Effective Irradiance Ratios to Improve *I–V* Curve Measurements and Diode Modeling Over a Range of Temperature and Spectral and Total Irradiance

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***Abstract*—We present an integrated measurement and modeling approach based on the effective irradiance ratio, which is simply the ratio of the short-circuit current of a photovoltaic (PV) device under operating conditions to its short-circuit current under standard test conditions. Using a PV reference device to measure effective irradiance with respect to a standard spectrum, this approach handles device-specific and reference-device-specific temperature and spectral irradiance effects that are significant factors in performance measurements, such as IEC 61853-1, as well as in the diode-based equivalent circuit performance models that are calibrated from such measurements. Avoiding the use of spectrally dependent short-circuit current temperature coefficients, this approach uses a temperature-dependent spectral correction function that is a direct extension of the standardized spectral correction parameter used by numerous PV calibration laboratories. When a matched reference device is used, this function becomes identically one, and it need not be computed. This approach should be useful in the advancement of PV performance testing and modeling that use reference devices to monitor irradiance.**

***Index Terms*—Current–voltage (*I–V*) curve measurement, diode model, effective irradiance ratio, irradiance dependence, model calibration, short-circuit current temperature coefficient, spectral correction, spectral dependence, temperature dependence.**

I. Introduction

Temperature and irradiance are the main influence factors on the performance of flat-plate, single-junction photovoltaic (PV) devices. Standards such as IEC 61853-1 [1] are intended to realize more consistent measurement of such PV devices over a wide range of temperature and irradiance. This range is designed to be more relevant to actual operating conditions than the standard test conditions (STC) of 25° C and $1000\ \mathrm{W/m^2}$ under a standard air mass (AM) hemispherical spectrum (e.g., “AM 1.5 global” in [2] or [3]). The resulting information is supposed to improve device performance predictions such as power, energy production, and performance ratio [1, Sec. 1].

IEC 61853-1 specifies the determination of a device’s short-circuit current I_{SC}, maximum power P_{MAX}, voltage at maximum power V_{MAX}, and open-circuit voltage V_{OC} at the 22 temperature and standard total irradiance combinations given in

TABLE I
IEC 61853-1 Matrix of Temperature and “AM 1.5 Global” Irradiance: N/A= Not Applicable

	Module Temperature (°C)			
Irradiance ($\mathrm{W/m^2}$)	15	25	50	75
1100	N/A			
1000				
800				
600				
400				N/A
200			N/A	N/A
100			N/A	N/A

Table I. IEC 61853-1 permits the use of either indoor or outdoor measurements to construct this “matrix” of results. Producing these tables of performance parameters raises the issue of the proper handling of temperature and irradiance *together* in the underlying measurements, which for this work we assume are a relevant set of current–voltage (*I–V*) curves.

Both temperature and irradiance present specification and measurement issues. For this work, temperature refers to cell temperature, which under testing or operating conditions may not be spatially uniform between cells, temporally stable, or equal to the temperature determined from the exterior of the device and/or the ambient conditions [4], [5]. With regard to (total) irradiance at the plane of array (POA),[1] the underlying spectral irradiance and angular distribution (radiance) are important factors [6], [7]. Interaction effects between temperature and spectral irradiance include the effect of spectrum on the short-circuit current temperature coefficient. This effect may be considerable in some situations, such as translations of short-circuit current over large temperature changes (e.g., 40 °C) under a wide variety of spectra [8].

I–V curves are also commonly used to calibrate the parameters of physics-based performance models of PV devices, such as single- or double-diode models. From such a calibrated model, the device’s performance parameters (I_{SC}, P_{MAX}, etc.) can be predicted over a considerable range of operating conditions, including any combination in the IEC 61853-1 matrix in Table I. If both the model and its calibration are sufficiently accurate over a device’s operating range, then the physical modeling approach provides a flexible alternative to the IEC 61853-1

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[1] We use the common term POA, even for individual flat-plate PV devices, such as a module or cell.

method of temperature-only or irradiance-only linear interpolations/regressions of individual device performance parameters [1, Sec. 9.1].

IEC 61853-1 specifies four methods for constructing tables of performance parameters. The first method [1, Sec. 8.2] requires performance parameter linearity with respect to both temperate and irradiance in order to enable a reduction in the number of required measurements. The second and third methods employ outdoor measurements with and without a sun tracker, respectively [1, Sec. 8.3], [1, Sec. 8.4]. The last method is an indoor procedure for use with a solar simulator [1, Sec. 8.5]. For any of these methods, IEC 61853-1 (see Section 8.1) refers to IEC 60891 [9] if measured values need to be translated to specific temperature and irradiance combinations in Table I. IEC 60891 offers three translations methods, two of which rely on device temperature coefficients. For determination of irradiance, IEC 60891 also requires a short-circuit temperature coefficient for the reference device (RD), which typically corresponds to a different spectrum than the device translations.

The indoor method of IEC 61853-1 specifies an RD that is linear with respect to total irradiance and that may or may not be spectrally matched to the device. In particular, Section 8.5.7 parts a–e provide five ways to adjust the irradiance without changing the spectrum. Section 8.5.7 part f refers to a potentially changing spectral irradiance corresponding to a decaying solar simulator flash. If the spectrum does change and the RD is not spectrally matched to the device, then employing a spectral correction according to IEC 60904-7 [10] is indicated (also see IEC 60891 [9]). IEC 60904-7 and IEC 60891 provide little to no guidance on the possible interactions of temperature with spectral effects. ASTM E973-10 [11] is similarly limited in regard to the temperature dependence of the spectral correction.

In its introduction, IEC 61853-1 states that "it is written to be applicable to all PV technologies including nonlinear devices" [1]. However, no guidance is provided for the indoor method in the case of a nonlinear device. If the RD were sufficiently matched to a nonlinear device, then a sufficiently complete nonlinear RD calibration could be used to properly set and monitor the various combined temperature and irradiance levels. However, this matching criterion necessarily makes the RD nonlinear, which contraindicates the RD linearity requirement stated in Section 8.5.1 of IEC 61853-1.

In order to produce more consistent and reliable results, PV calibration laboratories routinely perform spectral corrections in their *I–V* curve measurements. In their usual implementation, these corrections rely on sufficient linearity with respect to irradiance of both the device and the RD [10], [11]. Furthermore, changing the lamp voltage of a solar simulator is a practical way to achieve a range of irradiance settings, and the spectral correction can readily accommodate any spectral changes in the simulator irradiance due to varying lamp voltage. Spectral corrections also require the (relative) spectral responses of the device and RD to be measured. These responses are typically measured at STC temperature, but they can also be readily measured over a significant range of temperature, at least for cells.[2]

In this work, we employ a temperature-dependent spectral correction to both set and monitor the irradiance during near-normal-incidence indoor measurements of *I–V* curves. This approach, using a temperature-dependent *effective irradiance ratio*, circumvents errors that can easily arise from ignoring/neglecting the spectral dependence of short-circuit current temperature coefficients for both the device and the RD. Such an approach should be readily implementable by PV calibration laboratories that routinely apply spectral corrections in their *I–V* measurements. We find the guidance provided by existing standards, including IEC 61853-1, to be lacking in this regard, and we hope to spur the advancement of the relevant standards. We are also careful in this work to ensure that the proposed measurement approach allows effective calibration of single- and double-diode models of PV devices from temperature and irradiance-dependent *I–V* curve measurement data, and we develop the appropriate model formulations to enable this.

We also consider the implications of this work for the outdoor measurement methods specified by IEC 61853-1 and their validation (e.g., [12]), as well as for energy ratings. Recent work [13] continues to document potentially significant effects of spectrum on PV performance modeling and energy prediction, and previous work [14] has established a significant reduction in measurement uncertainty that results from using spectrally matched RDs instead of thermopile-based irradiance sensors in outdoor irradiance measurements relevant to PV. It stands to reason that analogous uncertainty reduction in calibrated model parameters is also possible through the use of matched RDs. This work provides a more thorough definition of RD matching, including temperature and angular response considerations that might violate the required/assumed matching conditions.

In addition to [14], this work builds significantly on prior efforts. The works of Seaman [6] and Osterwald [15] are fundamental to spectral correction methods in PV. The diode-based equivalent circuit modeling literature is vast, but, in particular, we cite the works by Bishop [16], Nann and Emery [17], De Soto *et al.* [18], Elies *et al.* [19], Reich *et al.* [20], and Tian *et al.* [21]. In particular, this work extends the diode modeling approach of Zaharatos *et al.* [22] to include temperature effects in the effective irradiance ratio that is measured using a spectrally mismatched reference cell. With respect to IEC 61853-1, we contrast this modeling approach to recent work related to PVsyst [23] and to the System Advisor Model [24], both of which do not address the spectral dependence of the temperature coefficient for short-circuit current that is used in the auxiliary equation for the photocurrent.

This paper is organized as follows. Section II defines the effective irradiance ratio, which is fundamental to consistent measurement of *I–V* curves over a range of operating temperature and irradiance. Section III derives both single- and double-diode models in terms of the effective irradiance ratio. Section IV discusses some implications of the approach using

[2]This includes a representative cell for a given module being tested.

effective irradiance ratios for both measurements and modeling. Section V summarizes and concludes the paper.

II. Effective Irradiance Ratio

The primary definition for this work is the *effective irradiance ratio*, which is a unit-less measure of the "effective" (total) irradiance illuminating a PV device relative to STC. STC specify a cell temperature T_0 (typically, $T_0 = 25\,^\circ\mathrm{C}$) and a POA irradiance $H_0 > 0$ with underlying standard absolute spectral irradiance function $\bar{E}_0(\lambda) \geq 0$, where λ denotes wavelength. Specifically, the[3] standard relative spectral irradiance function E_0 is scaled to give the absolute spectral irradiance function $\bar{E}_0$ so that

$$H_0 = \int_{\lambda=0}^{\infty} \bar{E}_0(\lambda)\, d\lambda.$$

For example, $\bar{E}_0(\lambda)$ may be determined from the standard relative spectral irradiance defined by the table in ASTM G173-03 with $H_0 = 1000\ \mathrm{W/m^2}$ total hemispherical irradiance on a 37°-tilted, sun-facing, flat surface at AM 1.5 [3].

In contrast with STC, *operating conditions* are denoted by a prevailing cell temperature T, relative spectral irradiance $E(\lambda)$, and total irradiance H. Analogously

$$H = \int_{\lambda=0}^{\infty} \bar{E}(\lambda)\, d\lambda$$

where $\bar{E}(\lambda)$ is the absolute spectral irradiance function for the operating conditions.

The effective irradiance ratio, denoted F, is defined as the ratio of the device's short-circuit current under operating conditions, denoted I_{SC}, to the device's short-circuit current under STC, denoted I_{SC_0}. That is, the effective irradiance ratio is defined as the unit-less quantity

$$F := \frac{I_{\mathrm{SC}}}{I_{\mathrm{SC}_0}}.$$

In particular, the cell temperatures T and T_0 may differ, and the relative spectral irradiance $E(\lambda)$ underlying the total irradiance H need not be the same as the standard relative spectral irradiance $E_0(\lambda)$ underlying the standard total irradiance H_0. In particular, $F = 1$ means that the device is "effectively" generating short-circuit current as though it were under STC irradiance.

In many situations, the effective irradiance ratio is readily measured using a calibrated RD. This requires a spectral correction parameter M, which compensates for spectral response differences between the device and the RD. The spectral correction parameter is defined as

$$M := \frac{I_{\mathrm{SC}}\, I_{\mathrm{SC,RD}_0}}{I_{\mathrm{SC}_0}\, I_{\mathrm{SC,RD}}} \tag{1}$$

where $I_{\mathrm{SC,RD}_0}$ is the RD's short-circuit current under STC, and $I_{\mathrm{SC,RD}}$ is the RD's short-circuit current under the operating conditions of the RD, which may differ from operating conditions of the device itself. In this fundamental definition of M, either the device or the RD (or both) can be nonlinear. In typical practice, linearity of both is required, as described next.

A PV device is operating *linearly* (under a given spectrum) if, at the given T, $E(\lambda)$, and H, the short-circuit current responds linearly with respect to irradiance down to zero irradiance. For a device and RD both responding linearly under the same spectral irradiance, the spectral correction parameter M is a function of

1) T, cell temperature of the device;
2) T_{RD}, cell temperature of the RD;
3) T_0, STC cell temperature;
4) $S(\lambda, T)$, nonnegative relative spectral response function of the device at operating cell temperature T, corresponding to some positive scalar α_S;
5) $S(\lambda, T_0)$, nonnegative relative spectral response function of the device at STC cell temperature T_0, corresponding to some positive scalar α_S;
6) $S_{\mathrm{RD}}(\lambda, T_{\mathrm{RD}})$, nonnegative relative spectral response function of the RD at operating cell temperature T_{RD}, corresponding to some positive scalar $\alpha_{S_{\mathrm{RD}}}$;
7) $S_{\mathrm{RD}}(\lambda, T_0)$, nonnegative relative spectral response function of the RD at STC cell temperature T_0, corresponding to some positive scalar $\alpha_{S_{\mathrm{RD}}}$;
8) $E(\lambda)$, relative spectral irradiance function under operating conditions;
9) $E_0(\lambda)$, relative spectral irradiance function under STC.

Specifically, under linear operation of both the device and RD, the spectral correction parameter is given by the *spectral correction function*:

$$\begin{aligned} M &= f_M(S, S_{\mathrm{RD}}, E, E_0, T, T_{\mathrm{RD}}, T_0) \\ &= \frac{\overbrace{\int_{\lambda=0}^{\infty} S(\lambda, T)\, E(\lambda)\, d\lambda}^{\text{prop. to } I_{\mathrm{SC}}} \overbrace{\int_{\lambda=0}^{\infty} S_{\mathrm{RD}}(\lambda, T_0)\, E_0(\lambda)\, d\lambda}^{\text{prop. to } I_{\mathrm{SC,RD}_0}}}{\underbrace{\int_{\lambda=0}^{\infty} S(\lambda, T_0)\, E_0(\lambda)\, d\lambda}_{\text{prop. to } I_{\mathrm{SC}_0}} \underbrace{\int_{\lambda=0}^{\infty} S_{\mathrm{RD}}(\lambda, T_{\mathrm{RD}})\, E(\lambda)\, d\lambda}_{\text{prop. to } I_{\mathrm{SC,RD}}}} \end{aligned} \tag{2}$$

where the spectral response functions may be from either a power-mode or an irradiance-mode measurement [25]. In the case of a power-mode spectral response, the common device areas and RD areas cancel between numerator and denominator to give (2). The common relative scaling α_S (between the device spectral response functions at different temperatures) and $\alpha_{S_{\mathrm{RD}}}$ (between the RD spectral response functions at different temperatures) are required for their cancellation to give (2). Finally, in the diode model development to follow, we consider devices that consist of any number of parallel-wired, equal-length series strings of single-junction cells. In this case, when a representative cell for/from a device is used for the spectral response measurement, then homogeneity assumptions allow the use of (2). In particular, any current multipliers corresponding to the number of parallel-wired series strings also cancel out to give (2).

[3]Unless otherwise distinguished, two relative spectral irradiance functions are considered the "same" if one is a nonnegative scalar multiple of the other. Thus, we may refer to *the* relative spectral irradiance distribution function, even though there are actually infinitely many such functions.

From (1) and (2), it follows that the effective irradiance ratio is given by

$$F := \frac{I_{\mathrm{SC}}}{I_{\mathrm{SC}_0}} = M \frac{I_{\mathrm{SC,RD}}}{I_{\mathrm{SC,RD}_0}} = f_M(S, S_{\mathrm{RD}}, E, E_0, T, T_{\mathrm{RD}}, T_0) \frac{I_{\mathrm{SC,RD}}}{I_{\mathrm{SC,RD}_0}}. \quad (3)$$

In particular, (3) requires no temperature correction using a spectrally dependent $I_{\mathrm{SC,RD}}$ temperature coefficient that assumes a straight-line relationship. Instead, this dependence is fully captured by the spectral correction function. In principle, this formulation can fully capture any significant nonlinearities in temperature dependence.

A *matched* RD denotes that the spectral correction function is identically unity over all operating conditions, greatly simplifying the determination of the effective irradiance ratio F. In particular, measurement of the spectral irradiance is avoided. Considering (3), sufficient matching conditions are that $S = S_{\mathrm{RD}}$ (same spectral response functions over wavelength and temperature) and that $T = T_{\mathrm{RD}}$ (devices operating at the same cell temperature). In most real situations, matching is necessarily an idealization, because of issues such as variability between cells in the device, temperature nonuniformity, and spatial nonuniformity of solar simulator irradiance.

The derivation of (3) for the effective irradiance ratio actually assumes matching of the relative angular response of the short-circuit currents of the device and RD with respect to the incident angle of light. For near-normal incidence illumination, such as from a solar simulator, this is typically a safe assumption. If the illumination includes significant nondirect components, such as global illumination outdoors, then matching also includes the angular responses of the devices. If the mismatch is significant, then additional corrections should be applied [7].

For nonmatched cases, there are multiple ways to determine the spectral correction function f_M in (3). Given a set of temperature-dependent measurements of the spectral response function for the device and RD, one can interpolate these functions with respect to temperature to determine $S(\lambda, T)$ and $S_{\mathrm{RD}}(\lambda, T_{\mathrm{RD}})$. These functions can then be used to compute M for any E, E_0, T, T_{RD}, and T_0. Alternatively for a fixed solar simulator spectrum, one can first compute particular M values using a set of spectral responses and choices for E, E_0, and T_0, and then fit a function for M over a range of T and T_{RD}. In some scenarios, the RD might have essentially the same temperature as the device (i.e., $T = T_{\mathrm{RD}}$), which can lead to further simplification in the construction of the spectral correction function. See also [26].

III. Single- and Double-Diode Model Derivations

This section develops single- and double-diode models in terms of the effective irradiance ratio described in the previous section. In particular, the use of the effective irradiance ratio circumvents inaccuracies that arise from not considering the spectral dependence of short-circuit temperature coefficients.

A. Single-Diode Model

Our development of a single-diode model with auxiliary equations is most closely related to the work of De Soto *et al.* [18] and Tian *et al.* [21]. Three notable differences with De Soto *et al.*, are 1) the use of shunt conductance in place of shunt resistance, 2) the use of the effective irradiance ratio in the auxiliary equations for photocurrent and photoconductive shunt, and 3) a reparameterization in terms of the short-circuit current at STC and open-circuit voltage at STC instead of the photocurrent at STC and reverse saturation current at STC. Following Tian *et al.*, the flat-plate PV device can be any number of parallel-wired equal-length series strings of single-junction cells.

For nonnegative terminal voltages, the following single-diode lumped-parameter equivalent-circuit model adequately describes the current–voltage (*I–V*) performance of many flat-plate single-junction PV devices:

$$I = N_{\mathrm{P}} I_{\mathrm{L}}^* - N_{\mathrm{P}} I_{\mathrm{D}}^* \left(e^{\frac{V + I \frac{N_{\mathrm{S}}}{N_{\mathrm{P}}} R_{\mathrm{S}}^*}{N_{\mathrm{S}}\, n\, V_{\mathrm{th}}}} - 1 \right) - \frac{N_{\mathrm{P}}}{N_{\mathrm{S}}} G_{\mathrm{P}}^* \left(V + I \frac{N_{\mathrm{S}}}{N_{\mathrm{P}}} R_{\mathrm{S}}^* \right), \quad V \geq 0 \quad (4)$$

where the thermal voltage is defined by

$$V_{\mathrm{th}} := k_{\mathrm{B}}\, T / q$$

and where

- T cell temperature;
- k_{B} Boltzmann constant;
- q electron charge (positive);
- N_{S} number of series-wired cells in each string;
- N_{P} number of parallel-wired strings;
- I device-level terminal current;
- V device-level terminal voltage;
- I_{L}^* cell-level photocurrent;
- I_{D}^* cell-level diode reverse saturation current;
- n cell-level diode ideality factor;
- R_{S}^* cell-level series resistance;
- G_{P}^* cell-level parallel (shunt) conductance.

This model has the significant assumptions that all cells have identical physical properties and that they experience exactly the same operating conditions. These assumptions clearly become more tenuous for arrays than for the cells in a single module. Typical measurement laboratory calibrations involve individual cells or a single-series string of cells in a single module.[4]

For notational convenience, we define the following:

- I_{L} device-level photocurrent, where $I_{\mathrm{L}} := N_{\mathrm{P}}\, I_{\mathrm{L}}^*$;
- I_{D} device-level diode reverse saturation current, where $I_{\mathrm{D}} := N_{\mathrm{P}}\, I_{\mathrm{D}}^*$;
- R_{S} device-level series resistance, where $R_{\mathrm{S}} := \frac{N_{\mathrm{S}}}{N_{\mathrm{P}}} R_{\mathrm{S}}^*$;
- G_{P} device-level parallel (shunt) conductance, where $G_{\mathrm{P}} := \frac{N_{\mathrm{P}}}{N_{\mathrm{S}}} G_{\mathrm{P}}^*$.

With these definitions, the model given by (4) simplifies to

[4] We note that the model given by (4) does not include bypass diode behavior that is significant when $V < 0$ and when irradiance is significantly mismatched between cells.

$$I = I_{\mathrm{L}} - I_{\mathrm{D}} \left(e^{\frac{V + I\,R_{\mathrm{S}}}{N_{\mathrm{S}}\,n\,V_{\mathrm{th}}}} - 1 \right) - G_{\mathrm{P}} (V + I\,R_{\mathrm{S}}), \quad V \geq 0. \tag{5}$$

In general, the five parameters $I_{\mathrm{L}}, I_{\mathrm{D}}, n, R_{\mathrm{S}}$, and G_{P} can depend on temperature, irradiance, and/or terminal voltage. For this single-diode model, we assume that there is no dependence on terminal voltage. Thus, auxiliary equations are given that define how each device parameter varies with temperature and/or irradiance from a reference value defined under STC, i.e., (T_0, H_0). (Model parameter values under STC are also denoted with a single subscript 0.) Note that our choices for auxiliary equations for the single-diode model are meant to be representative and not exclusive.

We assume that n and R_{S} depend on neither temperature nor irradiance. Thus, the auxiliary equations for these parameters are given by

$$n = n_0 \tag{6}$$

$$R_{\mathrm{S}} = R_{\mathrm{S}\,0} \tag{7}$$

where

n_0 cell-level diode ideality factor under STC;
$R_{\mathrm{S}\,0}$ device-level series resistance under STC.

We include a photoconductance effect in the auxiliary equation for G_{P}, namely

$$G_{\mathrm{P}} = F\,G_{\mathrm{P}\,0} \tag{8}$$

where

$G_{\mathrm{P}\,0}$ is the device-level parallel conductance under STC (where $F = 1$).

The auxiliary equation for I_{D}, which depends only on temperature, is given by

$$I_{\mathrm{D}} = I_{\mathrm{D}\,0} \left(\frac{T}{T_0} \right)^3 e^{\left(\frac{E_{\mathrm{g}\,0}}{T_0} - \frac{E_{\mathrm{g}}}{T} \right) \Big/ k_{\mathrm{B}}} \tag{9}$$

where

$I_{\mathrm{D}\,0}$ device-level diode reverse saturation current at T_0;
$E_{\mathrm{g}\,0}$ material band gap energy at T_0;
E_{g} material band gap energy at cell temperature T.

The functional dependence of E_{g} on T is given by a straight-line model passing through $\left(T_0, E_{\mathrm{g}\,0}\right)$, i.e.,

$$E_{\mathrm{g}} = E_{\mathrm{g}\,0} \left(1 + \alpha_{E_{\mathrm{g}\,0}} (T - T_0) \right) \tag{10}$$

where

$\alpha_{E_{\mathrm{g}\,0}}$ is the temperature coefficient of E_{g}.

This straight-line model may only be an approximation to a more complicated functional relationship, but it is usually adequate over the typical range of PV operating temperatures (e.g., 0–75 °C). Altogether, I_{D} depends on the three parameters: $I_{\mathrm{D}\,0}$, $E_{\mathrm{g}\,0}$, and $\alpha_{E_{\mathrm{g}\,0}}$.

The auxiliary equation for the photocurrent I_{L} depends on both temperature and irradiance. For any given T and H, solving (5) for I_L and evaluating at short circuit, i.e., $V = 0$ and $I = I_{\mathrm{SC}}$, gives

$$I_{\mathrm{L}} = I_{\mathrm{SC}} + I_{\mathrm{D}} \left(e^{\frac{I_{\mathrm{SC}}\,R_{\mathrm{S}}}{N_{\mathrm{S}}\,n\,V_{\mathrm{th}}}} - 1 \right) + G_{\mathrm{P}}\,I_{\mathrm{SC}}\,R_{\mathrm{S}}.$$

This can be rewritten equivalently as

$$\begin{aligned} I_{\mathrm{L}} &= I_{\mathrm{SC}\,0} \frac{I_{\mathrm{SC}}}{I_{\mathrm{SC}\,0}} + I_{\mathrm{D}} \left(e^{\frac{I_{\mathrm{SC}\,0} \frac{I_{\mathrm{SC}}}{I_{\mathrm{SC}\,0}} R_{\mathrm{S}}}{N_{\mathrm{S}}\,n\,V_{\mathrm{th}}}} - 1 \right) + G_{\mathrm{P}}\,I_{\mathrm{SC}\,0} \frac{I_{\mathrm{SC}}}{I_{\mathrm{SC}\,0}} R_{\mathrm{S}} \\ &= I_{\mathrm{SC}\,0}\,F + I_{\mathrm{D}} \left(e^{\frac{I_{\mathrm{SC}\,0}\,F\,R_{\mathrm{S}}}{N_{\mathrm{S}}\,n\,V_{\mathrm{th}}}} - 1 \right) + G_{\mathrm{P}}\,I_{\mathrm{SC}\,0}\,F\,R_{\mathrm{S}}. \end{aligned} \tag{11}$$

The last line gives the auxiliary equation for the photocurrent I_{L} in terms of the parameter $I_{\mathrm{SC}\,0}$ and the effective irradiance ratio F, where the remaining parameters are given by their respective auxiliary equations. In particular, this formulation does not use a spectrally dependent short-circuit current temperature coefficient. Instead, the use of (3) to compute F captures the spectrally dependent temperature effects.

For convenience and better numerical scaling, we reparameterize in terms of the device's open-circuit voltage under STC, denoted $V_{\mathrm{OC}\,0}$, instead of the diode reverse saturation current under STC, $I_{\mathrm{D}\,0}$. Evaluating (5) under STC and at open circuit, i.e., $V = V_{\mathrm{OC}\,0}$ and $I = 0$, gives

$$0 = I_{\mathrm{L}\,0} - I_{\mathrm{D}\,0} \left(e^{\frac{V_{\mathrm{OC}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}} - 1 \right) - G_{\mathrm{P}\,0}\,V_{\mathrm{OC}\,0}. \tag{12}$$

Evaluating (5) under STC and at short circuit, i.e., $V = 0$ and $I = I_{\mathrm{SC}\,0}$, gives

$$I_{\mathrm{SC}\,0} = I_{\mathrm{L}\,0} - I_{\mathrm{D}\,0} \left(e^{\frac{I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}} - 1 \right) - G_{\mathrm{P}\,0}\,I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0}. \tag{13}$$

Using (12) to substitute for $I_{\mathrm{L}\,0}$ into (13) gives

$$\begin{aligned} I_{\mathrm{SC}\,0} = \; & I_{\mathrm{D}\,0} \left(e^{\frac{V_{\mathrm{OC}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}} - 1 \right) + G_{\mathrm{P}\,0}\,V_{\mathrm{OC}\,0} \\ & - I_{\mathrm{D}\,0} \left(e^{\frac{I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}} - 1 \right) - G_{\mathrm{P}\,0}\,I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0} \end{aligned}$$

and solving this for $I_{\mathrm{D}\,0}$ gives

$$I_{\mathrm{D}\,0} = \frac{I_{\mathrm{SC}\,0} - G_{\mathrm{P}\,0}\,V_{\mathrm{OC}\,0} + G_{\mathrm{P}\,0}\,I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0}}{e^{\frac{V_{\mathrm{OC}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}} - e^{\frac{I_{\mathrm{SC}\,0}\,R_{\mathrm{S}\,0}}{N_{\mathrm{S}}\,n_0\,V_{\mathrm{th}\,0}}}}. \tag{14}$$

Altogether, single-diode model given by (5) depends on the cell temperature T, reference temperature T_0, and on the effective irradiance ratio F, and it is parameterized by $I_{\mathrm{SC}\,0}$, $V_{\mathrm{OC}\,0}$, $E_{\mathrm{g}\,0}$, $\alpha_{E_{\mathrm{g}\,0}}$, n_0, $R_{\mathrm{S}\,0}$, and $G_{\mathrm{P}\,0}$ through auxiliary equations (6)–(11) and (14).

B. Double-Diode Model

The single-diode model development readily extends to a double-diode model. Based on conventional doped crystalline semiconductor theory, the first diode models recombination losses in the neutral regions, while the second diode models recombination losses in the space charge region [20]. Similar to the single-diode model, and despite its physical origins, this model is used for a variety of technologies including thin film devices. The general double-diode model is

$$I = I_{\mathrm{L}} - I_{\mathrm{D}_1}\left(e^{\frac{V+I\,R_{\mathrm{S}}}{N_{\mathrm{S}}\,n_1\,V_{\mathrm{th}}}} - 1\right) - I_{\mathrm{D}_2}\left(e^{\frac{V+I\,R_{\mathrm{S}}}{N_{\mathrm{S}}\,n_2\,V_{\mathrm{th}}}} - 1\right) - G_{\mathrm{P}}(V + I\,R_{\mathrm{S}}), \quad V \geq 0 \tag{15}$$

where

I_{D_1} device-level first diode reverse saturation current;
I_{n_1} cell-level first diode ideality factor;
I_{D_2} device-level second diode reverse saturation current;
I_{n_2} cell-level second diode ideality factor.

In contrast with the single-diode model development, we leave the auxiliary equations as very general functions to suit the device at hand, i.e.,

$$\begin{aligned} I_{\mathrm{D}_1} &= f_{I_{\mathrm{D}_1}}(V, T, F, T_0, \boldsymbol{\theta}_{I_{\mathrm{D}_1}}) \\ n_1 &= f_{n_1}(V, T, F, T_0, \boldsymbol{\theta}_{n_1}) \\ I_{\mathrm{D}_2} &= f_{I_{\mathrm{D}_2}}(V, T, F, T_0, \boldsymbol{\theta}_{I_{\mathrm{D}_2}}) \\ n_2 &= f_{n_2}(V, T, F, T_0, \boldsymbol{\theta}_{n_2}) \\ R_{\mathrm{S}} &= f_{R_{\mathrm{S}}}(V, T, F, T_0, \boldsymbol{\theta}_{R_{\mathrm{S}}}) \\ G_{\mathrm{P}} &= f_{G_{\mathrm{P}}}(V, T, F, T_0, \boldsymbol{\theta}_{G_{\mathrm{P}}}) \end{aligned} \tag{16}$$

where $\boldsymbol{\theta}_{I_{\mathrm{D}_1}}$, $\boldsymbol{\theta}_{n_1}$, $\boldsymbol{\theta}_{I_{\mathrm{D}_2}}$, $\boldsymbol{\theta}_{n_2}$, $\boldsymbol{\theta}_{R_{\mathrm{S}}}$, and $\boldsymbol{\theta}_{G_{\mathrm{P}}}$ denote device-specific model parameter vectors.[5] As with the single-diode model, assuming that the photocurrent I_{L} is independent of voltage gives

$$I_{\mathrm{L}} = I_{\mathrm{SC}\,0}\,F + I_{\mathrm{D}_1,\mathrm{SC}}\left(e^{\frac{I_{\mathrm{SC}\,0}\,F\,R_{\mathrm{S,SC}}}{N_{\mathrm{S}}\,n_{1,\mathrm{SC}}\,V_{\mathrm{th}}}} - 1\right) - I_{\mathrm{D}_2,\mathrm{SC}}\left(e^{\frac{I_{\mathrm{SC}\,0}\,F\,R_{\mathrm{S,SC}}}{N_{\mathrm{S}}\,n_{2,\mathrm{SC}}\,V_{\mathrm{th}}}} - 1\right) + G_{\mathrm{P,SC}}\,I_{\mathrm{SC}\,0}\,F\,R_{\mathrm{S,SC}} \tag{17}$$

where the SC subscript denotes auxiliary equations evaluated at short circuit, i.e., $V = 0$. In contrast with the double-diode model implementations such as [19], a spectrally dependent short-circuit current temperature coefficient does not appear in this auxiliary equation for photocurrent.

Altogether, the double-diode model given by (15) depends on the cell temperature T, reference temperature T_0, and on the effective irradiance ratio F, and it is parameterized through auxiliary (16) and (17) by $I_{\mathrm{SC}\,0}$, $\boldsymbol{\theta}_{I_{\mathrm{D}_1}}$, $\boldsymbol{\theta}_{n_1}$, $\boldsymbol{\theta}_{I_{\mathrm{D}_2}}$, $\boldsymbol{\theta}_{n_2}$, $\boldsymbol{\theta}_{R_{\mathrm{S}}}$, and $\boldsymbol{\theta}_{G_{\mathrm{P}}}$. Note that eliminating both I_{D_1} and I_{D_2} is typically not possible when reparameterizing the model in terms of $V_{\mathrm{OC}\,0}$.

IV. Discussion and Implications

In this section, we discuss some key aspects and implications of the integrated measurement and modeling approach presented here.

A. *Short-Circuit Current Temperature Coefficients*

The approach detailed here employs a temperature-dependent effective irradiance ratio that relies on a spectral correction function. One of the most salient features of this approach is that the spectral correction function builds off of an established measurement methodology using the spectral correction parameter, circumventing spectrally dependent short-circuit current temperature coefficients. In both their measurement and their use, these coefficients' spectral dependence is often underappreciated or neglected [8]. If it is argued that the effects of spectrally dependent temperature coefficients are negligible in certain modeling scenarios (e.g., year-long energy predictions), then the more accurate modeling approach presented here can be used for validation of such claims.

B. *Spectral Response Measurements*

The spectral correction function given in (2) requires the measurement of both the device's and RD's spectral response as a function of cell temperature [26]. These can be relative measurements, as long as the unknown scalars are consistent in the computation of (2). Many spectral responsivity measurement testbeds are designed to control device temperature; therefore, the newest aspect is likely to be the construction of the functions S and S_{RD} over a sufficient range of T and T_{RD}. In cases with a fixed solar simulator spectrum, the spectral correction function f_M could instead be constructed over the range of T and T_{RD} using the discrete set of measurements of S and S_{RD}. The use of a matched RD, as defined earlier, circumvents the need for these measurements and is discussed in a section to follow.

This work has not explored the potential use of absolute differential spectral responsivity [27] in the computation of short-circuit current for potentially nonlinear devices under a variety of spectral conditions. This may be a viable option in some situations.

C. *Spectral Irradiance Measurements*

The spectral correction function given in (2) requires the measurement of the prevailing spectral irradiance. For laboratory controlled indoor measurements using a solar simulator, these measurements are usually routine and periodic. For outdoor measurements, the requirement to measure spectral irradiance becomes more onerous. The use of a matched RD, as defined earlier, circumvents the need for these measurements and is discussed in the following section.

D. *Matched Reference Devices*

Recall that we defined a matched RD to have a spectral correction function that is identically unity over all operating conditions. Assuming that angular response differences are not an issue, this greatly simplifies the determination of the effective irradiance ratio F using (3), for which sufficient matching conditions are that $S = S_{\mathrm{RD}}$ (same spectral response functions over wavelength and temperature) and that $T = T_{\mathrm{RD}}$ (devices operating at the same cell temperature). In particular, matching avoids the need to measure spectral responsivities, prevailing spectral irradiance, and device temperatures.

Matching capability is limited by the availability of stable RDs for various PV technologies (e.g., mono-Si versus thin

[5] Some model parameters may be common among $\boldsymbol{\theta}_{I_{\mathrm{D}_1}}$, $\boldsymbol{\theta}_{n_1}$, $\boldsymbol{\theta}_{I_{\mathrm{D}_2}}$, $\boldsymbol{\theta}_{n_2}$, $\boldsymbol{\theta}_{R_{\mathrm{S}}}$, and $\boldsymbol{\theta}_{G_{\mathrm{P}}}$.

films). If the short-circuit current of the device has been calibrated and is stable, then the device itself can be used as a matched RD if entire *I–V* curve sweeps are measured under sufficiently stable operating conditions (possibly outdoors). Additional matching considerations for outdoor measurements are discussed in a section to follow.

E. Homogeneity Assumptions

We emphasize the homogeneity assumptions that have entered into the present work, in the derivation of both the effective irradiance ratio and the diode models. In particular, temperature and irradiance may not be spatially uniform, and the cells in a device have some variability between them. We claim that these assumptions are certainly no stronger than recent comparable approaches (e.g., [21]). Furthermore, this work has made considerable effort to clearly document all important assumptions, thereby enabling further analysis to quantify the effects of actual inhomogeneity as compared with the assumptions of perfect homogeneity.

F. Outdoor Measurements

An IEC 61853-1 validation study was conducted outdoors by Mani *et al.* [12]. This study employed "closely" matched reference cells for four module technologies: mono-Si, a-Si, CdTe, and CIGS [12, Tab. 2]. A main recommendation of this study is the use of two-axis sun tracking with calibrated irradiance filters on clear days with AM < 2.5. These requirements lessen the advantage of the outdoor method over the indoor method, which requires an expensive large area solar simulator with temperature and irradiance control. It is interesting that the rather stringent tracking and AM limitations were required despite the use of matched RDs. In addition, this study intercompared four curve correction procedures in order to produce the matrix of P_{MAX} values.

The approach presented in this work offers an alternative to the above methodology. In particular, the use of effective irradiance ratios to calibrate a sufficiently accurate diode model may enable the use of fixed-tilt outdoor datasets over a range of AM conditions. However, if sufficiently matched RDs are unavailable, then this approach would require spectral response and spectral irradiance measurements, which add complexity and expense.

In outdoor scenarios with a wide field of view and highly variable spectral (ir)radiance distribution, a matched RD should also have an angular response identical to the device. Common packaging is usually helpful in meeting this requirement. Furthermore, larger systems may require distributed sets of matched RDs to accommodate considerable operating condition variability across the system. This work enables further analysis to quantify the effects of actual mismatch under a perfectly matched assumption [14].

G. Diode Model Calibration

A full discussion of diode model calibration with quantified parameter uncertainty is beyond the scope of this paper. However, we highlight some important aspects of such calibration using the present formulations. The calibration of a diode model to predict device performance stands in contrast with the IEC 61853-1 method of temperature-only or irradiance-only linear interpolations/regressions of individual device performance parameters [1, Sec. 9.1]. Perhaps most important, the use of the effective irradiance ratio, which is a ratio of currents, makes the calibration much more robust to a potentially wide variety of conditions that may have generated the model calibration dataset.

The essential data for model calibration consist of a collection of measured (I, V, F, T) 4-tuples acquired during the measurement of one or more *I–V* curves. F and/or T may or may not be taken as constant for each *I–V* curve, depending on the characteristics of the specific measurement testbed. The noise in the measurement of F and/or T may be much more significant than in I and V [22]. If the cell temperature T is not readily available, then there may be an additional parameterized translation model that relates the measured temperature(s) to the cell temperature T.

As shown in [22] for fixed-temperature conditions, model calibration using effective irradiance ratios does not require any initial *I–V* curve corrections, which can introduce systematic errors into the data. This also eliminates hard-to-quantify uncertainties from such corrections (cf., IEC 60891 [9]). The single-diode model calibration in [22] did not consider measurement calibration chain uncertainties, such as errors in $I_{\mathrm{SC,RD}_0}$ or in the various current sense resistors of the data acquisition system. These can readily be accommodated with additional model refinement, e.g., substituting the measurement of F by using (3) and the measurement of $I_{\mathrm{SC,RD}}$ and T_{RD}. This entails greater potential for parameter estimability and non-identifiability issues [28] as more uncertain parameters are included in the model. In some situations, such issues present problems only for physical parameter identification but not for the predictive capability of the model.

Accommodating the uncertainty in the spectral correction function (2) during model calibration is perhaps the most challenging prospect, even though the determination of a nominal function is relatively straightforward. We compare this with the similar challenge of quantifying uncertainty in the temperature coefficients for short-circuit current of the device and RD, with their significant spectral-dependence.

H. Performance Prediction

The planned series of four IEC 61853 standards have the ultimate goal of producing useful energy ratings with a minimum of performance testing [1]. The integrated measurements-to-model approach that we develop here is aligned with these goals. We think that the planned "reference climatic profiles" [1, Introduction] should be able to readily accommodate the use of effective irradiance ratio in diode-based equivalent circuit performance models, which are quite commonly used in PV energy modeling software [29]–[31]. Interfacing the models to the resource data via the effective irradiance ratio described here appears to be an efficient way to incorporate device-specific and climate-specific temperature and spectral irradiance effects into an easy to exchange model input parameter. The effective irradiance ratio also obviates the need to exchange and use spectrally dependent short-circuit current temperature coefficients.

V. Conclusion

We have presented an integrated measurement and modeling approach based on the effective irradiance ratio, which is simply the ratio of the short-circuit current of a PV device under operating conditions to its short-circuit current under STC. Using a PV RD to measure effective irradiance with respect to a standard spectrum, this approach handles device-specific and RD specific temperature and spectral irradiance effects that are significant factors in performance measurements, such as IEC 61853-1, and in the diode-based equivalent circuit performance models that are calibrated from such measurements. Avoiding the use of spectrally dependent short-circuit current temperature coefficients, this approach uses a temperature-dependent spectral correction function that is a direct extension of the standardized spectral correction parameter used by numerous PV calibration laboratories. When a matched RD is used, then this function becomes identically one, and it need not be computed. This approach should be useful in the advancement of PV performance testing and modeling that use RDs to monitor irradiance.

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