NREL/TP-411-20402 • UC Category: 1250 • DE96007888

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B. Kroposki, T. Strand, and R. Hansen
National Renewable Energy Laboratory

R. Powell and R. Sasala
Solar Cells, Inc.

Presented at the 25th IEEE Photovoltaic Specialists Conference, May 13–17, 1996, Washington, D.C.

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of
the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
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Prepared under Task No. PV660103

May 1996

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TECHNICAL EVALUATION OF SOLAR CELLS, INC. CdTe MODULE AND ARRAY AT NREL

B. Kroposki, T. Strand, and R. Hansen
National Renewable Energy Laboratory
Golden, CO

R. Powell and R. Sasala
Solar Cells, Inc.
Toledo, OH

ABSTRACT

The Engineering and Technology Validation Team at the National Renewable Energy Laboratory (NREL) conducts in-situ technical evaluations of polycrystalline thin-film photovoltaic (PV) modules and arrays. This paper focuses on the technical evaluation of Solar Cells, Inc., (SCI) cadmium telluride (CdTe) module and array performance by attempting to correlate individual module and array performance. This is done by examining the performance and stability of the modules and array over a period of more than one year. Temperature coefficients for module and array parameters (P_{max}, V_{oc}, V_{max}, I_{sc}, I_{max}) are also calculated.

INTRODUCTION

The Engineering and Technology Validation Team at NREL conducts in-situ technical evaluations of polycrystalline thin-film PV modules and arrays. The focus of this research is on the performance of CdTe PV modules from SCI. The research team is attempting a "first effort" attempt to correlate individual module performance with array performance for this polycrystalline thin-film technology. This is done by looking at module and array performance over time. Also, temperature coefficients for different PV parameters (P_{max}, V_{oc}, V_{max}, I_{sc}, I_{max}) are determined on the module and array level. These evaluations on module/array performance and stability are conducted at the NREL Photovoltaic Outdoor Test Facility (OTF) in Golden, CO. The modules and arrays are located at 39.7 °N latitude, 105.2° W longitude and at 1782 meters elevation.

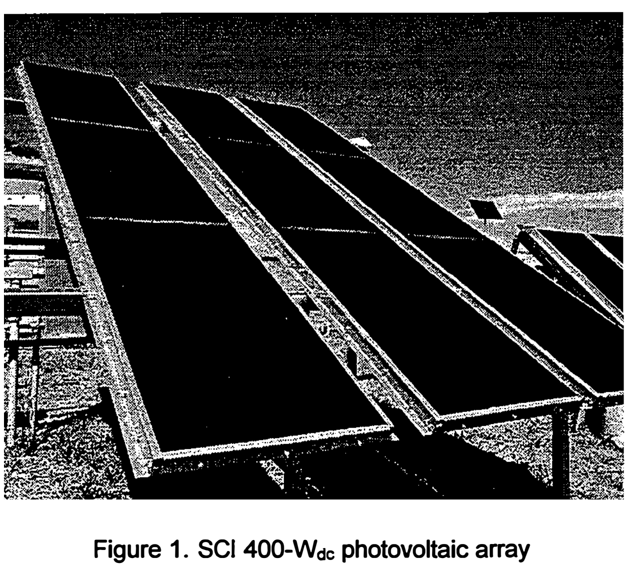

Figure 1. SCI 400-W_{dc} photovoltaic array

EXPERIMENTAL PROCEDURE

Module and Array Description

The SCI CdTe module is a glass-on-glass construction with CdS/CdTe as the active semiconductor. The modules used in this experiment were early production modules. These modules incorporate the old junction box and framing structure, which has been converted to a pigtail lead and frameless mount in new SCI designs. The modules used in this experiment had an aperture area of 0.68 m^2 (57.7 cm by 117.7 cm). Figure 1 shows a picture of the SCI array.

The individual 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 module started April 1994 and ended December 1995. The module had the following electrical characteristics prior to deployment: P_{max} = 49.3 W, V_{oc} = 89 V, I_{sc} = 0.89 A, V_{max} = 64 V, and I_{max} = 0.77 A.

The array consists of eight modules mounted at a 30° tilt and comprises two monopoles; each monopole uses four series-connected modules. The summation of module max-powers (as measured by NREL) was approximately 400 W_{dc}. The array is operated at its max-power point by an Omnion series 2200 inverter. The output of the Omnion inverter was fed to the local utility's power distribution grid. The modules in the array were deployed at intervals beginning February 1994 and ending May 1994. Data collection on the array began on July 1994 and ended July 1995. The average module from this group had the following electrical characteristics prior to deployment: P_{max} = 51 W, V_{oc} = 89 V, I_{sc} = 0.93 A, V_{max} = 65 V, and I_{max} = 0.79 A.

Individual Module Data Acquisition

Individual module performance is monitored with a multiple I-V curve-tracing unit. The unit is capable of testing up to 15 individual modules. For this experiment, the module is loaded at its maximum power point except when I-V curves are taken. These data are acquired every half hour between irradiances of 975-1025 W/m^2.

Array/System Data Acquisition

In monitoring and evaluating system performance, two sets of data are collected: instantaneous and long-term data measurements. The instantaneous array performance is monitored via a portable I-V curve tracer. These I-V traces are acquired once a month (weather permitting) at plane-of-array (POA) irradiances between 900 and 1100 W/m^2. Long-term array/system performance is monitored via a datalogger. Data collected include current, 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

Solar Cells, Inc., CdTe Module Performance

Figure 2 shows the normalized P_{max} (to 1000 W/m^2) and back-of-module temperature versus time for the module. This graph shows that the CdTe module has a weak inverse correlation between P_{max} and the back-of-module temperature. This effect can be attributed to the wider bandgap of the CdTe material as compared to other polycrystalline thin-film modules. Gaps in the data occur where the data acquisition system was down, but the module remained exposed.

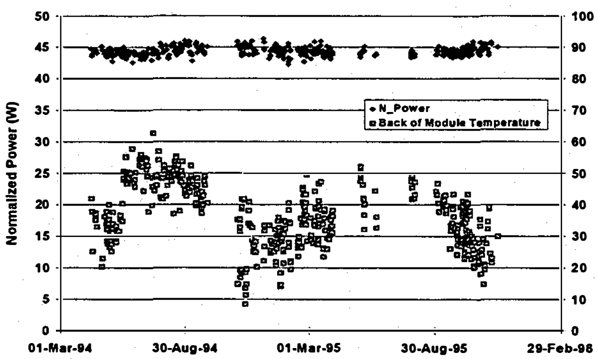

Figure 2. Normalized power and module temperature vs. time

To correct the performance data to 25°C, a temperature coefficient for the module was calculated. Using a linear regression of power (normalized to 1000 W/m^2) vs. back-of-module temperature, a temperature coefficient was calculated (Figure 3). The coefficient was obtained through a first-order regression analysis and was calculated to be -0.08 %/°C. This temperature coefficient had an R^2 of 0.2. The R^2 values are provided as a means by which to evaluate the quality or fit of the model. Given the R^2 value obtained for the P_{max} coefficient above, the coefficient will only describe 20% the variation in P_{max} due to temperature. For this module, the P_{max} and back-of-module temperature data are noisy, but the trend of the data appears valid. This module was calculated to have a P_{max} rating of 44.4 W at 25°C.

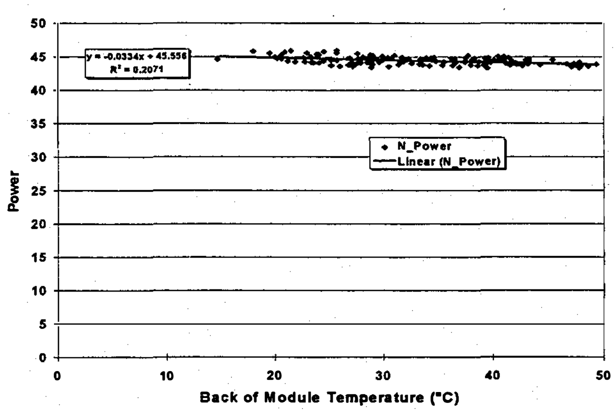

Figure 3. Normalized power vs. module temperature

Figure 4 shows the P_{max} data corrected to 25°C using the P_{max} temperature coefficient of -0.08%/C°. Because the temperature coefficient is very small, there is little change from figure 2. The figure shows that this module had good stability over the test period and that temperature has little effect on the module output.

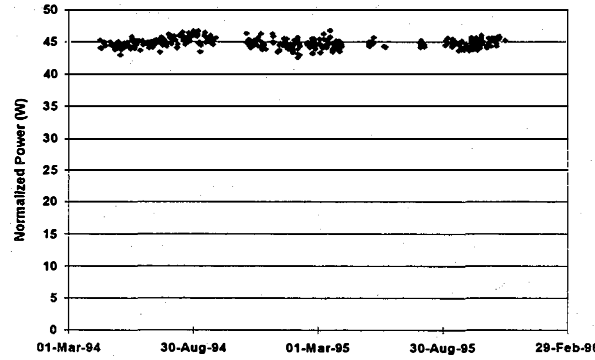

Figure 4. Normalized and temperature corrected power vs. time

To examine why the P_{max} temperature coefficient was so low, the same procedure was used to obtain temperature coefficients for current and voltage. Figure 5 shows normalized currents I_{sc} and I_{max} versus temperature. The low R^2 values and low line slope indicate that there is little correlation between temperature and current, although the I_{max} values show a slight increase with increasing temperatures. The temperature coefficients for I_{sc} and I_{max} were 0.06%/°C and 0.07%/°C respectively.

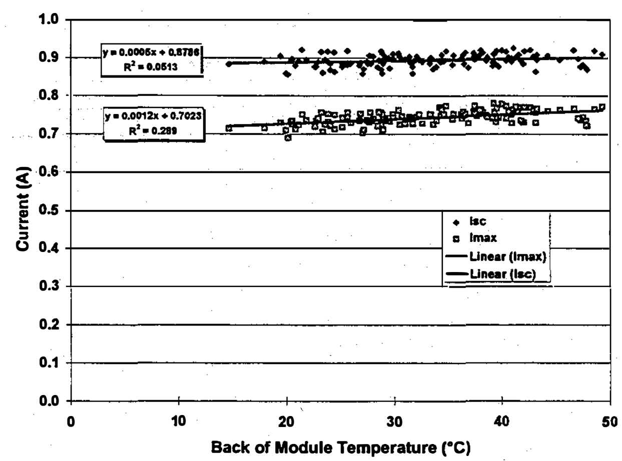

Figure 5. Normalized I_{sc} and I_{max} vs. temperature

Figure 6 shows that the voltage decreases as temperature increases for the module. This figure shows less scatter in the data compared with current and a relatively good correlation between voltage and temperature.

The temperature coefficients for V_{oc} and V_{max} were -0.24%/°C and -0.25%/°C respectively. The R^2 values were reasonably high with the data showing good correlation. Because there is a slightly negative temperature coefficient for V_{max} and a slightly positive temperature coefficient for I_{max}, this causes the temperature coefficient for P_{max} to become close to zero for this module.

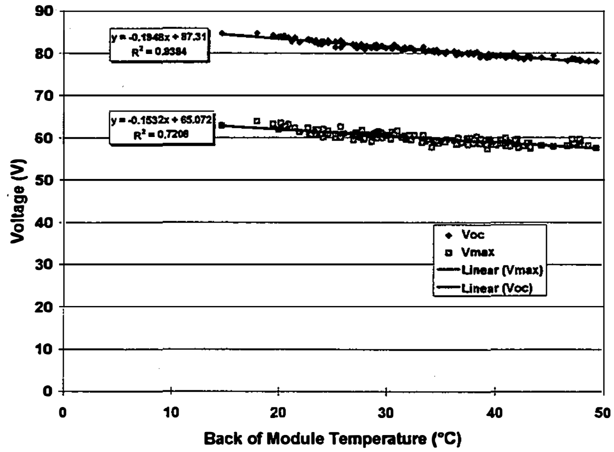

Figure 6. Normalized V_{oc} and V_{max} vs. temperature

Solar Cells, Inc., CdTe System/Array Performance

Figure 7 shows dc power, ac power, back-of-module temperature, and ambient temperature versus time for the 400 W_{dc} array. The data are fit with moving-average trend lines to aid visually in establishing any trends. The dc power before October 1994 is not shown because of problems with the data acquisition system. The data used in the figure were restricted to POA irradiance between 900 W/m^2 and 1000 W/m^2. Dc and ac power were normalized to 1000 W/m^2 for the figure. The back-of-module temperature ran at an average of 26°C above the ambient. This figure shows that temperature had little effect on ac power output at or near one-sun. However, dc power shows a weak inverse correlation with temperature. This discrepancy is possibly due to the low input level at which the 400 W_{dc} array operated the 2- kW_{ac} Omnion inverter. The figure further shows that array/system performance was relatively stable over this test period.

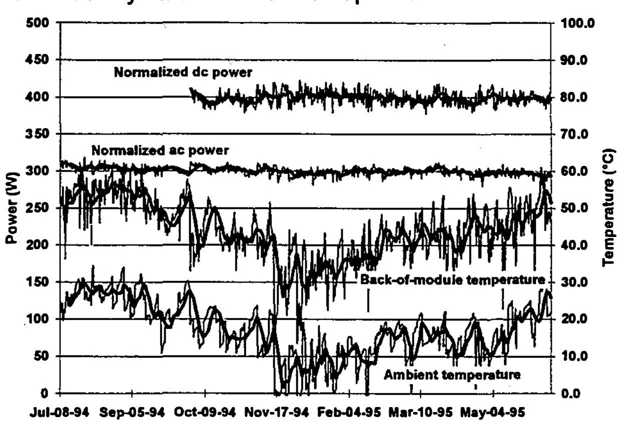

Figure 7. Normalized ac and dc power vs time

Figure 8 shows the performance of the positive and negative monopoles of the system. The temperature coefficient data are based on the performance of the two monopoles of the system.

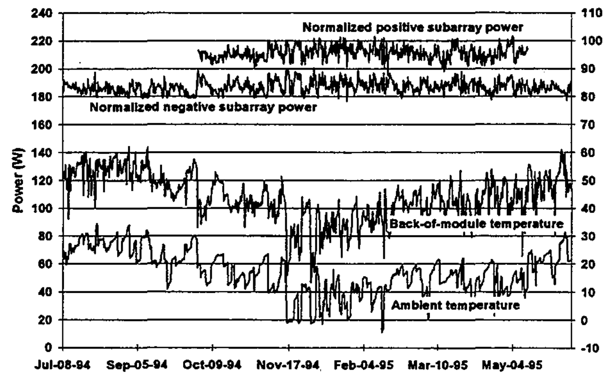

Figure 8. Normalized dc power for both monopoles

Figure 9 shows normalized power versus back of module temperature for the two monopoles. . Based on these data a preliminary temperature coefficient for P_{max} was calculated. The coefficient obtained was calculated to be -0.11%/°C and -0.16 %/°C for the positive and negative monopoles, respectively. The corresponding R^2 values for these coefficients are 0.14 and 0.33. Even though the P_{max} temperature coefficient has a low R^2, the trend appears valid.

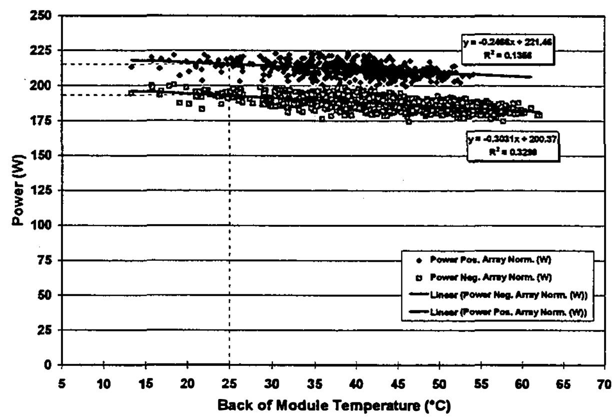

Figure 9. Normalized dc power vs. temperature

Figure 10 shows the two monopoles' dc power corrected for temperature and normalized to 1000 W/m^2 versus time. Note that the temperature coefficient used slightly reduces the variation in P_{max} due to temperature. Even though the P_{max} temperature coefficient has a low R^2, the trend appears valid.

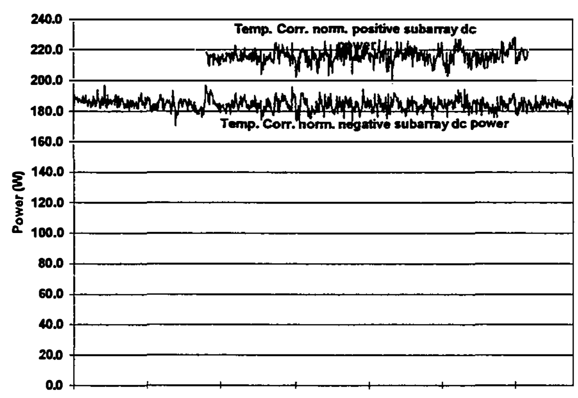

Figure 10. Normalized and temperature-corrected dc power for both sub-arrays

Again a similar approach was taken to obtain the temperature coefficients for I_{max} and V_{max}. For I_{max} the temperature coefficients were calculated to be 0.011%/°C and -0.06%/°C for the positive and negative monopoles respectively. For V_{max}. the temperature coefficients were calculated to be -0.1%/°C and -0.1%/°C for both the positive and negative monopoles. A summary of the array temperature coefficients is given in Table 1. The same type of module was examined under a pulsed-simulator indoors and was found to have a temperature coefficient for Pmax of -0.36%/°C[1]. The difference in these results show there are some artifacts when measuring CdTe under different light sources.

Table 1. Temperature Coefficients

	Module	R^2	Pos. mono-pole	R^2	Neg. mono -pole	R^2
P_{max}	-0.08	0.21	-0.11	0.14	-0.16	0.33
I_{sc}	0.06	0.05	*	*	*	*
I_{max}	0.07	0.29	0.01	0.0	-0.06	0.05
V_{oc}	-0.24	0.94	*	*	*	*
V_{max}	-0.25	0.72	-0.10	0.06	-0.10	0.06

- no data taken

CONCLUSIONS

Temperature coefficients for P_{max}, I_{sc}, I_{max}, V_{oc}, and V_{max} for CdTe at the module and array level were calculated. Opposite signs in I_{max} and V_{max} with temperature results in a weak negative temperature dependence of -0.08%/°C for the modules power. Table 1 summarizes these results. The data were not corrected for spectrum. Therefore, these preliminary temperature coefficients could change due to spectral influences.

Temperature was shown to have little effect on P_{max}, I_{sc}, and I_{max} at both the module and array level. Temperature did show a slight effect on voltage. Both module and array/system performance were relatively stable over the test period. One note is that because these modules were made in early production runs, these coefficients may not be applicable to SCI's current CdTe module technology.

The values for temperature coefficients for P_{max} show good correlation between the module and array data. Given the low R^2 values obtained for the P_{max} temperature coefficient, these values should be examined more closely, but may be considered to be marginally acceptable because their basic trends appear valid.

The current coefficients for the module and array data are extremely small. This shows that the current is not affected very much by temperature.

The voltage coefficients for both the module and array are slightly negative. Even though the coefficients for voltage are negative, they are relatively small and this keeps the power temperature coefficient small.

There are two facts about CdTe module and array performance that show excellent promise for commercialization. Our observations show that the Solar Cells, Inc. CdTe modules have a very small temperature coefficient as compared to crystalline silicon. The CdTe modules also appear to be very stable over the time period tested. These facts show that CdTe module and array output stays very constant over periods of time. This can be very helpful when designing a system because the array output appears to be constant throughout the year.

ACKNOWLEDGMENTS

The authors would like to thank Dick DeBlasio and Roland Hulstrom for their support in module and system testing at NREL. We thank Keith Emery, Steve Rummel, and Larry Ottoson for their support in module measurement and characterization. We also thank Ken Zweibel and Harin Ullal for their work in the Thin-Film PV Partnerships. Finally, this work was supported by the U.S. Department of Energy under contract No. DE-AC36-83CH10093.

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