the array. The megohmmeter is then connected between ground and the array's negative lead (or between the two leads shorted together). When turned on, the megohmmeter raises potential of the array segment by about 500V above ground, measures the resulting current flow that "leaks" back to ground through the module's front and back surfaces, wiring, etc., and calculates the resistance to leakage of the insulation system (Ohm's Law: R=I/V). Done dry (a "dry-megger test") the test will detect gross faults—for example if the washer in the bottom left photo in Figure 18 had completely cut through the insulation on the wire and caused a dead short—and is often performed on wire pulled through conduit to ensure the insulation has not been cut.

When sprayed on the array, front and back, the surfactant solution provides a continuous, slightly conductive path between voids in the insulation system and ground. Unlike plain water, the

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[6] Whitaker, C., A Ryes, T. Townsend, D. King, "The PVUSA Field Wet Resistance Test Procedure", Proceedings of the 16th European Photovoltaic Solar Energy Conference, May 2000.

surfactant increases the surface tension of the solution causing it to "sheet", or create a continuous path, as well as to "wick" into cracks and crevasses. The bottom right photo in Figure 18 shows a nick in the wire that was easily detected even though the exposed conductor was not directly touching any grounded metal parts.

The test is extremely effective at finding loose junction box covers, insufficiently coupled connectors, cuts and gouges in the module backskin. It also tends to reduce the bulk resistivity of the module front and back surfaces as might occur with morning dew or following passing rain. ASTM has established a procedure for performing the test: E 2047-99 *Test Method for Wet Insulation Integrity Testing of Photovoltaic Arrays*.

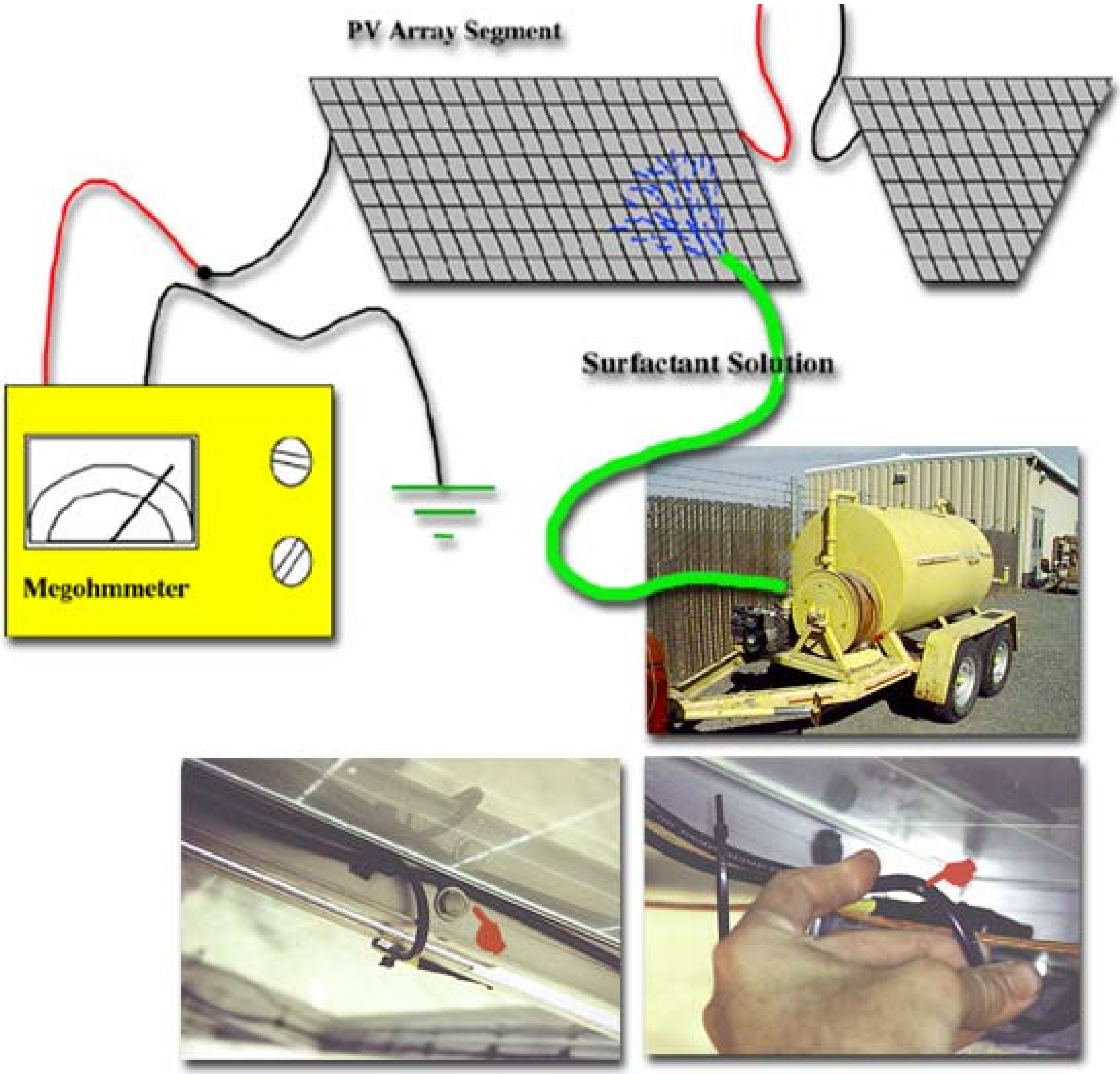

Figure 18 Field Wet Resistance test setup and examples of insulation faults detected

5.4.2 Pass/Fail Criterion

The FWRT has, as its basis, a factory module test[7] that defines an area-related pass/fail criterion of 40 MΩ-m^2, a factor that is divided by the module or array section area to determine an allowable leakage resistance[8]. Originally, the criterion was intended to express corrosion susceptibility in amorphous silicon modules based on charge transfer considerations. Eventually the above criterion was arrived at based on what the industry could deliver and what appeared to be reasonable. Meeting the criterion does not define a level of safety, but failing can indicate a problem or problems with the insulation. Historically, PV array's either pass the test easily or fail miserably; rarely does an array barely pass or barely fail. Thus the test is best often used as an indicator of manufacturing and installation quality.

Table 5 describes each array segment and provides the allowable Leakage resistance for both a single module and the full array. For the PowerLight array, minimum allowable leakage impedance for the array was determined to be 254 kΩ

5.4.3 PowerLight Results

FWRT testing was performed on the PowerLight system on January 6, 2004. The size and configuration of the array made it difficult to keep wet (the first sections drying before the last sections could be wetted) and wetting the back of the array was nearly impossible due to the rear wind deflectors. Measured resistance values (minimum's during the time the meter was being observer) were 6.5 MΩ and 2 MΩ dry and wet, respectively. While wetting the module back surface would have surely reduced the measured values significantly, it does not appear that there are any systemic module design flaws or any installation damage, at least from the data collected.

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[7] See IEEE Std 1262-1995, "IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules." and IEC 60146, "Thin-Film Terrestrial Photovoltaic (PV) Modules - Design Qualification And Type Approval"

[8] For the field test, PVUSA typically allowed an additional 10%—to 36 MΩ-m^2— to account for the additional field wiring, connections, etc

Table 5 Field Wet Resistance Data and Criteria

System Name	Module				Test Segment				
	Model	Voc @ STC, V	Area, m^2	Min Leakage[†], MΩ	No. in Series	No. in Parallel	No. in Segment	Voc @ STC, V	Min Leakage[††], kΩ
1 PowerLight PG	HIP-190BA1	68.0	1.18	33.9	8	15	120	544	254
2 RWE Schott Sunroof	ASE-300-DGF/50-300	60.0	2.43	16.5	8	10	80	480	185
3 Multiple Systems									
a Unisolar	US-116	49.3	1.87	21.4	10	2	20	493	963
b Unisolar	PVL-128	65.7	2.16	18.5	9	2	18	591	926
c Shell Solar	ST40	20.7	0.43	94.0	20	3	60	414	1410
d First Solar	FS-45-D	90.0	0.77	51.7	6	10	60	540	776
e AstroPower	APx-130	18.9	1.72	23.3	20	1	20	378	1048
f Evergreen	EC-102	20.0	1.03	38.7	24	1	24	480	1450
g BP Solar	SX-140	42.8	1.26	31.8	9	2	18	385	1590
h RWE Schott Solar	SAPC-123	21.6	0.90	44.5	20	1	20	432	2003
i Shell Solar	SP-140	42.8	1.32	30.3	9	2	18	385	1515
j AstroPower	AP-110	20.7	0.97	41.0	22	1	22	455	1679

† - Minimum Allowable Leakage Resistance = 400MΩ or 40MΩ-m^2 divided by the module area in m^2, whichever is less.

†† - Includes a 10% reduction to allow for array wiring and other array factors

5.5 Initial System Performance

5.5.1 Rating Conditions

The primary parameter that affects PV system output is the intensity of the sun, or irradiance. PV systems are typically given a peak rating based on an irradiance of 1000 W/m^2, which is a level seen on clear days for several hours around noon throughout much of the US. Other parameters may also be used to specify the cell temperature (or the conditions that affect cell temperature, including ambient temperature and wind speed), spectral content, and operating voltage point. Two sets of ambient conditions are commonly used to specify module and system ratings. Standard Test Conditions (STC)[9] are used by cell and module manufacturers to rate their devices. STC is particularly convenient because the cell temperature specified—essentially room temperature—is easily achievable in laboratory test equipment. However, because PV output decreases with increasing cell temperature and because STC uses a relatively low cell temperature, it tends to overestimate the performance of a system in the field

The Photovoltaics for Utility Systems Applications (PVUSA) project standardized the use of outdoor test conditions considered more indicative of actual array performance. PVUSA Test

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[9] STC = 1000 W/m^2 irradiance, 25 °C cell temperature, Air Mass 1.5 spectrum.

Conditions, sometimes referred to as Performance Test Conditions (PTC)[10], also take into account the impact of module and array design on cell temperature. Under PTC, commercial PV modules typically operate at temperatures of 45 to 50 °C or 20-25°C hotter than the STC-defined cell temperature. Combining the 25°C temperature increase with the cell power-temperature coefficient of -0.25%/°C to -0.5%/°C yields a difference in power of 5 to 13 percent between STC and PTC.

Though the situation is improving, STC and PTC ratings are not applied consistently, and it is not always clear which one is being used. Modules are sold based almost universally on their STC nameplate rating and many novice designers discuss their systems in terms of an STC dc rating. Converting this nameplate rating into a system rating is often done improperly resulting in an overestimation of actual performance. In addition to the temperature relationship, there are other factors to consider, including soiling of modules, inverter operating efficiency, wiring losses, shading, etc. As a rule of thumb, field data from many systems throughout the U.S. suggest that the typical conversion factor from STC module nameplate rating to PTC system rating ranges between 0.7 and 0.8. For example, a system that consists of 200 modules each with an STC rating of 100W (20 kW total STC nameplate rating) will typically produce 14 to 16 kW of ac power at PTC conditions.

In addition to championing the PTC rating conditions, PVUSA instituted a procedure for monitoring the performance of a PV system and calculating the rating of that system[11,12,13,14]. Briefly, the procedure involves measuring system output power, plane–of–array irradiance, ambient temperature, wind speed, and other parameters and performing a regression analysis on the data to find the coefficients A, B, C, and D for the equation

$$P = Irr*(A+B*Irr+C*Tamb+D*WS)$$

where

P = system output power

Irr = Plane-of-array irradiance, W/m^2

Tamb = Ambient temperature, C

WS = wind speed, m/s

The rating is determined by substituting the calculated coefficients for A, B, C, and D and the appropriate PTC conditions for Irr, Tamb, and WS into the above equation and calculating P. PVUSA's experience has shown that the regression model can predict power most accurately when it is used to interpolate, that is, when the range of conditions in the input data set are similar to and surround the conditions under which the predicted power is desired. Because of inherent non-linearity in PV system response as input conditions vary, the model uncertainty increases with the degree of extrapolation.

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[10] PTC = 1000 W/m^2 global irradiance for flat-plate modules, 850 W/m^2 direct normal irradiance for concentrator modules, 20 °C ambient air temperature, 1 m/s wind speed.

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

[12] Whitaker, C, et al, “Acceptance Testing And Rating Grid-Connected PV Systems: Experience at PVUSA”, Presented at Solar '95, Minneapolis, MN, July, 1995

[13] Newmiller, J., et al, PVUSA Instrumentation and Data Analysis Techniques for Photovoltaic Systems, DOE/AL/82993-25, PG&E R&D Report no 95-30910000.3, October, 1995.

[14] Whitaker, C, et al, “Application and Validation of a New PV Performance Characterization Method”, Proceedings of the 26th IEEE PV Specialists Conference, Sept. 1997, Anaheim, CA.

A balanced and well distributed data set may be obtained by requiring that a portion of the irradiance observations be at least as great as the reference irradiance (1000 W/m^2 for flat-plate arrays). A threshold of 10 kWh/m^2 of irradiation at or above the reference irradiance has proven useful to ensure that an adequate input data set is available for calculating PTC ratings. Depending on the time of year, it may take a few days or a few weeks to gather the needed data.

5.5.2 System AC Rating

Mid-winter is a particularly difficult time to meet the irradiance levels needed for this procedure. Due to the low elevation of the sun during the winter and the resulting high solar incidence angle with horizontal and shallow tilt arrays, the plane-of-array irradiance remains below the 1000W/m^2 reference from roughly October through March. Thus, PVUSA ratings on shallow tilt arrays are not performed during this period. For this initial characterization, which occurred in the middle of the winter period, a preliminary rating was developed based on IV curves taken on the PV array plus inverter efficiency estimates from the Sandia evaluation.

Since the IV curves were taken at the input to inverter, all wire losses are included for the dc side of the system. The inverter efficiencies provided in the inverter characterization section also include the ac transformer and ac-side wire losses. This simplified rating includes adjustments to the IV curve maximum power point based on the difference between measured irradiance and module operating temperature and those values at PTC. The effects of incidence angle (between the sun and the array or pyranometer) on module performance and measured irradiance are substantial, particularly in November thru February further complicating an accurate rating of the array. A more accurate rating using the above techniques will be presented in an Interim Report in the April-May time frame.

The high efficiency Sanyo HIT cells appear to be more capacitive than traditional cells[15]. This can potentially cause problems for inverters that attempt quick changes in operating point and with high speed IV curve tracers, such as the Daystar model we use. To lessen the impact of this capacitance IV curves for the PowerLight array were taken by dividing the array into three even segments and taking a curve of each segment. Since the curves were taken in succession and time was necessary to reconfigure the array, each curve was taken under slightly different conditions as shown in Figures 19, 20, and 21. There remains a question as to the accuracy of these curves since the anomalous capacitance may still be affecting the accuracy of the curve tracer measurements. They are presented here for this preliminary rating.

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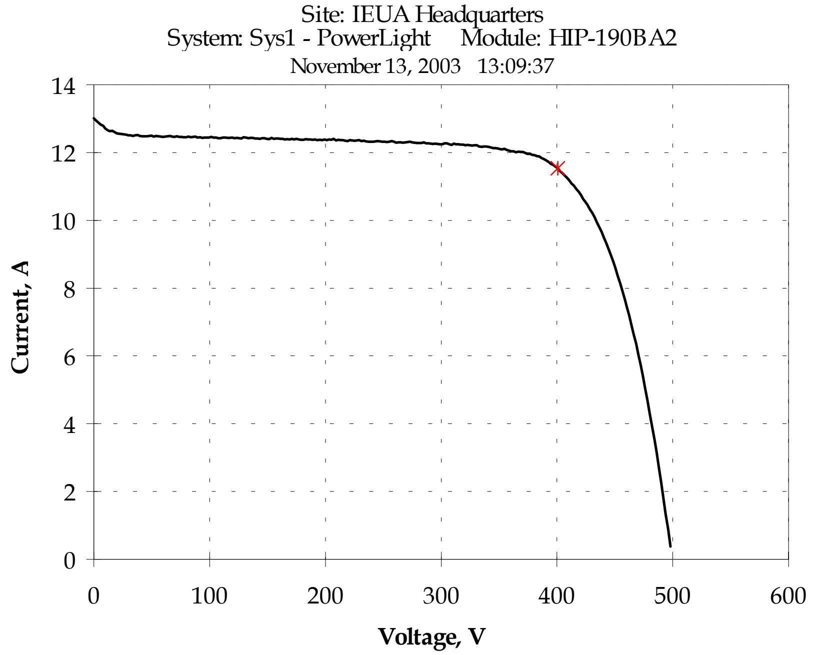
[15] - A result of the cell's high minority carrier lifetime, a measure of how long a freed electron can roam around the cell before recombining with a hole or escaping across the junction and contributing to current generation

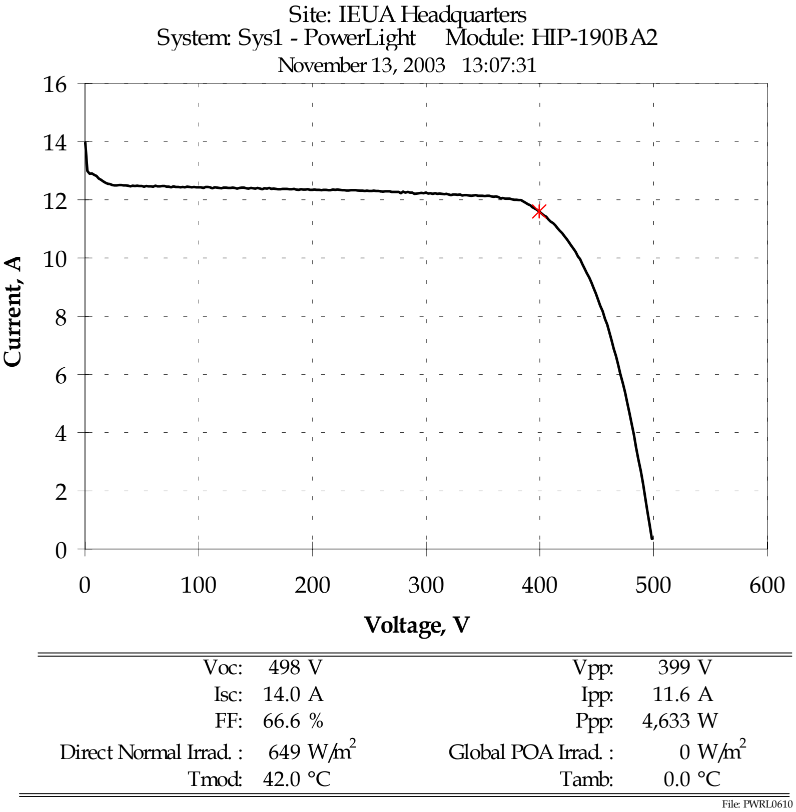


Voc:	498 V	Vpp:	401 V
Isc:	13.0 A	Ipp:	11.5 A
FF:	71.3 %	Ppp:	4,623 W
Direct Normal Irrad. :	640 W/m^2	Global POA Irrad. :	0 W/m^2
Tmod:	41.0 °C	Tamb:	0.0 °C

File: PWRL0105

Figure 19 IV Curve for 1st Third of PowerLight Array

Figure 19 was taken at an irradiance of 651 W/m^2 with the array operating at 42°C and an ambient temperature of 17°C. Under these conditions, the maximum dc power was 4,671 Watts at 395 Vdc and 11.8 Adc. At a PTC irradiance of 1000 W/m^2 and at 20°C ambient temperature the array is expected to rise about 6°C above the temperature measured during the IV curve test. The power loss due to temperature defined by Sandia is –0.32%/°C so the temperature impact will reduce the irradiance-adjusted value by about 2% (6°C x (–0.32%/°C) = -1.92%). The simple method for estimating the performance at a different irradiance than measured is to take the ratio of the measured irradiance to desired irradiance (1000 W/m^2 in our case) and multiply that value by the original performance (1000/651 x 4671 Watts x 0.98(temp) = 7,032 Watts).



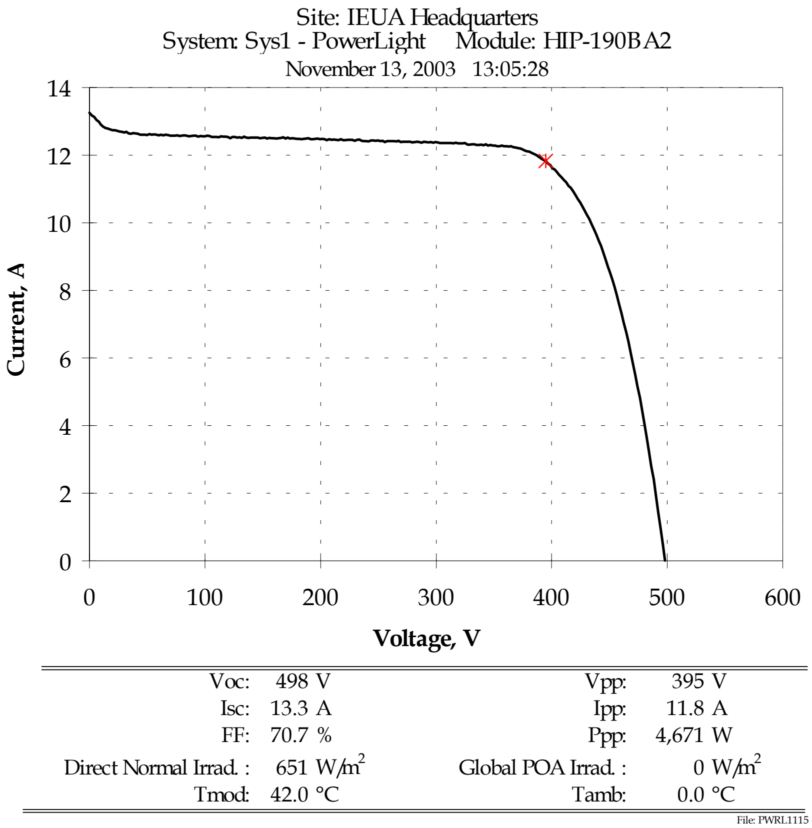
Voc:	498 V	Vpp:	399 V
Isc:	14.0 A	Ipp:	11.6 A
FF:	66.6 %	Ppp:	4,633 W
Direct Normal Irrad. :	649 W/m^2	Global POA Irrad. :	0 W/m^2
Tmod:	42.0 °C	Tamb:	0.0 °C

Figure 20 IV Curve for 2nd third of PowerLight Array

The IV curve in Figure 20 was taken at an irradiance of 640 W/m^2 with the array at an operating temperature of 41^{o}C and an ambient temperature of 17^{o}C. Under these conditions, the maximum dc power was 4,623 Watts at 401 Vdc and 11.5 Adc. Adjusting for the improved performance due to irradiance at 1000 W/m^2 and multipling that value by the original performance (1000/640 x 4623 Watts x 0.98(temp) = 7,079 Watts).

Finally, Figure 21 was taken at an irradiance of 649 W/m^2 with the array at an operating temperature of 42^{o}C and an ambient temperature of 17^{o}C. Under these conditions, the maximum dc power was 4,633 Watts at 399 Vdc and 11.6 Adc. Adjusting for the improved performance due to irradiance at 1000 W/m^2 and multiplying that value by the original performance (1000/649 x 4633 Watts x 0.98(temp) = 6,996Watts).

The sum of these three IV curves makes up the overall dc performance of the array at 21,107 Watts. Adjusting this value by 6% for inverter efficiency yields a preliminary rating of 19.8 kW$_{AC}$ PTC (21,107 Watts x 0.94 (inverter efficiency) = 19,841 kW). It is possible that this value is in error by as much as 15% due to errors caused by incidence angle, measurements, and translation of values to PTC.



Voc:	498 V	Vpp:	395 V
Isc:	13.3 A	Ipp:	11.8 A
FF:	70.7 %	Ppp:	4,671 W
Direct Normal Irrad. :	651 W/m^2	Global POA Irrad. :	0 W/m^2
Tmod:	42.0 °C	Tamb:	0.0 °C

Figure 21 IV Curve for 3rd Third of PowerLight Array

The California Energy Commission and California Public Utilities Commission both use a unique procedure for identifying the size of the system for rebate purposes. Although their sizing calculation takes into account some real-world performance factors, it is not meant to be a system rating, and contractors and system buyers who use this number as a system rating are disappointed when their actual performance does not meet this value. There are many reasons why the measured output of a PV system may never meet the power calculated in the rebate formula, even when the system is operating to its fullest potential. These issues will be discussed further in the subsequent report on system ratings. Using the CEC/CPUC method for determining system size, this PowerLight Sloped PowerGuard system is considered a 20.6 kW system (178.7 W/module x 120 modules x 0.96 inverter efficiency = 20,586 Watts), a value is 4% greater than the rating estimated with limited field data.

5.5.3 System Start-Up Difficulties

During the initial startup testing of the Sloped PowerGuard system, an unexplained performance issue developed in the inverter operation. As the inverter began producing power above the 3- to 5-kW range, the inverter would begin cycling between the maximum power voltage of 430 Vdc to the minimum operating voltage of 285 Vdc every two seconds. Overall energy production was reduced by about 15%. This was estimated by the fact that the inverter would oscillate any time the output was above 5 kW. Since this is when approximately 80% of the energy is delivered by the system, and the actual energy delivered during this condition is about 80% of what it should be, the net effect is about 15%. Neither PowerLight nor Xantrex had any prior knowledge of this issue. Although not completely unique, this system was among the first to marry the high efficiency Sanyo HIP-190BA2 module to a Xantrex PV Series inverter. This module has an aluminum backsheet to enhance its moisture resistance. This aluminum backsheet, combined with the unique characteristics of the high-efficiency cell, produces an input that the inverter struggled to maximum power track.

After several tests on the array, and seeing no improvement from a more aggressive array grounding, it was decided that changes needed to be made to the inverter itself. Xantrex attempted a variety of software changes to try to solve the problem. Ultimately, the majority of the operating issue was resolved by readjusting the expected maximum power voltage of the inverter. Xantrex will continue to refine the software to improve the performance of the inverter with this array. As of the publication of the report, those refinements are still under development, but should be available by the end of May 2004.

5.5.4 Array Area Requirements

System conversion efficiency affects the area required to provide a given output power. With 1000 W/m^2 of incident irradiance, a 5 percent efficient system requires 20 m^2 of array area to produce 1kW of power (215 ft^2/kW) while a 10 percent efficient system requires 10 m^2/kW (108 ft^2/kW, which is often rounded to100 ft^2/kW and used as a rule-of thumb). The Sloped PowerGuard system has an overall footprint area of 227 m^2 (2440 ft^2). The preliminary rating for this system is approximately 19.8 kW so the area requirements for this system are 11.5 m^2/kW (123 ft^2/kW), or 8.72% efficiency. The extra area needed for row spacing, higher operating temperatures, and system losses due to wiring and inverters all contribute to the difference between module efficiency and system efficiency. Even with all these losses, the power density of this system is the highest in the project.

5.5.5 Energy Production

The energy produced by a PV system is a function of local solar resource, the system rating (PTC), the orientation of the system (flat, tilted, or tracking), shading that might occur due to adjacent structures or obstructions such as trees, and a few other minor factors. Estimating energy for a year is easier than for a day, because many of these factors tend to average out over a year (temperature effects, for example).

Energy production is a complex combination of all of these parameters each varying independently over time. The output of the PV system varies hourly, daily, monthly, even from year to year. Nonetheless, rules of thumb can be used to provide a planning estimate of annual energy production. To help estimate energy production, daily solar irradiation is calculated by month or by year from a solar reference handbook or other data source. From this average number, monthly and yearly energy production estimates can be made.

If the average daily irradiation (a measure of solar energy) incident on a given photovoltaic surface in Chino, California (in kWh/m^2) is divided by the irradiance at rated system output (in kW/m^2), the result is the number of hours per day that the system would have had to operate at its rated output to collect the same amount of input energy[16]. Conveniently, the rating irradiance is 1000 W/m^2 or 1.0 kW/m^2, thus the listed daily irradiation values are numerically equivalent to peak operating hours (e.g. 5.0 kWh/m^2 ÷ 1.0 kW/m^2 = 5.0 h)

If the system rating does not account for factors such as soiling, inverter and array operating efficiencies, etc., it may be necessary to reduce the energy estimate by a factor of 0.9 to 0.95. Again, it is important to note that normal month-to-month weather variations can cause much greater deviations from expected performance than this.

The system rating used by the California Energy Commission (CEC) for the rebate program ignores a number of system performance details and thus tends to overpredict system output. Therefore, it is wise to apply a factor of 0.8 to 0.9 to account for those performance details and bring the rating values in line with field performance of PV systems. For simplicity of cost analysis, the CEC rating is often used as the defacto system rating since the financial incentives are based upon this rating procedure. Note that this over-prediction is a known consequence of the CEC rating method, which was designed to be as simple as possible for consumers to understand.

So, for example, an estimate of the annual energy produced by a horizontal system rated at 10 kW (using the CEC/CPUC rating system, and annual average irradiation in Chino, CA) can be calculated as:

10 kW * 5.0 h * 0.9 = 45 kWh/day or 16,425 kWh/year

In July, with an average of 8.2 kWh/m^2 of irradiation, the system would provide

10 kW * 8.2h *0.9 = 74 kWh/day or 2289 kWh for the month.

Taking the CEC rating for the PowerLight Sloped PowerGuard system of 20.6 kW and multiplying by a factor of 0.80 to 0.90 as suggested above yields an estimated ac rating of between 16.5 and 18.5 kW. This range slightly more conservative than the IV-curve -based rating of 19.8 kW. If the annual average daily irradiation in Chino for a 12^{o} tilt facing SSW is 5.7 kWh/m^2/day, then the expected annual energy production from this system will be:

19.8 kW * 5.7 h = 112.86 kWh/day or 41,194 kWh/year

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[16] This assumes the rating is truly indicative of system performance at that location and for the period in question. Again, for this planning estimate, the assumptions are reasonably conservative.

6 Monitoring, Data Acquisition, and Outreach

A primary focus of the Commonwealth BIPV Evaluation Project is to enhance the awareness of the owner (Commonwealth Energy) and the site host (Inland Empire Utilities Agency) as to the relative attributes and benefits of various commercial PV systems. Another important aspect of this project is that of educating the public, including consumers and PV installers, about important characteristics of various systems.

From an O&M point of view, the consistent scrutiny of system performance will also help to identify system malfunctions quickly so they can be rectified. Experience has shown that systems that are installed out of sight are often neglected. In systems with no monitoring provisions, small malfunctions can cause a system to trip offline and remain in that state for extended periods before site personnel notice the problem.

The monitoring system used at the IEUA headquarters includes a Campbell Scientific CR23X datalogger that monitors the dc output of the PV array and the ac output of the inverter (see Figure 22). This monitoring system also measures and records the solar irradiance, ambient temperature, wind speed, and selected operating temperature of the PV arrays. Ten-minute averages of this data are stored on an on-site computer and transmitted to an off-site computer that places the data into a database. Information from the database is automatically extracted, summarized, and made available via the Internet (http://www.pierminigrid.org/pubproject32.html).

Initially access to the data will be limited to the PIER project team and the Technical Review Committee. However, once the data flow process is found to be effective and reliable, the information will be made available on the Internet to the general public. One of the goals of the project is to make this information readily available so that those involved in the purchase and installation of PV systems have a means of gathering unbiased information and formulating their system selections. Product manufacturers are also encouraged to view and comment on this information to ensure that this resource provides a balanced perspective that can augment materials that they routinely supply with their products.

Figure 22 Data Logger Box, Transducer Box, and Overall Setup

7 Review of Costs

7.1 Availability of cost-share and rebate funds

Initially established through the State's Electric Utility Restructuring plan, both the California Energy Commission and the California Public Utilities Commission manage rebate programs to offset the capital cost and encourage the use of PV equipment. The CPUC Self-Generation Program offers $4,500/kW for PV and other systems between 30 kW to 1 MW, with a cap of 50 percent of the installed cost. The PowerLight system was installed simultaneously with 11 other systems totaling a rebate system size of 60 kW and is therefore eligible for the CPUC Self-Gen Program.

7.2 Cost Summary

The following table provides a breakdown of the costs for a 20 kW PV system. These costs come from the actual expenditures on the project. See Table 6 for a summary of these costs. Some of the costs for site engineering and maintenance are estimated by the percentage of time and effort relative to the overall project since several of the activities were parallel for all 60 kW of the project.

Table 6 Cost Summary of 20 kW PV System

Item	Costs
System Hardware and PowerLight Engineering	$150,000
Shipping	$2,400
Site Engineering and Installation	$13,000
Total Costs	$165,400
CPUC Self-Gen Incentive	$82,700
Funding Provided by Commonwealth Energy	$82,700

Annex A Sandia Inverter Performance Report

Sandia National Laboratories

Operated for the U.S. Department of Energy by

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Sigifredo Gonzalez
SMTS

November 14, 2003

Chuck Whitaker
Bill Brooks
Endecon Engineering

Ward Bower
Sandia National Laboratories

Gentlemen,

Sandia National Laboratories Distributed Energy Technologies Laboratory (DETL) recently evaluated three grid-tied photovoltaic inverters provided by the California Energy Commission's Public Interest Energy Research (PIER) program. The purposes of the evaluations were to benchmark performance of the inverters for PIER and to exercise the draft "Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic systems". Sandia National Laboratories and Endecon Engineering have developed this test protocol jointly. When completed, it is intended to be used for evaluating and certifying the performance of grid-interconnected photovoltaic inverters.

The draft test protocol includes procedures to evaluate functionality and to verify selected inverter performance characteristics. It includes a relatively extensive series of tests procedures intended to validate the manufacturer's inverter performance specifications. Due to the time that would have been required to exercise the entire protocol, a subset of tests was agreed upon and performed. As is standard procedure at DETL, dc power was provided by a PV array, which replicates the actual conditions in the field and avoids uncertainties introduced by using a dc power supply in place of an array. A limitation of using an array is the lack of flexibility in the dc operating voltage, which is dependent on the number of modules in series and the array temperature. Evaluations focused on inverter efficiency, maximum power point tracking accuracy, and the tare losses at different power levels, different voltage levels, and different ambient temperature levels.

Data Acquisition System

Data was monitored and recorded using a National Instruments LabView-based data acquisition system (DAQ). The DAQ consists of a 333 ksample/second 16-bit resolution A/D digitizer (5052E), several 100 ksample/second amplifier/multiplexer signal conditioning modules (SCXI1100) and TBX-1303 terminal blocks. Ac and dc voltages transducers are Tektronix P5200 High Differential voltage probes. Dc current transducers are Empro shunts with OSI VT7-016D isolation amplifers. Ac current transducers are Ion Physics C1L CT's. The DAQ is calibrated end-to-end (voltages and currents are introduced at transducers and readings are recorded in LabView) using calibrated NIST-traceable secondary ac and dc voltage and current standards.

Xantrex PV20208 tests

The PV20208 is a three-phase, grid-connected inverter with a maximum continuous power rating of 20 kWac. Its nominal output voltage of 208 V line-to-line was stepped up to the utility interconnection voltage of 480 V line-to-line using a 20-kVA low-loss transformer provided by Xantrex for use with the inverter.

PV20208 Test Configuration

The Xantrex PV20208 grid-interconnected PV inverter was connected and evaluated as shown in figure 1. Figure 2 shows the inverter inside the temperature chamber used to conduct evaluations at elevated ambient temperatures.

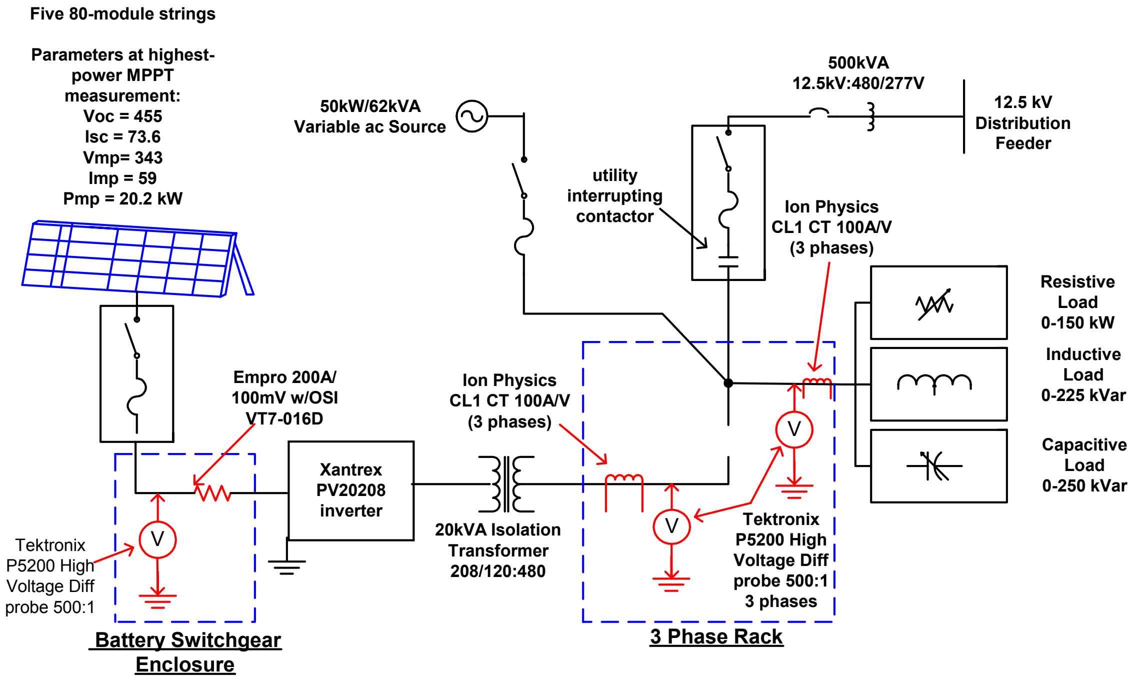

Figure 1. PV20208 Test Configuration

Figure 2. PV20208 inside temperature chamber

PV20208 Tare Loss

The first tests conducted on the PV20208 were measurements of tare losses, which are defined as power losses when the inverter is not operating. These occur when there is insufficient PV power for inverter operation (such as at night) or when the inverter is not operating due to either loss of utility or to anomalies on the utility that are outside the inverter's operating range. A tare loss consists of ac power required to magnetize the isolation transformer plus a relatively small amount of power required to energize the inverter's controls. Tare loss evaluations were conducted at the inverter's lower, nominal, and upper operating ac voltage ranges, and then averaged at each of the 3 voltage levels. Figure 3 shows the results of these evaluations, and table 1 shows the corresponding data. These evaluations were conducted with the transformer relatively cool, e.g. the inverter was off all night with no ac applied to the inverter, and the tests were conducted after ac was applied to the transformer and inverter. Slightly higher losses could be expected after the transformer was energized for a period of time sufficient to raise its operating temperature.

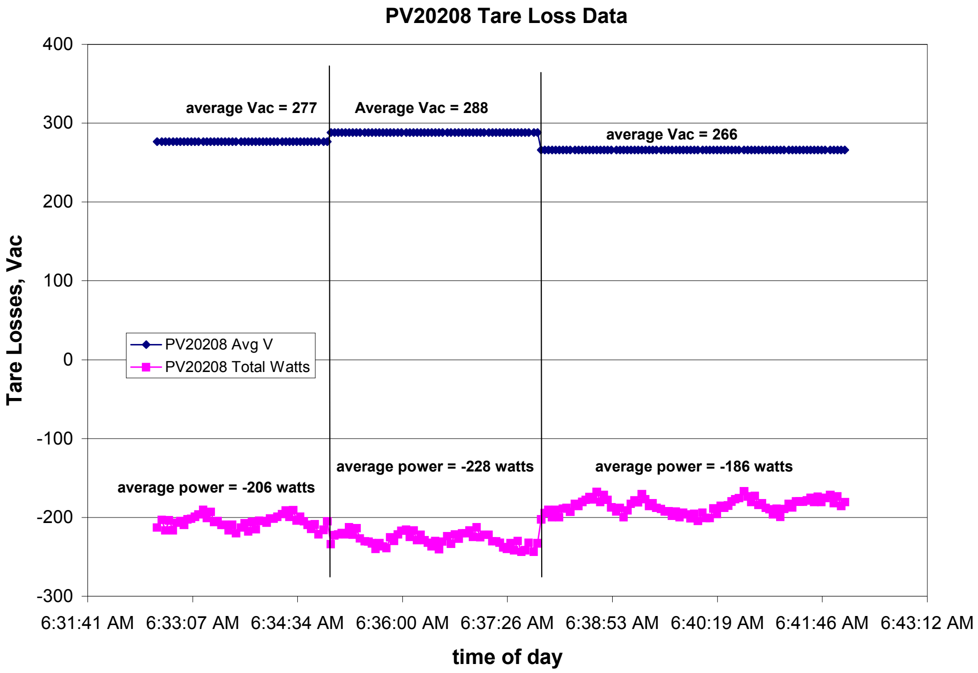

Figure 3. PV20208Tare loss (non-operational loss)

Table 1. PV20208 Average tare loss data

Average Line-to-Neutral Voltage (Vac)	Average Power Loss (Wac)
266	186 watts
277	206 watts
288	228 watts

PV20208 Efficiency

Conversion efficiency is defined as the ratio of total three-phase ac output to dc input power. Efficiency data were obtained at ambient temperatures of 25 °C and 45 °C for three different ac line voltages. The inverter was placed in a temperature chamber as shown in figure 2, and ambient temperature was maintained to within ± 3°C per the test protocol. A power-electronics-based variable ac power source (Pacific Power Source MS Series) was utilized in place of the grid to provide the ability to adjust the ac voltage. Dc power was provided by a PV array consisting of 5 PV strings, each having a rated power of approximately 4 kW. Different power levels (percentages based on a nominal 20kW rating of the inverter) were obtained by varying the number of strings in the array and by acquiring data at various irradiance levels. Tables 2 and 3 summarize average data characterizing the inverter's efficiency at the two temperatures. The data underlying these tables is being provided to Endecon separately from this report.

Table 2. PV20208 Efficiency at 25° C ± 3°C, % of rated based on 20kW inverter rating

Test #	Vdc	Vac	Power Level	% of rated power	Ambient Temperature	% Efficiency
A	337	267	3466	17%	27	89%
A	340	267	7592	38%	27	93%
A	347	268	11298	56%	27	93%
A	341	268	15041	75%	27	93%
A	339	268	18798	94%	28	93%
Test #	**Vdc**	**Vac**	**Power Level**	**% of rated power**	**Ambient Temperature**	**% Efficiency**
B	316	279	1239	6%	24	76%
B	316	279	2862	14%	24	87%
B	318	280	6812	34%	24	93%
B	319	279	10602	53%	24	94%
B	318	279	14630	73%	24	94%
B	318	279	20441	102%	24	94%
Test #	**Vdc**	**Vac**	**Power Level**	**% of rated power**	**Ambient Temperature**	**% Efficiency**
C	339	287	1015	5%	25	71%
C	349	287	2007	10%	24	82%
C	372	287	4014	20%	25	88%
C	393	287	6019	30%	25	91%
C	390	288	10003	50%	25	93%
C	376	288	15020	75%	25	93%
C	344	288	19366	97%	27	94%

Table 3. PV20208 Efficiency at 45° C ±3°C, % of rated based on 20kW inverter rating

Test #	Vdc	Vac	Power Level	% of rated power	Ambient Temperature	% Efficiency
A	312	267	1039	5%	42	76%
A	311	267	2054	10%	43	85%
A	360	268	4027	20%	45	90%
A	367	268	6024	30%	44	92%
A	376	268	10075	50%	45	92%
A	360	269	15180	76%	44	93%
A	351	269	17528	88%	45	93%
Test #	**Vdc**	**Vac**	**Power Level**	**% of rated power**	**Ambient Temperature**	**% Efficiency**
B	337	277	1116	6%	42	75%
B	381	278	1997	10%	43	81%
B	333	278	3861	19%	45	89%
B	338	278	6002	30%	45	92%
B	318	276	9989	50%	46	94%
B	363	277	14984	75%	44	93%
B	328	277	20175	101%	41	94%
Test #	**Vdc**	**Vac**	**Power Level**	**% of rated power**	**Ambient Temperature**	**% Efficiency**
C	341	286	3484	17%	45	88%
C	337	287	7286	36%	44	92%
C	343	287	10870	54%	44	93%
C	349	288	14360	72%	44	93%
C	354	288	17690	88%	46	93%

PV20208 Maximum Power Point Tracking (MPPT)

Correctly implemented MPPT algorithms enable photovoltaic inverters to fully utilize the available power from the PV array. To determine how effectively the inverter did this, first the dc power into the inverter was measured. The array was then disconnected, and an IV curve was quickly taken using a Daystar IV curve tracer. Table 4 shows the comparison between the maximum available power measured by the curve tracer and the power extracted by the inverter for different power levels. MPPT functionality was evaluated over the lower-to-middle range of operating voltages.

Table 4. PV20208 Array Utilization Data

Curve Tracer Pmax (W)	Inverter Pdc (W)	Array Utilization
4055	4069	100
8007	7808	98
12043	11922	99
16253	16171	99
20235	20104	99

Conclusion

The Xantrex PV20208 inverter has undergone efficiency evaluations while operating at different ac voltages and different ambient temperatures. Tare losses and array utilization were also measured. The test protocol required tests to be conducted at different ac and dc voltages. The tests were conducted at the required ac voltages but the tests requiring minimum and maximum dc voltages could not be conducted within the allotted time utilizing a PV array as the dc source.

Because of time constraints, power fold-back was not evaluated. The PV20208 initially had a fan that became disconnected during shipment, therefore during operation at rated power the inverter would quickly reach high operating temperatures and shut down in a locked out condition, meaning power needed to be manually cycled by the operator to clear the fault. The unit never experienced a high-temperature trip after the fan was properly connected. The high-temperature trip should be repeated to determine if the locked out condition was characteristic of the inverter or an artifact of the loose fan connection.

This preliminary evaluation did find one area where the draft test protocol needed to be slightly adjusted. The ac voltage limits per UL1741 and IEEE 1547 are –12% and +10% of nominal, but inverter manufacturers may choose a narrower operating window. If so, the inverter will not operate at the lowest voltage required by the draft test protocol.

Exercising the draft test protocol and examining the data have emphasized the desirability of performing different voltage and temperature tests at the same power levels. Unless this is done, it may be difficult to come up with any conclusion. This may require developing confidence that a dc power supply or PV simulator can be used to obtain results that are consistent with those obtained using a PV array. As the draft protocol points out, disabling the operation of the inverter's MPPT may be necessary.

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