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

Performance Report of the First Six Months of Exposure and Operation for the Comprehensive Large PV System Comparison

Project 3.2 Building Integrated PV Testing and Evaluation Project

Task 3.2.2a (6) 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 six-month report summarizes the performance of the 12 system segments and is based on the installed data acquisition systems. After this series of performance reports are written summarizing the performance over a 12-month period, a Consumer Confidence Guideline will summarize all of this information in a format that is more consumer friendly.

Six-Month Performance: The initial performance ratings were established when the sun was at very low angles and since the arrays is nearly horizontal, the peak irradiance on the arrays was too low to provide an official rating—the official rating is presented in this report. Table ES-1 shows system efficiencies and system ratings calculated for each individual system segment. The Rating$_{PTC}$ column represents actual field measurements whereas Rating$_{CEC}$ and Rating$_{STC}$ are based on manufacturer-supplied data and are not intended to reflect actual field performance. The ratio of PTC/STC provides a limited indication of the value of the system relative to the STC rating.

Table ES-1: Summary of System Efficiencies and Ratings

Array	Manufacturer	Model	Mount	Area	Eff$_{SYS}$	Rating$_{PTC}$	Rating$_{CEC}$	Rating$_{STC}$	**PTC/STC**	Technology
				sq.m.	%	kW	kW	kW	rating ratio	
PL	Sanyo	HIP-190BA2	Sloped PG	226.7	7.93	17.97	20.59	22.80	0.79	HIT c-Si/a-Si
RWE	RWE/Schott	300-DGF/50	SunRf FS	241.5	7.61	18.38	20.67	24.00	0.77	EFG-poly-Si
A	UniSolar	US-116	Quilt	45.4	4.09	1.86	2.07	2.32	0.80	3-a-Si
B	UniSolar	PVL-128	SIT	52.0	3.63	1.89	2.05	2.30	0.82	3-a-Si
C	Shell Solar	ST40	Custom	37.7	5.66	2.13	1.99	2.40	0.89	CIS
D	First Solar	FS-45	EZ Mnt	60.9	3.44	2.10	2.41	2.70	0.78	CdTe
E	AstroPower	APx-130	Quilt	44.5	3.66	1.63	2.11	2.60	0.63	pc-Si-Film
F	Evergreen	EC-102	Custom	34.4	5.54	1.90	2.06	2.45	0.78	SR-poly-Si
G	BP Solar	SX-140	Custom	31.3	6.23	1.95	2.09	2.52	0.77	pc-Si
H	RWE/Schott	SAPC-123	Custom	28.4	6.83	1.94	2.03	2.46	0.79	pc-Si
I	Shell Solar	SP140	Custom	32.7	5.85	1.91	2.13	2.52	0.76	mc-Si
J	AstroPower	AP-110	Custom	30.3	6.03	1.83	2.02	2.42	0.75	mc-Si
TOT				865.9	5.54	55.49	62.22	71.49	0.78	

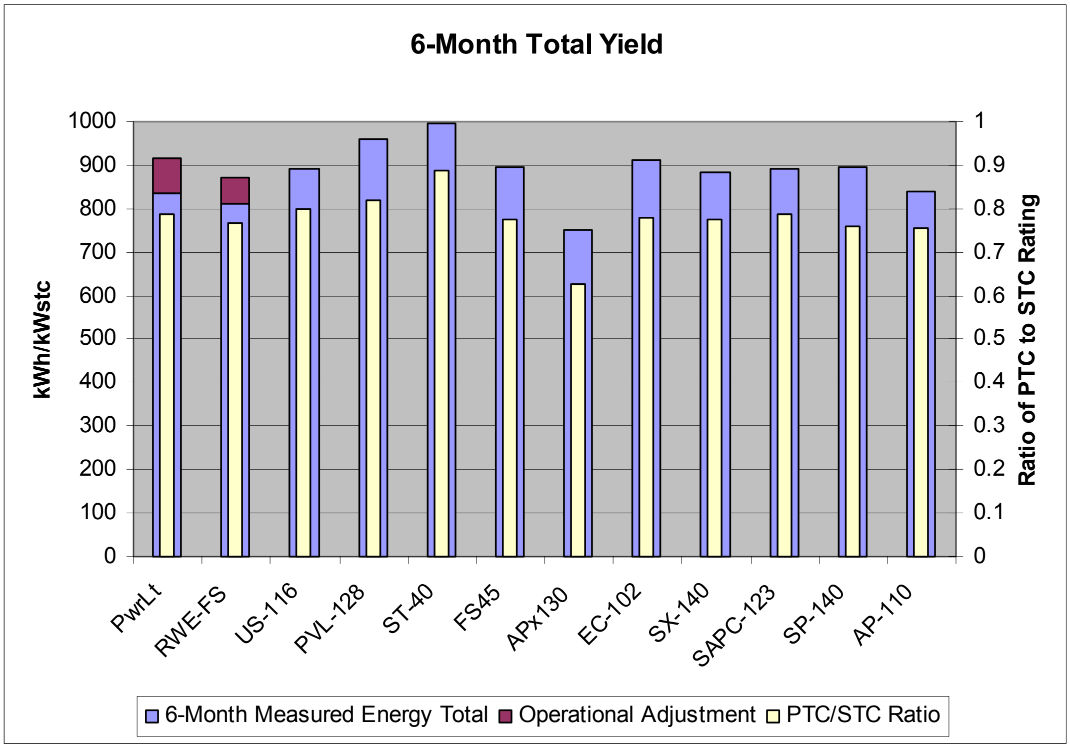

Figure ES1: Summary of Energy Performances and Rating Ratios

Conclusions

The 12 separate system segments under test in the project provide a unique opportunity to evaluate commercially available products in a side-by-side comparison. Figure ES-1 shows that the ratio of PTC/STC rating tracks the delivered energy from each system. This correlation illustrates that the energy production of a variety of systems is very similar per rated PTCac Watt, but not similar per rated STC Watt. This confirms that properly rated systems perform consistently in comparison to one another.

However, challenges still exist in designing and rating systems appropriately particularly for new systems and new mounting configurations. This was evident in the fact that measured and predicted operating temperatures and voltages did not always match as expected. The Solar Quilt systems operated at temperatures higher than expected, particularly for the AstroPower APx-130 array, causing that system segment to operate below initial performance expectations.

The ac voltage window of the Xantrex PV-20208 inverters is very narrow, which caused some operation problems. These problems subsided when the voltage window was expanded with the permission of the serving utility. The few minor issues encountered during the first 6 months of operation—most of which can be related to the more developmental nature of some of the products selected—do not detract from the basic conclusion that PV systems designed and installed properly, and rated appropriately, perform as expected.

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1. Introduction

A key aspect of energy system affordability is a realistic assessment of component and system performance and longevity. For years, the PV industry has relied on manufacturer literature to judge the performance and suitability of products for various applications. As a result, installing contractors are confronted with products that have no third-party evaluation and must use their clients as field-test guinea pigs. Equipment often has optimistic performance claims, and the customer is routinely disappointed with the actual performance of their system. This report is the first of a series of reports on the performance of the 12 systems that make up the Large PV System Comparison for the Commonwealth Biogas/PV Micro-Grid Renewable Research Program. This report covers the first six months of operation for these systems.

This performance information is intended to be used initially by the Commonwealth team for upcoming purchase decisions, and it is intended to be used by participants in the Energy Commission Emerging Renewables Program to supplement and field-verify performance ratings established by others. It is anticipated that the demand for this information will become strong as this information becomes available and as the value of third-party performance is better understood by the PV industry.

1.1. Comprehensive Large PV System Comparison

The Large system evaluation covers the selection, installation, operation, monitoring, and evaluation of three independent 20 kW PV systems. These systems are intended to be indicative of the kinds of Building Integrated PV hardware that is to be installed under Project 3.3 of the Commonwealth PIER program. While these sample systems may not all represent actual building integrated products (i.e., those designed to replace traditional building roofing, glazing, or cladding materials), they are representative of currently available electrical technologies (PV cells/modules, structures, inverters, wiring, etc.) that are or can be used to make BIPV products.

The performance measures in this report are categorized by whether special tests or long-term testing is needed to obtain the necessary information. Special tests are of a short-term nature and are typically done at the initial startup of a system. These special tests may also be repeated throughout the life of the system to determine how the initial characteristics may have changed. Long-term tests are essentially performed on a continuous basis to track performance relative to established standards.

2. Special Short-term tests

Special short-term tests are those that are performed to provide input on specific components and their operation that are relevant in the system evaluation. These tests may be performed over a few hours or days, and may be performed on components of the system rather than on the system as a whole or with the system operating in a particular mode. These short-term tests are generally accomplished with apparatus that is setup for a short duration. Examples of some special testing that is performed follow.

2.1. System Ratings

The first concern of a new PV system owner is, "did I get what I paid for?" While the amount of energy delivered better defines "what I paid for", a key (and more immediately available) measure of system performance is the system rated output power. Regardless of how well the advertised rating matches actual system performance, rated output power is the value used most often in economic calculations (for example, the Emerging Renewable Rebate Program administered by the California Energy Commission: www.consumerenergycenter.org/erprebate). In addition, the ability to estimate the expected hours of "peak" (i.e. at rated output) operation over a year provides a simple energy estimate for the system, one that can be quite accurate if the system is rated at conditions that are indicative of peak conditions for the installation.

Each system installed under the project is rated according to the methods established by PVUSA. This rating (Rating$_{PTC}$ in Table 1 below) is compared to the value provided by the manufacturer (Rating$_{STC}$, the simple sum of module STC ratings) and the rating established by the Emerging Renewable Rebate program (Rating$_{CEC}$).

Table 1: Summary of System Efficiencies and Ratings

Array	Manufacturer	Model	Mount	Area	Eff$_{SYS}$	Rating$_{PTC}$	Rating$_{CEC}$	Rating$_{STC}$	**PTC/STC**	Technology
				sq.m.	%	kW	kW	kW	rating ratio	
PL	Sanyo	HIP-190BA2	Sloped PG	226.7	7.93	17.97	20.59	22.80	0.79	HIT c-Si/a-Si
RWE	RWE/Schott	300-DGF/50	SunRf FS	241.5	7.61	18.38	20.67	24.00	0.77	EFG-poly-Si
A	UniSolar	US-116	Quilt	45.4	4.09	1.86	2.07	2.32	0.80	3-a-Si
B	UniSolar	PVL-128	SIT	52.0	3.63	1.89	2.05	2.30	0.82	3-a-Si
C	Shell Solar	ST40	Custom	37.7	5.66	2.13	1.99	2.40	0.89	CIS
D	First Solar	FS-45	EZ Mnt	60.9	3.44	2.10	2.41	2.70	0.78	CdTe
E	AstroPower	APx-130	Quilt	44.5	3.66	1.63	2.11	2.60	0.63	pc-Si-Film
F	Evergreen	EC-102	Custom	34.4	5.54	1.90	2.06	2.45	0.78	SR-poly-Si
G	BP Solar	SX-140	Custom	31.3	6.23	1.95	2.09	2.52	0.77	pc-Si
H	RWE/Schott	SAPC-123	Custom	28.4	6.83	1.94	2.03	2.46	0.79	pc-Si
I	Shell Solar	SP140	Custom	32.7	5.85	1.91	2.13	2.52	0.76	mc-Si
J	AstroPower	AP-110	Custom	30.3	6.03	1.83	2.02	2.42	0.75	mc-Si
TOT				865.9	5.54	55.49	62.22	71.49	0.78	

Technology abbreviations for Table 1:
3-a-Si: Triple-Junction Amorphous Silicon
HIT c-Si/a-Si: Mono-Crystalline Silicon surrounded by Thin Amorphous Silicon layer
CdTe: Cadmium Telluride
CIS: Copper Indium Disellinide
EFG: Edge-defined Film-fed Growth Poly-Crystalline Silicon
mc-Si: Mono-Crystalline Silicon
pc-Si: Poly-Crystalline Silicon
pc-Si Film: Poly-Crystalline Silicon Film
SR-poly-Si: String Ribbon Poly-Crystalline Silicon

The STC and CEC rating methods are not as accurate in determining actual field performance and tend to over predict instantaneous performance by 10-20%. Note that there are three reasons for the superiority of the PTC_{ac} rating in predicting system performance [1, 2]. First, the PTC_{ac} rating represents actual measured performance of the system whereas the STC and CEC ratings are based on manufacturer's published module data. Second, PTC_{ac} takes into account all of the loss mechanisms (cell conversion efficiency, cell and module mismatch losses, array operating point, various wiring losses, inverter efficiency, etc.); STC rating only considers losses at the module level; CEC rating adds to that a best case inverter efficiency correction. Finally, both PTC_{ac} and CEC use realistic ambient conditions (PTC_{ac}) representative of most of the United States, whereas STC are defined primarily for convenience of testing in a laboratory setting. Throughout this report and this project, PTC_{ac} ratings are the primary standard for parameters that use system rating. However, STC or CEC rating-based parameters are also reported for comparison purposes. The ratio of PTC_{ac} to STC rating is one indicator of the value of a PV system. The higher the ratio, the closer the individual product rating compares with the actual field performance of the whole system.

2.2. Inverter Efficiency

The efficiency with which array dc output power is converted to ac power will vary due to several effects, including output power level, input and output voltages, and the operating temperature of the power electronics (which depends on power level and ambient temperature). As reported in the initial characterization report, each inverter model was evaluated for efficiency over a range of conditions..

Energy-based inverter efficiency (based on measured input and output energy over some period) takes into account the effects of system design (nominal array operating voltage and peak output power) and climate (how changes in irradiance, temperature, soling, etc. affect actual array voltage and output power). For a system-level evaluation such as this, annual, semi-annual, or daily inverter efficiency is a more relevant number than peak efficiency. Table 2 below shows the efficiency values from the field-measured data for the first six months of operation to establish the average efficiency for the unit. The Operating Energy Efficiency of the inverter refers to the daytime efficiency based on the available operating data over the six month period. The period from June 2-12 was removed from the analysis of the PV-20208 inverters since a faulty firmware upgrade caused the inverters to operate at extremely low power and thus low efficiency. Figure 1 and Figure 2 show a portion of the field-measured data that was used to develop Table 1. Estimated Net Efficiency in Table 1 includes the night energy losses that are not captured in the Operating Energy Efficiency. These losses average nearly 2% for the PV-20208 inverters and are primarily the result of the isolation transformer idle losses. The SB-2500U inverters do not have night energy losses since these inverters disconnect their output transformers at night. Also provided is the stated inverter efficiency from the Emerging Renewable Rebate Program list of eligible equipment (www.consumerenergycenter.com/cgi-bin/eligible_inverters.cgi).

Table 2: Measured Average Inverter Efficiencies

Inverter	System	AC	CEC List	Operating	Estimated Net Efficiency
		(Volts)	Efficiency	Energy Efficiency	(with Nighttime Losses)
PV-20208	PwrLt	480	96	91.5%	89.8%
PV-20208	RWE	480	96	92.5%	90.7%
SB-2500U	EC-102	208	94	91.3%	91.3%

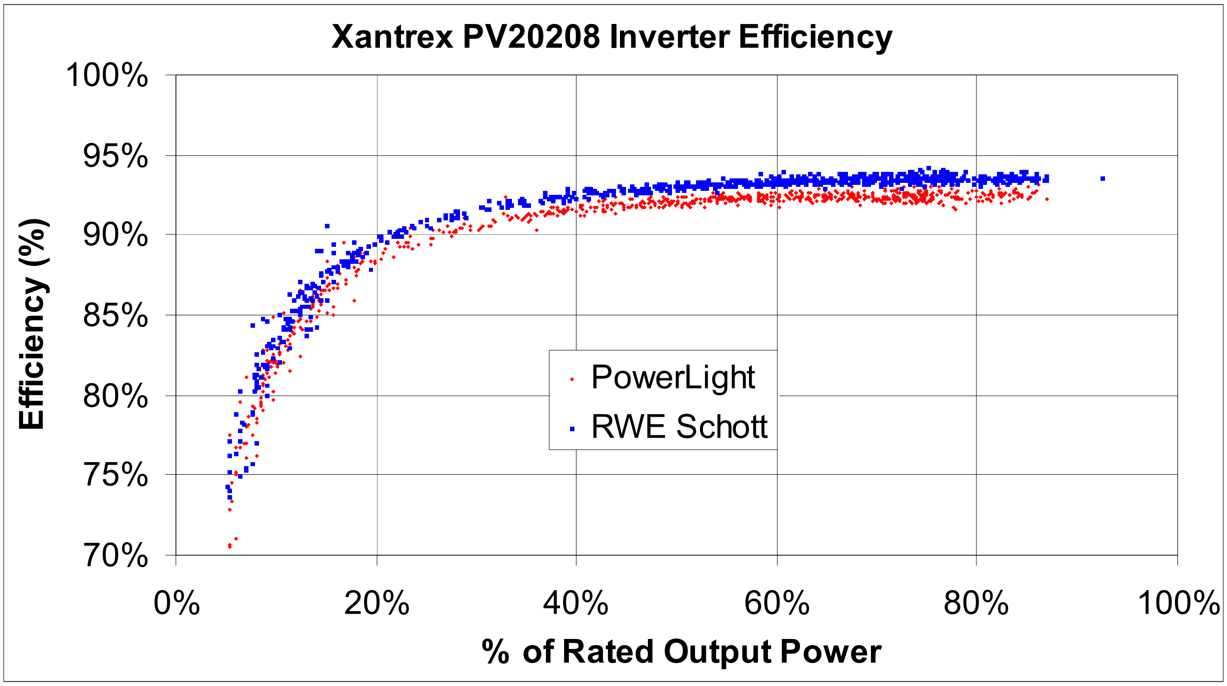

Figure 1: Field-Measured Inverter Efficiency for Xantrex Inverters

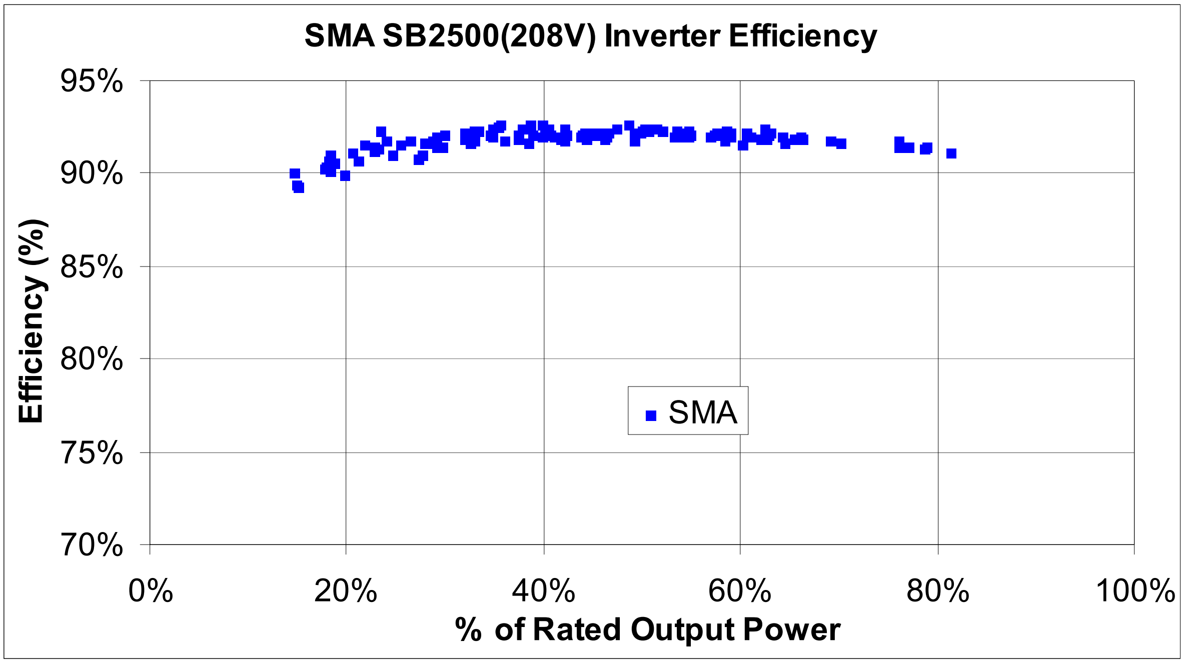

Figure 2: Field-Measured Inverter Efficiency for SMA Inverter

2.3. System Efficiency

For a specific location and orientation, the area required to provide a given output power is defined by the system efficiency. System efficiency takes into account all of the loss mechanisms between the incident sunlight and the ac output—PV array conversion efficiency, wiring losses, inverter efficiency, etc. 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 efficiency with which solar irradiance is converted to dc power will depend on the cell technology, the prevailing ambient weather conditions, and how the inverter controls the dc operating point of the array. Sorting out the effects attributable to the module construction from those of inverter operation requires additional measures, such as I-V curve results (operation independent of the inverter) or an accurate evaluation of the inverter's MPPT, as described above.

Once the system array efficiency has been characterized and the loss mechanisms have been determined, other measures may be used to track long-term performance changes, and special tests may be repeated at intervals if desired. Many people are often surprised to see how low the overall system efficiency is for PV systems. Cell efficiencies are often shown by manufacturers to be in the 14-18% range and module efficiencies in the 10-16% range, but system efficiencies tend to be much lower (3-8% range). 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.

2.3.1 PowerLight Array

The module used in the PowerLight Sloped PowerGuard array is the Sanyo Model HIP-190BA2, 190-Watt$_{STC}$ (at Standard Test Conditions-STC). This module is a unique hybrid of mono-crystalline silicon with a surface layer of amorphous-silicon. The 190-Watt Sanyo module is 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 160.8 W/m^2 (16.1 % efficient) making it the highest efficiency module of the test group.

The 20 kW Sloped PowerGuard system uses 120 of the Sanyo Model HIP-190BA2 modules and has an overall footprint area of 227 m^2 (2440 ft^2). The PVUSA Test Conditions (PTC$_{ac}$) rating for this system is approximately 17.97 kW so the area requirements for this system are 12.6 m^2/kW (136 ft^2/kW), or an overall system efficiency of 7.93% at rated output. The power density of this system is the highest in the project.

2.3.2 RWE Schott Array

The module used in the RWE Schott SunRoof FS array is the RWE Schott Solar (formerly ASE Americas) ASE-300-DGF/50, 300-Watt$_{STC}$. These modules are the largest and among the heaviest available with a distributed weight of over 4 lbs/ft^2. The modules are made with Ribbon Silicon PV cells using RWE's Edge-defined Film-fed Growth (EFG) process. The module dimensions are 74.5" x 50.5" (1.89 m x 1.28 m) for an area of 26.1 ft^2 or 2.43 m^2, the largest module under test. Its STC rated power-to-area ratio is 124.0 W/m^2 (12.4 % efficient) making it among the higher efficiency modules of the test group.

The 20 kW SunRoof FS System uses 80 of the RWE Schott Solar (formerly ASE Americas) ASE-300-DGF/50 modules and has an overall footprint area of 242 m^2 (2600 ft^2). The PTC$_{ac}$ rating for this system is approximately 18.38 kW so the area requirements for this system are 13.1 m^2/kW (141 ft^2/kW), or 7.61%. The power density of this system is among the highest in the project.

2.3.3 Multi-Array System, Array A

The module used in the array A of the Multi-array system is the Uni-Solar US-116, 116-Watt (at Standard Test Conditions-STC), one of the few amorphous-silicon modules currently available on the market. The module dimensions are 96.0" x 30.2" for an area of 20.1 ft^2 or 1.87 m^2. Its STC rated power-to-area ratio is 62.1 W/m^2 (6.2 % efficient) making it among the lower efficiency modules of the test group.

This 2 kW Solar Quilt mounted system uses 20 of the Uni-Solar US-116 modules and has an overall footprint area of 45.4 m^2 (489 ft^2). The PTC$_{ac}$ rating for this system is approximately 1.86 kW so the area requirements for this system are 24.5 m^2/kW (263 ft^2/kW), or a system efficiency of 4.09%. As expected with amorphous-silicon, the power density of this system is among the lowest in the project.

2.3.4 Multi-Array System, Array B

Array B uses the Uni-Solar PVL 128 (DM), 128-Watt$_{STC}$., also an amorphous-silicon module. The module dimensions are 216.0″ x 15.5″ for an area of 23.3 ft^2 or 2.16 m^2. Its STC rated power-to-area ratio is 59.3 W/m^2 (5.9 % efficient) making it among the lower efficiency modules of the test group.

This 2 kW Solar Integrated Technologies system uses 18 of the Uni-Solar PVL-128 modules and has an overall footprint area of 52.0 m^2 (560 ft^2). The PTC$_{ac}$ rating for this system is approximately 1.89 kW so the area requirements for this system are 27.6 m^2/kW (297 ft^2/kW), or 3.63%, among the lowest in the project.

2.3.5 Multi-Array System, Array C

The module used in the array C is the Shell Solar ST40, 40-Watt$_{STC}$. This module is the only copper-indium diselenide (CIS) module currently on the U.S. market. The module dimensions are 50.9″ x 13.0″ for an area of 4.59 ft^2 or 0.427 m^2. Its STC-rated power-to-area ratio is 93.8 W/m^2 (9.4 % efficient) is among the higher efficiency thin-film modules and in the mid range efficiency overall for the test group.

This 2 kW custom mounted system uses 60 of the Shell Solar ST40 modules and has an overall footprint area of 37.7 m^2 (406 ft^2). The PTC$_{ac}$ rating for this system is approximately 2.13 kW so the area requirements for this system are 17.7 m^2/kW (190 ft^2/kW), or 5.66%, in the mid-range of systems in the project.

2.3.6 Multi-Array System, Array D

The module used in the array D is the First Solar FS-45-D, 45-Watt$_{STC}$. This module is currently the only cadmium-telluride (Cd-Te) module on the market in the U.S. The module dimensions are 47.25″ x 25.37″ for an area of 8.32 ft^2 or 0.77 m^2. Its STC rated power-to-area ratio is 58.2 W/m^2 (5.8 % efficient) making it among the lower efficiency modules of the test group. It is also available in a 50-Watt version that has a 6.5% efficiency.

This 2 kW First Solar EZ Mount system uses 60 of the First Solar FS-45-D modules and has an overall footprint area of 60.9 m^2 (656 ft^2). The PTC$_{ac}$ rating for this system is approximately 2.10 kW so the area requirements for this system are 29.1 m^2/kW 313 ft^2/kW, or 3.44% efficiency, among the lowest in the project.

2.3.7 Multi-Array System, Array E

The module used in the array E is the AstroPower APx-130, 130-Watt$_{STC}$. This module is currently the only crystalline-film module on the market in the U.S. The module dimensions are 77.2″ x 34.5″ for an area of 18.5 ft^2 or 1.72 m^2. Its STC rated power-to-area ratio is 75.7 W/m^2 (7.6 % efficient) making it among the lowest efficiency crystalline modules of the test group. It is also available in a 150-Watt version that has an 8.7% efficiency.

This 2 kW Solar Quilt mounted system uses 20 of the AstroPower APx-130 modules and has an overall footprint area of 44.5 m^2 (479 ft^2). The PTC$_{ac}$ rating for this system is approximately 1.63 kW so the area requirements for this system are 27.3 m^2/kW (294 ft^2/kW), or 3.66%, among the lowest in the project.

2.3.8 Multi-Array System, Array F

The module used in the array F is the Evergreen EC-102, 102-Watt$_{STC}$. The cell technology for this module is described as a String Ribbon polycrystalline silicon manufacturing process and has characteristics similar to standard polycrystalline silicon cells. The module dimensions are 62.41″ x 25.69″ for an area of 11.1 ft^2 or 1.03 m^2. Its STC rated power-to-area ratio is 98.7 W/m^2 (9.9 % efficient) making it in the mid range of efficiencies for the modules of the test group. It is also available in a 115-Watt version that has an 11.1 % efficiency.

This 2 kW custom mounted system uses 24 of the Evergreen EC-102 modules and has an overall footprint area of 34.4 m^2 (370 ft^2). The PTC$_{ac}$ rating for this system is approximately 1.90 kW so the area requirements for this system are 18.1 m^2/kW (194 ft^2/kW), or 5.54%, in the mid-range of systems in the project.

2.3.9 Multi-Array System, Array G

The module used in the array G is the BP Solar SX-140, 140-Watt$_{STC}$. The cell technology for this module is polycrystalline silicon. The module dimensions are 62.7″ x 31.1″ for an area of 13.5 ft^2 or 1.26 m^2. Its STC rated power-to-area ratio is 111 W/m^2 (11.1 % efficient) making it in the mid range of efficiencies for the modules of the test group. It is also available in a 160-Watt version that has a 12.7 % efficiency.

This 2 kW custom mounted system uses 18 of the BP Solar SX-140 modules and has an overall footprint area of 31.3 m^2 (337 ft^2). The PTC$_{ac}$ rating for this system is approximately 1.95 kW so the area requirements for this system are 16.0 m^2/kW (172 ft^2/kW), or 6.23%, in the mid-range of systems in the project.

2.3.10 Multi-Array System, Array H

The module used in the array H is the RWE Schott Solar SAPC-123, 123-Watt$_{STC}$. The cell technology for this module is polycrystalline silicon. The module dimensions are

59.02″ x 26.50″ for an area of 10.86 ft^2 or 1.01 m^2. Its STC rated power-to-area ratio is 122.0 W/m^2 (12.2% efficient) making it in the higher range of efficiencies for the modules of the test group. This module is manufactured by Sharp Electronics and relabeled by RWE Schott Solar.

This 2 kW custom mounted system uses 20 of the RWE Schott Solar SAPC-123 modules and has an overall footprint area of 28.4 m^2 (306 ft^2). The PTC_{ac} rating for this system is approximately 1.94 kW so the area requirements for this system are 14.6 m^2/kW (158 ft^2/kW), or 6.83%, in the upper range of systems in the project.

2.3.11 Multi-Array System, Array I

The module used in the array I is the Shell Solar SP-140, 140-$Watt_{STC}$. The cell technology for this module is monocrystalline silicon. The module dimensions are 63.86″ x 32.05″ for an area of 14.2 ft^2 or 1.32 m^2. Its STC rated power-to-area ratio is 106 W/m^2 (10.6% efficient) making it in the mid range of efficiencies for the modules of the test group. It is also available in a 150-Watt version that has an 11.4 % efficiency.

This 2 kW custom mounted system uses 18 of the Shell Solar SP-140 modules and has an overall footprint area of 32.7 m^2 (352 ft^2). The PTC_{ac} rating for this system is approximately 1.91 kW so the area requirements for this system are 17.1 m^2/kW (184 ft^2/kW), or 5.85%, in the mid-range of systems in the project.

2.3.12 Multi-Array System, Array J

The module used in the array J is the AstroPower AP-110, 110-$Watt_{STC}$. The cell technology for this module is monocrystalline silicon. The module dimensions are 58.1″ x 26.0″ for an area of 10.5 ft^2 or 0.974 m^2. Its STC rated power-to-area ratio is 112.9 W/m^2 (11.3 % efficient) making it in the mid range of efficiencies for the modules of the test group. It is also available in a 120-Watt version that has a 12.3% efficiency.

This 2 kW custom mounted system uses 22 of the AstroPower AP-110 modules and has an overall footprint area of 30.3 m^2 (326 ft^2). The PTC_{ac} rating for this system is approximately 1.83 kW so the area requirements for this system are 16.6 m^2/kW (178 ft^2/kW), or 6.03%, in the mid-range of systems in the project.

Table 3 Summary of Module Characteristics

Array	Manufacturer	Model	P_{STC}	$Area_{Mod}$	$PMod_{density}$	Eff_{STC}	$Area_{SYS}$	Eff_{SYS}	Technology
			Watts	sq.m	W/sq.m	%	sq.m.	%	
PL	Sanyo	HIP-190BA2	190	1.18	160.8	16.1	226.7	7.93	HIT c-Si/a-Si
RWE	RWE/Schott	300-DGF/50	300	2.43	123.7	12.4	241.5	7.61	EFG-poly-Si
A	UniSolar	US-116	116	1.87	62.1	6.2	45.4	4.09	3-a-Si
B	UniSolar	PVL-128	128	2.16	59.3	5.9	52.0	3.63	3-a-Si
C	Shell Solar	ST40	40	0.43	93.8	9.4	37.7	5.66	CIS
D	First Solar	FS-45	45	0.77	58.2	5.8	60.9	3.44	CdTe
E	AstroPower	APX-130	130	1.72	75.7	7.6	44.5	3.66	pc-Si-Film
F	Evergreen	EC-102	102	1.03	98.7	9.9	34.4	5.54	SR-poly-Si
G	BP Solar	SX-140	140	1.26	111.3	11.1	31.3	6.23	pc-Si
H	RWE/Schott	SAPC-123	123	1.01	122.0	12.2	28.4	6.83	pc-Si
I	Shell Solar	SP140	140	1.32	106.1	10.6	32.7	5.85	mc-Si
J	AstroPower	AP-110	110	0.97	112.9	11.3	30.3	6.03	mc-Si

Table 3 summarizes the module sizes and states the power density and efficiency at STC conditions. Eff_{STC} only relates to the module properties and can be misleading if taken independently. Each one of these modules is affected by their mounting configuration.. Therefore, each system also has a column for the system efficiency, Eff_{SYS}, which takes into account the overall efficiency for the footprint area of the system with all the system inefficiencies factored into the final percentage. As Table 3 shows, many of the system efficiencies approach half the stated efficiency of the module.

3. Long-Term PV System Tests and Six-Month Performance

As with any complex system, there is no single parameter that fully defines the performance of a PV system. The function of a car is to transport people and things from one location to another, but just measuring miles driven or pounds of cargo transported will likely be insufficient to make a selection between two choices. What is the fuel efficiency? How much horsepower does it have? How does it handle in high speed cornering? There are a lot of ways of describing the performance of a car.

The function of a PV system is to generate electricity, and while the amount of energy it generates (even relative to the size and cost of the system) is of great interest to any PV system owner, there are a number of other relevant ways of measuring and expressing PV system performance. The intent of this evaluation is to quantify the performance of the systems in enough detail and from enough perspectives that a potential PV system buyer will be able to determine which product best suits their needs. The performance measures in this section take longer periods to develop and so are categorized as long-term tests.

3.1. Performance Indexes

Performance Index (PI) was developed by PVUSA [3] as a simple means for determining system health. The simplest definition for PI is the actual system output divided by the predicted or "expected" system output. Output may be defined as instantaneous power or accumulated energy over an arbitrary period. The strength of this measure is that it is a direct indication of system function with environmental conditions factored out. Its weakness is that the predicted output model is valid only under fairly moderate environmental conditions. Extremes of irradiance or temperature can produce inaccurate results.

Power-based PI has proven to be very useful as a real-time performance meter though, for the reasons describe above, it tends to yield inaccurate results in the morning and evening. An alternative is to present power based PI only during the middle four hours of the day or when the irradiance is above a nominal level. Daily energy-based PI is presented so that the overall performance can be quickly viewed on a daily basis. This daily number is what is used on the PIER Project 3.2 data site (http://pierminigrid.showdata.org/data/index.cfm).

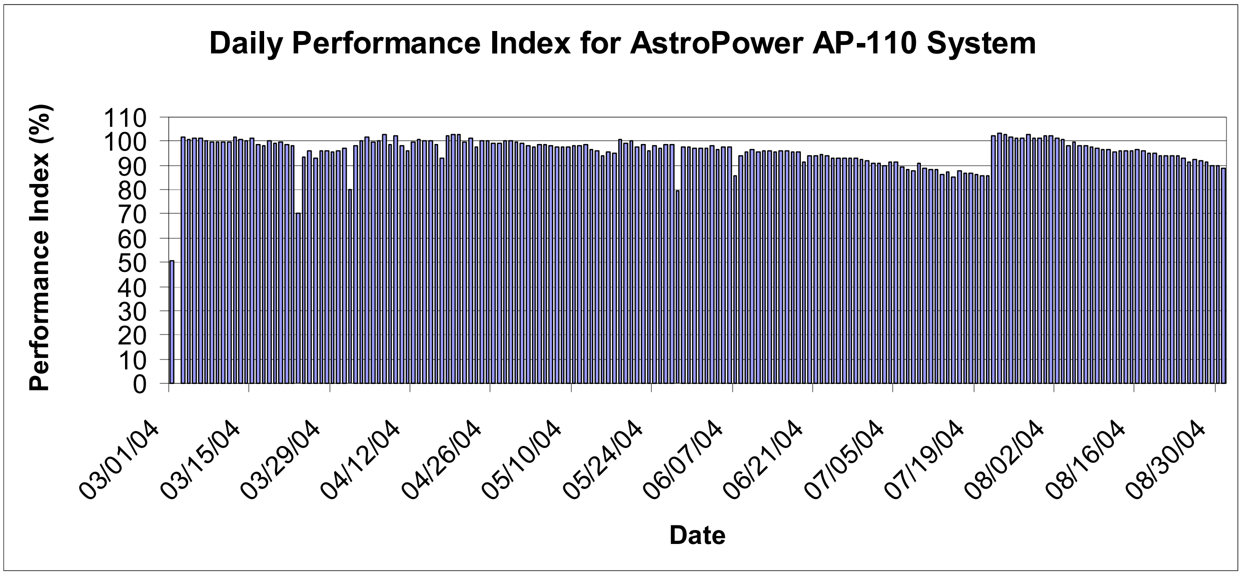

Figure 3: Performance Index for Over Six Month Period

Figure 3 shows the PI for the AP-110 array for each day during the six month evaluation period. This graphic is particularly useful to review a long period of data and make higher level observations about a system's performance. One of the most noticeable characteristics of Figure 3 is the soiling/washing cycle. The array was washed on May 17, the beginning of the dry season. Dust build-up results in the drop off in PI from mid May through mid-July. The stepped increase in PI in mid-July is the result of washing the array on July 22.

The low PI on March 23 was due to the system being shut down during part of the day for a data acquisition system repair. Low PI's on April 2 and May 28 were due to extremely cloudy days (the predicted energy is typically overestimated under very low irradiance conditions.. Extreme irradiance and temperature conditions represent relatively low fractions of the total long-term energy, so calculations based on long-term energy values tend to be most accurate since these short-term values are weighted along with more typical conditions. Extremely cloudy days cause the inverter to operate at very low power levels, well down in efficiency, possibly even at the limit of it operating voltage. These low level non-linearities are not well addressed in PI energy prediction model.

To ensure proper evaluation, it is necessary to sort out any downtime for special testing (which shouldn't count against the system's performance) from downtime for maintenance and failures. In Figure 4 below, March 23 is an example of testing-related downtime that should be removed from any evaluation.

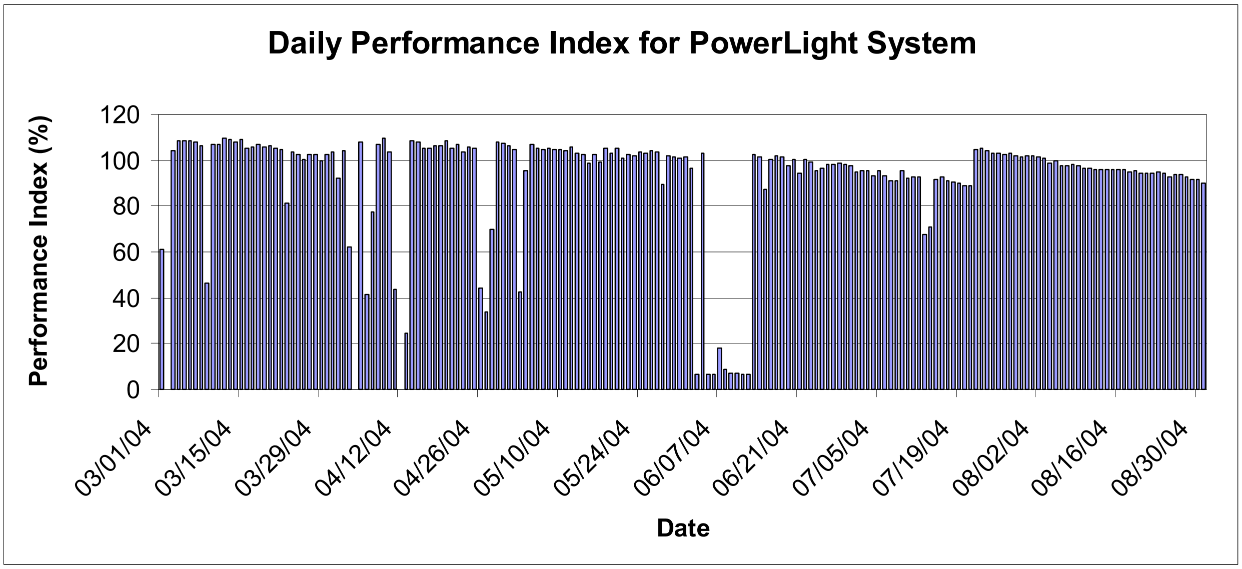

Figure 4: PowerLight Performance Index

The PowerLight and RWE Schott systems experienced two operational problems with their Xantrex PV-20208 inverters that impacted their PIs, as shown in Figure 4 and Figure 5. The first issue was that of the site ac voltage. On several occasions the site ac voltage dipped below the inverter under voltage trip settings. Xantrex default trip point settings are ±5% of nominal voltage. Whenever the site voltage dropped below – 5% (456 Volts) for more than 2 seconds, the inverter would shut down. This setting is, in one sense, stricter than interconnection standards require (-12%, +10%)[1]. On more than one occasion, the inverter shutdown and had to be manually restarted.

After this voltage trip on the inverter occurred several times, a request was made of the serving utility to allow the operating range of the inverter to be widened. Permission was granted to increase the trip settings to ±9%, and undervoltage tripping has not been experienced with either inverter since. It should be noted that the SMA SB2500U inverters also measure line-to-line voltage but did not trip during these low voltage excursions because they come set from the factory at about -10%, +9% of nominal voltage. The difference between the two inverter's settings has more to do with the manufacturer's interpretation of the voltage limits than it does the testing method of the actual inverter.

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[1] This has to do with the fact that the inverter measures line-to-line voltage. A 10% drop in a single line-to-neutral utility voltage (which, ostensibly, the inverter should respond to) will result approximately in a 5% drop in line-line voltage. This is, however, overly sensitive for the normal condition of reduction of all three phases

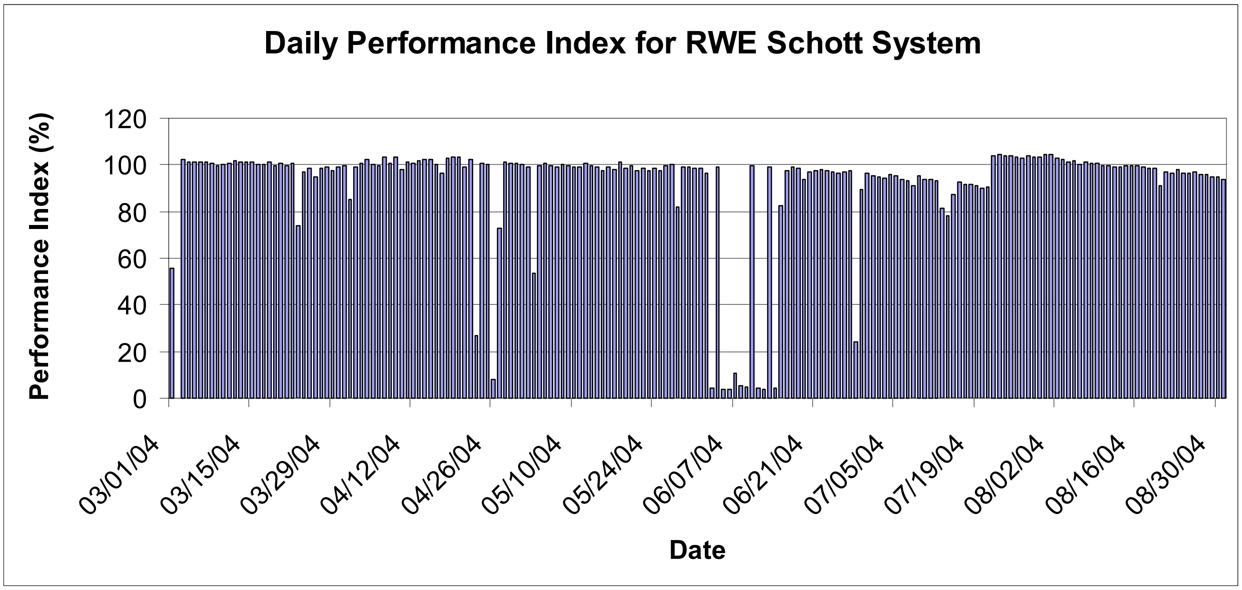

Figure 5: RWE Schott Performance Index

The second clearly visible operational problem for the two PV-series inverters occurred between June 2 and June 13. One June 2, Xantrex installed a new version of the operational firmware in each unit. Unfortunately, the new firmware revision had a problem that would often cause the maximum power point tracking algorithm to get stuck at high voltage at the beginning of a very clear day. This dramatically affected the energy production of these two systems for the 10-day period while this software was loaded on the machines. On June 13, the old software was reloaded and good performance resumed. A month later, on July 13, an improved version of the new firmware was uploaded and has operated well since that time.

3.2. Energy Capture

Energy capture, as defined here, is the portion of the available radiant energy the system was prepared to accept. Algebraically, it is the ratio of the irradiation received while the inverter was "running"[2] to the total irradiation for the period of interest. This term is similar to availability (number of hours that unit was running divided by the number of hours of sunlight) except that high irradiation periods receive greater weighting than low irradiation periods. So, an inverter that for whatever reason runs during low irradiation days and shuts down during high irradiation days will have a poorer energy capture than one that does exactly the opposite.. Should one system start later in the morning than another system, the impact on energy capture would be small compared to an outage at noon.

Energy Capture does not measure how much energy was actually transferred to the grid or battery storage, but it can be used to distinguish excessive downtime from

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[2] where running is defined as inverter ac output greater than some minimum value, nominally 100 Watts.

excessive losses while operating. The weakness of this measure is that it depends on the existence of an "inverter operating" status signal that is rarely present on commercial inverters. This signal is sometimes synthesized by using a small, positive, nonzero threshold ac output power value to indicate "on" status. This can help determine how much of the time the system was available and producing power. As expected, those days when the inverters shut down because of utility voltage issues produced the lowest Energy Capture values. Since the Xantrex inverters voltage windows were adjusted in mid-July, only brief inverter interruptions were observed so that the overall Energy Capture for all the systems were at or near 100% for the remainder of the summer.

3.3. Energy Performance Testing Results

Energy is a common basis for evaluating long-term system performance. A limitation of this measure is that it is specific to the attributes (size, components, etc), location, and prevailing operating conditions (e.g., weather, utility conditions, etc.) of the system tested. Energy output normalized by array size for co-located systems can provide a much more relevant comparison.

3.3.1 Energy Per Unit Area

Another key metric for consideration when selecting a building applied PV system is the energy produced (yield) per unit of area that the system covers on a building. This value describes the output of the system on the basis of array area—the physical size of the system. In many cases, limited space is available for system installation and this is a useful measure for constrained space locations. This measure is also useful for describing and comparing array packing density. A system using highly efficient modules mounted on a structure with poor packing density (modules widely spaced) may not perform as well as system with a moderate efficiency modules and a very space-efficient mounting scheme.

The energy per square meter per day and efficiency for each system segment is shown in Figure 6. The figure shows that the two largest systems have the best energy density and system efficiency. This is partly because these two systems have the two highest efficiency modules and because larger systems tend to use space more efficiently. Both the larger systems were designed around on specific module, whereas the custom mounting system used for several of the smaller systems had some wasted space due to the relationship of the module geometry to the mounting structure. Had the custom-mounted systems been applied in a configuration designed around each individual module like the two large systems, it is likely that those overall system efficiencies would be higher. Figure 6 also shows that the a-Si, Cd-Te, and pc-si Film arrays have nearly half the efficiency and energy density of the more standard crystalline silicon products. This represents a barrier to these technologies for area-constrained roofs.

The daily energy per unit area numbers based on 12-month data are expected to decrease somewhat in this location since over 60% of the annual energy is delivered from March through August in a typical year. Adjusting these numbers for an annualized number would reduce the Energy per unit area numbers by about 20% to a range from 0.17 -0.38 kWh/m^2-day or 62-139 kWh/m^2-year. If a customer wanted to generate 100,000 kWh in a year, it would require an available roof area of 1613 m^2 to 719 m^2(17362-7739 ft^2). Obviously, if a customer only had 1,000 m^2 of available roof space, and they were intent on producing the full 100,000 kWh in a year, they would need to limit their system choices to those systems that had sufficient energy density.

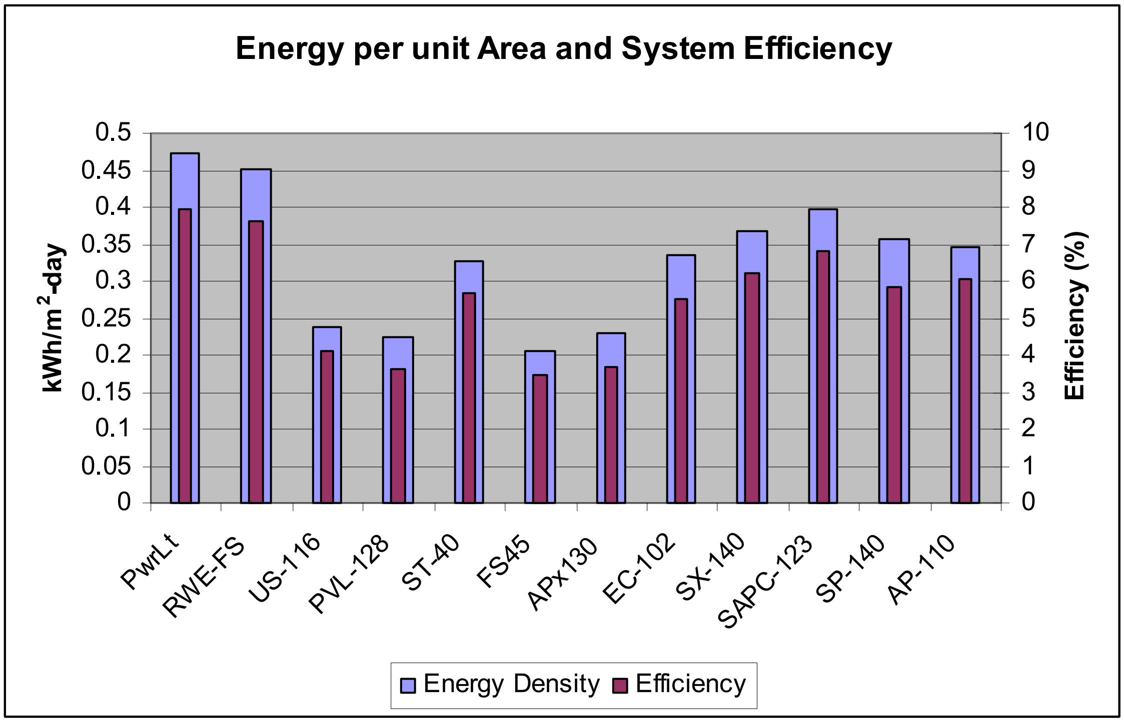

Figure 6 System Energy Density and Efficiency

3.3.2 Energy per rated power (Yield)

One effective method for comparing the performance of several systems is to evaluate the energy generated by the system per unit of rated power—the electrical “size” of the system. Energy per unit power, sometimes called “yield”, has units of kWh/kW or hours and can be thought of as the number of hours that the system operated at rated output. Yield, is also useful for comparing the operational characteristics of co-located systems by removing differences in size and nominal efficiency. This value is computed using energy over some period (day, month year, typically) divided by the PTC$_{ac}$ rating established for the system. Yield is sensitive to the system rating value and is often calculated using the array STC$_{dc}$ rating; however, other ratings can be used as well. This measure takes into account the effects of all loss and downtime mechanisms. Yield varies with weather conditions and in particular for co-located systems, how one cell technology responds to changes in weather conditions versus another: yields from maximum power tracked PV systems using crystalline silicon technology are sometimes used to describe the solar resource of a location. As long as the tested systems are similarly oriented, unshaded, clean, and working properly, yield can also be normalized by measured irradiation so that the performance of a small system in Davis can be compared to a large system in Chino.

Since this comparison includes 12 separate systems, each with individual monitoring, it is straightforward to make this comparison. Yield is particularly helpful for comparing these systems since two of them have CEC ratings of about 20 kW and the remaining 10 systems have CEC ratings of about 2 kW. By normalizing the energy performance by system size, an effective side-by-side comparison can be made.

In addition to normalizing the systems for the obvious power differences, it is also useful to make slight adjustments for the differences in irradiation received by each system. Since all commercial roofs have slight tilt angles for drainage purposes, an attempt was made to normalize these differences to prevent biasing of the side-by-side comparison. Although these adjustments are small, they were not insignificant. Seven small systems on the north side of a 2-degree roof slope, ,disadvantaged by the roof layout. For the six-month period for this report, those systems saw 1.7% less irradiation than their counterparts on the south slope of the roof. If all the systems were able to have the optimal placement on the roof, the results would be as found in Figure 7. Note that this normalization only corrects for differences in roof tilt, not differences in design mounting system orientation.

Figure 7 has also been adjusted for the outages experienced by the two larger systems. These outages were the result of utility anomalies and maximum power point tracking problems that occurred during the beta testing of updated software for the large inverters. The stacked bars in Figure 7 represent what the values would have been had these problems not occurred.

Figure 7 shows the energy production per rated STC watt, or yield, adjusted for roof tilt and irradiation differences. Looking at yield based on STC ratings, the Shell ST-40 (CIS) system performed the best of these 12 systems with 996 kWh/kW_{STC} and the AstroPower APx130 system performed the worst with 750 kWh/kW_{STC}. The seven crystalline silicon products were all of similar performance ranging from 839 kWh/kW_{STC} to 913 kWh/kW_{STC}. Both the UniSolar US-116 system at 891 kWh/kW_{STC} and First Solar FS45 system at 897 kWh/kW_{STC} systems are also within the upper part of this same range. The only system other than the Shell ST-40 system to exceed the crystalline silicon systems was the UniSolar PVL-128 system at 959 kWh/kW_{STC}. The good STC-based yields of the Shell ST-40 and UniSolar PVL-128 systems can be attributed to the fact that these systems were the closest to their STC rating than the other products.

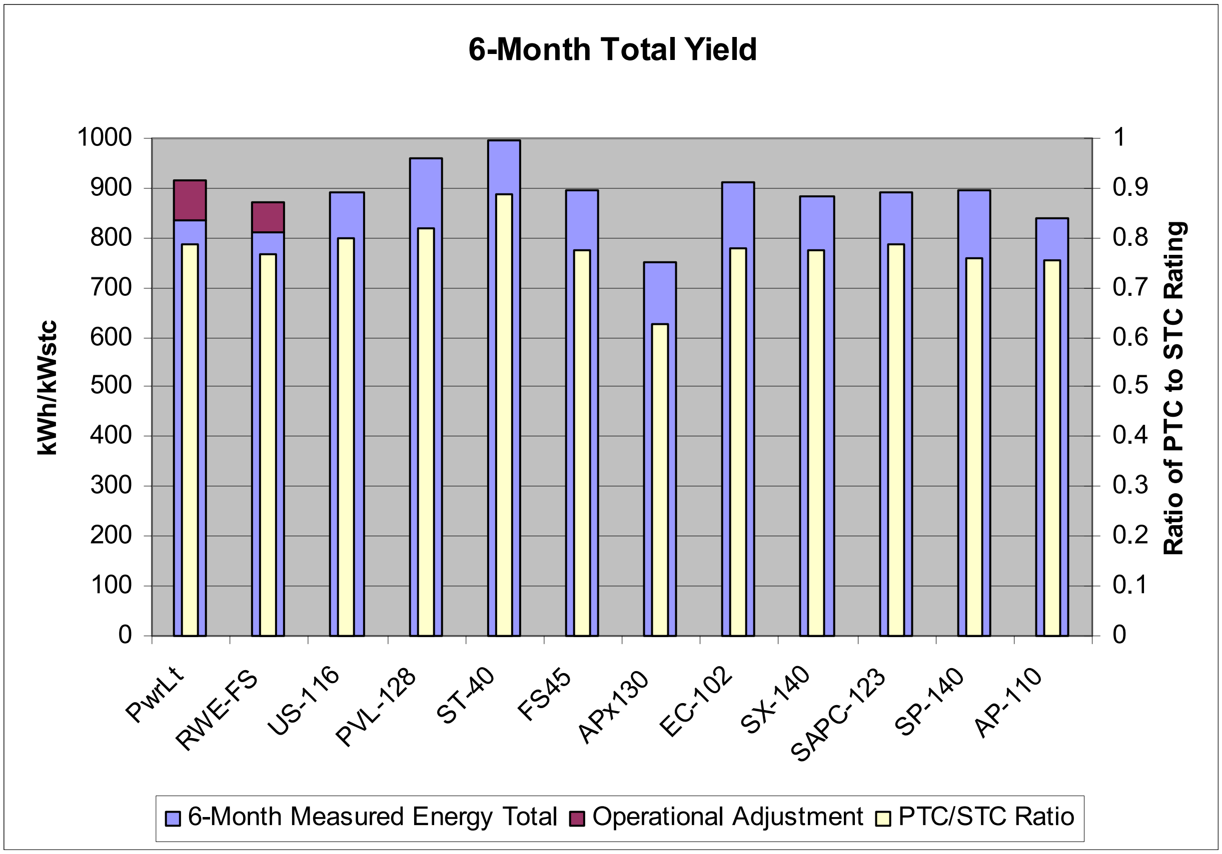

Figure 7: Yield of Each PV System Segment Adjusted for Size and Roof Location

This can be seen when looking at the ratio of PVUSA rating to STC rating shown in Figure 7. There are two primary reasons for the close agreement between the sum of the STC rating of the modules and the overall PVUSA system rating. The first factor is that the manufacturer provided a very conservative STC rating for these modules. Some reasons for a conservative rating are either that the manufacturer is expecting the product to degrade a greater amount during the course of the warranty, or the manufacturer is trying to gain a marketing advantage by showing that their product performs closer to the original specification. In the case of the UniSolar product, the temperature coefficient for the loss of power due to rise in temperature is roughly half that of standard crystalline silicon products. This lower temperature dependence means that the higher temperature conditions of the PVUSA test will have less of an effect on the power output, keeping it closer to its STC rating.

Yields based on PTC ratings show a slightly different story in Figure 8. This figure shows a close relationship between the average energy production of a PV system normalized for irradiation and the PTC rating. This close relationship between an accurate field ac rating and the energy produced by the system means that once a true PTCac rating is established for a system, the energy production of the system is fairly simple to predict. This relationship is particularly important as California and other states begin to pursue performance-based incentives. The cornerstone of consumer confidence in a performance-based incentive is an accurate understanding of the predicted energy production of PV systems.

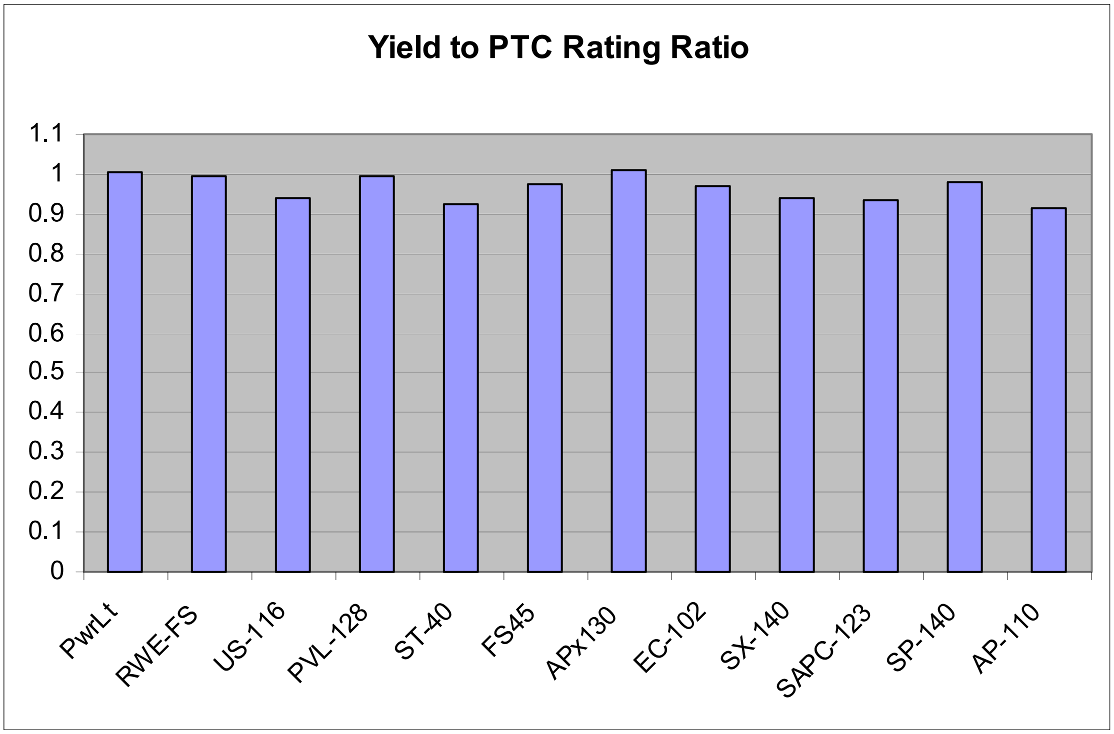

Figure 8: Ratio of Yield to PTC Rating

Monthly yield values for March through August 2004 are shown in Figure 9. This figure is normalized for differences in irradiation due to roof tilt so that each system can be compared fairly. An interesting coincidence in this data is that the monthly energy production for each system is nearly identical for May, June, July, and August. Although the 30-year data for nearby Los Angeles is fairly similar during these months, it is not necessarily common for these months to be nearly identical. On average, July has more sun than any other month, but July also is the hottest month. These counteracting impacts of heat and sunlight made the monthly delivered energy essentially the same for May through August even though the monthly irradiation varied by nearly 10% during that period.

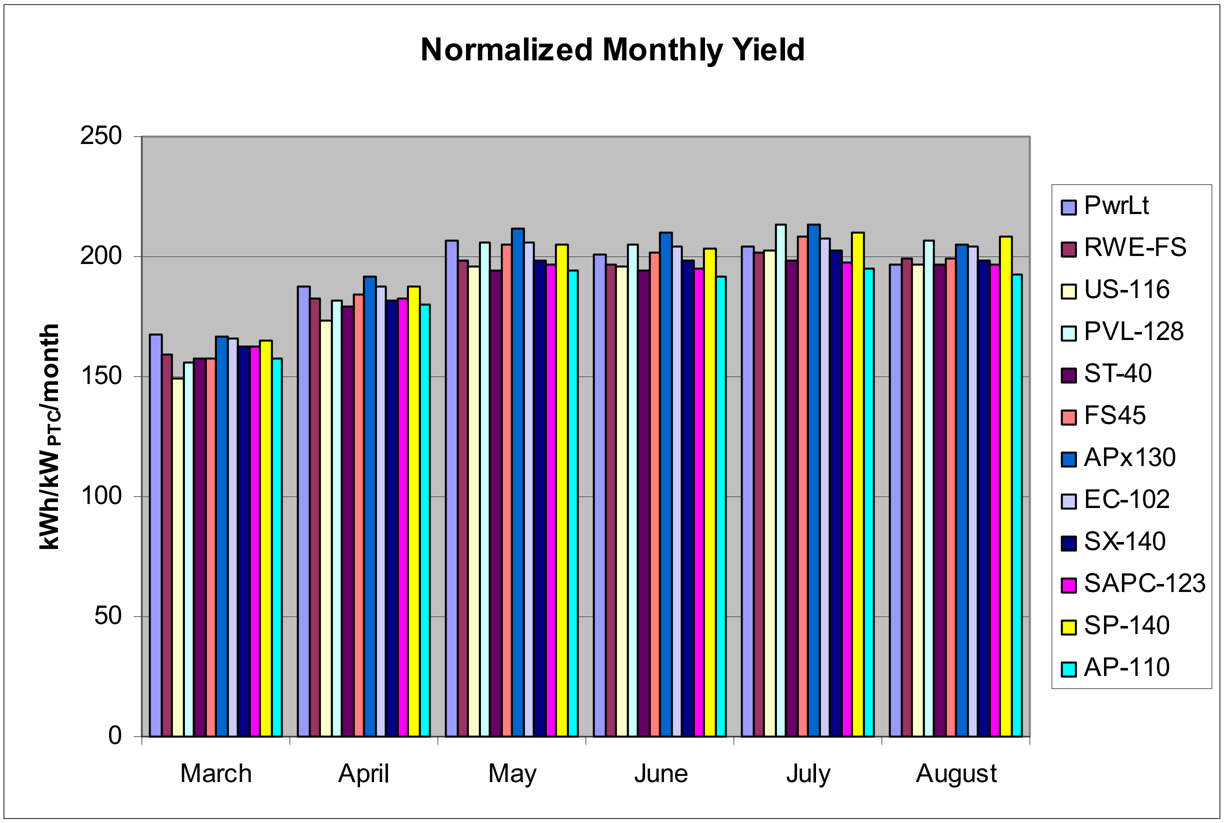

Figure 9: March-August 2004 Monthly Yield (Normalized for roof tilt/irradiation differences)

3.4. Actual Performance Relative to Modeled Performance

It is critical for PV system designers and installers to understand the relationship between how systems perform in the field compared to a computer simulation. In this section, we evaluate how the dc voltage of each array changes based upon operating temperature. We then compare the expected operating temperature for a given ambient temperature, and, finally, look at expected operating voltage based on expected operating temperature.

One of the challenges that a PV system designer faces is sizing the array to match the input characteristics of a specific inverter. In this study, the 10 smaller 2 kW PV systems each had to be sized to match the characteristics of the SMA SB2500U operating at 208Vac, for which the manufacturer lists a 207 to 600 Vdc operating range. The First Solar Easy Mount array configuration was prescribed by the manufacturer. The other nine systems were designed by BEW (formerly Endecon Engineering)[3] to meet the inverter dc input voltage window of the inverter using the module manufacturer's voltage and temperature correction data and the expected temperature of the arrays. The Powerlight and RWE-Schott 20kW systems were both sized by the suppliers.

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[3] Endecon Engineering has been acquired by Behnke, Erdman, and Whitaker Engineering, Inc.

The difficulty that faces the PV array designer is how to choose the proper maximum temperature and the corresponding minimum voltage resulting from that temperature. Maximum temperature is fairly straightforward for common roof mounting techniques, but several of the roof mounts in this project are enough different from standard mounts that the operating temperature is difficult to estimate.

Table 4: Array Temperatures and Corresponding Maximum Power Voltages

Summary Table of Array Temperatures and Maximum Power Voltages												
Array	Mfgr	Model	Mount	NOCT	INOCT	INOCT	Tmax	Tmax	Pwr Coeff	Vmp	VmpMin	VmpMin
				(°C)	Est (°C)	Act (°C)	Est (°C)	Act (°C)	Loss/°C	STC(Vdc)	Est (Vdc)	Act (Vdc)
PL	Sanyo	HIP-190BA2	SLPG	44.2	46	50	71	75	-0.0033	438.4	371.9	366.1
RWE	RWE	300-DGF/50	SRFS	45	42	47	67	72	-0.0047	408.0	327.5	317.9
A	UniSolar	US-116	Quilt	46	55	61	80	86	-0.0021	300.0	265.4	261.6
B	UniSolar	PVL-128	SIT	55	53	57	78	82	-0.0021	297.0	263.9	261.4
C	Shell Slr	ST40	Custom	47	44	51	69	76	-0.006	332.0	244.4	230.4
D	First Slr	FS-45	EZ Mnt	45	45	52	70	77	-0.002	378.0	344.0	338.7
E	AstroPwr	APX-130	Quilt	48.2	57	65	82	90	-0.005	296.0	211.6	199.8
F	Evergrn	EC-102	Custom	44	41	48	66	73	-0.0049	388.8	310.7	297.4
G	BP Solar	SX-140	Custom	47	44	50	69	75	-0.00524	306.0	235.4	225.8
H	RWE	SAPC-123	Custom	47.5	45	48	70	73	-0.005	344.0	267.5	261.4
I	Shell Slr	SP140	Custom	45	42	50	67	75	-0.0045	297.0	240.9	230.2
J	AstroPwr	AP-110	Custom	44.7	42	48	67	73	-0.005	367.4	290.8	279.2

Table 4Table 4 shows the estimates of maximum array temperature and corresponding minimum operating voltage used to size the arrays and compares them with the actual temperatures and voltages measured in the field. The red shading in the table shows that the voltage is at or below the minimum voltage of the inverter. The yellow shading indicates that the voltage is near the minimum voltage of the inverter.

As a consequence of underpredicting module temperature, the minimum operating voltage is overpredicted. The AstroPower APx-130 system (Array E) acutely demonstrates this problem. Table 4 shows that the expected array minimum voltage (VmpMin Est) of 211.6 Vdc was very close to the inverter minimum operating voltage of 207V. The measured data (VmpMin Act) shows that the APx-130 array often operated at the inverter minimum voltage on hotter days.[4] Operating an inverter at minimum voltage suggests that the actual array peak power voltage was lower during those periods, but that the inverter hit the lower dc voltage limit, forcing the array off of its peak power point. Note that power (current) drops quickly as a PV array's voltage is increased above its maximum power point. In extreme cases, the array open circuit voltage can pass below the inverter minimum voltage causing the inverter to shut down for lack of available array power.

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[4] It should be noted that the measured value of 199.8 Vdc is less that the 207 Vdc minimum stated in the inverter specifications. Since the minimum voltage for an inverter is often tested at nominal ac voltage, lower than nominal ac voltage allows the inverter to run at minimum dc voltages below those stated in the published specifications.

Manufacturing tolerances can result a 2 – 5% voltage reduction from nominal specifications and a voltage degradation of as much as 1% per year is not an unrealistic assumption. Table 5**Error! Reference source not found.** shows the possible impact of these two additional voltage losses on the systems in this study.

Table 5: Additional Voltage Losses Due To Specification and Field Impacts

Summary Table of Array Temperatures and Maximum Power Voltages

Array	Mfgr	Model	Mount	Inverter	Inv Vmin	Vmp	VmpMin	VmpMin	VmpMin	VmpMin	VmpMin
					(Vdc)	STC(Vdc)	Est (Vdc)	Act (Vdc)	Mfg (Vdc)	Old1 (Vdc)	Old2 (Vdc)
PL	Sanyo	HIP-190BA2	SLPG	PV20208	300.0	438.4	371.9	366.1	347.8	313.0	278.2
RWE	RWE	300-DGF/50	SRFS	PV20208	300.0	408.0	327.5	317.9	302.0	271.8	241.6
A	UniSolar	US-116	Quilt	SB2500U	207.0	300.0	265.4	261.6	248.5	223.6	198.8
B	UniSolar	PVL-128	SIT	SB2500U	207.0	297.0	263.9	261.4	248.4	223.5	198.7
C	Shell Slr	ST40	Custom	SB2500U	207.0	332.0	244.4	230.4	218.9	197.0	175.1
D	First Slr	FS-45	EZ Mnt	SB2500U	207.0	378.0	344.0	338.7	321.8	289.6	257.4
E	AstroPwr	APX-130	Quilt	SB2500U	207.0	296.0	211.6	199.8	189.8	170.8	151.8
F	Evergrn	EC-102	Custom	SB2500U	207.0	388.8	310.7	297.4	282.5	254.2	226.0
G	BP Solar	SX-140	Custom	SB2500U	207.0	306.0	235.4	225.8	214.5	193.1	171.6
H	RWE	SAPC-123	Custom	SB2500U	207.0	344.0	267.5	261.4	248.4	223.5	198.7
I	Shell Slr	SP140	Custom	SB2500U	207.0	297.0	240.9	230.2	218.7	196.8	174.9
J	AstroPwr	AP-110	Custom	SB2500U	207.0	367.4	290.8	279.2	265.3	238.7	212.2

The column labeled "Mfg Vdc" represents the voltage of modules that are 5% below voltage specifications (which would be within the typical 5 to 10% stated tolerance). Starting from the Mfg Vdc numbers, the columns labeled "Old1 Vdc" and "Old2 Vdc" assume a 10% (Old1 Vdc), and a 20% (Old2 Vdc) loss of voltage at the end of module life As Table 5 indicates with all the yellow and red regions, there is potential concern that many of these systems will not operate optimally throughout their useful life. However, care should be exercised when interpreting this graph since the voltage projections in the rightmost three columns are not guaranteed and represent worst-case conditions.

Table 6 shows how actual module voltages compare with voltages produced by a computer model using measured maximum array temperature (that is, removing the temperature prediction from the uncertainty). The computer simulation for the array was tuned until the predicted temperature matched the measured temperature for the given set of conditions. The corresponding maximum power voltages are recorded compared in Table 6. Four days in the same July 2004 week were used for the comparison. These days were chosen because they were among the hottest summer days that also corresponded with light winds. These simultaneous ambient conditions produced the highest module temperatures and the lowest operating voltages at high power levels.

Table 6: Measured Vs. Predicted Max Power Voltage for 4 Hot, Calm Days

Date	07/14/04	07/15/04	07/16/04	07/18/04	average of 4 days
Time, Pacific Standard Time	11:00	12:15	11:30	11:15	
$T_{AIR,}$ °C	38	36	35.5	36	36
Wind Speed, m/s	1	2	1.5	1.5	2
Irradiance, W/m^2	860	1150	910	900	955
Powerlight Sloped Powerguard HIP-190B2 (HIT-Si)					
measured Vmp	378	372	380	380	378
final predicted Vmp	365	353	367	367	363
% diff, pred relative to meas.	-3.41%	-5.19%	-3.47%	-3.51%	-3.90%
RWE Schott SunRoof FS (EFG mc-Si)					
measured Vmp	320	315	327.5	323.9	322
final predicted Vmp	323	314	327	326	323
% diff, pred relative to meas.	1.05%	-0.29%	-0.24%	0.77%	0.32%
Unisolar US-116 (a-Si)					
measured Vmp	240	231	240	239	238
final predicted Vmp	270	259	270	270	267
% diff, pred relative to meas.	12.67%	12.04%	12.39%	12.94%	12.51%
Unisolar PVL-128 (a-Si)					
measured Vmp	232	232	238	233	234
final predicted Vmp	270	259	269	269	267
% diff, pred relative to meas.	16.36%	11.60%	13.13%	15.64%	14.18%
Shell Solar ST40 (CIS)					
measured Vmp	301	304	307	305	304
final predicted Vmp	261	259	264	264	262
% diff, pred relative to meas.	-13.31%	-14.74%	-13.86%	-13.42%	-13.83%
First Solar FS45 (CdTe)					
measured Vmp	299	297	303	301	300
final predicted Vmp	297	287	297	297	294
% diff, pred relative to meas.	-0.79%	-3.51%	-2.04%	-1.39%	-1.93%
Astropower APx-130 (pc-Si film)					
measured Vmp	194	194	196	199	196
final predicted Vmp	191	170	192	192	187
% diff, pred relative to meas.	-1.58%	-12.14%	-1.79%	-3.27%	-4.69%
Evergreen Solar EC-102 (SR-poly-Si)					
measured Vmp	312	304	313	319	312
final predicted Vmp	257	245	264	263	257
% diff, pred relative to meas.	-17.49%	-19.40%	-15.66%	-17.54%	-17.52%
BP Solar SX-140 (pc-Si)					
measured Vmp	236	229	237	237	235
final predicted Vmp	259	254	261	260	258
% diff, pred relative to meas.	9.63%	10.72%	10.02%	9.91%	10.07%
RWE/Schott SAPC-123 (pc-Si)					
measured Vmp	274	269	278	280	275
final predicted Vmp	247	236	252	251	247
% diff, pred relative to meas.	-9.82%	-12.13%	-9.50%	-10.36%	-10.45%
Shell Solar SP-140 (mc-Si)					
measured Vmp	245	241	253	248	247
final predicted Vmp	230	223	233	232	229
% diff, pred relative to meas.	-6.25%	-7.47%	-8.00%	-6.29%	-7.00%
Astropower AP-110 (mc-Si)					
measured Vmp	292	289	294	299	294
final predicted Vmp	295	287	299	298	295
% diff, pred relative to meas.	1.10%	-0.75%	1.65%	-0.20%	0.45%

Several interesting observations should be made from Table 6. The maximum ambient temperatures for the simulation data were all near 36°C (97°F), which was well below the maximum temperature of 43°C (110°F) recorded in this area. This means that the worst case voltages are between 2-4% below those recorded. The simulation does not account for any degradation, so end of life voltages could be another 10-20% lower. The most important results are those that show a significant positive percent difference between predicted measured results. This would include three arrays: (1) UniSolar US-116; (2) UniSolar PVL-128; and, (3) BP Solar SX-140. All three of these examples show an operating voltage that is 10% below that expected for the given array at that given temperature.

Voltage prediction is a fairly straightforward evaluation that is based upon manufacturer's supplied data and field verified data. Given the simplicity of the modeling for dc array voltage, there remain two plausible reasons for the discrepancy in measured voltage being below predicted voltage. The first reason might be that the module manufacturer may have delivered a product that was below specifications. The second possible reason is that the product degraded in voltage well beyond what the manufacturer expected in their module specification. In either case this throws an additional uncertainty into the long-term voltage characteristics of these arrays making it very difficult to predict what voltage these systems might be operating at toward the end of their useful life.

All three arrays that show measured voltages significantly below expected voltage are on the borderline in terms of voltage window of the inverter as shown in Table 5, so additional voltage shortfalls will cause additional operational issues. This is not to say that these systems will all fall short on voltage at the end of their useful life, nor does it suggest that the remaining nine systems will follow the voltage degradation paths suggested in Table 5. Voltage reduction over time is not always linear and some technologies have shown higher degradation rates than others. Step changes in voltage are also possible due to degradation mechanisms that are triggered after a certain number of temperature cycles, or hours of light exposure. Some of these losses are understood by the manufacturer and planned into the product specifications. Others may be unknown to anyone since the combination of outdoor exposure issues may be difficult to replicate in the various longevity tests that are currently used by manufacturers.

On the positive side of the voltage evaluation shown in Table 6, there are several products with voltages significantly above expected voltage. Should those products have typical rates of voltage degradation over time, the predictions shown in Table 5 relative to reaching the minimum voltage of the inverter would be excessive. One last important observation relative to Table 6 is that the AstroPower APx-130 shows a voltage above predicted only because the inverter was unable to track that array to the maximum power voltage. This array is already in the red range as predicted in Table 4 and Table 5.

4. Conclusions

The 12 separate system segments under test in the project provide a unique opportunity to evaluate commercially available products in a side-by-side comparison. This evaluation showed many differences and similarities between these systems. Clearly, the efficiency of these systems varied widely with module efficiencies ranging from 5.6% to 16.1% and system efficiencies ranging from 3.4% to 7.9%. However, once an accurate field ac rating, the PTCac rating, was developed for each system, the energy production of each system was very similar per rated PTCac Watt. This correlation confirms that PV systems designed and installed properly, and rated appropriately, perform as expected.

However, challenges still exist in designing and rating systems appropriately particularly for new systems and new mounting configurations. This was evident in the fact that measured and predicted operating temperatures and voltages did not always match as expected. The Solar Quilt systems operated at temperatures higher than expected, particularly for the AstroPower APx-130 array, causing that system segment to operate below initial performance expectations.

The ac voltage window of the Xantrex PV-20208 inverters is very narrow, which caused some operation problems. These problems subsided when the voltage window was expanded with the permission of the serving utility. The few minor issues encountered during the first 6 months of operation—most of which can be related to the more developmental nature of some of the products selected—do not detract from the basic conclusion that PV systems designed and installed properly, and rated appropriately, perform as expected.

5. References

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