

Temperature-Dependent Spectral Mismatch Corrections

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Abstract—This paper develops the mathematical foundation for a translation of solar cell short-circuit current from one thermal and spectral irradiance operating condition to another without the use of ill-defined and error-prone temperature coefficients typically employed in solar cell metrology. Using the partial derivative of quantum efficiency with respect to temperature, the conventional isothermal expression for spectral mismatch corrections is modified to account for changes of current due to temperature; this modification completely eliminates the need for short-circuit-current temperature coefficients. An example calculation is provided to demonstrate use of the new translation.

Index Terms—Characterization, metrology, measurement, photovoltaic (PV) cells, PV modules, solar cells, short-circuit current, spectral irradiance, temperature coefficient (TC).

I. INTRODUCTION

IN previous work [1], we demonstrated that values of short-circuit current (I_{SC}) temperature coefficients (TCs, α) available in databases of commercial photovoltaic (PV) module characteristics and used in PV system sizing and rating software are inconsistent with each other and that these values can be physically unrealistic. Two primary causes of these problems were identified: 1) measurement techniques that produce module I_{SC} values uncorrelated with changing temperature and 2) the large dependence of α on spectral irradiance. For crystalline-Si devices, the database values can vary by more than a factor of 10 among similar products from the same manufacturer; consideration of how α is a function of photocurrent and semiconductor parameters revealed that the values should instead vary over much smaller ranges. If such wide-ranging values are used to correct I_{SC} data, then errors as large as 3–4% can easily arise with temperature differences of 40 °C. Such errors have serious implications for PV system ratings [1].

Translations or corrections of I_{SC} data to other temperatures (T) are typically done with expressions such as (1), in which T_0 is the temperature to which I_{SC1} is corrected (corresponding to I_{SC0}), and T_1 is the actual temperature of the device during the measurement of I_{SC1} [1], [2]:

$$I_{SC0} = \frac{I_{SC1}}{1 + \alpha(T_1 - T_0)}. \quad (1)$$

Manuscript received June 2, 2015; revised July 15, 2015; accepted July 17, 2015. Date of publication August 19, 2015; date of current version October 19, 2015.

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Digital Object Identifier 10.1109/JPHOTOV.2015.2459914

With the short-circuit TC α defined as the normalized derivative of I_{SC} with respect to T , (1) assumes that α is a fundamental property of the device, which is to say that α is invariant with both temperature and spectral irradiance [2], [3]. When the device's short-circuit current is linear with respect to irradiance, and irradiance is measured with a linear calibrated reference cell, temperature corrections can be combined with spectral corrections by including the spectral mismatch factor, M :

$$I_{SC0} = I_{SC1} \frac{I_R(T_{R,2})}{I_R(T_{R,3})} \cdot \frac{1}{M} \cdot \frac{1 + \alpha_R(T_{R,3} - T_{R,2})}{1 + \alpha_T(T_{T,1} - T_{T,0})}. \quad (2)$$

Here, the subscript T refers to the cell being tested, and the subscript R refers to the reference cell. $T_{R,2}$ is the temperature at which the reference cell is calibrated, and $T_{R,3}$ its temperature when measured. $T_{T,0}$ is the temperature to which I_{SC1} will be corrected (I_{SC0}), and $T_{T,1}$ is the measured temperature of the cell being tested. Typically, $T_{R,2} = T_{T,0} = 25$ °C, but this is not a necessary condition of the correction.

Equation (2) is derived from [4, eqs. (1)–(3)], with the exception that the TC term for the test cell (α_T) has been added. Equation (2) is also consistent with the expression for total irradiance (G) in [5, Sec. 3.1].

M is defined as a function of four convolution integrals that represent four current densities, J [2], [6]:

$$\begin{aligned} M &= \frac{J_T(E_M) J_R(E_0)}{J_R(E_M) J_T(E_0)} \\ &= \frac{\int_{\lambda_1}^{\lambda_2} R_T(\lambda) E_M(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} R_R(\lambda) E_0(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} R_R(\lambda) E_M(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} R_T(\lambda) E_0(\lambda) d\lambda} \\ &= \frac{\int_{\lambda_1}^{\lambda_2} \lambda Q_T(\lambda) E_M(\lambda) d\lambda \int_{\lambda_3}^{\lambda_4} \lambda Q_R(\lambda) E_0(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} \lambda Q_R(\lambda) E_M(\lambda) d\lambda \int_{\lambda_1}^{\lambda_2} \lambda Q_T(\lambda) E_0(\lambda) d\lambda}. \end{aligned} \quad (3)$$

$R_T(\lambda)$ and $R_R(\lambda)$ are the power-mode spectral responsivities in A/W of the test and reference cells as functions of wavelength λ , and $Q_T(\lambda)$ and $Q_R(\lambda)$ are the corresponding quantum efficiencies (QEs), with units of electrons per photon. $E_M(\lambda)$ is the spectral irradiance during the I_{SC} measurement, and $E_0(\lambda)$ is the reference spectral irradiance to which the reference cell is calibrated, and to which the test cell is corrected (not shown are the active areas of the two cells that convert J_{SC} to I_{SC} , which cancel in the ratios). $E_0(\lambda)$ and $E_M(\lambda)$ have units of W/m²/nm. The integration limits in (3) are the upper and lower bounds of the respective QE wavelength ranges. Spectral mismatch equations have become consensus standards [7], [8] and are commonly used in PV measurements [4], [5] and for translations of PV performance data [9].

In (3), power-mode spectral responsivity has been converted to QE with the following identity, where q is the electron charge, h is Planck's constant, and c is the speed of light; these constants cancel after substitution into the integrals [7]:

$$R(\lambda) = (q\lambda/hc) Q(\lambda). \quad (4)$$

Note that if M is expressed in terms of irradiance-mode spectral responsivity, with units of $A/(W/m^2)$, the four integrals are then currents rather than current densities, and the active areas are not present. In addition, any multiplicative calibration constants on the QEs and spectral irradiances cancel, allowing the use of relative quantities that can be normalized by any arbitrary value. Because of this canceling, absolute QEs are not needed, eliminating the requirement for much more difficult measurements.

II. ASSUMPTIONS

The TC of I_{SC} under an arbitrary spectral irradiance $E(\lambda)$ and normalized to the value at an arbitrary reference temperature T_0 can be defined as [1]

$$\alpha = \frac{dI_{SC}}{dT} \Big|_{T=T_0} / I_{SC0}. \quad (5)$$

Determinations of α are performed by measuring the I_{SC} of a test device at a series of fixed temperatures, fitting the I_{SC} versus T data to a straight line, and then dividing the slope of the linear fit by the current at the reference temperature.

Unfortunately, these measurements are easily made with little or no attention paid to spectral irradiance, beyond the common knowledge that xenon emission lines in solar simulator spectra can introduce artifacts [3]. As an example, the I_{SC} TC measurement procedure in IEC 60891 specifically allows solar simulators that have only a medium match (i.e., "Class B") to the reference spectral irradiance [5].

However, there are two assumptions implicit in (2) that are normally not recognized or overlooked. First, the spectral mismatch correction was developed without considering temperature effects, which is to say that the QEs are assumed to be invariant with temperature. Second, the constants α_T and α_R completely describe the variation of I_{SC} with temperature. Solar cell QEs do vary with temperature; therefore, the first assumption is only true when $T_{R,0} = T_{R,3}$ and $T_{T,1} = T_{T,2}$, i.e., under isothermal conditions. This same restriction also holds for (3).

Because I_{SC} TCs are, in fact, strong functions of spectral irradiance [1], the second assumption is only true when $E_0(\lambda) = E_M(\lambda)$, which is to say only when spectral irradiance is fixed, and α was measured under the fixed $E(\lambda)$.

The limitations of (2) are then that the standard definition of M assumes that the QEs do not change with temperature. In addition, through the fixed values of α , an implicit assumption is made that spectral irradiance is invariant. Therefore, (2) is inadequate in the general case for combined temperature and spectral irradiance corrections to short-circuit current.

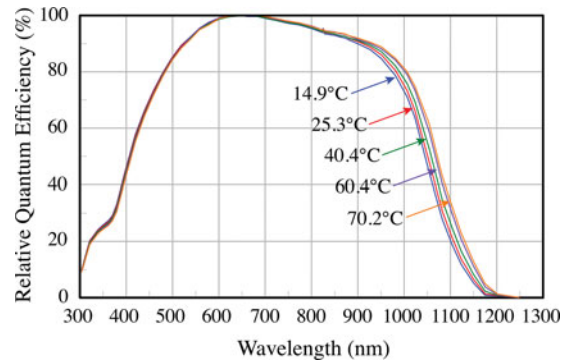


Fig. 1. quantum efficiency versus wavelength at several discrete temperatures for a polycrystalline silicon solar cell.

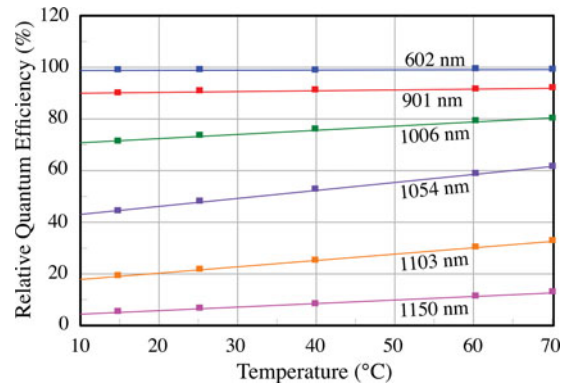


Fig. 2. Relative quantum efficiency versus temperature at several discrete wavelengths, extracted from the data plotted in Fig. 1. The lines are straight-line fits to the individual QE data points.

III. TEMPERATURE VARIATION OF SHORT-CIRCUIT CURRENT

Recognizing that I_{SC} is a spectral function of both $Q(\lambda)$ and $E(\lambda)$, the simple definition of α [see (5)] can be expanded into (6), which describes the variation of current with temperature through the partial derivative of $Q(\lambda)$ with respect to T , $\partial Q/\partial T(\lambda)$:

$$\alpha = \frac{dI_{SC}}{dT} \Big|_{T=T_0} / I_{SC0} = \frac{\int \lambda \frac{\partial Q}{\partial T}(\lambda) E(\lambda) d\lambda}{\int \lambda Q(\lambda, T_0) E(\lambda) d\lambda}. \quad (6)$$

Although this derivative is not a common PV device characterization, it can be determined with a relatively simple procedure that uses multiple QE measurements across a temperature range. Fig. 1 shows the QE of a generic polycrystalline silicon solar cell, repeated at a number of temperatures over the 15–70 °C temperature range.

As the temperature increases, the cutoff in the near-infrared region shifts toward longer wavelengths, which is the cause of the positive I_{SC} versus temperature characteristic. The shift is easier to see in Fig. 2, in which the same QE data are plotted versus T at several wavelengths between 600 and 1150 nm. For Si and GaAs cells at single wavelengths, $Q(\lambda, T)$ has been found to be linear, as seen in Fig. 2 [1]. As the QE decreases with longer wavelengths, the slope of $Q(\lambda, T)$ with respect to T increases from essentially zero to a peak value at 1050 nm

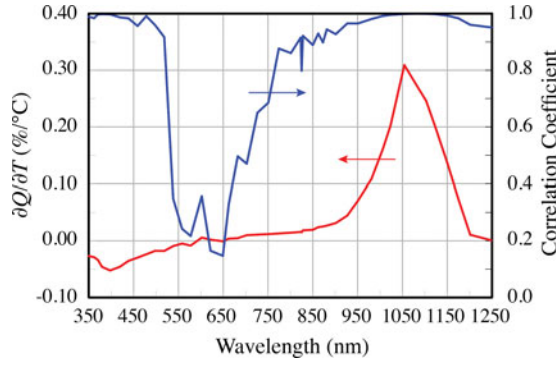


Fig. 3. Derivative of quantum efficiency with respect to temperature, calculated from the slopes of the straight-line fits at single wavelengths shown in Fig. 1. Also shown are the correlation coefficients of the fits at each wavelength.

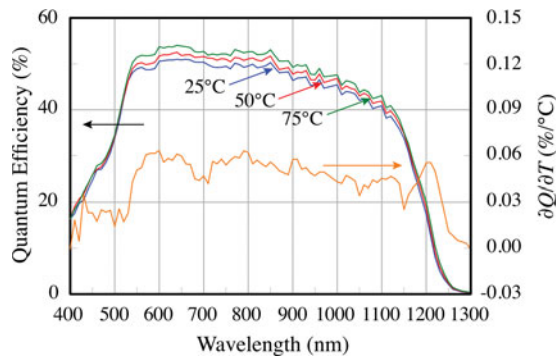


Fig. 4. Quantum efficiency at three temperatures for the CdS/Cu(Ga,In)(S,Se) cell in [3] and the $\partial Q/\partial T(\lambda)$ characteristic calculated from these QE data.

and then rapidly drops to zero. Thus, taking $\partial Q/\partial T(\lambda)$ as only a function of λ is justified, and this partial derivative can be determined numerically by calculating the $Q(\lambda, T)$ slope at each wavelength using straight-line fits [1]. Fig. 3 shows the results of applying this procedure to the data in Fig. 1.

The TC of I_{SC} in Si cells has been shown to have a strong sensitivity to spectral irradiance: In sunlight, α can change by more than 30% as air mass changes from 1.0 to 4.0 [1]. It is the area under the $\partial Q/\partial T(\lambda)$ curve that determines the spectral sensitivity (along with changing spectral irradiance, of course) [10].

Solar cells composed of semiconductors other than Si should also be expected to have unique $\partial Q/\partial T(\lambda)$ curves. Fig. 4 shows $Q(\lambda, T)$ for a CdS/Cu(Ga,In)(S,Se) cell, previously published [3], along with the $\partial Q/\partial T(\lambda)$ curve derived from these data. There is a visible peak at 1200 nm corresponding to the shift of bandgap with temperature, plus a somewhat constant value of about 0.05%/°C between this peak and the CdS band edge at 540 nm. Without attempting to provide any physical explanations, we instead note that these curves might be useful for investigating carrier transport phenomena in solar cells.

IV. TEMPERATURE-DEPENDENT SPECTRAL MISMATCH

We now return to the problem of correcting I_{SC} measurements from one temperature and irradiance condition to another, using a reference cell to measure total irradiance. A first attempt to

overcome the inadequacy in (2) identified in Section II might be to write

$$I_{SC2} = I_{SC1} \frac{I_R(T_{R,2})}{I_R(T_{R,3})} \times \frac{1}{M(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1}, T_{R,2}, T_{R,3})} \times \frac{1 + \alpha_R(E_0(\lambda), E_M(\lambda), T_{R,2}, T_{R,3})}{1 + \alpha_T(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1})}. \quad (7)$$

A modified spectral mismatch function can be constructed if $Q(\lambda, T)$ is known, but functions for α_T and α_R , which are no longer simple constants, are not obvious. Comparing (3) and (6), however, notice that identical definite integrals for current density appear in both expressions, and (2), in the general case, can be regarded as having redundant information.

In light of this, we will then assume that I_{SC} TCs are simply not needed and can be replaced with a temperature-dependent M correction that calculates four current densities. Therefore, assuming that the QEs of the two cells are known at all four temperatures, the TC correction terms are eliminated and (7) can be rewritten as

$$I_{SC2} = I_{SC1} \frac{I_R(T_{R,2})}{I_R(T_{R,3})} \times \frac{1}{M(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1}, T_{R,2}, T_{R,3})}. \quad (8)$$

The four current densities in (3) can be expressed as functions of temperature using

$$M(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1}, T_{R,2}, T_{R,3}) = \frac{J_T(E_M, T_{T,1}) J_R(E_0, T_{R,2})}{J_R(E_M, T_{R,3}) J_T(E_0, T_{T,0})} = \frac{\int \lambda Q_T(\lambda, T_{T,1}) E_M(\lambda) d\lambda \int \lambda Q_R(\lambda, T_{R,2}) E_0(\lambda) d\lambda}{\int \lambda Q_R(\lambda, T_{R,3}) E_M(\lambda) d\lambda \int \lambda Q_T(\lambda, T_{T,0}) E_0(\lambda) d\lambda}. \quad (9)$$

Notice that the integrals in (9) completely describe the spectral and temperature dependence at each measurement state.

The temperature-dependent QEs have to be quantified before (8) and (9) are useful. One way to do this might be with multiple QE curves that span the range of temperatures, such as in Fig. 1, and interpolate between them to calculate the QEs of the test and reference cells. However, if the $\partial Q/\partial T(\lambda)$ characteristic (see Fig. 3) has been calculated, the interpolation can be expressed as offsets from the QEs at $T_{R,0}$ and $T_{T,2}$. Then, with $\Delta T_R = T_{R,3} - T_{R,2}$ and $\Delta T_T = T_{T,1} - T_{T,0}$, (9) becomes

$$M(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1}, T_{R,2}, T_{R,3}) = \frac{\int \lambda \left[Q_T(\lambda, T_{T,0}) + \frac{\partial Q_T}{\partial T}(\lambda) \Delta T_T \right] E_M(\lambda) d\lambda}{\int \lambda \left[Q_R(\lambda, T_{R,2}) + \frac{\partial Q_R}{\partial T}(\lambda) \Delta T_R \right] E_M(\lambda) d\lambda} \times \frac{\int \lambda Q_R(\lambda, T_{R,2}) E_0(\lambda) d\lambda}{\int \lambda Q_T(\lambda, T_{T,0}) E_0(\lambda) d\lambda}. \quad (10)$$

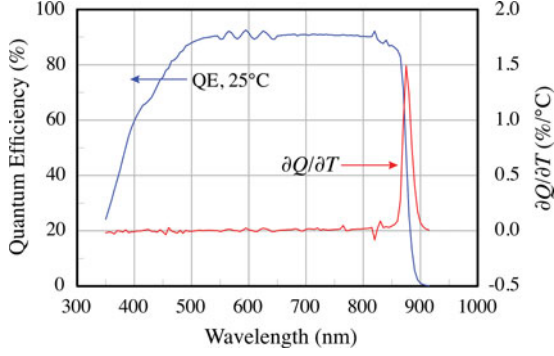


Fig. 5. Quantum efficiency at 25 °C for the GaAs cell from [1] and its $\partial Q/\partial T(\lambda)$ characteristic.

The summed $Q(\lambda, T)$ and $\partial Q/\partial T(\lambda)$ terms in (10) are to be understood as being formed point-by-point at identical wavelengths. Recognizing that these are definite integrals, the summations can then be split into separate integrations:

$$\begin{aligned}
 & M(E_0(\lambda), E_M(\lambda), T_{T,0}, T_{T,1}, T_{R,2}, T_{R,3}) \\
 &= \frac{\int \lambda Q_T(\lambda, T_{T,0}) E_M(\lambda) d\lambda + \int \lambda \frac{\partial Q_T}{\partial T}(\lambda) \Delta T_T E_M(\lambda) d\lambda}{\int \lambda Q_R(\lambda, T_{R,2}) E_M(\lambda) d\lambda + \int \lambda \frac{\partial Q_R}{\partial T}(\lambda) \Delta T_R E_M(\lambda) d\lambda} \\
 & \quad \times \frac{\int \lambda Q_R(\lambda, T_{R,2}) E_0(\lambda) d\lambda}{\int \lambda Q_T(\lambda, T_{T,0}) E_0(\lambda) d\lambda} \\
 &= \frac{J_T(E_M(\lambda), T_{T,0}) + \Delta J_T(E_M(\lambda), \Delta T_T)}{J_R(E_M(\lambda), T_{R,2}) + \Delta J_R(E_M(\lambda), \Delta T_R)} \\
 & \quad \times \frac{J_R(E_0(\lambda), T_{R,2})}{J_T(E_0(\lambda), T_{T,0})}. \tag{11}
 \end{aligned}$$

Although this six-integral expression for the temperature-dependent M looks cumbersome at first sight, it is only a slight modification of the usual expression and it is still a linear function of four current densities. Four of the integrals are identical to those of (3), and when $T_{T,0} = T_{R,2}$ and $\Delta T_R = \Delta T_T = 0$, (11) reduces to (3).

V. EXAMPLE I_{SC} TRANSLATION

To illustrate use of the temperature-dependent spectral mismatch correction, the following example is presented, in which the polycrystalline-Si cell from Figs. 1 and 3 is tested at an elevated temperature in a xenon solar simulator. A GaAs reference cell (see Fig. 5), calibrated to the hemispherical (global) reference spectral irradiance [11], was used to measure irradiance. With the sample stage set to 25 ± 0.5 °C, the I_{SC} of each cell was measured in succession; after increasing the temperature to 40 ± 0.8 °C, the current measurements were repeated. Before each measurement, the cell temperature was allowed to equilibrate with the stage. Table I contains the numeric parameters measured and calculated for this example.

The spectral irradiance of the simulator was measured prior to the I_{SC} translation test. Using this information and the QE information previously determined for the two cells, all of the numeric integrations needed for (3) and (9) were then computed. These results are listed in Table I.

TABLE I
 I_{SC} TRANSLATION EXAMPLE PARAMETERS

	Test Cell, poly-Si	Ref. Cell, GaAs
25 °C Calibrated I_{SC} (A)	—	0.10662
25 °C Measured I_{SC} (A)	3.1722	0.10389
40 °C Measured I_{SC} (A)	3.1894	0.10531
Measured ΔT (°C)	14.4	16.2
$\int \lambda Q(\lambda, 25^\circ\text{C}) E_0(\lambda) d\lambda$ (A/m ²)	3689.9	2763.7
$\int \lambda Q(\lambda, 25^\circ\text{C}) E_M(\lambda) d\lambda$ (A/m ²)	3988.2	2935.4
$\int \lambda Q(\lambda, 40^\circ\text{C}) E_M(\lambda) d\lambda$ (A/m ²)	4003.2	2969.0
$\int \lambda \partial Q/\partial T(\lambda) E_M(\lambda) d\lambda$ (A/m ² /°C)	1.5848	2.0186

Next, the spectral mismatch at 25 °C was calculated using (3):

$$M(25^\circ\text{C}) = \frac{(3988.2)(2763.7)}{(2935.4)(3689.9)} = 1.0176. \tag{12}$$

Using (2) without the α correction terms, the I_{SC} of the test cell corrected to 1000 W/m² with the 25 °C calibrated reference cell current is

$$\begin{aligned}
 I_{SC}(25^\circ\text{C}) &= (3.1722\text{A}) \frac{(0.10662\text{A})}{(0.10389\text{A})} \frac{1}{(1.0176)} \\
 &= 3.1994 \text{ A}. \tag{13}
 \end{aligned}$$

Then, the temperature-dependent M is obtained with (11) (noting that ΔT_R and ΔT_T are constants, which can be factored outside of the integrals):

$$\begin{aligned}
 M(\Delta T_T, \Delta T_R) &= \frac{[3988.2 + (1.5848)(14.4)](2763.7)}{[2935.4 + (2.0186)(16.2)](3689.9)} \\
 &= 1.0122. \tag{14}
 \end{aligned}$$

Finally, the 40 °C I_{SC} corrected to 25 °C is

$$\begin{aligned}
 I_{SC}(40^\circ\text{C} \rightarrow 25^\circ\text{C}) &= (3.1894\text{A}) \frac{(0.10662\text{A})}{(0.10531\text{A})} \frac{1}{(1.0122)} \\
 &= 3.1903 \text{ A}. \tag{15}
 \end{aligned}$$

Comparing the correction as the ratio of (13) to (15) gives a value of $(3.1994) \div (3.1903) = 1.0029$, which is a percent difference of 0.29%.

For this dataset, the QEs of both the reference and test cells at 40 °C were measured, which permits calculation of the temperature-dependent M using (9), without using $\partial Q/\partial T(\lambda)$:

$$M(40^\circ\text{C} \rightarrow 25^\circ\text{C}) = \frac{(4003.2)(2763.7)}{(2969.0)(3689.9)} = 1.0099. \tag{16}$$

Substituting this value of M into (15) gives a 25 °C corrected I_{SC} value of 3.1974 A, which is just 0.06% less than the value from (13).

VI. DISCUSSION

Despite the ΔT in this example $M(\Delta T)$ correction being only a moderate value of 15 °C, it is large enough to demonstrate how the mathematics are used and show that I_{SC} translations can be performed without the usual TCs. The thermal dependence of

I_{SC} is instead quantified with the partial derivative of quantum efficiency with respect to temperature, which is a function that can be derived from a series of QE measurements over a range of temperatures. There are several points that deserve attention regarding the QE data needed to calculate $\partial Q/\partial T(\lambda)$.

In the traditional M calculation [see (3)], absolute spectral quantities are not necessary because the $Q(\lambda)$ and $E(\lambda)$ terms appear twice in the numerator and denominator, which means that multiplicative calibration or scaling constants cancel, allowing the use of easier-to-measure relative spectral quantities. The same is true of the $E(\lambda)$ terms in the temperature-dependent M expression [see (10)]. However, preservation of the cancellation properties for the $Q(\lambda)$ and the corresponding $\partial Q/\partial T(\lambda)$ terms requires that they have identical calibration constants because of the summations inside the integrals. This can be achieved by measuring the series of QE curves (see Fig. 1) using the same test system in succession, changing only the test cell temperature. In addition, the set of temperatures should include the temperature to which I_{SC} data are corrected, i.e., $T_{R,0}$ and $T_{T,2}$. If, for example, $Q(\lambda, T_{R,0})$ is not available, then it should be derived from the QE curve set using interpolation. Adhering to these precautions will preserve the constant scalar cancellation properties in (9)–(11).

Measurements of $\partial Q/\partial T(\lambda)$ for Si cells have shown that $Q(\lambda)$ versus T at single wavelengths is remarkably linear over common terrestrial operating temperatures, as in Fig. 2 for 15–70 °C. It is possible that outside of this range, the linearity no longer holds; this should be expected to occur considering that the characteristic bandgap versus temperature curves for Si and GaAs are slightly nonlinear over 200–400 K [16]. Any nonlinearity can be observed by plotting the correlation coefficient (r^2) of the straight-line fits versus wavelength, which is the blue curve in Fig. 3. Although the wavelength resolution of this measurement is limited, Fig. 3 shows that r^2 for this cell is highest where $\partial Q/\partial T$ is high, i.e., where $Q(\lambda)$ is changing.

Equation (9) is only valid if $Q_R(\lambda, T_{R,3})$, and $Q_T(\lambda, T_{T,1})$ are the QEs of the two solar cells at their operating temperatures. If they are not, then error will be introduced by the correction, one that depends on four spectral quantities in a complex way. As noted above, the QE at a specific operating temperature can be calculated using interpolation at each wavelength between two QE curves at nearby temperatures. Using $\partial Q/\partial T(\lambda)$ and (11) is a convenient way to avoid the interpolation when $Q(\lambda)$ versus T is linear; if a device is found to be nonlinear, however, then it is still possible to use (9) and interpolation as an alternative.

For reference cells that will never be operated at higher temperatures typically encountered outdoors, three or four $Q(\lambda)$ measurements over the 15–40 °C range should be completely adequate for a $\partial Q/\partial T(\lambda)$ determination. For other devices, examination of $Q(T)$ at individual wavelengths, as in Fig. 2, should be used to gauge how many QE curves are needed to adequately model the temperature dependence.

Equation (11) shows why (2) is not a rigorous model of the I_{SC} translation—not only does (2) assume that M is invariant with temperature, it also assumes that constant values of α completely describe the change of I_{SC} with temperature between

any two arbitrary points on the $E(\lambda)$ versus T plane. Lacking knowledge of how (6) varies with spectral irradiance for a particular device, and how a value of α was determined, it is quite likely that using I_{SC} TC corrections will actually increase the error in a measurement, and the magnitude of the error increase will be directly proportional to ΔT . Thus, it is very easy to use (2) blindly, and current PV metrology practices do just this.

The assumption of a constant α is valid for cases in which the spectral irradiance is fixed; the most obvious of these are those outside of the Earth's atmosphere, i.e., extraterrestrial PV applications (air mass zero, or AM0). In addition, by placing restrictions on the correction, such as limiting ΔT and measuring α under similar spectral conditions as those of the test, (2) can still be useful for reducing temperature errors. Even so, it should be recognized that measuring $Q(\lambda, T)$ is a much preferred method of quantifying I_{SC} temperature behavior. Given all the problems and errors inherent in α measurements [1], the QE characterization is actually a simpler measurement. This is especially true for modules, as the characterization can be done on a single cell in a module package.

VII. CONCLUSION

By expanding the formulation of short-circuit current TCs (6), these coefficients have been shown to be highly dependent on spectral irradiance. In addition, because these coefficients are assumed to be independent of spectral irradiance in typical PV metrology use, using TC corrections can actually increase the error in a measurement. These errors are large enough to have profound implications for system sizing and rating software.

The most important conclusion is that a new procedure for spectral and temperature corrections to solar cell current has been demonstrated. This procedure completely eliminates the need for I_{SC} TCs.

As of this writing, all the current PV measurement standards are constructed around (2) and assume α is a constant. The formulations for spectral mismatch in ASTM E973 and IEC 60904-7 specify (3) for the spectral mismatch correction [7], [8]; therefore, substituting a $Q(\lambda, T \neq 25^\circ\text{C})$ term into this equation is a change or extension to the standard, and using temperature-dependent spectral mismatch is technically not allowed.

Because these standards form a body of references for good practice, it is strongly recommended that they should at least reflect the pitfalls and problems identified here and preferably revised to allow temperature-dependent spectral mismatch corrections.

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