TEMPERATURE DEPENDENCE OF PHOTOVOLTAIC CELLS, MODULES, AND SYSTEMS

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ABSTRACT

Photovoltaic (PV) cells and modules are often rated in terms of a set of standard reporting conditions defined by a temperature, spectral irradiance, and total irradiance. Because PV devices operate over a wide range of temperatures and irradiances, the temperature and irradiance-related behavior must be known. This paper surveys the temperature dependence of crystalline and thin-film, state-of-the-art, research-size cells, modules, and systems measured by a variety of methods. The various error sources and measurement methods that contribute to cause differences in the temperature coefficient for a given cell or module measured with various methods are discussed.

INTRODUCTION

This paper investigates temperature-dependent current *versus* voltage (I-V) measurements performed on several continuous light sources and the SPIRE 240A pulsed solar simulator. Simulator-based temperature coefficients (*TC*) are also compared with *TCs* for a wide variety of PV technologies derived from regression analysis of data taken under natural sunlight at the module and system level.

The temperature coefficient *TC* for a given parameter *Z* can be written as:

$$TC(part\,/\,°C) = \frac{1}{Z}\frac{\delta Z}{\delta T}\bigg|_{T_n = 25°C}, \quad (1)$$

where the normalization temperature T_n is chosen to be 25°C because it corresponds to the standard reference temperature for terrestrial and most space PV. It is important for comparison purposes that the normalization temperature be standardized or at least explicitly stated. Once *TC* is measured for a parameter *Z*, it can be translated from a given temperature *T* to another temperature *T*′ using:

$$Z' = Z + \frac{TC \cdot Z \cdot (T' - T)}{1 - TC \cdot (T_n - T)}. \quad (2)$$

For multijunction devices and any device where different current conduction mechanisms occur at different temperatures, *Z* is nonlinear. The value of *TC* can also change with the spectral content of the light source that *Z* is measured under because the quantum efficiency *TC* varies with wavelength. The value of *TC* also varies with irradiance because in Eq. 1 the value of *Z* changes with irradiance. Equation 2 assumes that *Z* is a linear function of temperature. Commercial data-acquisition systems often require the *TC* to be expressed in units of amps/°C and volts/°C at a given irradiance. Expressing the *TC* in absolute units allows the entire I-V curve to be translated for temperature. Corrections for temperature using absolute temperature coefficients require the number of cells in series and the number of parallel strings in a module or array.

MEASUREMENT METHODS

The temperature coefficient can be measured under simulated or natural light. Determining system temperature dependence requires measurement under actual operating conditions. Typically, the irradiance level is restricted to minimize variations in the temperature dependence with total or spectral irradiance.

Temperature-dependent I-V measurements can be grouped into the categories of pulsed-light or continuous-light solar simulators. In pulsed light solar simulators, the light-induced temperature gradient across the PV sample is negligible except at very high concentrations. This results in a very low error in the temperature of the PV device. The uncertainty in *TCs* determined by pulsed-light measurements can be affected by bias-rate-related artifacts and noise in the measured data.

Continuous-light sources allow for a very low random error in the measured I-V characteristics when long-integration-time, high-accuracy voltmeters are used to simultaneously measure the voltage, current, and irradiance. Bias-rate-related errors that occur in many thin-film material systems, high-lifetime silicon, and any high-capacitance PV design can be minimized or eliminated with a data-acquisition system using a continuous-light source [1]. Under continuous illumination, a temperature gradient will exist between the PV junction and the measured front- or back-surface temperature. A procedure employed at the National Renewable Energy Laboratory and elsewhere is to place the sample at the desired temperature in the dark at open-circuit conditions after "light soaking," if any, has been performed. The open-circuit voltage (V_{oc}) is then monitored as the shutter is opened. The highest V_{oc} observed is the V_{oc} at the desired temperature. The sample is then cooled, if possible, until this maximum V_{oc} is reached. The uncertainty associated with this method is limited by the shutter speed, voltage sampling rate, response time of the V_{oc} to the shutter being opened, and the amplitude stability of the light source.

A variety of methods have been employed to vary the temperature for simulator based temperature dependent measurements including:

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- Control the cell temperature with a temperature-controlled vacuum plate. This method minimizes temperature gradients.
- Heat a module in an environmental chamber and then place the heated module in an insulated box and measure the sample's I-V characteristics as it slowly cools down. This method results in the back of the module being warmer than the front because heat is radiated off the front surface, while the back surface is insulated.
- Heat the cell or module in a temperature controlled chamber with a window. This method minimizes temperature variations.
- Heat the module with a blanket from below and measure the I-V characteristics after the temperature has reached equilibrium. This procedure also has a typical temperature gradient between the back and front surface of 2°C.
- Adjust the room temperature to obtain the I-V characteristics at different temperatures. This method has a minimal thermal gradient and temperature range. The *TC* of the equipment may add to the error.

Ideally the temperature, spatial uniformity, and contacting should not be changed as the I-V characteristics are measured at different temperatures. This is because differences in spatial uniformity, irradiance level, or contacting can exceed the variation with temperature. Hysteresis in the I-V characteristics as a function of temperature can also occur because of different temperature gradients between the sample and sensor in the heating and cooling modes, sample degradation, or transient behavior. Hysteresis loops are especially evident in CdS/CdTe cells and modules because of light-soaking effects [1].

Careful placement of the temperature sensor on the back surface or front surface is essential to minimize errors introduced because the measured temperature is different than the junction temperature.

EXPERIMENTAL RESULTS

The measured *TCs* for a variety of cell and module PV technologies under "1-sun" illumination are summarized in Fig. 1. Table 1 illustrates the range of *TCs* for silicon cells and modules that have been measured.

Fig. 3 illustrates how the *TC* changes with irradiance for a multicrystalline silicon module. The *TC* for the CdS/CuInSe$_2$ module shown in Fig. 2 was representative of the modules in the Siemens Solar array deployed at the NREL Outdoor Test Facility. This module was also measured outdoors over the restricted irradiance range of 950–1050 W/m^2, giving a normalized maximum-power temperature coefficient of -6720 ppm/°C [8]. The maximum-power *TC* for the CIS system, determined by measuring the array performance with a portable I-V tracer over the restricted irradiance range of 900–1100 W/m^2 is -7690 ppm/°C with a correlation coefficient of 0.87.

For many outdoor *TC* measurements, the random error in the maximum power (P_{max}) and efficiency is correlated with the random error in I_{sc}. By looking at the P_{max} or efficiency *TC* as P_{max}/I_{sc}. instead of P_{max}/E_{tot}, the random error can be substantially reduced. This method assumes that I_{sc} is linear with irradiance over the irradiance range being corrected and that I_{sc} is corrected for temperature. An additional negligible source of error in this normalization procedure for P_{max} is the assumption that the *TC* of I_{sc} is constant over the irradiance range being corrected for. For the portable I-V tracer data above the P_{max} *TC* was -7410 ppm/°C with a correlation coefficient of 0.94.

The *TC versus* current density (Fig.4) is most appropriate for characterizing thermophotovoltaic devices because the spectral and total irradiance of the thermal emitter is application specific and not standardized. The TC were measured with a continuous light source and the V_{oc} method to obtain the I-V at a known temperature.

The nonlinear temperature dependence of a multijunction a-Si/a-Si:Ge module is illustrated in Figure 5. The nonlinear behavior occurs because the voltage *TC* for each junction is different. The temperature dependence will vary greatly, depending on the spectrum of the light source under which the temperature dependence was measured [9, 10].

The hysteresis in Fig. 6 is not temperature-related because there was no measurable hysteresis in *Voc versus* temperature. This module is typical of the modules in the CdTe system described elsewhere [11]. The P_{max} *TC* for the system was 1100 ppm/°C for the positive subarray and 1600 ppm/°C for the negative subarray [10]. One of the modules of the same type as the system was evaluated outdoors and a P_{max} *TC* of -800 ppm/°C was obtained. This P_{max} *TC* for this module measured under a pulsed solar simulator was -3600 ppm/°C.

The measured I_{sc} *TC* varies, depending on the light source, because the quantum efficiency does not vary with temperature in a multiplicative manner (Figs. 7,8). This changing quantum efficiency with temperature gives rise to a changing spectral mismatch error with temperature, the magnitude of which depends on how well the light source and reference spectrum are matched. An unexpectedly large variation (>50%) in the I_{sc} *TCs for* the same samples with temperature sensors attached circulated between various laboratories have been observed [11,12]. Table 2 shows *TCs* measured for a monocrystalline Si reference cell with an attached temperature sensor under the spectra shown in Fig. 9. The spectra of the 950 nm long wave pass filtered Spectrolab X25 spectrum cause the short-circuit temperature coefficient to increase dramatically. This increase can be explained by the variation in quantum efficiency with temperature (Fig. 7). For multijunction devices this difference in temperature coefficient between the top and bottom cell can cause the sign of the temperature coefficients to change with temperature.

SUMMARY

The temperature coefficients for a variety of PV technologies have been presented. Various strategies and precautions for measuring simulated and natural sunlight have been discussed. The *TC* varies within given technologies with irradiance level and spectrum.

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Table 1. Single-crystal and multicrystalline silicon *TCs*in units of ppm/°C [2-5].

Type	V_{oc}	I_{sc}	*FF*	P_{max}
Space Si cell [3]	-3490- -4510	380- 710	-1000- -1600	-4070- -1600
PESC Si cell [4]	-2690	650	-940	-3200
c-Si module	-2817	411	-1265	-3619
c-Si module	-3413	130	-1642	-5035
p-Si module	-2632	435	-1172	-3318
p-Si module	-3675	675	-1732	-4690
p-Si module	-2925	407	-1556	-3996
p-Si cell production	-4330- -679	738- 1230	-84- -2159	-3067- -5569
Thin film Si	-2429	493	-993	-2929
Si Conc.1/ 250 suns [5]	-2584/ 1724	488/ 168	-1079/ -680	-2916/ -2282

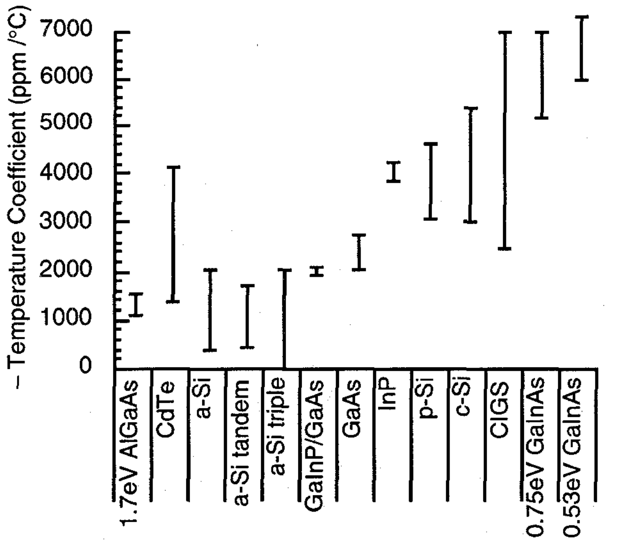

Figure 1. Range of P_{max} *TC* of cells and modules evaluated at NREL [2,6,7].

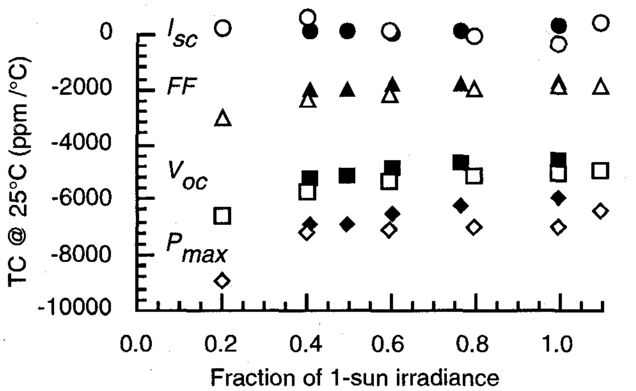

Figure 2. *CdS/CuInSe*$_2$ *module TC as a function of light* level measured under the SPIRE 240A pulsed solar simulator (closed symbols) and Atlas Climatic SC1600 environmental chamber with metal halide lamps (open symbols).

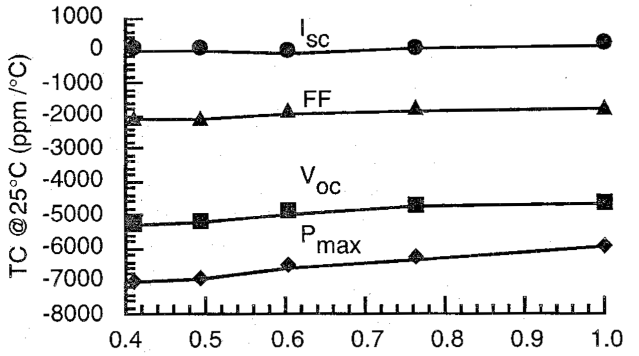

Figure 3. Multicrystalline Si module *TC* as a function of light level.

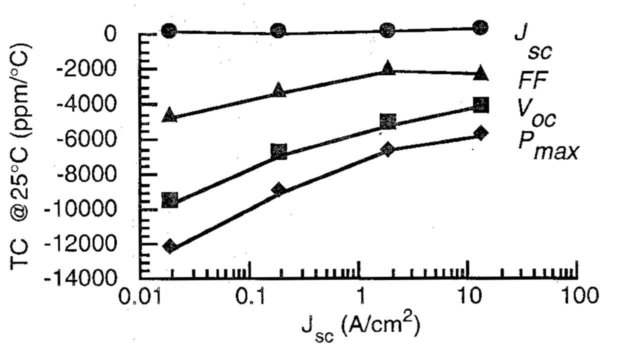

Figure 4. Variation in the *TC*t for a thermophotovoltaic cell with an energy gap of 0.626 eV.

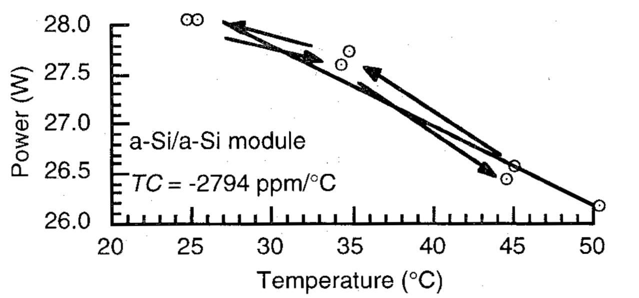

Figure 5. Variation in the *TC* for a multijunction amorphous silicon module.

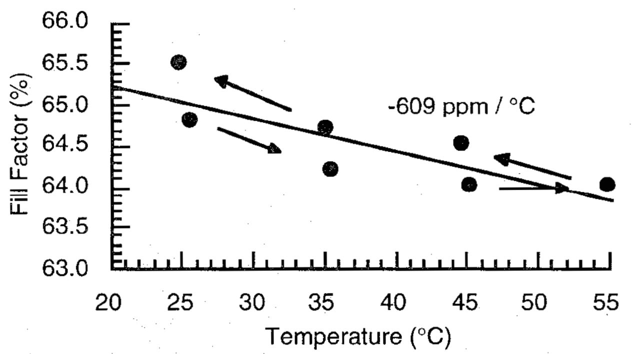

Figure 6. Change in the fill factor for a CdS/CdTe module showing significant hysteresis. This same module showed no significant hysteresis in V_{OC} or I_{SC}.

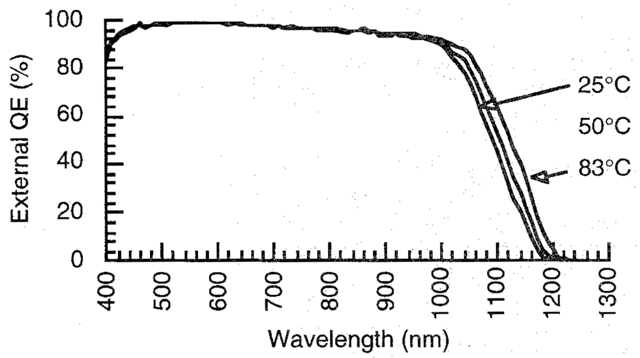

Figure 7. Variation in the absolute external quantum efficiency with temperature for a silicon cell showing the temperature dependence of the energy gap.

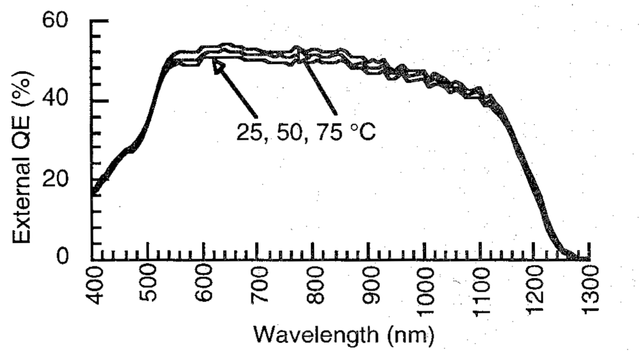

Figure 8. Variation in the quantum efficiency with temperature for a state-of-the-art CdS/Cu(Ga,In)(S,Se) cell showing minimal wavelength shift.

Table 2. The *TC* (ppm/°C) for a monocrystalline solar cell depends on the spectral nature of the light source used. The first three sources were set to generate the current equivalent to 1/7-sun illumination.

Source	I_{SC}	V_{OC}	*FF*
X25	736	-2968	-1106
EKE Lamp	990	-3018	-1138
950 LWP filtered X25	5608	-2467	-1172
X25 (1 sun)	829	-3335	-

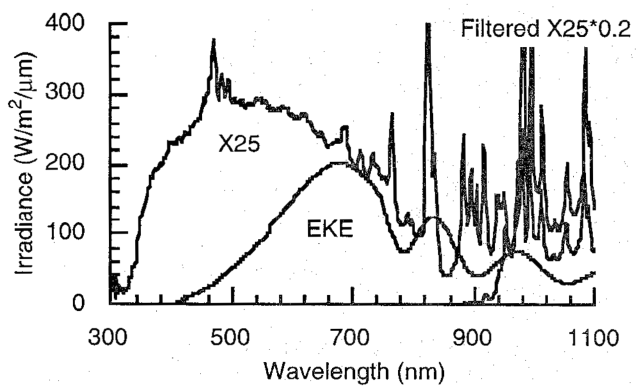

Figure 9. Spectra for the sources used to measure the temperature coefficients reported in Table 2. X25 indicates the Spectrolab X25 solar simulator. The EKE projector bulb (21V, 150W with dichroic reflector) operated at 11V.