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SIEMENS SOLAR CIS PHOTOVOLTAIC MODULE AND SYSTEM PERFORMANCE AT THE NATIONAL RENEWABLE ENERGY LABORATORY

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ABSTRACT

This paper evaluates the individual module and array performance of Siemens Solar Industries' copper indium diselenide (CIS) polycrystalline thin-film technology. This is accomplished by studying module and array performance over time. Preliminary temperature coefficients for maximum power, maximum-power voltage, maximum-power current, open-circuit voltage, short-circuit current, and fill factor are determined at both the module and array level. These coefficients are used to correct module/array performance to 25°C to evaluate stability. We show that CIS exhibits a strong inverse correlation between array power and back-of-module temperature. This is due mainly to the narrow bandgap of the CIS material, which results in a strong inverse correlation between voltage and temperature. We also show that the temperature-corrected module and array performance has been relatively stable over the evaluation interval (≈2 years).

INTRODUCTION

The Engineering and Technology Validation Team at the National Renewable Energy Laboratory (NREL) conducts in situ technical evaluations of photovoltaic (PV) modules and arrays at NREL's Photovoltaic Outdoor Test Facility (OTF) in Golden, CO. The OTF is located at 39.7°N latitude, 105.2°W longitude, at an elevation of 1,782 meters. Siemens Solar Industries' polycrystalline thin-film technology is the focus of the research presented here.

The module structure is $Cu(In,Ga)Se_2$ (CIS) [1]. These modules are vintage CIS modules and do not represent the current state-of-the-art for Siemens Solar. Furthermore, all modules were subjected to accelerated testing at Siemens Solar before deployment at NREL. Note that these are research modules, so they do not all come from a common process or production stream, and this may be the source of some variation in the data.

The research team is attempting to correlate individual module performance with array performance. Also, temperature coefficients (TCs) are determined at the module, array, and system level. Results presented here are based on the outdoor performance of an individual module and of an array consisting of 34 modules (≈1 kW). Figure 1 shows the Siemens Solar 1-kW PV array being evaluated at NREL's OTF.

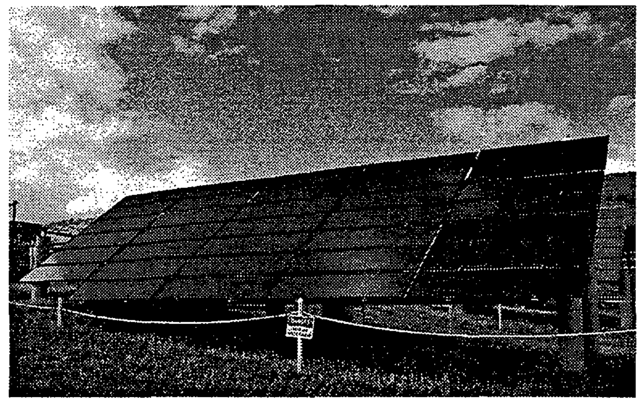

Fig. 1. The Siemens Solar 1-kW PV array.

EXPERIMENTAL PROCEDURE

Long-term performance data are acquired at the individual module, array, and system levels. Individual module, array, and system data are then evaluated and compared for correlation.

Individual Module Data Acquisition

Individual module performance is monitored with an RD-1200 multi-tracer. The module is loaded at its maximum power (max-power) point, except when current versus voltage (I-V) curves are taken. I-V curves are swept from short-circuit current (I_{sc}) to open-circuit voltage (V_{oc}) and are acquired every half-hour. The module data presented in this paper were restricted to plane-of-array (POA) irradiances between 950 and 1050 W/m^2. Data were collected over a period of about 1-1/2 years for this module.

Array/System Data Acquisition

In monitoring and evaluating system performance, two sets of data are collected. The two data sets include instantaneous measurements and real-time data acquisition. The instantaneous array performance is monitored via a portable I-V curve tracer and is termed "array performance" for this paper. These I-V traces are acquired once a month (weather permitting) at POA irradiances between 900 and 1100 W/m^2. Real-time array/system performance is monitored via a Campbell

Scientific CR10 datalogger, and these results are termed "system performance" here. Data collected include array current and voltage, back-of-module and ambient temperatures, and POA irradiance. Data are sampled every 5 s and are stored as 15-min. averages.

RESULTS AND DISCUSSION

Module Performance

One Siemens Solar CIS module was used for the module performance evaluation. The module's aperture-area was measured to be 3946.3 cm^2 (127.3 cm x 31.0 cm). This module is from a process or production stream similar to those deployed in the system. The module was installed at a 40° tilt and is loaded at maximum power during the day, except when I-V curves are taken. Data collection for this study started July 11, 1994, and ended December 13, 1995. Figure 2 shows maximum power (P_{max}) normalized to 1000 W/m^2 and back-of-module temperature versus time. In Fig. 2, the CIS module shows a strong inverse correlation between P_{max} and back-of-module temperature. This effect can be attributed to the narrow (about 1 eV) bandgap of the CIS material. V_{max}, V_{oc}, I_{max}, I_{sc}, and temperature were plotted against time. V_{max} and V_{oc} exhibited a strong inverse correlation with back-of-module temperature. I_{max} exhibited a larger inverse correlation with back-of-module temperature than that of I_{sc}. This is the result of an inverse correlation between fill factor (FF) and back-of-module temperature (see Table 1). Gaps in the data occur because the multi-tracer was unavailable when being used for other experiments.

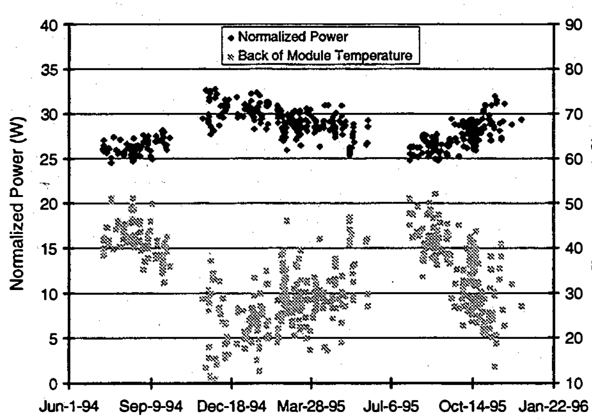

Figure 2. Normalized power and back-of-module temperature versus time.

To examine the long-term stability of this module, we corrected the performance data to a 25°C reference temperature by calculating TCs for the module. For example: using a linear regression of power (normalized to 1000 W/m^2) versus back-of-module temperature, the TC for P_{max} was determined to be -0.67%/°C, with an R^2 of 0.96 (Fig. 3). This R^2 indicates that P_{max} is well-correlated with temperature. The TC of -0.67%/°C is consistent with previously reported results for the CIS material [2].

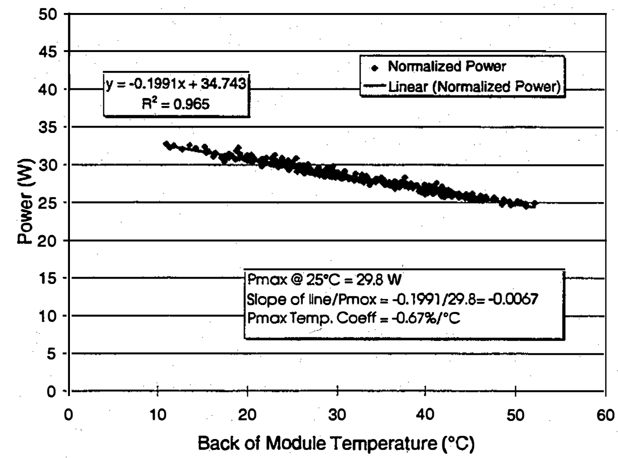

Figure 3. Normalized power versus module temperature.

Figure 4 shows P_{max} corrected to 25°C versus time for the CIS module. In this figure, note that the scatter due to temperature is greatly reduced (indicating a valid TC) and that the module shows good stability over time.

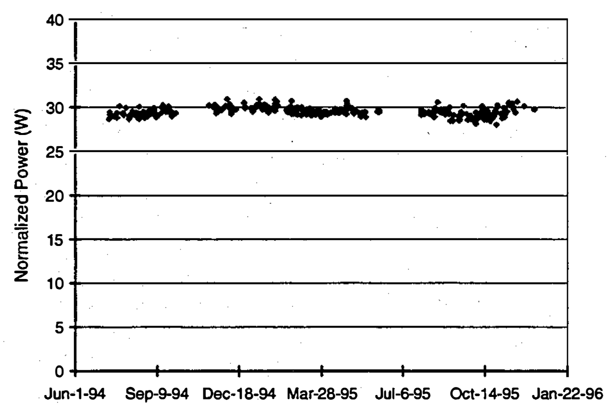

Figure 4. Normalized and temperature-corrected power versus time.

In a similar manner, TCs were calculated for V_{max}, V_{oc}, I_{max}, I_{sc}, and FF for the CIS module. These were also found to be consistent with previously reported results [2] and are summarized in Table 1.

Table 1. CIS Module Temperature Coefficients

	P_{max}	I_{max}	V_{max}	I_{sc}	V_{oc}	FF
TC	-0.67	-0.07	-0.60	0.00	-0.54	-0.15
R^2	0.96	0.21	0.96	0.00	0.98	0.85

Using the coefficients presented in Table 1, V_{max}, V_{oc}, I_{max}, and I_{sc} for the CIS module were also corrected for temperature and plotted against time. This exercise revealed that these coefficients greatly reduced the scatter in the module data due to temperature, thus indicating their validity. These graphs were omitted from the paper for brevity.

Array/System Performance

The Siemens Solar CIS array comprises 34 modules located at NREL's PV Outdoor Test Facility. The average module from this group had the following electrical characteristics (measured at NREL before deployment): P_{max}= 28.3 W, V_{max}= 15.56 V, V_{oc}= 22.38 V, I_{max}= 1.832 A, and I_{sc}= 2.264 A. Using the average max-power, the summation of module max-powers at STC is 962 W. Array installation was completed September 15, 1993, and data acquisition began April 1, 1994. The evaluation period for this data set covers about 2 years.

The array is fixed at a 40° tilt and is aligned true south. The array is divided into three separate subarrays. Two of the subarrays (1 and 3) are each composed of six parallel strings of two modules in series. Subarray 2 is composed of five parallel strings of two modules in series. Each subarray feeds dc power to a separate max-power tracker. The outputs of the three max-power trackers are paralleled and tied to a 0.95-ohm, 2-kW fixed resistive load. Subarrays 1 and 2 contain modules that have been physically damaged. These two subarrays have been showing a degradation trend in both power and current. Discussion of the system performance is therefore limited to subarray 3 (≈340 W at STC).

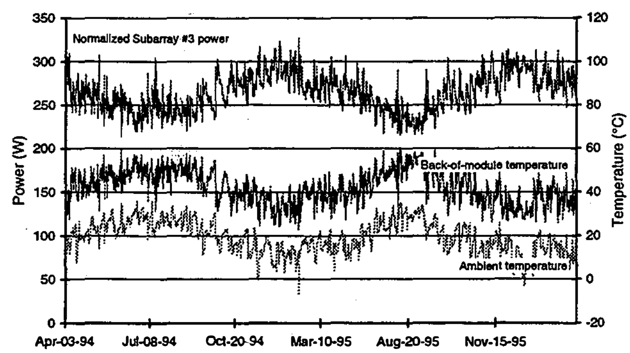

Figure 5. Normalized subarray power, back-of-module temperature, and ambient temperature versus time.

Figure 5 shows subarray 3 power, back-of-module temperature, and ambient temperature versus time. The data in this chart were restricted to POA irradiances between 900 and 1100 W/m^2. Power is normalized to 1000 W/m^2. The figure shows a strong inverse correlation between subarray power and back-of-module temperature. The max-power current (normalized to 1000 W/m^2), max-power voltage, and back-of-module temperature for subarray 3 were also plotted against time. We observed that both max-power current and max-power voltage exhibited a notable inverse correlation with temperature.

The array performance is monitored via a portable I-V curve tracer. Based on this data set, preliminary TCs for P_{max}, V_{max}, V_{oc}, I_{max}, I_{sc}, and FF were calculated. The data were not corrected for spectral effects. Figure 6 presents the TC calculation for P_{max}, -0.79%/°C, with an R^2 of 0.89. Table 2 presents the TCs calculated from the I-V curve-trace data. These TCs are also consistent with previously reported results [2]. The TC for FF was determined to be -0.25%/°C, again showing that fill factor for this material is influenced by temperature [2].

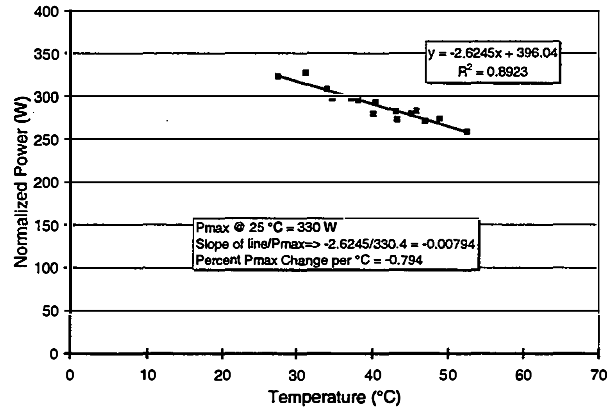

Figure 6. Array P_{max} temperature coefficient derivation.

Table 2. CIS Array Temperature Coefficients

	P_{max}	I_{max}	V_{max}	I_{sc}	V_{oc}	FF
TC	-0.79	-0.19	-0.63	-0.03	-0.56	-0.25
R^2	0.89	0.43	0.86	0.05	0.94	0.80

The subarray power presented in Figure 5 was corrected for temperature based on the TC of -0.79%/°C. The subarray performance, normalized to 1000 W/m^2 and corrected to 25°C back-of-module temperature, is shown in Figure 7. The temperature-corrected power is shown to be relatively stable, with only slight fluctuations that still follow temperature inversely. This indicates that the temperature coefficient for power may be slightly larger than that used here.

Table 3. CIS System Temperature Coefficients

	P_{max}	I_{max}	V_{max}
TC	-0.89	-0.53	-0.43
R^2	0.97	0.88	0.93

In an attempt to further mitigate the fluctuations in Fig. 7, we calculated TCs based on the system performance data. Using these TCs, shown in Table 3, subarray P_{max}, I_{max}, and V_{max} were corrected for temperature. Figure 8 shows the temperature-corrected power (using the larger coefficient of -0.89%/°C) for subarray 3. The amplitude of the variation in power due to temperature is slightly less than that seen in Fig. 7.

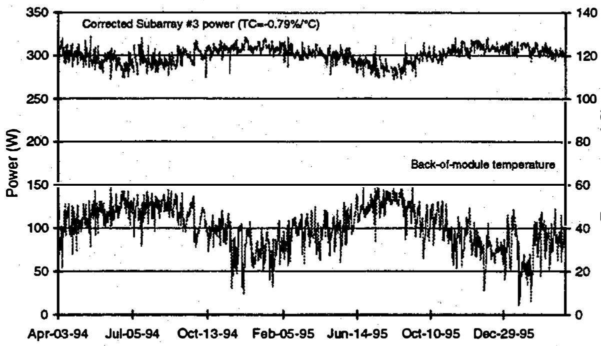

Figure 7. Normalized and temperature-corrected subarray power versus time (array temperature coefficient).

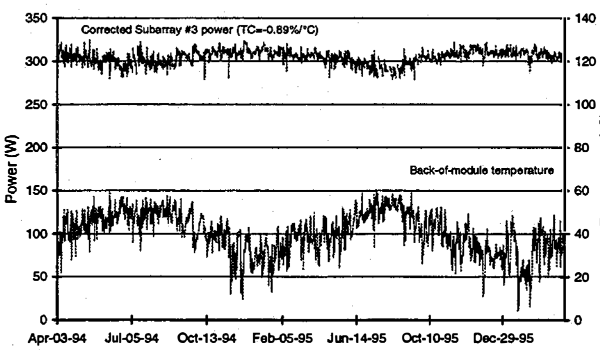

Figure 8. Normalized and temperature-corrected subarray power versus time (system temperature coefficient).

We also found that the TCs calculated at the system level, when applied to the real-time data, were far better at smoothing the variation in V_{max} and I_{max} due to temperature than those determined at the module and array level. Therefore, we conclude that using temperature coefficients calculated from the I-V characteristics of an individual module in predicting array performance may lead to discrepancies with actual system performance. This is due in part to the accuracy at which the max-power tracker finds the max-power point and the accuracy at which the temperature sensor measures the junction temperature (i.e., back-of-module temperature measurements versus imbedded-junction temperature measurements). Here, the accuracy at which the max-power tracker finds the max-power point was determined to be the major cause of variations in TCs among those calculated at the module and array levels (I-V curve-trace data) versus the system level (real-time data).

State-of-the-Art $Cu(In,Ga)(Se,S)_2$

The current state-of-the-art polycrystalline thin-film technology from Siemens Solar is a graded alloy with the notable addition of sulfur. This material is most properly designated as $Cu(In,Ga)(Se,S)_2$. By adding sulfur, the V_{oc} of the device was increased. This increased V_{oc} has the net affect of decreasing the TC for voltage, thus decreasing the TC for P_{max} to -0.55%/°C.

CONCLUSIONS

Preliminary temperature coefficients for P_{max}, V_{max}, I_{max}, V_{oc}, I_{sc}, and FF based on individual module, array, and system data were calculated. Table 4 summarizes these results. Note that the data were not corrected for spectral effects; thus, these preliminary coefficients may be influenced by spectrum. The cause of the elevated P_{max} temperature coefficient determined at the system level is attributed to max-power-point tracking error.

Max-power current was found to exhibit a weaker inverse correlation with temperature at the module level than at the array level. Power and voltage exhibited a strong inverse correlation with back-of-module temperature at both the module and array levels. This is mainly due to the narrow (about 1 eV) bandgap of the CIS material, which results in a strong inverse correlation between voltage and temperature. Fill factor was shown to exhibit an inverse correlation with temperature. Finally, the temperature-corrected module and array powers are shown to be relatively stable over the period of evaluation.

Table 4. Temperature Coefficients

	Module		Array		System	
	TC	R^2	TC	R^2	TC	R^2
P_{max}	-0.67	0.96	-0.79	0.89	-0.89	0.97
I_{max}	-0.07	0.21	-0.19	0.43	-0.53	0.88
V_{max}	-0.60	0.96	-0.63	0.86	-0.43	0.93
I_{sc}	0.00	0.00	-0.03	0.05	na	na
V_{oc}	-0.54	0.98	-0.56	0.94	na	na
FF	-0.15	0.85	-0.25	0.80	na	na

ACKNOWLEDGMENTS

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