Modeling the Irradiance and Temperature Dependence of Photovoltaic Modules in PVsyst

Kenneth J. Sauer, Thomas Roessler, and Clifford W. Hansen

***Abstract*—In order to reliably simulate the energy yield of photovoltaic (PV) systems, it is necessary to have an accurate model of how the PV modules perform with respect to irradiance and cell temperature. Building on a previous study that addresses the irradiance dependence, two approaches to fit the temperature dependence of module power in PVsyst have been developed and are applied here to recent multi-irradiance and temperature data for a standard Yingli Solar PV module type. The results demonstrate that it is possible to match the measured irradiance and temperature dependence of PV modules in PVsyst. Improvements in energy yield prediction using the optimized models relative to the PVsyst standard model are considered significant for decisions about project financing.**

***Index Terms*—Current–voltage characteristics, mathematical model, minimization, photovoltaic (PV) cells, PV systems, silicon, solar power generation.**

I. Introduction

IN ORDER to make reliable statements regarding the expected energy yield of photovoltaic (PV) systems based on available meteorological data, it is necessary to know the dependence of the maximum power output $\mathrm{P_{max}}$ of the modules comprising those systems on the two most important environmental conditions: global plane-of-array irradiance G and operating cell temperature T.

To describe this dependence, it is convenient to use the quantity $\Delta\eta_{\mathrm{rel}}$(G, T), i.e., the deviation of the module efficiency at the given conditions G and T relative to the value at the corresponding reference conditions $\mathrm{G_{ref}}$ and $\mathrm{T_{ref}}$, which is calculated according to the formula

$$\Delta\eta_{\mathrm{rel}}(G,T) = \frac{P_{\mathrm{max}}(G,T)}{P_{\mathrm{max,ref}}} \cdot \frac{G_{\mathrm{ref}}}{G} - 1 \tag{1}$$

where $\mathrm{P_{max,ref}}$ is the maximum power output at the reference conditions. Fig. 1 visualizes this dependence for an example module type, using a false color plot of $\Delta\eta_{\mathrm{rel}}$(G, T) with the reference conditions here, and throughout the remainder of this paper, taken to be standard test conditions (STC), i.e., $\mathrm{G_{ref}} =$ 1000 W/m^2, $\mathrm{T_{ref}} = 25$ °C, and the reference solar spectrum [1].

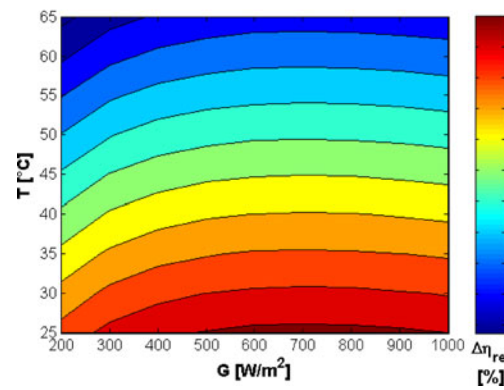

Fig. 1. Two-dimensional false color contour plot displaying the deviation $\Delta\eta_{\mathrm{rel}}$ of module efficiency relative to the value at STC for an example crystalline silicon module type provides a visualization of the dependence of this quantity on irradiance G and cell temperature T.

Various commercial and noncommercial software programs are available for energy yield simulation, each with a different application and purpose [2]. The study presented here limits itself to the modeling and simulation of PV modules of crystalline silicon technology in the commercial software program PVsyst from the University of Geneva [3], which is well established worldwide with independent engineering companies that specialize in the prediction and analysis of the energy yield of large PV systems.

A previous publication [4] describes a systematic approach to determine four free empirical parameters of the one-diode model used for modeling PV modules in PVsyst [5]. This approach is based on an algorithm to minimize the root mean square deviation (RMSD) between modeled and measured module power as a function of irradiance only. In [4], it was assumed that the dependence of the module behavior on temperature could then be reasonably well described by following the PVsyst standard approach of actively inserting the nameplate value of the temperature coefficient of the maximum power for the parameter μ_{Pmpp} in PVsyst. For cases with no additional information about the temperature dependence available beyond the temperature coefficient of $\mathrm{P_{max}}$, this is still a perfectly valid approach.

The main innovative aspect of the study presented here is the fact that it overcomes this restriction, fully considering and modeling the dependence of the module power on irradiance and cell temperature. In fact, two different approaches to model the temperature dependence more accurately are presented, including a simultaneous fitting of the dependence on irradiance and temperature. Furthermore, a detailed comparison of the quality

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of the model fits for different variants of modeling approaches and the corresponding impact on energy yield estimates are given.

Clearly, these model fitting tasks heavily depend on the availability of suitable measurement data. In close cooperation with well-known, independent PV testing institutes, methods have been developed at the Yingli Americas PV Testing Lab (PVTL) in South San Francisco, CA, USA for collecting high-quality measurements of the power output of PV modules across a matrix of irradiance and cell temperature conditions with acceptable effort and in good alignment with the testing practices outlined in the standard IEC 61853-1 [6]. This capacity fulfills the important need to collect such data relatively easily for a statistically relevant sample of PV modules for rapid implementation into module performance models with reliable predictive power.

In the following, it will first be explained how the measurement data recently collected at the PVTL and used for this study were obtained (see Section II). Then, in Section III, it will be briefly reviewed how the dependence of the maximum module power on irradiance and temperature is realized in the one-diode model in PVsyst. Section IV details how the correctness of the representation of the temperature dependence in PVsyst can be improved using straightforward means. Possible modeling approaches are described in Section V, and the corresponding fit results are compared and discussed in Section VI. In Section VII, the impact of the fit quality on energy yield estimates is demonstrated for various geographical locations. Finally, the study presented here will be summarized, and an outlook on future investigations will be sketched.

II. Input Data for Modeling

The performance data used in this study were obtained across a matrix of G and T conditions for a sample of 20 Yingli Solar 72 cell multicrystalline silicon PV modules of type YL310P-35b with a nameplate power value of 310 W. This sample was randomly selected from incoming shipments to the customers of Yingli Solar and delivered to the PVTL for indoor current–voltage characterization using a class AAA flash tester with an integrated temperature control unit and thermally insulated test chamber. Such an apparatus is essential to ensure that a module under test reaches a homogeneous and steady-state temperature condition prior to electrical characterization [7].

For each module, key points on the *I–V* curve, i.e., short-circuit current I_{sc}, open-circuit voltage V_{oc}, and current I_{mp} and voltage V_{mp} at the maximum power point, were measured across a matrix of irradiance and cell temperature conditions covering the ranges of 200 to 1000 W/m^2 and 25 to 65 °C in increments of 100 W/m^2 and 5 °C, respectively.

Following IEC 61853-1 [6], the so-called "self-reference method" can be applied for devices that are linear with irradiance G in short-circuit current I_{sc}, in order to adjust for slight spectral mismatch or spatial nonuniformity effects leading to less than 1% deviation from I_{sc} linearity. Under these conditions, which apply in the present case, in (1) the ratio of the reference irradiance G_{ref} to the irradiance under test G can be replaced by the ratio of I_{sc} values at the corresponding irradiances to determine $\Delta\eta_{rel}$(G, T), i.e.,

$$\begin{aligned}\Delta\eta_{\mathrm{rel}}(G,T) &= \frac{P_{\max}(G,T)}{P_{\max,\mathrm{ref}}}\cdot\frac{G_{\mathrm{ref}}}{G}-1\\ &= \frac{P_{\max}(G,T)}{P_{\max,\mathrm{ref}}}\cdot\frac{I_{\mathrm{sc}}(G_{\mathrm{ref}},T)}{I_{\mathrm{sc}}(G,T)}-1. \qquad (2)\end{aligned}$$

Once the values of $\Delta\eta_{rel}$(G, T) have been determined for each module, an overall average value is taken at each G and T condition, resulting in a single matrix of $\Delta\eta_{rel}$(G, T) values representing the average performance of the sample. With measurements at any given condition having a spread of at most 1.1%, the average value is considered to be representative of the entire sample.

This matrix of $\Delta\eta_{rel}$(G, T) can be converted back to a matrix of P_{max}(G, T) by rearranging (1) and solving for P_{max}(G, T). To obtain a matrix that is consistent with a specific nameplate module power at the reference conditions, $P_{max,ref}$ is set equal to that power value. The resultant P_{max}(G, T) matrix is used as input for modeling and in all cases serves as the reference for comparison with the modeled power across all G and T test conditions.

III. One-Diode Model in PVsyst

The mathematical representation of the I–V curve in the one-diode model is given in the most general form by the following transcendental equation [4], [5]:

$$I(V) = I_{\mathrm{ph}} - I_0\cdot\left\{e^{\left[\frac{q}{N_{\mathrm{cs}}\cdot k\cdot T\cdot\gamma}\cdot(V+I\cdot R_s)\right]}-1\right\} - \frac{V+I\cdot R_s}{R_{\mathrm{sh}}} \qquad (3)$$

where I and V are the current and voltage of the PV module, respectively, N_{cs} is the number of cells in series in the PV module, T is the cell temperature (K), q is the elementary charge, and k is the Boltzmann constant. The free model parameters are thus initially the photoelectric current I_{ph}, the saturation current of the diode I_0, the series resistance R_s, the shunt resistance R_{sh}, and the ideality factor of the diode γ.

In PVsyst, it is assumed that the photoelectric current is dependent on G and T as follows:

$$I_{\mathrm{ph}}(G,T) = \frac{G}{G_{\mathrm{ref}}}\cdot\left[I_{\mathrm{ph,ref}}+\mu_{I_{\mathrm{sc}}}\cdot(T-T_{\mathrm{ref}})\right] \qquad (4)$$

where μ_{Isc} is the temperature coefficient of the short-circuit current I_{sc} of the module type under test. In addition, the saturation current of the diode is assumed to vary with T as follows:

$$I_0(T) = I_{0,\mathrm{ref}}\cdot\left(\frac{T}{T_{\mathrm{ref}}}\right)^3\cdot e^{\left[\frac{q\cdot\varepsilon_G}{\gamma\cdot k}\cdot\left(\frac{1}{T_{\mathrm{ref}}}-\frac{1}{T}\right)\right]} \qquad (5)$$

where ε_G is the energy of the band gap of the cell material. Furthermore, the shunt resistance is assumed to vary with G as follows:

$$R_{\mathrm{sh}}(G) = R_{\mathrm{sh,base}} + (R_{\mathrm{sh},0} - R_{\mathrm{sh,base}}) \cdot e^{-R_{\mathrm{sh,exp}} \cdot \left(\frac{G}{\mathrm{G_{ref}}}\right)} \tag{6}$$

with

$$R_{\mathrm{sh,base}} = \max\left[\left(\frac{R_{\mathrm{sh,ref}} - R_{\mathrm{sh},0} \cdot e^{-R_{\mathrm{sh,exp}}}}{1 - e^{-R_{\mathrm{sh,exp}}}}\right), 0\right] \tag{7}$$

where $\mathrm{R_{sh,exp}}$ and the shunt resistance in the absence of irradiance $\mathrm{R_{sh,0}}$ are two parameters describing this dependence empirically [5].

In the original version of the PVsyst model, it is assumed that the series resistance $\mathrm{R_s}$ and the diode ideality factor γ are not dependent on G or T. Thus, this model requires values for the following nine parameters: $\mathrm{I_{ph,ref}}$, μ_{Isc}, $\mathrm{I_{0,ref}}$, ε_G, $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, $\mathrm{R_{sh,exp}}$, and γ. Two of these parameters, μ_{Isc} and ε_{G}, are assumed to be known *a priori* [5]. As described in [4], provided values of $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$, the remaining model parameters can be computed. Consequently, there are four free parameters to fit the characterized behavior of a specific module.

In [4], a systematic approach to determine these four parameters, with T fixed at $\mathrm{T_{ref}}$, is set forth in detail. Using this approach, it is demonstrated that the measured dependence of the maximum power output of PV modules on G is faithfully reproduced and thus a considerable improvement of the fit quality over the PVsyst standard modeling approach is achieved. The present study further extends this approach by also considering the measured dependence of the maximum power output on T.

IV. Dependence of Power on Temperature in PVsyst

The dependence of the power output of a PV module on T is usually assumed to be linear and is quantified by the relative temperature coefficient of the maximum power expressed in units of %/°C. To determine this coefficient in accordance with IEC 60891 [8], measurements of the module power are taken over a temperature range of at least 30 °C, in steps of about 5 °C, with G fixed at $\mathrm{G_{ref}} = 1000$ W/m^2. Example measurements are indicated as squares in Fig. 2. The value of the temperature coefficient, which is denoted here as $\mu_{\mathrm{Pmpp,slope}}$, is derived from the slope in W/°C of the linear fit over the full temperature range, which is shown as the dash-dotted line in Fig. 2, and converted to relative terms of %/°C by dividing by $\mathrm{P_{max,ref}}$.

For convenience, denote $\mathrm{P_{max}(G_{ref}, T)}$ simply as $\mathrm{P_{max}(T)}$ in the following. In PVsyst, the parameter called μ_{Pmpp}, which is denoted herein for clarity as $\mu_{\mathrm{Pmpp,PVsyst}}$, corresponds to the derivative $\mathrm{dP_{max}(T)/dT}$ of the modeled $\mathrm{P_{max}(T)}$ at $\mathrm{T} = \mathrm{T_{ref}}$, rather than to the slope of the linear fit to the curve over some given temperature range [9]. The basic one-diode model described in (3)–(7) has the disadvantage that the derivative of the modeled $\mathrm{P_{max}(T)}$ at $\mathrm{T_{ref}}$ is completely determined by the choice of the free model parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$ and is often not consistent with the measured value [5].

Therefore, in PVsyst, in order to have more flexibility in modeling the thermal behavior of the module power, a linear

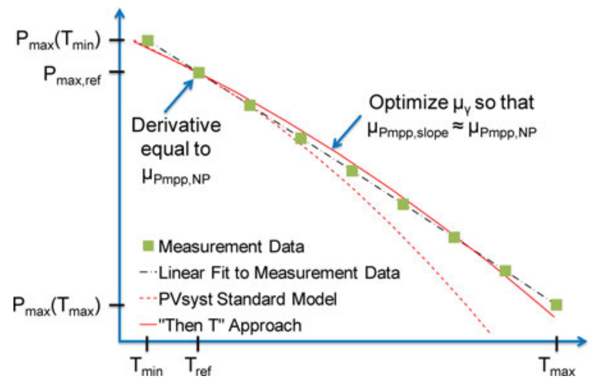

Fig. 2. Comparison of the dependence of the maximum power output $\mathrm{P_{max}}$ on temperature T, with irradiance fixed at the reference condition, as measured and as modeled in PVsyst. The squares represent the measurement data over the temperature range $[\mathrm{T_{min}}, \mathrm{T_{max}}]$, fitted linearly with the dash-dotted line to determine the slope corresponding to the measured or nameplate temperature coefficient $\mu_{\mathrm{Pmpp,NP}}$. For a PVsyst standard model, the additional free empirical model parameter μ_γ is adjusted such that the derivative of the modeled behavior, which is shown as the dashed line, with respect to T at $\mathrm{T_{ref}}$ equals $\mu_{\mathrm{Pmpp,NP}}$. Over the entire temperature range, this clearly does not provide as good a fit as the "Then T" approach, which is shown as the solid line, which targets an agreement between the slope of the model over this range and $\mu_{\mathrm{Pmpp,NP}}$.

temperature dependence of the diode ideality factor γ was subsequently empirically accepted as follows:

$$\gamma(T) = \gamma_{\mathrm{ref}} + \mu_\gamma \cdot (T - \mathrm{T_{ref}}) \tag{8}$$

replacing the model parameter γ with γ_{ref} and introducing an additional free parameter μ_γ, thus increasing the total number of free parameters to five. In order to match the temperature dependence in the PVsyst standard modeling approach, μ_γ in (8) is adjusted such that $\mu_{\mathrm{Pmpp,PVsyst}}$ is equal to the inserted measured or nameplate temperature coefficient value $\mu_{\mathrm{Pmpp,NP}}$ for the given module type [5]. However, because this procedure equates the derivative of $\mathrm{P_{max}(T)}$ at $\mathrm{T} = \mathrm{T_{ref}}$ (i.e., $\mu_{\mathrm{Pmpp,PVsyst}}$) to a value derived from the slope of experimental data over a range of temperatures (i.e., $\mu_{\mathrm{Pmpp,NP}}$), as indicated in Fig. 2, and since the derivative of $\mathrm{P_{max}(T)}$ varies with T in the one-diode model [9], this results in discrepancies between the measured and modeled temperature dependence of the maximum power away from $\mathrm{T_{ref}}$. This therefore allows some room for optimization of the free parameter μ_γ such that the modeled $\mathrm{P_{max}(T)}$ better matches the nearly linear measured behavior over the temperature range of interest.

The approach described in [4] can be extended relatively easily in a modular way to optimize μ_γ accordingly. To demonstrate this with a concrete example, the same approach as described in [4], which is referred to here as the "Only G" model, is repeated to establish values for the free model parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$, with $\mu_\gamma = 0$. Then, the value of μ_γ is iteratively adjusted until the slope of the modeled $\mathrm{P_{max}(T)}$ agrees well with the slope of the measured $\mathrm{P_{max}(T)}$ over the full temperature range under test. The resulting modeled temperature dependence behaves qualitatively like the solid line in Fig. 2 and, together with the already fitted irradiance dependence, constitutes what is referred to here as the "Only G-Then T" model.

For the example dataset described, the measured values correspond to $\mu_{\mathrm{Pmpp,slope}} = -0.429\%/^\circ\mathrm{C}$. In the remainder of this paper, this value is taken to be equal to $\mu_{\mathrm{Pmpp,NP}}$. However, when this value is inserted into PVsyst (as $\mu_{\mathrm{Pmpp,PVsyst}}$) with the allowable precision of two decimals such as with PVsyst Version 6.23 [3], one obtains a slope of $-0.442\%/^\circ$C from the modeled $\mathrm{P_{max}(T)}$ over the temperature range of the test data, overestimating the measured coefficient by nearly 3%. The explicit "Only G-Then T" optimization, on the other hand, results in a coefficient of $-0.430\%/^\circ$C, which is almost an exact reproduction of the measured value.

Therefore, by adding this "Then T" approach as an extension to the systematic methodology described in [4], the measured dependence of the maximum power output of a module on cell temperature T can also be reproduced very well in a PVsyst model.

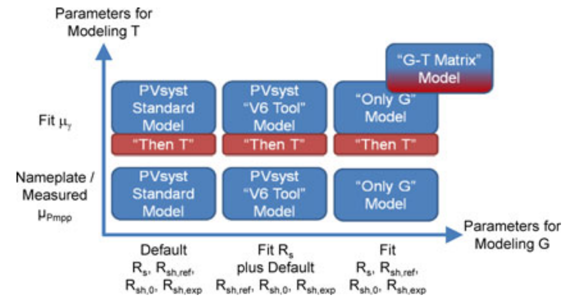

Fig. 3. Various modeling approaches explored in this study, sorted by the number of fitted free parameters for modeling the irradiance G (x-axis) and temperature T (y-axis) behavior of PV modules in the one-diode model in PVsyst. The "Then T" approach introduced in this study to adjust μ_γ to better match the measured temperature dependence of PV modules (red) can be added as a modular extension to any of the three approaches to modeling the multi-irradiance behavior at 25 °C (blue), resulting in six modeling approaches plus the simultaneous optimization of the G and T dependence, which is referred to here as the "G-T Matrix" model.

V. Overview of Modeling Approaches

The "Then T" approach to determine the value of the free module parameter μ_γ to fit the measured temperature coefficient described in Section IV in the context of the so-called "Only G-Then T" model can be combined with any approach to modeling the module behavior at 25 °C that results in values for the free model parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$. In the following, several of the most frequently used modeling approaches are described and the extensions made possible by this study are explained.

A. *PVsyst Standard Model*

In order to generate what is denoted here the "PVsyst Standard Model" for the module type under test, default values prescribed by PVsyst are used for the parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$. As mentioned earlier, in this model the measured, or, equivalently here, the nameplate temperature coefficient of the maximum power is also inserted into PVsyst as $\mu_{\mathrm{Pmpp,PVsyst}}$ in order to determine the value for μ_γ by setting $\mathrm{dP_{max}(T)/dT} = \mu_{\mathrm{Pmpp,PVsyst}}$ at $\mathrm{T = T_{ref}}$, which in turn determines the temperature dependence of the modeled $\mathrm{P_{max}(T)}$.

B. *PVsyst "V6 Tool" Model*

As of Version 6, PVsyst itself offers a tool to adjust the free model parameter $\mathrm{R_s}$ to fit to a measured irradiance dependence of the module power, while keeping the parameters $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$ at the default values for the given module type. This approach, combined with setting $\mu_{\mathrm{Pmpp,PVsyst}}$ to the measured temperature coefficient as for the PVsyst standard model, constitutes the PVsyst "V6 Tool" model.

C. *"Only G" Model*

The "Only G" model corresponds to the modeling approach described in [4], which determines the free model parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$ and is complemented by inserting the measured temperature coefficient for $\mu_{\mathrm{Pmpp,PVsyst}}$, from which μ_γ is determined in the same manner as for the PVsyst standard model.

These three modeling approaches have been explained previously in order of increasing number of optimized free parameters for modeling the irradiance dependence of module power in PVsyst, with zero for the PVsyst standard model, one ($\mathrm{R_s}$) for the PVsyst "V6 Tool" model, and four ($\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$) for the "Only G" model. To each of these approaches, the "Then T" approach to determine the additional free model parameter μ_γ described in Section IV can be added, in order to better match the measured temperature dependence, resulting in three additional modeling approaches.

Clearly, with all of these modeling approaches, no more than one row and one column of the matrix of measured values of $\mathrm{P_{max}(G,T)}$ are taken into account when fitting the free model parameters. The row and column correspond to the measured power values at $\mathrm{T_{ref}}$ at all available irradiances and the measured power values at $\mathrm{G_{ref}}$ at all available cell temperatures. It is obviously questionable whether the PVsyst models that result from these modeling approaches achieve the best global agreement of modeled and measured values of $\mathrm{P_{max}(G,T)}$ across the entire G–T variable space of conditions under test, given that these approaches use only a subset of the available measurement data. To explore this, a numerically expensive simultaneous adjustment of all five free model parameters, including μ_γ, to the full matrix of measured $\mathrm{P_{max}(G,T)}$ values, which hereinafter is referred to as the "G–T Matrix" model, is required. A numerical approach to the parameter optimization, involving the trust-region-reflective algorithm related to the Levenberg–Marquardt method for multidimensional minimization, was implemented to make the corresponding determination of a global minimum in the 5-D model parameter space feasible.

The hierarchy of the seven modeling approaches described previously is visualized in Fig. 3, explicitly using the number of optimized free parameters for modeling the G and T dependence as a way to distinguish between them.

VI. Fit Results

All seven modeling approaches discussed in Section V were applied to obtain models for the example dataset described

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TABLE I
COMPARISON OF MODELING APPROACHES

Modeling Approach		**RMSD [W]**	**MBE [W]**	**Dev. from $\mu_{\mathrm{Pmpp,NP}}$ [%]**	**Diff. from $\Delta\eta_{\mathrm{rel,LIC}}$ [%]**
G–T Matrix		0.25	−0.18	0.78	−0.16
Only G	Then T	0.40	−0.33	0.04	0.01
V6 Tool	Then T	0.47	−0.39	0.52	0.12
Only G	Input $\mu_{\mathrm{Pmpp,NP}}$	0.89	−0.73	2.68	0.01
V6 Tool	Input $\mu_{\mathrm{Pmpp,NP}}$	0.97	−0.79	3.19	0.12
Standard Model	Then T	1.52	−1.39	0.27	−1.59
Standard Model	Input $\mu_{\mathrm{Pmpp,NP}}$	1.92	−1.79	2.96	−1.59

in Section II. Table I compares the RMSD and mean bias error (MBE) between the modeled and measured maximum power across the entire G–T variable space, with the convention for calculating residuals here, and throughout the remainder of this paper, of modeled minus measured power. Relations to key nameplate quantities are also compared in Table I, i.e., the percent deviation from $\mu_{\mathrm{Pmpp,NP}}$ and the difference from the average measured $\Delta\eta_{\mathrm{rel}}$ at the low irradiance condition (LIC) of 200 W/m^2 irradiance, 25 °C cell temperature, and the reference solar spectrum [6], which is denoted here as $\Delta\eta_{\mathrm{rel,LIC}}$, which is reported on datasheets in accordance with EN 50380 [10] and, for this sample, almost exactly equals the nameplate value of -3.3%. For the PVsyst "V6 Tool" model, the RMSD value of 0.97 W is almost a factor of 2 smaller than the RMSD of 1.92 W resulting from the PVsyst standard model. While this is a clear improvement of the global fit quality, the negative MBE value of -0.79 W for the PVsyst "V6 Tool" model still indicates a systematic underestimation of the module power (as is also apparent from Fig. 5, which is discussed below). The "Only G-Then T" model, with an RMSD of 0.40 W and an MBE of -0.33 W, improves the fit quality by another factor of more than 2 over the PVsyst "V6 Tool" model, but the best global fit is obtained, as expected, by the "G-T Matrix" model, with an RMSD of 0.25 W and an MBE of -0.18 W.

From Table I, where the modeling approaches are listed in order of increasing RMSD, it can be seen that the global model fit quality increases with the number of optimized free model parameters, with the "Then T" approach to fitting the temperature dependence providing significant improvement, and the "G-T Matrix" model still with an additional edge. On the other hand, in terms of reproducing more closely the nameplate parameters $\mu_{\mathrm{Pmpp,NP}}$ and $\Delta\eta_{\mathrm{rel,LIC}}$, the "Only G-Then T" model yields the best results, with a relative deviation of 0.04% and a difference of 0.01%, respectively, compared with 0.78% and -0.16% for the "G–T Matrix" model. It is important to note that the question about the "best" modeling approach cannot be answered unequivocally as the choice depends on the planned usage of the model.

For a visualization of the most important results, Fig. 4 compares modeled $\Delta\eta_{\mathrm{rel}}(\mathrm{G,T})$ at all irradiances and at a selection of cell temperatures with the average measurement data (squares).

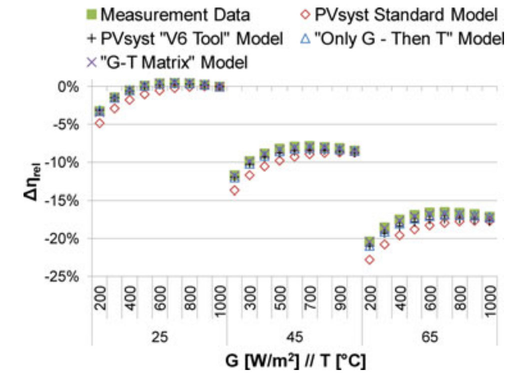

Fig. 4. Plot of $\Delta\eta_{\mathrm{rel}}(\mathrm{G,T})$ curves at a selection of cell temperatures, including 25, 45, and 65 °C for the measurements discussed here, as well as the PVsyst standard model for the module type under test and the PVsyst "V6 Tool," "Only G-Then T," and "G-T Matrix" models with optimized settings. Clearly, the more advanced models, especially the latter two introduced in this study, are more reflective of the measurement data compared with the PVsyst standard model, as can be seen with some distinction at higher temperatures.

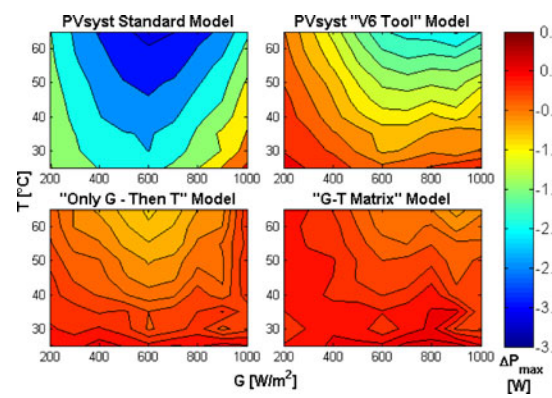

Fig. 5. False color contour plot of maximum power $\mathrm{P_{max}}$ residuals, with the convention of modeled minus measured power, as a function of irradiance G and cell temperature T across the entire G–T variable space of measurement conditions for the nameplate 310 W Yingli Solar module type under test. While the PVsyst "V6 Tool" model shows an improvement over the PVsyst standard model, resulting in smaller power residuals, clearly, the distributions of residuals for the "Only G-Then T" and "G-T Matrix" models arising from this study are more randomly distributed and uniformly close to zero, indicating a globally well-fitting model.

The PVsyst "V6 Tool" model (plus signs) and, even more so, the "Only G-Then T" (triangles) and "G-T Matrix" (crosses) models introduced in this paper, clearly describe the measured behavior more faithfully than does the PVsyst standard model (diamonds). From the graph, the remaining differences between the models resulting from these three more advanced modeling approaches can at most be seen qualitatively, in particular at the higher temperatures.

Fig. 5 provides further insight into the differences between modeling approaches, using a false color contour plot of power residuals for the same four models. The PVsyst standard model exhibits large negative residuals in particular at intermediate irradiances and higher temperatures. In comparison, the PVsyst "V6 Tool" model is already greatly improved, but the residuals increase systematically for cell temperature conditions further away from $\mathrm{T} = 25$ °C at all irradiances. This is expected, since

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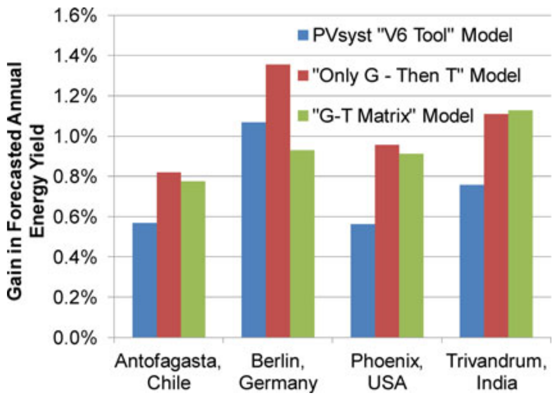

Fig. 6. Four geographically distributed locations were chosen as examples for assessing the deviations of the forecasted energy yields obtained with the PVsyst "V6 Tool," "Only G-Then T," and "G-T Matrix" models discussed in this study, relative to the PVsyst standard model. The impact of a specific modeling approach on the estimated module and, thus, system output at a given irradiance and temperature will scale with the frequency of those conditions in the simulated meteorological year. Some variance in the results reported for a given model across the different locations is therefore expected.

only multi-irradiance data at that temperature were used to adjust model parameters. Clearly, the residuals for the "Only G-Then T" model and, even more so, for the "G–T Matrix" model are more randomly distributed and uniformly close to zero, indicating a better global fit to the data.

It is noteworthy that the values for the difference from the average measured $\Delta\eta_{\mathrm{rel,LIC}}$ in the last column of Table I clearly indicate that the PVsyst "V6 Tool" model considerably improves the fit to the irradiance behavior at 200 W/m^2 as compared with the PVsyst standard model scrutinized in [4]. Looking at the $\mathrm{P_{max}}$ residuals along the x-axis of the false color plots in Fig. 5, it is obvious that this still holds true, albeit to a lesser extent for intermediate irradiances. However, only the "Only G-Then T" and "G-T Matrix" models introduced in this study achieve a good fit over the entire irradiance range considered.

VII. Impact on Energy Yield Estimates

PVsyst was used to generate annual energy yield forecasts for a fixed PV system design at a diversity of geographical locations covering a wide range of climatic conditions for the Yingli Solar module type under test. Baseline simulations using the PVsyst standard model were run at each location at the optimal tilt angle reported by PVsyst and compared with simulations using the parameter values determined for the PVsyst "V6 Tool," "Only G-Then T," and "G-T Matrix" models, with all other modeling parameters held fixed or at the PVsyst default settings.

The results shown in Fig. 6 are reported as deviations of the annual forecasted energy yields (in this case, gains) from those simulated using the PVsyst standard model, using PVsyst default settings for losses. Because the impact of a specific modeling approach on the estimated module and, thus, system performance at a given irradiance and temperature scales with the frequency of occurrence of those conditions in the simulated meteorological year, some variance is expected in the results for a given model across the different geographical locations.

It is apparent that the models resulting from the more advanced approaches predict approximately 0.8–1.0% more annual energy yield than the PVsyst standard model. Furthermore, for the three lower latitude locations, the models resulting from the two approaches introduced in this study systematically predict a 0.20–0.25% higher annual energy yield than the PVsyst "V6 Tool" model. This is consistent with the fact that the PVsyst "V6 Tool" model underestimates the module power at the higher temperatures predominant at these locations, as seen in the upper right false color plot of power residuals in Fig. 5. Although these differences may seem minor compared with other uncertainties in modeling the performance of a PV system, for project financing, differences even of this magnitude can be decisive.

For Berlin, Germany, where conditions of low temperature and irradiance make a more significant contribution to the annual energy yield, the results are not as easily explained. Possibly, the overestimation of the module power for cell temperatures below 25 °C results in a relative increase in the energy yield as simulated with the PVsyst "V6 Tool" model, whereas the underestimation at conditions near LIC reduces the prediction in the case of the "G-T Matrix" model. For this location, it may be necessary to extend the range of measured temperature conditions to values below 25 °C and perform a more detailed analysis of the contribution of the low temperature and irradiance conditions to gain a better understanding of the results.

VIII. Summary and Outlook

For reliable energy yield simulation, it is necessary to have an accurate module model of $\mathrm{P_{max}(G,T)}$. In [4], a method for the systematic adjustment of parameters of the one-diode model in PVsyst to reproduce the measured dependence of the maximum power output of a PV module on the irradiance G is presented. Building on this, two approaches have been developed to better represent the dependence of the maximum power output on cell temperature T. These were applied to model high quality module power measurements for a sample of Yingli Solar multicrystalline PV modules.

The first such approach, denoted as "Then T," can be combined with any approach to modeling the module power at 25 °C as a function of irradiance that results in values for the free model parameters $\mathrm{R_s}$, $\mathrm{R_{sh,ref}}$, $\mathrm{R_{sh,0}}$, and $\mathrm{R_{sh,exp}}$. The "Then T" approach obtains an excellent model fit of the temperature coefficient of the maximum power derived from the measured slope of $\mathrm{P_{max}(G_{ref},T)}$ over the full temperature range under test. Combined with the "Only G" approach to fitting the irradiance dependence of the module power introduced in [4], this reproduces the global dependence of the maximum power output on both irradiance and temperature. As of Version 6.26, which was released shortly after the submission of this paper, the modeling of the temperature dependence in PVsyst has reportedly been improved in line with the proposed "Then T" approach presented here.

The second approach, which is termed the "G-T Matrix" approach, determines all five free model parameters simultaneously by optimizing the fit of the model to the measured maximum power output across the full matrix of irradiance and temperature conditions. For the example dataset used here, the "G-T Matrix" approach improved the global fit of the model, as expected, but at the expense of accurately modeling two key nameplate quantities, i.e., the temperature coefficient of the maximum power and the deviation of the module efficiency at the low irradiance condition, i.e., 200 W/m^2, 25 °C, and the reference solar spectrum, relative to the value at STC.

Either of these approaches significantly improves the global fit quality of the resulting models compared with the PVsyst standard model and its variants. Thus, in principle, this study has demonstrated that it is possible to reliably reproduce in PVsyst the measured irradiance and temperature behavior of a PV module. These model improvements were shown to result in noteworthy gains of simulated annual energy yield on the order of 0.8–1.0% at diverse geographical locations.

Additional studies with measurement data from other module types and technologies are required to test the general applicability of these methodologies. This will also prove whether consistently better global fits can be obtained by the "G–T Matrix" model compared with the "Only G-Then T" model, which may justify the additional measurement and computational expense of the former.

The capability to generate a PVsyst model based on the "G–T Matrix" approach now opens several enticing avenues of investigation. It would, for instance, be interesting to combine this approach with a weighting of environmental conditions according to their contribution to the annual energy yield at a specific location to build what could be denoted a "location-optimized" PVsyst model. In addition, it would be interesting to determine the minimum conditions for module measurements that are required to obtain a PVsyst model with an acceptable accuracy over the full ranges of irradiance and temperature.

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