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Technical Evaluation of a USSC Integrated/Direct Mount PV Roofing Module System at NREL

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Technical Evaluation of a USSC Integrated/Direct Mount PV Roofing Module System at NREL

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Abstract. The results of a 16 month technical evaluation performed on a nominal 1 kW_{ac} utility-interconnect amorphous silicon PV system deployed at the National Renewable Energy Laboratory's PV outdoor test site are given here. The system employs 64 prototype United Solar Systems Corp. Integrated/Direct Mount PV Roofing Modules mounted on simulated attic/roof structures. In this paper we show that the PV array fill factor has been relatively stable with respect to time and that the seasonal variations in performance can be largely attributed to seasonal variations in current. We also show that in determining the summer and winter ac power output, the summation of the manufacturer-supplied module peak powers at STC for a similarly located and configured a-Si PV array should be derated by factors of approximately of 0.83 and 0.78 for summer and winter operation, respectively.

INTRODUCTION

Several grid-connected and stand-alone Photovoltaic (PV) systems have been deployed at the National Renewable Energy Laboratory's (NREL) PV outdoor test site. These systems include advanced thin-film and crystalline silicon PV technologies of amorphous silicon (a-Si), $CuInSe_2$ (CIS), CdTe/Cds (CdTe), single crystalline silicon, and multi-crystalline (EFG-ribbon) silicon. These systems were deployed to conduct ***in-situ*** technical evaluations of the PV array performance and long-term reliability. Based on the economic and reliable dc peak-power tracking capabilities offered by small residential power conditioning units (2 to 3 kW_{ac} in size), the local utility was selected as the load. Detailed array and system performance data is being acquired for each PV system under evaluation.

This paper details PV array and system performance for a nominal 1 kW_{ac} utility-interconnect a-Si PV system deployed at the NREL PV outdoor test site for the period of January 7, 1994 through May 2, 1995. This deployment was the result of a cooperative research agreement between United Solar Systems Corp. (USSC) and

NREL. The system is located at 39.7° N latitude, 105° W longitude, and 1782 m elevation (Golden, Colorado). The system employs prototype USSC Integrated/Direct Mount PV Roofing Modules mounted on simulated attic/roof structures. Figure 1 is a photograph of the PV array and the simulated attic/roof structures. The array is fixed at a 40° tilt angle from horizontal. Each module has a total area of 4856.5 cm^2 (130.2 x 37.3 cm). These prototype modules are identical to the USSC UPM-880 in structure and composition (a-Si, dual-junction, same-band-gap) and performance. The PV array consists of two positive and two negative monopoles. Each of the four monopoles is comprised of 16 roofing modules in series (64 modules total). A monopole is defined here as either the positive or negative half of a center-tapped (three-wire) string of PV modules. The summation of the manufacturer-supplied module peak powers at standard test conditions (STC) is 1408 W (64 modules x 22 W). The output of the PV array is tied to a three-wire grid-connected inverter. The as-installed total area of the PV array was measured at 33.0 m^2. Table 1 lists the array ratings (based on the manufacturer's specifications for a UPM-880 PV module) at STC: 1000 W/m^2, 25 °C, AM1.5 global spectrum.

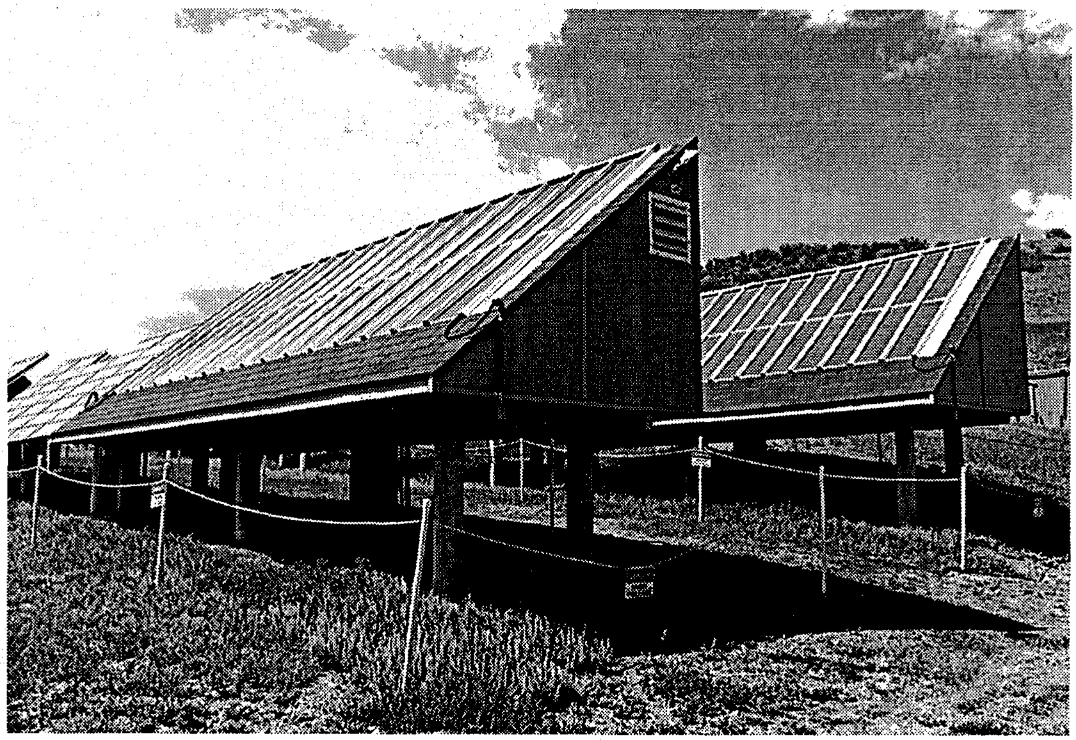

FIGURE 1. PV array and the simulated attic/roof structures

TABLE 1. Photovoltaic array ratings at STC.

V_{OC}	V_{MAX}	I_{SC}	I_{MAX}	P_{MAX}	**Array Total Area**
±352 V_{dc}	±249.6 V_{dc}	±3.6 A_{dc}	±2.8 A_{dc}	1408 W_{dc}	33.0 m^2

Construction of the simulated attic/roof structures and installation of the roofing modules was completed on September 3, 1993. Each string was then left in a short-circuit state pending balance-of-system (BOS) and data acquisition system (DAS) installation. BOS and DAS installations were completed on January 6, 1994. Data collection commenced on January 7, 1994. The PV array and BOS have operated without anomaly since installation. Array and system performance have been presented in a previous publication (1).

DATA ACQUISITION

The DAS is centered around a Campbell Scientific 21X data logger. Data are sampled every 2.25 s (changed to 5 s on July 28, 1994) and stored as 15 min averages. Data collected include positive and negative dc currents and voltages; plane-of-array (POA) irradiance; ac current, voltage, and power; and back-of-module, ambient, inverter, roof, and attic temperatures. Meteorological data are provided by the Reference Meteorological and Irradiance Station (RMIS) located at the test site.

Current versus voltage (I-V) curve traces are acquired monthly (weather permitting), at POA irradiance levels between 900 and 1100 W/m^2 (near solar noon), using a portable I-V curve tracer. The spectrum at the time of the I-V curve trace is either measured by a LiCor spectroradiometer or is calculated based on data from RMIS. Prior to deployment, all modules had baseline I-V curve traces acquired both by a Spire 240A solar simulator at STC and outdoors under prevailing conditions at the NREL PV outdoor test site.

RESULTS

Figure 2 (next page) shows system ac and dc powers (normalized to 1000 W/m^2) versus back-of-module and ambient temperatures, and time. The data for this graph was restricted by POA irradiance levels greater than 850 W/m^2. The figure shows the well-documented seasonal change in performance exhibited by a-Si PV modules (2, 3, 4). This correlation was studied in depth for a similarly configured PV system employing 102 USSC UPM-880 modules at the NREL outdoor test site. The results of this study were presented in a previous publication (4).

Figure 2 shows that the power output decreased by approximately 6% and 7% from the summer of 1994 to the winter of 1994-1995 for dc and ac power, respectively. An increase (similar in magnitude) is seen from January 1994 to the summer of 1994. There are at least two competing factors influencing the seasonal variations in performance of a-Si PV devices. These are the thermal and spectral effects described below.

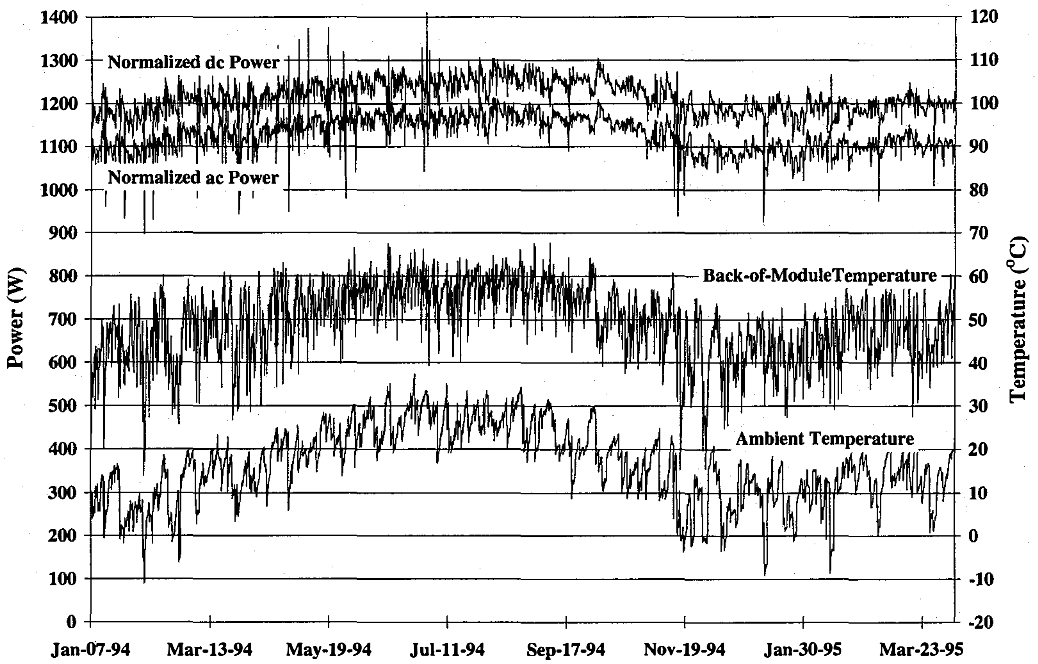

FIGURE 2. System dc and ac power (normalized to 1000 W/m2) versus back-of-module and ambient temperatures and time.

Thermal effects: Light-induced degradation (LID) and thermal-induced annealing (TIA) affect the number of metastable defect states in the energy gap of a-Si material. In the warm summer months, TIA can dominate, reducing the number of gap defects, and hence recombination of electron-hole pairs is also reduced. This leads to a slight increase in fill factor, because more carriers are collected, producing more current at a given voltage, hence more power. Figure 3 (next page) shows array peak power (normalized to 1000 W/m^2) and fill factor as measured by a portable I-V curve tracer versus instantaneous back-of-module temperature, air mass, average daily back-of-module temperature (fit with a moving-point trend line), and time. This figure shows the array peak power increasing with the average daily back-of-module temperature. Fill factor is also seen to slightly increase with temperature. In the cold winter months, TIA decreases, and LID (which is an ongoing phenomenon) dominates, increasing the number of gap defects, and hence recombination of electron-hole pairs, resulting in a decrease in fill factor (less current at a given voltage, resulting in less power). Figure 3 shows that, as the back-of-module temperature decreases in the cold winter months, so does power. Fill factor also showed a slight decrease in the cold winter months as compared to the warm summer months.

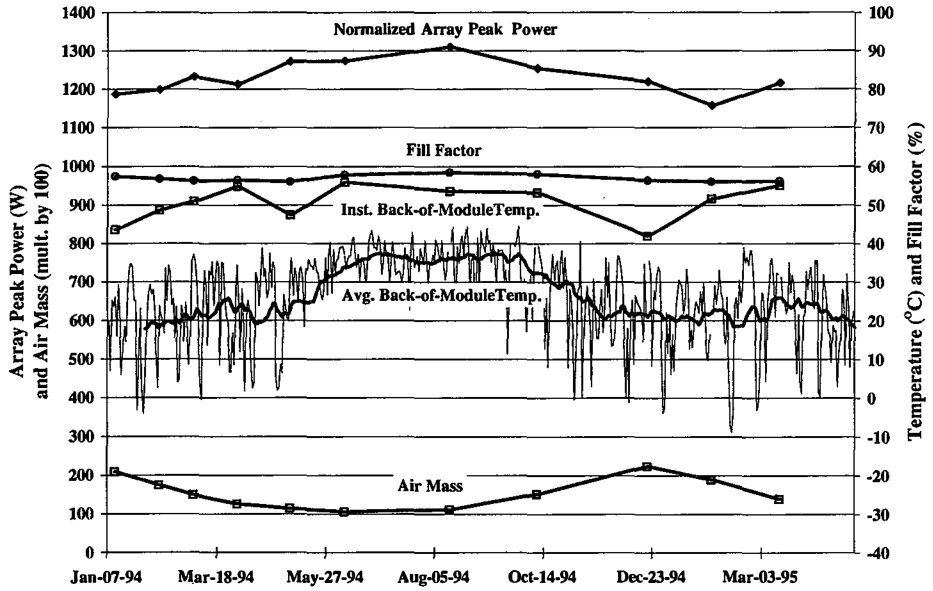

FIGURE 3. Array peak power (normalized to 1000 W/m^2) and fill factor versus back-of-module temperatures, air mass, and time.

Figure 4 shows maximum power and open-circuit array voltages versus instantaneous and average daily back-of-module temperatures and time as measured by a portable I-V curve tracer. It is seen in Figure 4 that these voltages had a small negative correlation with the instantaneous back-of-module temperature. The open-circuit voltage appears to be a little more sensitive to temperature. Figure 5 plots the average system subarray maximum power voltages versus back-of-module and ambient temperatures and time. The data used in plotting Figure 5 was restricted by POA irradiance levels greater than 850 W/m^2. Figure 5 shows that the maximum power voltage on the system level also exhibits only a slight inverse correlation with back-of-module temperature.

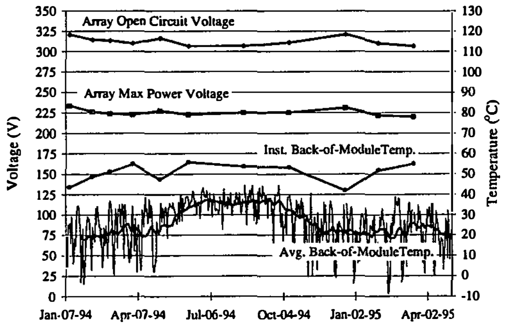

FIGURE 4. Array open-circuit and maximum power array voltages versus back-of-module temperatures and time.

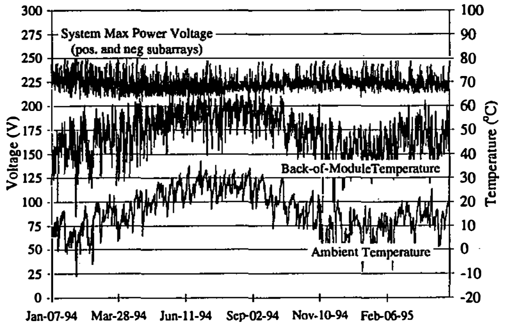

FIGURE 5. System subarray maximum power voltages versus back-of-module and ambient temperatures, and time.

Figure 6 shows maximum power and short-circuit currents, normalized to 1000 W/m^2, versus instantaneous and average daily back-of-module temperatures and time, as measured by a portable I-V curve tracer. An inverse correlation between current and air mass as well as a direct correlation between current and temperature is seen in this figure. Figure 7 plots the average system subarray maximum power currents (normalized to 1000 W/m^2) versus back-of-module and ambient temperatures, and time. The data in this graph was restricted by POA irradiance levels above 850 W/m^2. Figure 7 shows that the average system subarray maximum power current also exhibits an inverse correlation with air mass as well as a direct correlation with temperature.

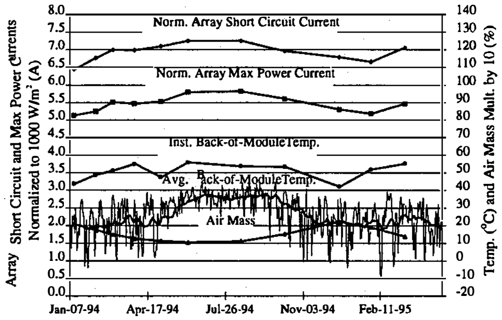

FIGURE 6. Array short-circuit and maximum power currents (normalized to 1000 W/m^2) versus back-of-module temperatures, air mass, and time.

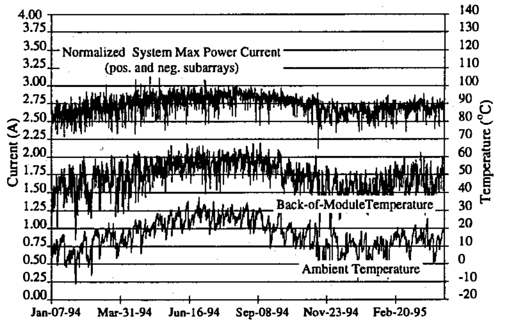

FIGURE 7. System subarray maximum power currents (normalized to 1000 W/m^2) versus back-of-module and ambient temperatures, and time.

Spectral effects: Multi-junction a-Si PV devices are influenced by the changing spectrum throughout the year. In the summer, the average air mass is lower and the blue-to-red ratio of the solar spectrum incident on the PV array is higher. For PV modules of this type of structure and composition, the higher blue spectral content leads to a more current-matched condition within the device, resulting in lower fill factors (less power at a given voltage). In the winter, the air mass is higher and the blue-to-red ratio is lower. This results in a more mismatched device (less blue light, less current in the top cell, more top-cell limited). The greater the current mismatch in modules of this type of structure and composition, the higher the overall fill factor (higher power at a given voltage).

In the dual-junction PV array under evaluation in this paper, the fill factor shows only a slight increase during the warm summer months (refer to Fig. 3). This is attributed to the opposing influences of thermal and spectral effects described above, causing a reduction in the seasonal variation (slight increase in the warm summer months) in fill factor. When these effects are superimposed on voltage (which slightly decreases with increasing temperature) and current (which increases with temperature, and is higher under bluer, low-air-mass summer skies), the variation in power, with season, is observed. Therefore, the reduction in power seen in winter is largely due to a reduction in current (refer to Figures 2, 5, and 7).

Due to the seasonal variations in system performance exhibited by a-Si, manufacturers, system designers, and users are faced with the challenge of properly rating and predicting a-Si PV system performance. Because this paper only studies the performance at one specific location (Golden, Colorado), for one specific device structure and composition, the results can only be applied to a-Si PV systems, of similar device structure and composition, and array configuration, which are to be located at similar latitude, elevation, and climate. However, some general conclusions can be drawn from these results. To facilitate this, system seasonal ratings for this system for each of the four seasons were calculated.

The seasonal ratings were based on the high (summer 1994), mid (spring 1994 and fall 1994), and low (winter 1994-1995) points of the seasonal variation observed in Figure 2. The data used for these ratings were bounded by 15 days about the seasonal high, mid, and low points seen in Figure 2, as well as at POA irradiance levels greater than 750 W/m^2. Linear regression analysis was performed on both dc and ac power versus POA irradiance. Figures 8, 9, 10, and 11 show the results of the regression analysis.

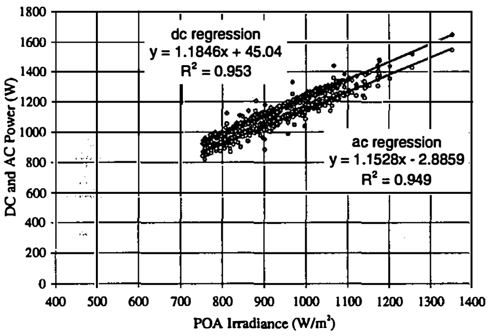

FIGURE 8. Spring 1994 power ratings.

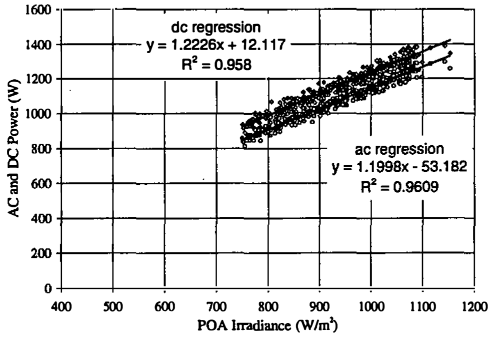

FIGURE 10. Fall 1994 power ratings.

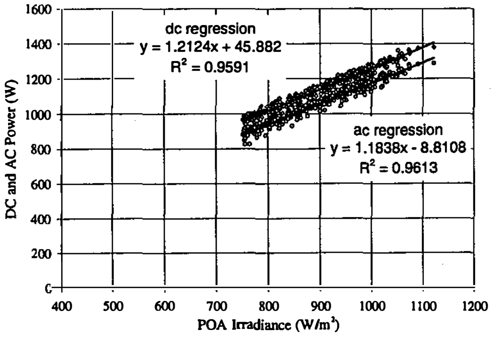

FIGURE 9. Summer 1994 power ratings.

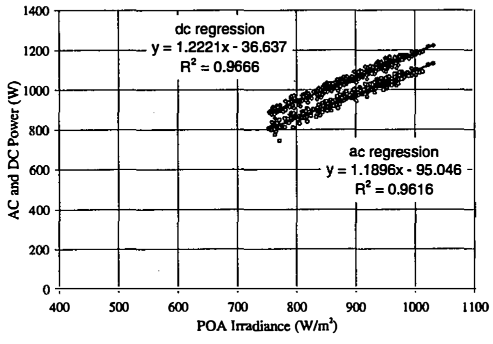

FIGURE 11. Winter 1994-1995 power ratings.

Table 2 summarizes the results of the seasonal ratings. The seasonal ratings were normalized to the summation of the manufacturer-supplied module peak powers at STC of 1408 W and are included in the table as dc power and ac power normalized to the array rating at STC. The corresponding back-of-module and ambient temperatures for the data used in calculating the ratings were averaged and are included in Table 2. Average delta temperature is the difference between the average back-of-module and ambient temperatures. The R^2 (correlation coefficient) values are included as an indicator of the variability of the data with respect to the linear regression used.

Referring to Table 2, it is seen that the spring 1994 and fall 1994 ratings for both dc and ac power are virtually the same. Therefore, equinox power ratings of 1230 W_{dc} and 1150 W_{ac} at 1000 W/m^2, 50 °C back-of-module temperature can be assigned. The summer power ratings for this system were 1258 W_{dc} and 1175 W_{ac} at 1000 W/m^2, 56 °C back-of-module temperature, and 27 °C ambient temperature. The winter power ratings for this system were 1185 W_{dc} and 1094 W_{ac} at 1000 W/m^2, 42 °C back-of-module temperature, and 10 °C ambient temperature. The data suggest that, in determining the summer and winter ac power output for this or similar PV systems, the summation of the manufacturer-supplied module peak powers at STC should be derated by factors of approximately of 0.83 and 0.78 for summer and winter operation, respectively.

TABLE 2. Seasonal ratings

Season	**DC Power, Watts (R^2)**	**AC Power, Watts (R^2)**	**DC Power Norm. to Array rating at STC**	**AC Power Norm. to Array rating at STC**	**Avg. Back-of-Module Temp., °C**	**Avg. Ambient Temp., °C**	**Avg. Delta Temp., °C**
Spring 1994	1230 (0.953)	1150 (0.949)	0.874	0.817	51.8	21.4	30.3
Summer 1994	1258 (0.959)	1175 (0.961)	0.893	0.834	56.5	27.1	29.5
Fall 1994	1235 (0.958)	1147 (0.961)	0.877	0.815	48.2	16.0	32.1
Winter 1994-1995	1185 (0.967)	1094 (0.962)	0.842	0.777	42.0	9.5	32.4

CONCLUSIONS

A nominal 1 kW_{ac} utility-interconnect photovoltaic (PV) system was deployed at the National Renewable Energy Laboratory's (NREL) photovoltaic outdoor test site for technical evaluation. The system employs USSC Integrated/Direct Mount PV

Roofing Modules (prototypes) mounted on simulated attic/roof structures. The PV array fill factor has been relatively stable with respect to time with only a slight decrease seen in the cold winter months as compared to the warm summer months. Both the maximum power and open-circuit voltages exhibited a small negative correlation with the instantaneous back-of-module temperature, with the open-circuit voltage appearing to be a little more sensitive to temperature. Maximum power and short-circuit currents showed an inverse correlation with air mass as well as a direct correlation with temperature. The seasonal variations in performance were largely attributed to seasonal variations in current.

Because of seasonal variations in system performance exhibited by a-Si, manufacturers, system designers, and users are faced with the challenge of properly rating and predicting a-Si PV system performance. The results presented in this paper suggest that in determining the summer and winter ac power output, the summation of the manufacturer-supplied module peak powers at STC for a similar a-Si PV array should be derated by factors of approximately of 0.83 and 0.78 for summer and winter operation, respectively. Furthermore, a rating methodology that takes into account the seasonal variations in performance on a regional basis for a-Si PV modules, arrays, and systems should be pursued.

ACKNOWLEDGMENTS

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