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Closed-Form Solutions and Parameterization of the Problem of Current-Voltage Performance of Polycrystalline Photovoltaic Modules Deployed at Fixed Latitude Tilt

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CLOSED-FORM SOLUTIONS AND PARAMETERIZATION OF THE PROBLEM OF CURRENT-VOLTAGE PERFORMANCE OF POLYCRYSTALLINE PHOTOVOLTAIC MODULES DEPLOYED AT FIXED LATITUDE TILT

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ABSTRACT

One obstacle to wider market penetration for thin-film polycrystalline photovoltaic (PV) modules is the lack of field performance data, notably temperature-coefficient data for the current-voltage (I-V) characteristics over all irradiance levels encountered in the field. Generally, temperature coefficient and performance data are available only in a restricted range of illumination around 1-sun intensity. In this paper, the I-V performance data are presented, analyzed, and parameterized across a wide range of illumination levels and temperatures, allowing the modeling of the performance for three polycrystalline PV technologies: cadmium telluride, copper indium diselenide, and polycrystalline silicon. The data are scrutinized for clear-sky and diffuse-illumination conditions.

INTRODUCTION

The prevalence of crystalline and polycrystalline silicon technologies (bulk-Si) may be ascribed to many factors that translate to overall comfort of PV integrators with bulk-Si technology. With thin films, in contrast, there is considerable unease in the industry for reasons including: lower efficiency, past failures, module-reliability issues, plus a general lack of field performance data and a dearth of temperature-coefficient data for thin-film modules [1]. Currently existing module-performance data, even for bulk-Si, tend to be quite limited, being available typically in a restricted range of illumination near 1-sun. Furthermore, even much of the data presented at lower irradiance levels are generally obtained by attenuating the simulator intensity [2], which ignores angle-of-incidence or spectral effects present at lower illumination [3]; most likely, this thereby renders an unrealistic simulation of how lower light intensities affect the I-V parameters. In this paper, the I-V performance for polycrystalline thin-film PV modules is parameterized based on outdoor measurements, and a set of closed-form parameters and formulae are presented from which these can be translated to a wide variation of conditions.

METHOD

Outdoor performance data for three distinct PV technologies are scrutinized: three cadmium telluride (CdTe) modules (A, B, C); two copper indium diselenide (CIS) modules (A, B), and two polycrystalline silicon (pc-Si) modules (A, B). Their I-V characteristics are analyzed: the behavior of the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), and their respective temperature coefficients are derived from outdoor measurements, for irradiance levels ranging from low (50 W/m^2) to high (1200 W/m^2), with module temperatures ranging 20°–65°C. Irradiance levels were measured with a broadband pyranometer mounted in the same plane-of-array and angle as the modules; the temperatures represent back-of-module measurements; both are sampled simultaneously with the I-V traces. The featured modules are deployed facing south at fixed latitude tilt on the Performance and Energy Ratings Testbed (PERT) on the roof of the Outdoor Test Facility at NREL. The scrutinized data were obtained from 4 years worth of records, representing 30,000 to 50,000 I-V traces for each module. The V_{oc}, I_{sc}, and FF data, plus their temperature derivatives, were subsequently fit, evaluated at 25°C, and parameterized as polynomial functions of irradiance. Additionally, the data were segregated for clear-sky and diffuse illumination conditions using a statistical filter and model. All the parameters needed to calculate module performance for a wide range of operating conditions are presented.

One approach to modeling module performance is to interpolate the I-V trace at arbitrary irradiance in terms of traces already measured at nearby values [4]. However, this involves some recursive evaluation, does not represent a closed-form approach, and it may not be clear which are the best traces to use. Another approach is to extend the definition of the temperature coefficients—defined as the derivative with respect to temperature of the I-V parameter in question divided by its value at standard test conditions (STC)—to cover that of the derivatives measured at other irradiance, with these divided by the parameter's value at the new irradiance and 25°C. Note that even though the temperature derivatives of the I-V parameters might be slowly varying functions of irradiance, when these are divided by the respective parameter values at 25°C at the same irradiance, the resulting coefficient is convoluted with complex irradiance dependence. Hence, one problem that is encountered in expressing module performance in closed-form is formulating the dependence of the I-V parameters themselves.

In its simplest form, a PV device is modeled via the diode equation with parasitic series- and shunt-resistance terms. Deriving irradiance and temperature dependence for the I-V parameters (I_{sc}, V_{oc}, and FF) is fairly complex when parasitic resistances are taken into account, the details of which calculations can be found in the literature [5]. This reference points out the dependence of the FF on the reciprocal V_{oc}, which translates to a logarithmic dependence with irradiance. In this analysis, the I-V parameters and their temperature derivatives were reduced and evaluated at 25°C module temperature across varying irradiance in 50 W/m^2-wide discrete intervals thereof. The data are subsequently fit to a polynomial function in powers of irradiance, or its logarithm. One to three such terms were employed in the fits, containing 17–23 evaluations spanning irradiance values 50–1200 W/m^2. The number of fitting terms was limited to three, with the criteria for keeping terms based on statistical significance using the F-Distribution test at the 99% level of confidence.

RESULTS

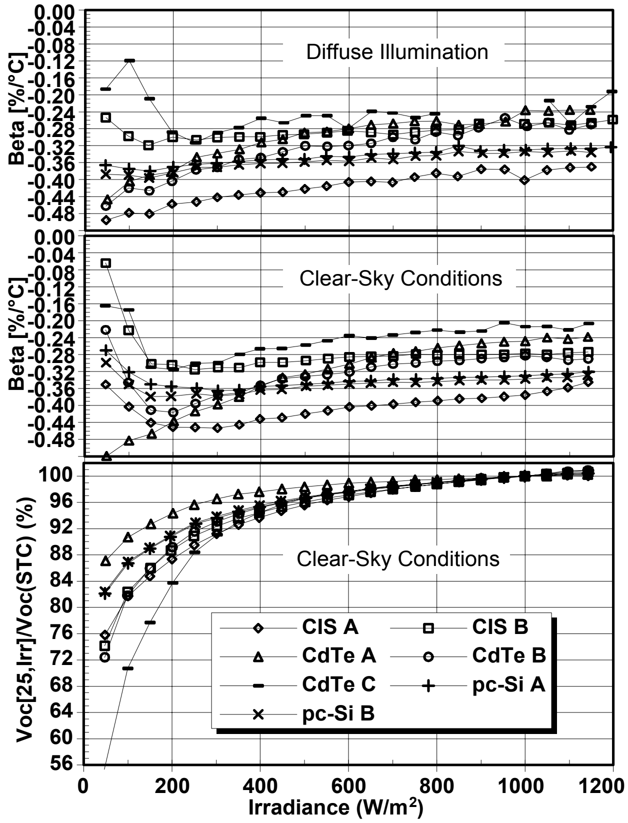

Fig. 1. V_{oc} data at 25°C and varying irradiance relative to values at STC at bottom, and beta values at middle, plotted against irradiance for 7 modules, for clear-sky conditions. Beta values at top are for diffuse illumination data.

Figure 1 depicts the ratio of module V_{oc} at 25°C across varying illumination as ratios to values at STC and its temperature coefficients, beta, respectively, in bottom and middle portions of the graph, plotted against irradiance along the ordinate axis, for predominantly clear-sky data. At top, the beta for diffuse illumination is depicted. Beta is defined as the derivative of V_{oc} with respect to temperature evaluated at a given irradiance, divided by the value V_{oc} at 25°C and the same irradiance. At 1000 W/m^2, beta values range from –0.28% to –0.20% per °C, –0.28% to –0.40% per °C, and –0.35% per °C, respectively, for CdTe, CIS, and pc-Si modules. The values of beta for clear-sky data become larger, more negative—about 25% larger—toward lower irradiance at 200 W/m^2. Thereafter, they appear to increase toward positive direction while still remaining negative down to 50 W/m^2 irradiance. There are slight differences between clear-sky and diffuse data, except at the lowest irradiance.

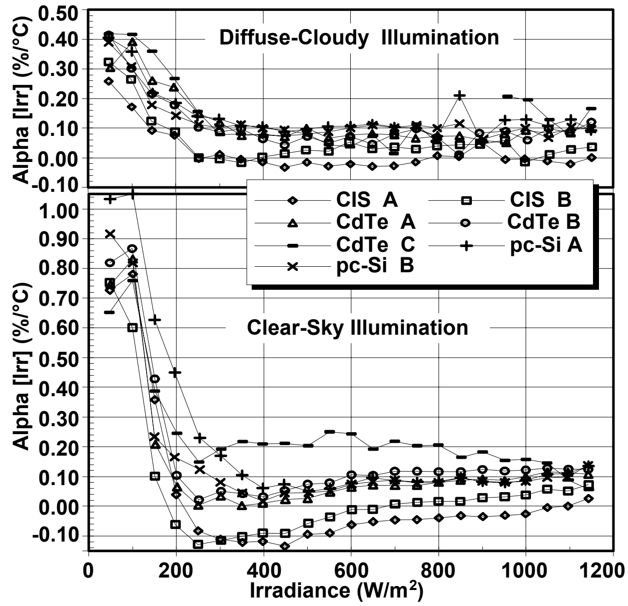

Fig. 2. Temperature coefficients of I_{sc}, alpha, plotted vs. irradiance for predominantly diffuse (top) and clear (bottom) conditions for seven polycrystalline PV modules.

In Fig. 2, the coefficients alpha are depicted for predominantly diffuse- and clear-sky illumination conditions, respectively, at top and bottom portions of the graph, plotted against irradiance along the ordinate axis. Alpha is defined as the derivative with respect to temperature of I_{sc} at a given irradiance divided by I_{sc} at 25°C and the same irradiance. If instead, alpha were defined as the derivative divided by the value of I_{sc} at STC, then the alpha values at low irradiance do not exhibit the increase depicted in Fig. 2. A striking feature of the data in Fig. 2 is the substantial difference between the two data sets at low illumination, below 250 W/m^2 irradiance: for diffuse illumination, the data do not exhibit as pronounced an increase as for the clear-sky data. Otherwise, above 300 W/m^2 irradiance, the alpha values between sets are quite similar, except for one of the CdTe modules (CdTe C). Also note that for the CIS modules under some irradiance conditions, the alpha values become negative. This behavior was observed for this module when measured under the Spire simulator.

Figure 3 portrays the FF data at 25°C under varying illumination, as ratios of their values at STC, and its temperature coefficients, respectively, in bottom and top portions of the graph, plotted against irradiance, for predominantly clear-sky conditions. Except for CdTe A, all the FF data vary smoothly in going from high to low illumination—typically exhibiting slight increases initially as the irradiance decreases, and then decreasing toward low irradiance. This behavior is consistent with series-resistance losses at high irradiance that become smaller at lower irradiance; and then by the functional dependence with V_{oc}, series and shunt resistance at low irradiance [5]. With the one exception (CdTe A), the temperature coefficients of the FF show monotonically decreasing values with increasing irradiance, varying from small positive values to negative values in the range 200–500 W/m^2. For diffuse illumination data, the FF and temperature coefficients are similar to those depicted in Fig. 3, except for CdTe A.

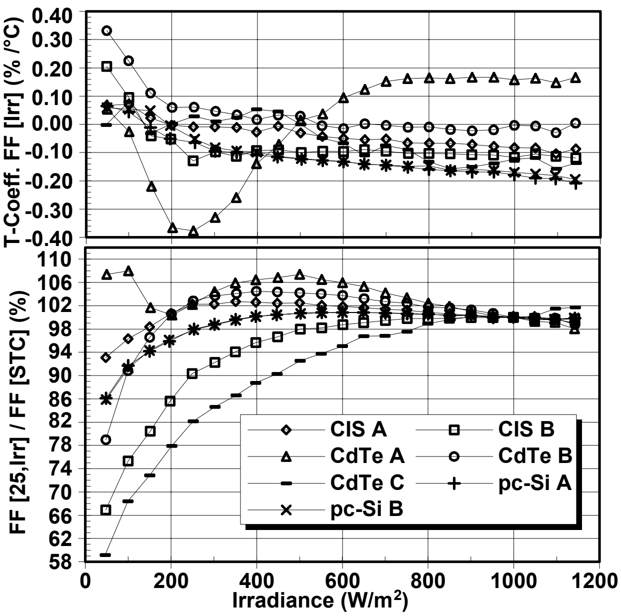

Fig. 3. FF ratios at 25°C relative to values at STC at bottom and its temperature coefficients at top, plotted against irradiance for seven modules, for clear-sky conditions.

For CdTe A, the FF behavior below 600W/m^2 irradiance is complex, but likely to be real as each point represents 500 to 700 I-V traces. In contrast, for diffuse illumination, the FF and temperature coefficients do not show the complex behavior seen at low irradiance in Fig. 3. Instead, the FF values increase at low irradiance and reach 110% of the value at STC at ~100 W/m^2. Its temperature coefficients obey a monotonic increase in values with irradiance, exhibiting nearly identical values to those shown in Fig. 3 for irradiance above 600 W/m^2.

ANALYSIS

Parametric representations for V_{oc}, I_{sc}, FF data plus their temperature coefficients beta, alpha, and Tcoeff FF are tabulated in the next section: Tables 1–6 and 7–12, respectively, for clear-sky and diffuse lighting. In these tables, the first, second, and third columns, respectively, denote the module, respective parameter value at STC, and one standard deviation of the fit. For V_{oc}, I_{sc}, and FF, the fourth and higher columns represent the coefficients of the terms (c_i) expressed as ratios of their STC values. For the temperature coefficients, the fourth and higher columns are simply the values of the coefficients of the fitting terms. The specific functional terms in the irradiance used are listed along the top row of each column, where the fourth column is the constant term, the fifth is the logarithm, the sixth is the linear, etc., as terms of the irradiance expressed in W/m^2. All the values of the temperature coefficients are evaluated as % change per °C with respect to the parameter evaluated at 25°C, at the same irradiance. To calculate any I-V parameter, P(x), or its temperature coefficient (*Tcoeff(x)*) at arbitrary irradiance, use Eqn. 1, with P^{STC} values taken from the second columns for V_{oc}, I_{sc}, and FF, and with P^{STC} = 1 for the temperature coefficients; and with x = irradiance expressed in units of W/m^2. Subsequently, to calculate the values of V_{oc}, I_{sc}, or FF at realistic module temperature T, multiply the *P(x)* by the temperature coefficient times the difference (T-25°C) as per Eqn. 2. The V_{oc}, I_{sc}, and FF are formulated such that their respective values at STC multiply a unitless function of irradiance inside the braces in Eqn. 1, which could accommodate similar modules simply by using their values at STC, rather than the ones studied.

$$P(x) = P^{STC} \cdot \{c_0 + c_L Ln(x) + c_1 x + c_2 x^2 + c_3 x^3 + c_{-1}/x + c_{-2}/x^2\} \quad (1)$$

$$P(x,T) = P(x) \cdot \{1 + Tcoeff(x) \cdot [T - 25]\} \quad (2)$$

More elaborate parameterization terms are used to represent I_{sc} due to complex behavior in low-illumination situations, with differences between clear-sky and diffuse lighting. For clear-sky data, the fit contains log and quadratic terms—not usually associated with the formulation of I_{sc}—whereas for diffuse data, these terms are missing (except for CdTe A). The source of the complexity lies in how low-illumination situations arise. For clear-sky conditions, this occurs when the angle-of-incidence (AOI) between the sun and the modules' surfaces is large and the direct-beam component becomes increasingly reflected and less absorbed. Diffuse illumination occurs either from obscuration by clouds or from lighting coming chiefly from the sky dome. It is instructive to analyze the effect that AOI has on I_{sc} via the photoresponse, which is defined as the short-circuit current density divided by the irradiance—a quantity that is independent of area with units of mA/W. These data are depicted in Fig. 5 plotted vs. AOI for six of the modules, along with the average irradiance at those AOI. When I_{sc} is strictly linear with irradiance, the photoresponse is constant: this is borne out at AOI < 60°. With increasing AOI, the direct-beam component is reflected away more rapidly than the pyranometer's response drops off, with the net effect that the modules do not absorb this measurable energy and the photoresponse decreases. Above ~84° AOI, more of the irradiance under clear skies becomes diffuse and behaves as if it were coming from the sky dome at an average AOI ~45°, thus becoming less reflected, increasing the photoresponse, and convoluting the function for I_{sc}.

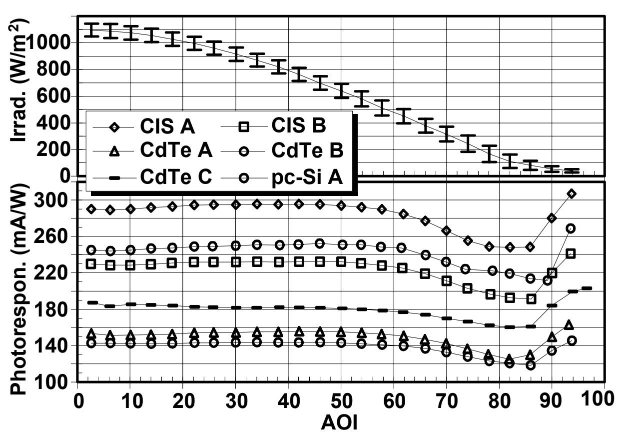

Fig. 5 Photoresponse at 25°C and irradiance plotted vs. AOI, respectively, at bottom and top for clear-sky data.

PARAMETRIC REPRESENTATION

Table 1. V_{oc} Parametric Representation [25°C, x = irradiance], Clear-Sky Conditions.

Module	V_{oc}^{STC} (V)	σ (V)	c_0 / V_{oc}^{STC}	c_L / V_{oc}^{STC} : Ln(x)	c_1 / V_{oc}^{STC} : x^1	c_2 / V_{oc}^{STC} : x^2	c_3 / V_{oc}^{STC} : x^3
CIS A	25.468	0.0471	0.4194	0.08658			-1.744E-11
CIS B	54.142	0.1243	0.3441	0.10491	-6.885E-05		
CdTe A	86.408	0.1811	0.6463	0.05770	-4.482E-05		
CdTe B	88.585	0.3716	0.2752	0.11882	-9.597E-05		
CdTe C	40.389	0.1337	-0.2375	0.20602		-4.159E-07	2.303E-10
pc-Si A	21.487	0.0216	0.5730	0.06379		-1.366E-08	
pc-Si B	21.369	0.0262	0.5768	0.06348		-1.528E-08	

Table 2. I_{sc} Parametric Representation [25°C, x = irradiance], Clear-Sky Conditions.

Module	I_{sc}^{STC} (A)	σ (A)	c_0 / I_{sc}^{STC}	c_L / I_{sc}^{STC} : Ln(x)	c_1 / I_{sc}^{STC}: x^1	c_2 / I_{sc}^{STC}: x^2
CIS A	2.3449	0.0090	0.2564	-0.070144	1.461E-03	-2.326E-07
CIS B	2.0024	0.0068	0.2367	-0.065320	1.432E-03	-2.173E-07
CdTe A	0.9074	0.0033	0.2797	-0.076025	1.513E-03	-2.678E-07
CdTe B	0.8858	0.0024	0.2018	-0.055979	1.371E-03	-1.865E-07
CdTe C	2.8345	0.0137	0.1374	-0.036841	1.188E-03	-7.067E-08
pc-Si A	2.1995	0.0081	0.2389	-0.065585	1.468E-03	-2.542E-07
pc-Si B	2.1960	0.0081	0.2390	-0.066055	1.476E-03	-2.589E-07

Table 3. Fill Factor (FF) Parametric Representation [25°C, x = irradiance], Clear-Sky Conditions.

Module	FF^{STC}(%)	σ (%)	c_0/FF^{STC}	c_L/FF^{STC}:Ln(x)	c_1/FF^{STC}:x	c_2/FF^{STC}: x^2	c_3/FF^{STC}: x^3	c_{-1}/FF^{STC}: 1/x	c_{-2}/FF^{STC}: $1/x^2$
CIS A	62.00	0.18	1.584	-0.07967				-34.673	872.63
CIS B	70.66	0.32	-0.221	0.21258	-2.481E-04				182.80
CdTe A	57.27	1.11	1.039		2.659E-05		-6.597E-11		
CdTe B	52.71	0.40	1.881	-0.11980				-55.036	1181.59
CdTe C	56.97	0.26	-0.225	0.18449		-5.436E-08		4.906	
pc-Si A	73.82	0.18	0.524	0.08792	-1.314E-04				
pc-Si B	74.34	0.15	0.517	0.08917	-1.328E-04				

Table 4. Beta Temperature-Coefficient Parametric Representation [25°C, x = irradiance] , Clear-Sky Conditions.

Module	$beta^{STC}$ (%/°C)	σ (%/°C)	c_0	c_L: Ln(x)	C_1: x^1	c_2: x^2	c_3: x^3	c_{-1}:1/x
CIS A	-3.671E-03	7.5348 E-05	-5.0413E-03		1.298E-06			0.07233
CIS B	-2.754E-03	6.4270 E-05	-4.4477E-03		2.991E-06	-1.474E-09		0.17667
CdTe A	-2.457E-03	4.4782 E-05	-5.4159E-03		5.648E-06	-2.689E-09		
CdTe B	-2.879E-03	8.8631 E-05	-5.8722E-03		5.915E-06	-3.086E-09		0.16383
CdTe C	-2.117E-03	1.9973 E-04	5.1144E-03	-1.820E-03	8.945E-06	-3.603E-09		
pc-Si A	-3.266E-03	3.5330 E-05	-3.8843E-03			1.379E-09	-8.198E-13	0.05860
pc-Si B	-3.349E-03	3.8321 E-05	-4.3989E-03		1.731E-06	-7.463E-10		0.06513

Table 5. Alpha Temperature-Coefficient Parametric Representation [25°C, x = irradiance], Clear-Sky Conditions.

Module	$alpha^{STC}$ (%/°C)	σ (%/°C)	c_0	c_L: Ln(x)	c_{-1}:1/x	c_{-2} :$1/x^2$
CIS A	8.915E-05	4.5082 E-04	-5.2416E-02	7.071E-03	3.767	-106.21
CIS B	6.840E-04	5.4406 E-04	-4.4044E-02	6.087E-03	2.749	-67.06
CdTe A	1.226E-03	6.6722 E-04	-4.3573E-02	6.050E-03	3.093	-85.62
CdTe B	1.400E-03	6.2247 E-04	-4.1258E-02	5.742E-03	3.079	-84.66
CdTe C	1.387E-03	7.5610 E-04	7.5033E-04		0.654	-17.38
pc-Si A	1.094E-03	2.2339 E-04	-4.0156E-02	5.468E-03	3.582	-105.03
pc-Si B	1.153E-03	5.4992 E-04	-3.4441E-02	4.789E-03	2.582	-66.09

Table 6. FF Temperature-Coefficient Parametric Representation [25°C, x = irradiance], Clear-Sky Conditions.

Module	Tcoeff-FF^{STC} (%/°C)	σ (%)	c_0	c_L: Ln(x)	c_1: x^1	c_2: x^2	c_3: x^3	c_{-1} : 1/x	c_{-2}: $1/x^2$
CIS A	-8.282E-04	1.02E-04	2.517E-03	-4.508E-04		-2.313E-10			
CIS B	-1.079E-03	2.21E-04	-1.502E-03		2.455E-07			0.1777	
CdTe A	1.925E-03	6.01E-04	2.792E-02	-7.386E-03	4.504E-05	-2.001E-08			
CdTe B	-4.031E-04	4.09E-04	-5.568E-05				-5.186E-13	0.1711	
CdTe C	-1.361E-03	3.81E-04	6.266E-04		-1.987E-06				
pc-Si A	-1.795E-03	8.31E-05	2.124E-03	-5.869E-04				0.1404	-4.893
pc-Si B	-1.727E-03	1.04E-04	9.449E-04	-4.255E-04				0.2784	-10.504

Table 7. V_{oc} Parametric Representation [25°C, x = irradiance] , Diffuse-Illumination Conditions.

Module	V_{oc}^{STC} (V)	σ (V)	c_0 / V_{oc}^{STC}	c_L / V_{oc}^{STC}: Ln(x)	c_1 / V_{oc}^{STC} : x^1	c_{-1} / V_{oc}^{STC} : 1/x	c_{-2} / V_{oc}^{STC}: $1/x^2$
CIS A	25.514	0.0570	0.1271	0.02597	-1.095E-05		
CIS B	54.038	0.1053	0.7044	0.04360		-5.616	
CdTe A	86.319	0.1295	0.6749	0.05225	-3.584E-05		
CdTe B	88.423	0.2620	0.7458	0.03789		-7.533	
CdTe C	40.420	0.1031	-0.0135	0.17166	-1.721E-04		-186.13
pc-Si A	21.482	0.0183	0.7024	0.04340		-2.192	
pc-Si B	21.376	0.0204	0.7007	0.04362		-2.057	

Table 8. I_{sc} Parametric Representation [25°C, x = irradiance], Diffuse-Illumination Conditions.

Module	V_{oc}^{STC} (V)	σ (V)	c_0 / V_{oc}^{STC}	c_L/ V_{oc}^{STC} : Ln(x)	c_1 / V_{oc}^{STC} : x^1	c_3 / V_{oc}^{STC} : x^3
CIS A	2.3322	0.0106	0.00236		1.012E-03	-1.472E-11
CIS B	2.0032	0.0106	-0.00146		1.015E-03	-1.365E-11
CdTe A	0.9126	0.0038	0.07805	-0.018616	1.099E-03	-4.841E-11
CdTe B	0.8923	0.0058	0.00350		9.965E-04	
CdTe C	2.8777	0.0151	0.00267		9.973E-04	
pc-Si A	2.2028	0.0116	0.00685		1.009E-03	-1.616E-11
pc-Si B	2.2029	0.0090	0.00352		1.017E-03	-2.047E-11

Table 9. Fill Factor Parametric Representation [25°C, x = irradiance], Diffuse-Illumination Conditions.

Module	FF^{STC} (%)	σ (%)	c_0 / FF^{STC}	c_L/ FF^{STC}: Ln(x)	c_1/ FF^{STC}: x	c_2/ FF^{STC} : x^2	c_{-1}/ FF^{STC} : 1/x
CIS A	61.66	0.24	0.632	0.0838	-2.562E-04	4.551E-08	
CIS B	70.74	0.21	0.071	0.1595	-1.725E-04		
CdTe A	57.16	0.31	1.148		-1.446E-04		-3.155
CdTe B	52.46	0.47	1.122		-1.071E-04		-15.039
CdTe C	59.74	0.38	0.107	0.1172	8.340E-05		
pc-Si A	73.40	0.49	0.691	0.0600	-1.029E-04		-2.384
pc-Si B	74.26	0.26	0.556	0.0827	-1.270E-04		-0.563

Table 10.Beta Temperature-Coefficient Parametric Representation [25°C, x = irradiance], Diffuse-Illumination Conditions.

Module	$beta^{STC}$ (%/°C)	σ (%/°C)	C_0	c_L: Ln(x)	c_1: x	c_2: x^2	c_{-1}: 1/x	c_{-2}:1/x^2
CIS A	-3.792E-03	6.593E-05	-8.029E-03	0.000608			0.03566	
CIS B	-2.708E-03	4.794E-05	-3.196E-03		4.866E-07			1.38084
CdTe A	-2.488E-03	8.467E-05	-7.330E-03	0.000701				
CdTe B	-2.773E-03	1.339E-04	-4.688E-03		3.736E-06	-1.820E-09		
CdTe C	-1.942E-03	2.218E-04	-2.006E-02	0.002481			1.00600	-28.00201
pc-Si A	-3.286E-03	3.397E-05	-5.646E-03	0.000337			0.03227	
pc-Si B	-3.371E-03	3.740E-05	-5.732E-03	0.000338			0.02556	

Table 11.Alpha Temperature-Coefficient Parametric Representation [25°C, x=irradiance], Diffuse-Illumination Conditions.

Module	$alpha^{STC}$ (%/°C)	σ (%/°C)	c_0	c_L: Ln(x)	c_1: x	c_{-1}:1/x	c_{-2} :1/x^2
CIS A	-4.781E-05	2.027E-04	8.976E-03	-0.001684	2.607E-06		
CIS B	3.668E-04	2.484E-04	-1.141E-02	0.001584		0.85674	-21.293
CdTe A	8.208E-04	1.870E-04	-1.223E-02	0.001718		1.22348	-40.083
CdTe B	6.931E-04	3.241E-04	1.186E-02	-0.002038	2.906E-06		
CdTe C	1.764E-03	3.099E-04	4.330E-02	-0.007749	1.245E-05	-0.46201	
pc-Si A	9.495E-04	3.680E-04	6.832E-04			0.27144	-5.089
pc-Si B	9.496E-04	1.736E-04	-5.150E-03	0.000806		0.54502	-12.441

Table 12. FF Temperature-Coefficient Parametric Representation [25°C, x = irradiance], Diffuse-Illumination Conditions.

Module	Tcoeff-FF^{STC} (%/°C)	σ (%/°C)	c_0	c_L: Ln(x)	c_1: x^1	c_2: x^2	c_3: x^3	c_{-1} :1/x
CIS A	-5.924E-04	2.153E-04	-5.924E-04					
CIS B	-1.172E-03	1.256E-04	4.583E-04	-0.000241				0.03215
CdTe A	1.567E-03	2.306E-04	-1.148E-04		2.332E-06		-6.503E-13	
CdTe B	-2.516E-06	3.641E-04	1.016E-04				-1.758E-13	0.07165
CdTe C	-2.991E-03	4.820E-04	1.714E-03		-4.706E-06			
pc-Si A	-1.732E-03	2.878E-04	3.299E-03	-0.000793	4.489E-07			
pc-Si B	-1.812E-03	2.486E-04	-9.084E-05		-3.848E-06	2.127E-09		

CONCLUSIONS

Parametric representations for V_{oc}, I_{sc}, FF, and their temperature coefficients were presented in closed form for seven polycrystalline PV modules, from which these three primary I-V parameters and their temperature coefficients may be calculated for irradiance ranging from 50 W/m^2 to 1200 W/m^2, and for module temperatures ranging from 20°–65°C, for predominantly clear-sky and diffuse-illumination conditions.

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One obstacle to wider market penetration for thin-film polycrystalline photovoltaic (PV) modules is the lack of field performance data, notably temperature-coefficient data for the current-voltage (I-V) characteristics over all irradiance levels encountered in the field. Generally, temperature coefficient and performance data are available only in a restricted range of illumination around 1-sun intensity. In this paper, the I-V performance data are presented, analyzed, and parameterized across a wide range of illumination levels and temperatures, allowing the modeling of the performance for three polycrystalline PV technologies: cadmium telluride, copper indium diselenide, and polycrystalline silicon. The data are scrutinized for clear-sky and diffuse-illumination conditions.

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