A New Photovoltaic Module Efficiency Model for Energy Prediction and Rating

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Abstract—**The IEC 61853 photovoltaic (PV) module energy rating standard requires measuring module power (and hence, efficiency) over a matrix of irradiance and temperature conditions. These matrix points represent nearly the full range of operating conditions encountered in the field in all but the most extreme locations and create an opportunity to develop alternative approaches for calculating system performance. In this article, a new PV module efficiency model is presented and compared with five published models using matrix data collected from four different PV module types. The results of the comparative analysis demonstrated that the new model improves on the existing ones exhibiting root-mean-square errors in normalized efficiency well below 0.01 for all cases and PV modules. The analysis also highlighted its ability to interpolate and extrapolate performance between and beyond measured matrix points of irradiance and temperature, establishing it as a robust yet relatively simple model for several applications that are detailed throughout this article.**

Index Terms—**Energy rating, modeling, performance analysis, photovoltaics.**

I. INTRODUCTION

ALTHOUGH the IEC 61215 [1] standard for photovoltaic (PV) module rating at standard test conditions (STC) is the basis for comparing nominal performances of different technologies or types, the procedure does not provide adequate information on how a module would respond to a range of operating conditions.

In order to simulate the performance of a specific PV system, one needs to know how efficiently the PV modules convert the available (or effective) irradiance into electrical power at a given operating temperature. For this purpose, the IEC 61853 [2]–[5] standard was developed, which includes the requirements for characterizing PV performance under different conditions and also provides the basis for realistic energy rating [6]. Part one of this standard (i.e., IEC 61853-1) [2] requires that module power (as well as other parameters) be measured and reported at 22 different combinations of irradiance and temperature (indicated by

the ■ symbol in Table I), covering nearly the full range of operating conditions in all but the most extreme locations. IEC 61853-3 [4] stipulates that to calculate module efficiency at arbitrary irradiance levels and temperatures, bilinear interpolation should be used within the range of the measurement matrix, and "linear extrapolation" outside this range. The standard also includes the possibility to use an "equivalent" method, which creates an opportunity to develop alternative approaches to existing models—such as the single-diode models (SDM) [7] and the Sandia Array Performance Model (SAPM) [8]—for calculating system performance.

Such models have been extensively used in the literature and industry and can calculate several useful parameters on current–voltage *IV* characteristic curves, or even full *IV* curves. Consequently, the calibration of these models extends beyond parameterization of power or efficiency, which is often not a trivial optimization task [9]. A potentially simpler approach, enabled by the IEC 61853 measurements, is presented, validated, and compared in this study for predicting power or efficiency. Existing model-based methods that calculate efficiency as a function of irradiance and temperature, namely 1) bilinear interpolation, 2) Heydenreich (HEY) model [10], 3) MotherPV model [11], 4) Photovoltaic Geographical Information System (PVGIS) model [12], 5a) Mechanistic Performance Model with five terms (MPM5) [13], and 5b) MPM with six terms (MPM6) [13] are also described and applied for comparative purposes. The study focuses on empirical models whose parameters are determined by regression; approaches based on machine learning (e.g., [14]) are not considered.

II. OVERVIEW OF EXISTING MODELS

Both power and efficiency will be referred to as "measured" in this study even though only power can be directly measured; efficiency is the calculated ratio of output (electrical power) to input (solar irradiance multiplied by area). These measured quantities can be converted freely although it should be noted that some operations are not equivalent when applied to one or the other. For example, linearly interpolated power is not equal to power calculated from linearly interpolated efficiency.

A. Bilinear Interpolation

Standard bilinear interpolation/extrapolation requires a rectilinear grid of known values. In order to apply bilinear interpolation to power matrix data, it is necessary to define how to extrapolate outside the confines of the irregular grid of matrix

TABLE I
22 Matrix Data Points Defined in IEC 61853-1

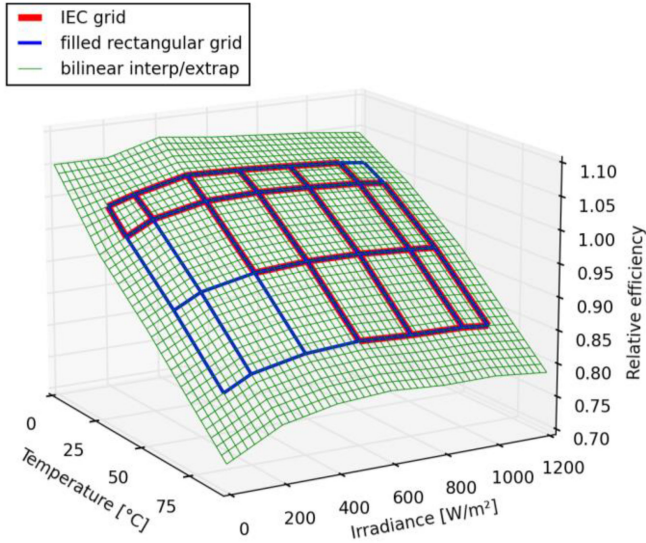| Irradiance	Module Temperature			
W/m²	15ºC	25ºC	50ºC	75ºC
1100		■	■	■
1000	■	■	■	■
800	■	■	■	■
600	■	■	■	■
400	■	■	■	⊠
200	■	■	⊠	⊠
100	■	■	⊠	⊠

Fig. 1.   Normalized PV module efficiency as a function of irradiance and temperature with bilinear interpolation and extrapolation.

data. Fig. 1 shows the result of a bilinear interpolation and extrapolation to normalized efficiency matrix data. The areas outlined by red rectangles are fully enclosed by matrix measurements and are easily defined by standard bilinear interpolation procedures. Areas outlined in blue are either partially bounded by measurements or not at all bounded (e.g., low irradiance–high temperature corner rectangle). Extrapolation of values in these areas require additional steps.

1) Each of the empty grid points may have a filled neighboring grid point at an adjacent temperature and/or irradiance, or at neither.
2) If an empty grid point has both adjacent neighbors, there is also a diagonal neighbor between the adjacent neighbors. These three points form a geometric plane.
3) Assign to the empty grid point a value that makes it coplanar with these three neighbors: Simply add the values of the adjacent neighbors and subtract the value of the diagonal neighbor.
4) Apply this procedure iteratively to fill the grid. The order in which this is done does not influence the end result.

For extrapolating diagonally away from each of the four corners of the completed grid, the usual bilinear interpolation/extrapolation equations are recommended, which may produce a flat or curved extrapolation plane. An open-source implementation of this algorithm is available on GitHub [15].

B. HEY Model

This model [10] is intuitively constructed using the same basic building blocks as the single-diode model [9], i.e., a current/voltage source with two loss mechanisms, similar to a series and a shunt resistance. The current and voltage are assumed to be linear and logarithmic, respectively, with irradiance [10]. Thus, the power can be written as the sum of these three components, weighted by the factors a, b, and c given as

$$P\ (G) =\ a\,G^2 + b\,G \ln\,(G) + c \ln^2\,(G) \tag{1}$$

where P is the power and G is irradiance. The efficiency (η) can be calculated by dividing (1) by G

$$\eta\ (G) =\ a\,G + b \ln\,(G) + c \left[\frac{(\ln^2\,(G))}{G} \right] \tag{2}$$

which is further modified to ensure that $\eta(0) = 0$ such as

$$\eta\ (G) =\ a\,G + b \ln\,(G + 1) + c \left[\frac{(\ln^2\,(G + \exp\,(1)))}{(G + 1)} - 1 \right] \tag{3}$$

whereas the effect of temperature is applied in a second step

$$\eta\ (G,\ T) =\ \eta\,(G) \left[1 +\ \gamma_{pmp}\,(T - 25) \right] \tag{4}$$

where γ_{pmp} is the temperature coefficient of power. Despite its intuitive development building on the physical components of the single-diode model, the resulting equation does not produce physically meaningful fits. One would expect the middle term, the power source, to have a positive coefficient, and the resistive losses to have negative coefficients, but the authors do not impose such restrictions. It is not uncommon to find fitting results where the power source appears to consume power ($b < 0$) and the series resistor generates power ($a > 0$).

C. MotherPV Model

MotherPV is an acronym for "meteorological, optical, and thermal histories for the energy rating of photovoltaics" and the efficiency is expressed as follows [11]:

$$\eta_{rel}\ (S) =\ 1 + a\,(S - 1) + b \ln\,(S) + c(S - 1)^2 + d\ln^2\,(S) \tag{5}$$

where S is the normalized irradiance (i.e., $G/1000$). The development of this expression not only follows a geometrical rather an electrical reasoning for the first two terms, but also incorporates the logarithmic relationship between voltage and irradiance. The rightmost two terms were a later addition to allow the expression to fit the wider variety of curves seen in thin-film modules [11].

The temperature coefficient γ is applied in a second step just like in HEY model, but it is a function of irradiance rather than a constant. This is given in [16] as

$$\gamma\ (S)\ =\ \gamma_{ref}\ \left[1 + a'\,(S - 1) + b' \ln\,(S) \right] \tag{6}$$

$$\eta_{rel}\ (S,\ dT) = \eta_{rel}\ (S) \left[1 +\ \gamma\,(S)\,dT \right] \tag{7}$$

where dT is the temperature difference from the reference (i.e., $T-25$ °C). In contrast to the HEY model, MotherPV is formulated to ensure that $\eta_{rel}(10) = 1$, which means that it can only be used for accurately normalized relative efficiencies (PR_{dc}). The authors also claim that the $\eta_{rel}(S{\to}0) = 0$, but this is incorrect.

D. PVGIS Model

The PVGIS model [12] has its origins in the early versions of the SAPM [8]. In fact, it simply uses the product of the equations for current and voltage at maximum power point (I_{mpp} and V_{mpp}, respectively) of the latter [17] (slightly reformulated here)

$$I_{\mathrm{mpp}}(S,\,dT) = c_1\,S + \alpha\,dT\,S \tag{8}$$

$$V_{\mathrm{mpp}}(S,\,dT) = c_2 + c_3\log S + c_4(\log S)^2 + \beta dT. \tag{9}$$

The product of (8) and (9) is then divided by irradiance and nominal power to obtain the PVGIS equation for relative efficiency [12] such as

$$\eta_{rel}(S,\,dT) = 1 + k_1\log S + k_2(\log S)^2 + k_3 dT$$
$$+ k_4 dT\log S + k_5 dT(\log S)^2 + k_6 dT^2. \tag{10}$$

The equation for I_{mpp} [i.e., (8)] is a simple temperature correction like usually done for short-circuit current, but the derivation of the equation for V_{mpp} [i.e., (9)] is not clear. According to King *et al.* [17], the equation "uses a second-order relationship for V_{mpp} that implicitly contains the influence of factors such as series resistance and nonideal shunting behavior of cells at low irradiance levels." Yordanov provides a sophisticated postanalysis of the PVGIS model and its parameters [18], but nevertheless the original reasoning appears lost.

On the practical side, the authors of the PVGIS model indicate that the coefficients k_1–k_6 are determined by a custom least-squares fitting procedure. The link to the source code is no longer available, but since the equation is an ordinary least squares (OLS) problem, which has a unique solution (given enough data points), any other approach should produce the same coefficients.

E. MPM Model

The MPM [13] comes in two variations, both of which include a term to model the effect of wind. Since the other models discussed here do not include the wind effects and considering that the performance matrices are not measured at different wind speeds, MPM was used without the wind factor. Therefore, the equations that follow have one term less than their names imply. The two variations are as follows:

$$\text{MPM5}: \eta(S, dT) = c_1 + c_2 dT + c_3\log S + c_4 S \tag{11}$$

$$\text{MPM6}: \eta(S, dT) = c_1 + c_2 dT + c_3\log S + c_4 S + \frac{c_6}{S} \tag{12}$$

where $c_6 \leq 0$. Thus, the second variation simply adds a term that is inversely proportional to irradiance. The constraint on c_6

is not found in publications but was recommended by the author in private correspondence.

III. NEW MODEL DESCRIPTION

A new model was developed in this work, from a starting point similar to Heydenreich, using a current source (A), a diode (D), and two resistive losses (series, Rs, and parallel, Rsh), hence the name "ADR"

$$P = P_{AD} - P_{Rs} - P_{Rsh}. \tag{13}$$

Without connecting these components as a circuit, this can also be written as

$$P = IV - I^2 R_s - \frac{V^2}{R_{sh}}. \tag{14}$$

Current is taken to be proportional to irradiance, or rather S

$$I(S) = k_i\,S \tag{15}$$

where k_i is a constant. Therefore, P can be rewritten as a function of S as

$$P(S) = k_i\,S \cdot V(S) - k_i^2 S^2 R_s - \frac{V(S)^2}{R_{sh}}. \tag{16}$$

In the single-diode models, R_{sh} has an inverse relationship with irradiance; an effect that is approximated by the following equation in the DeSoto model [19]:

$$R_{sh} = \frac{R_{sh,ref}}{S} \tag{17}$$

Incorporating (17) into (16) leads to

$$P(S) = k_i\,S \cdot V(S) - k_i^2 S^2 R_s - S\frac{V(S)^2}{R_{sh,ref}}. \tag{18}$$

Now all three terms on the right-hand have a factor S that conveniently divides out when calculating efficiency:

$$\eta(S) = \frac{P(S)}{1000\,S\,A} \tag{19}$$

$$\eta(S) = \frac{1}{1000\,A} \cdot \left[k_i V(S) - k_i^2 S R_s - \frac{V(S)^2}{R_{sh,ref}}\right] \tag{20}$$

$$\eta(S) = \frac{k_i}{1000\,A} \cdot \left[V(S) - k_i S R_s - \frac{V(S)^2}{k_i R_{sh,ref}}\right] \tag{21}$$

where G is written as $1000S$ and A is the module area.

The next steps make the model normalized and scalable in order to have the same coefficients for modules with same efficiency profiles yet different physical dimensions. $V(S)$ is replaced by a normalized voltage $v(S)$

$$v(S) = \frac{V(S)}{V(1)}. \tag{22}$$

Hence

$$\eta(S) = k_a\left[v(S) - k_{rs}S - k_{rsh}v(S)^2\right] \tag{23}$$

In order to get efficiency equal to k_a at reference conditions, (23) can be rewritten as

$$\eta\left(S\right) = k_a\left[\left(1 + k_{rs} + k_{rsh}\right)v\left(S\right) - k_{rs}S - k_{rsh}v(S)^2\right].$$
(24)

And finally, the influence of temperature on efficiency is added into the voltage function since this is the dominant temperature dependency [20]. This produces the main model equation (note: the four model equations are marked with an asterisk)

$$\eta\left(S,T\right) = k_a\Big[\left(1 + k_{rs} + k_{rsh}\right)v\left(S,T\right) - k_{rs}S$$
$$-k_{rsh}v(S,T)^2\Big].$$
*(25)

The dependency of voltage on irradiance and temperature is now developed from the expressions for V_{oc} of the single-diode equation. Series resistance does not influence V_{oc} because when no current is flowing, there is no voltage drop, so it can be ignored. Furthermore, shunt resistance in commercial modules is usually high enough (see PV module libraries in [21]) that its influence on V_{oc} is low and can also be ignored. The simplified equation is

$$V_{oc} \sim \frac{nkT}{q}\ln\left(\frac{I_L}{I_o} + 1\right)$$
(26)

where nkT/q is the thermal voltage, I_L is the light-generated current, and I_0 is the dark saturation current. Since the temperature dependency of I_0 is much stronger than thermal voltage, the latter is also ignored and replaced by a constant k_v

$$V\left(S,T\right) = k_v\ln\left(\frac{I_L\left(S\right)}{I_o\left(T\right)} + 1\right).$$
(27)

Similar to I_L, which is a scaled version of S, I_o is also scaled to create S_o (dark irradiance)

$$V\left(S,T\right) = k_v\ln\left(\frac{S}{S_o\left(T\right)} + 1\right).$$
*(28)

The temperature dependency of I_o is approximated by slightly different equations in various single-diode models, some of which take into account the temperature dependency of the semiconductor band gap as well (e.g., [19]). But the special effects are small, and $\log(I_o)$ plotted against temperature is actually not far from a straight line [22]. Therefore, the model's temperature dependency is finally represented by a single linear dependency in the exponent of the dark irradiance

$$S_o\left(T\right) = 10^{k_d + tc_d(T - 25\,°C)}.$$
*(29)

Finally, the normalized voltage becomes

$$v\left(S,T\right) = \frac{V\left(S,T\right)}{V\left(1,\ 25\,°C\right)}$$
*(30)

where the constant k_v conveniently cancels out in this normalization.

To summarize, the new ADR model consists of the four equations marked with an asterisk, (25), (28), (29), and (30), and has five fitting parameters: k_a, k_d, tc_d, k_{rs}, and k_{rsh}. The equations are used as follows to calculate efficiency.

1) Calculate $S_o(25\,°C)$ and then $V(1, 25\,°C)$ using (29) and (28), respectively.
2) Calculate $S_o(T)$ and then $V(S, T)$ using (29) and (28), respectively.
3) Calculate the normalized voltage, $v(S, T)$ using (30).
4) Calculate the efficiency, $\eta(S, T)$ using *(25).

Due to the normalization steps, the coefficients carry the following meanings.

1) k_a is the absolute scaling factor, which is equal to the efficiency at reference conditions. This factor allows the model to be used with relative or absolute efficiencies, and to accommodate data sets which are not perfectly normalized but have a slight bias at the reference conditions.
2) k_d is the "dark irradiance" or diode coefficient, which influences the voltage increase with irradiance.
3) tc_d is the temperature coefficient of the diode coefficient, which indirectly influences voltage. Because it is the only temperature coefficient in the model, its value will also reflect secondary temperature dependencies that are present in the PV module.
4) k_{rs} and k_{rsh} are the series and shunt resistance loss factors, respectively. Because of the normalization they can be read as power loss fractions at reference conditions. For example, if k_{rs} is 0.05, the internal loss assigned to the series resistance has a magnitude equal to 5% of the module output.

Despite these meaningful descriptions, the model remains an approximation of real performance where the model resistance factors, in particular, may not correspond exactly to physical resistance losses within the PV module. This caveat holds true for the single-diode models as well. Nevertheless, these factors will still be useful for comparisons, either between different modules, or data sets of the same module but from different sources or times; e.g., when studying degradation.

The ADR model, examples, and fitting coefficients for the investigated PV modules are available in the GitHub repository *pvpltools-python* [15].

IV. VALIDATION AND COMPARATIVE ANALYSIS

The six models (Bilinear, HEY, MotherPV, PVGIS, MPM, and ADR) were compared by fitting them to matrix data collected from four different PV module types: CdTe (First Solar S4v3), Poly-c-Si (Jinko Solar JKM260P-60), n-type Mono-c-Si (LG LG320N1K-A5), and HIT c-Si (Panasonic N325SA16). The different modules will be referred to with their corresponding manufacturer and cell technology for simplicity; i.e., First Solar CdTe, Jinko poly, LG mono, and Panasonic HIT. Module characterization reports and/or data are publicly available elsewhere [First Solar CdTe module in [23] and the remaining modules in the PV Performance Modeling Collaborative (PVPMC) website [24]]. The testing was performed by CFV Labs, an ISO 17025-accredited lab, in conformity with IEC 61853-1:2011 Section 8.1. All silicon modules were tested during the same period in 2019, whereas the First Solar CdTe module was characterized in 2016. The root-mean-square error (RMSE) of normalized
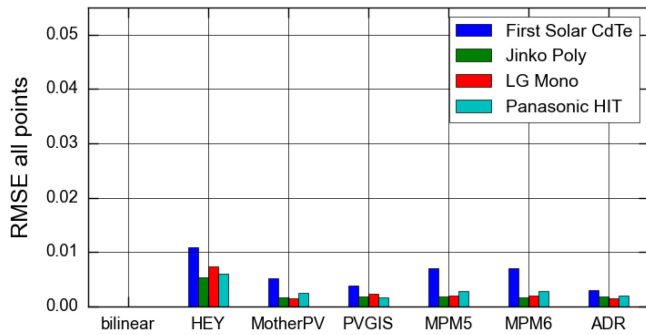
Fig. 2. Obtained RMSE values for all measured points when all points were also used to fit the models (i.e., Case 1). Bilinear interpolation is zero because it perfectly matches all points, by definition.
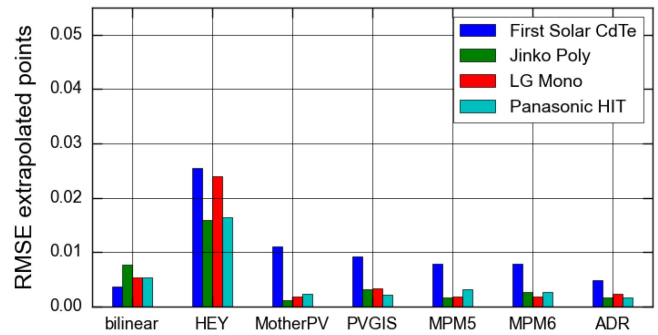

Fig. 3. Obtained RMSE values for the additional points (⊠ in Table I, which represent "abnormal" operating conditions) when IEC 61853 points were used to fit the models (i.e., Case 2).

Fig. 4. Obtained RMSE values for the high irradiance points (1000 and 1100 W/m²) when extrapolated from lower irradiance levels (i.e., Case 3).
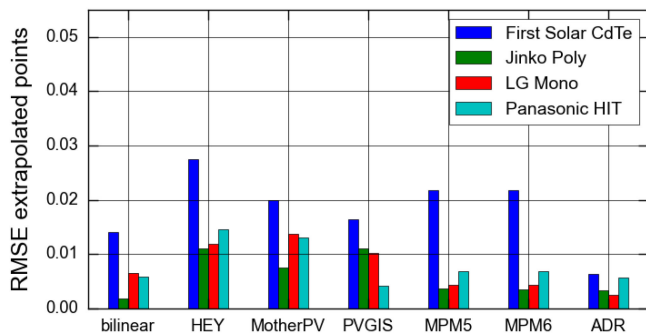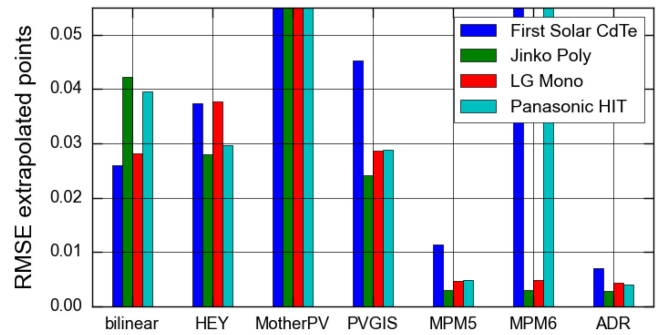

Fig. 5. Obtained RMSE values for the low irradiance points (100 and 200 W/m²) when extrapolated from higher irradiance levels (i.e., Case 4).

Fig. 6. Obtained RMSE values for points ≥ 100 W/m² by also considering a "measurement" close to 0 W/m², in addition to the remaining IEC 61853 points (i.e., Case 5). PVGIS, MPM5, and MPM6 exhibit increased RMSE values as compared with Fig. 2.

efficiency was used as a metric and following five cases were defined to enable the comparative analysis.

1) Fit with all (22) matrix data points specified in the IEC 61853 standard (■ in Table I) plus five additional points (⊠ in Table I). RMSE was calculated for all points (see Fig. 2).

2) Fit with all (22) matrix data points specified in the IEC 61853 standard (■ in Table I). RMSE was calculated for the five additional data points (⊠ in Table I), as shown in Fig. 3.

3) Fit with all data (■ and ⊠ in Table I) except for irradiance levels equal to 1100 and 1000 W/m² to see how well the models extrapolate to higher irradiance levels. RMSE was calculated for the high irradiance points (see Fig. 4).

4) Fit with all data (■ and ⊠ in Table I) except for irradiance levels equal to 100 and 200 W/m² to see how well the models extrapolate to lower irradiance levels. RMSE calculated for the low irradiance points (see Fig. 5).

5) Fit with all data (■ and ⊠ in Table I) plus a data point where power/efficiency = 0 when irradiance = 0 W/m² (since some of the models are undefined at irradiance = 0 W/m², a point at 1 mW/m² was added instead). RMSE calculated for points ≥ 100 W/m² (see Fig. 6).

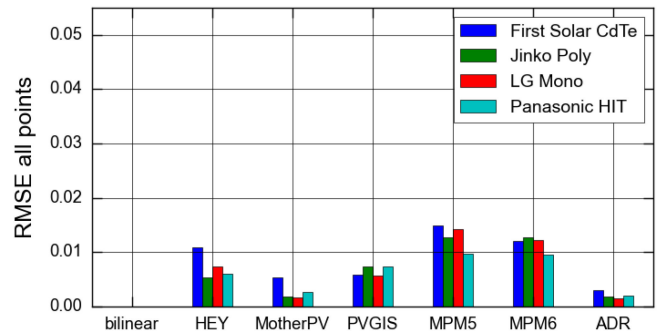Figs. 2–6 illustrate the models' RMSE values for each of the five test cases and all four PV modules. The lowest RMSE for all models was exhibited in Case 1, which fits to the most data points (Fig. 2). For this case, the RMSE for bilinear interpolation is zero because it perfectly matches all points by definition; all other models are below 0.01 (except in the case of First Solar CdTe and HEY). As shown in Fig. 3, the RMSE of "abnormal" operating conditions (low irradiance and high temperature, marked by ⊠ in Table I) increases up to ∼0.027 (First Solar CdTe and HEY, again) when only the 22 points defined in the IEC 61853 standard are used for fitting. In Fig. 4, the HEY model exhibits
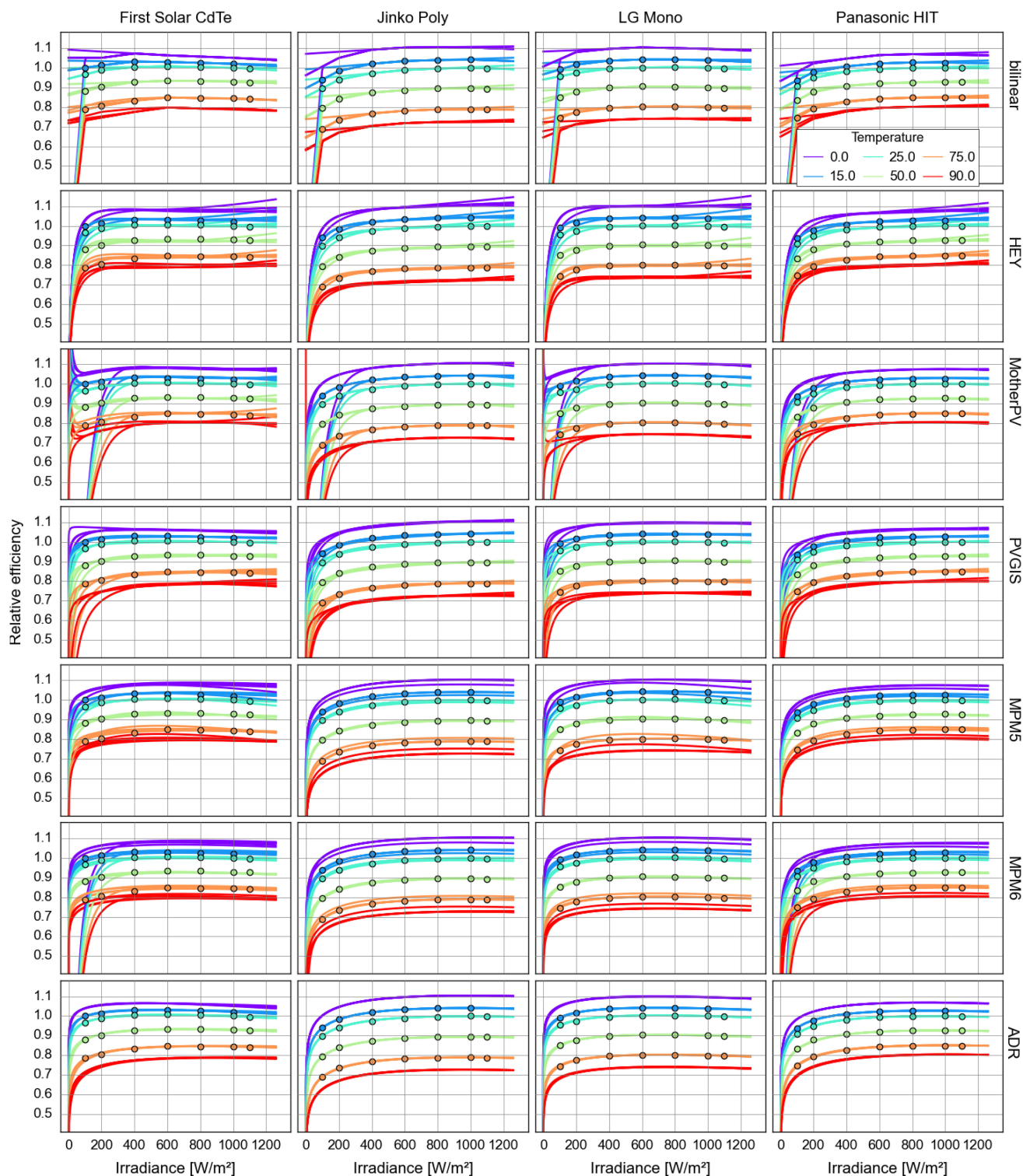
Fig. 7. Efficiency curves produced by each model for the four PV module types. Each graph shows the results of all the overlaid tests. The curves for the ADR model are nearly identical for all the test cases, demonstrating its ability to produce consistent model coefficients under a variety of "challenging" conditions.

the highest errors (up to ∼0.025) when extrapolating to higher irradiance values. The results for Case 4 (Fig. 5) demonstrate that all models, except for MPM5 and ADR, are not accurate when low irradiance data points are excluded from the fitting, exhibiting RMSE values beyond 0.02 or even 0.05 in the case of MotherPV and MPM6 (First Solar CdTe and Panasonic HIT).

Finally, when considering a "measurement" of zero efficiency at close to 0 W/m^2 (i.e., 1 mW/m^2), the PVGIS, MPM5, and MPM6 exhibit increased RMSE values as compared with Fig. 2. Overall, the ADR model exhibited RMSE values well below 0.01 at all cases; its performance can also be qualitatively verified from the plot matrix of relative module efficiency against irradiance

under different temperatures for all PV modules (columns) and models (rows) (see Fig. 7). The measured data points are plotted as circles and the lines are the model fits from all the overlaid test cases. The curves for the ADR model are nearly identical for all the test cases, demonstrating its ability to produce consistent model coefficients under a variety of challenging conditions, making it the most robust of the examined models. Furthermore, it can also be observed that for all models and test cases, the RMSE of the First Solar CdTe module is higher than the other modules; this could be attributed to the slightly higher scatter in the source data (not visible in Fig. 7) caused by measurement challenges, such as metastability. Nevertheless, the results demonstrated that most models cannot fit the First Solar CdTe performance surface as well as the ADR model.

All fitted coefficients for all modules and test cases are publicly available [25].

V. Discussion

The four previously published models (HEY, MotherPV, PVGIS, and MPM) are formulated primarily as linear combinations of terms in irradiance and/or temperature. Thus, the coefficients of those terms can generally be found by linear regression. In general, having more terms in a linear regression usually leads to better fits to the data. However, "closer" may not always be "better." The regression calculation is blind to what lies between and beyond the measured points, but the result of the regression will be used precisely for that purpose, i.e., to estimate efficiency between and beyond the measured points. This is where the choice of terms and the general form of the modeling equations play a crucial role by constraining the set of possible solutions to a set of reasonable or plausible ones. The HEY model illustrates this principle by constraining itself to zero efficiency at zero irradiance. But not every term in the model equation must be related to a physical explanation. This is seen in the PVGIS model where both current and voltage have the usual temperature coefficients, but when these equations are multiplied, the unusual term dT^2 is produced. When equations are rearranged and combined, the meanings may be obfuscated, but this does not invalidate any part of the equations.

One thing all the models have in common is a term in the logarithm of irradiance, whose origins lie in the single-diode model and is associated with the operating voltage of a PV module. However, the simplified term $\log(S)$ is positive for $G > 1000$ W/m^2, negative for $G < 1000$ W/m^2, and tends to large negative values at low irradiance levels. It appears, therefore, that some meaning was lost since this simplification no longer represents the true voltage behavior of a PV module.

Stepping back from the individual terms and looking at the ensemble, none of the models has purely orthogonal terms, which would mean they act independently of each other on module efficiency. A simple test for orthogonality is to remove a term from the model and observe whether the coefficients of the other terms change. But it also seems quite clear that terms based on the same variable cannot be orthogonal in this sense.

A related but more important criterion is that no term should be a linear combination of the other terms because this leads to nonunique solutions. The situation becomes somewhat treacherous if one term is *nearly* a linear combination of one or more other terms. In this case, the coefficients could go substantially in different directions with little influence on the quality of the fit because their effects nearly cancel each other out. This is the case with the term $1/S$ in (12) of the MPM6 model, which can be approximated quite well with a linear combination of the terms in MPM5 over the irradiance data range 100–1100 W/m^2. The same applies to the term $\ln^2 S$ in (9) of the MotherPV model.

A final aspect to consider is normalization. Efficiency is already a normalized quantity, but it can be convenient to normalize it further with respect to the efficiency at 1000 W/m^2 and 25 °C. Two of the models, MotherPV and PVGIS, include the constant 1.0, and can only be used with normalized efficiency; HEY and MPM are flexible in this regard, but will produce different coefficients depending on whether they receive absolute or normalized efficiency. The downside of the former is that when presented with poorly normalized data, the fits can suffer.

Ransome and Sutterlueti [13] claim that the coefficients of the MPM are normalized, whereas those of most other models are not. The normalization of a coefficient would imply dividing by a reference value of some sort, but this does not appear to be done in any of these models, including MPM. The only apparent normalization within the models is that of irradiance ($S = G/G_{STC}$), which is done in the majority of models and has the effect of keeping coefficients in a more reasonable numeric range. This is not to say that normalization is not useful or important, but only that it is not a differentiating factor in the models reviewed in this work.

The ADR model was developed expressly to address the shortcomings or disadvantages observed with the other models. Its single-diode model roots help it extrapolate realistically and reliably beyond the matrix measurement points with relatively few parameters. Those parameters are not orthogonal, but still largely independent of one another. Furthermore, the separate scaling parameter k_a ensures that the other four parameters capture the core qualities of the module and can be meaningfully compared between modules and models.

VI. Conclusion

It was demonstrated, in very concrete terms, how the IEC 61853-1 module power/efficiency measurement data can be leveraged for modeling and simulation purposes. In order to use the data as a basis for PV system simulation, a robust method is needed to interpolate and extrapolate from the matrix measurement conditions to the full range of outdoor operating conditions. This can be bilinear interpolation/extrapolation, as suggested in IEC 61853 for energy-rating purposes, or it can be one of several model-based methods—including the new ADR method described in this work.

Having access to several data sets for different module types has enabled an investigation of how well these methods and models perform at the task of representing and reproducing PV

module behavior. Multiple test criteria were developed for the methods incorporating not only the data, but also the overall knowledge on PV module behavior.

The new ADR PV module efficiency model has been developed using the well-established single-diode model as a starting point. Its advantage in relation to the single-diode models is that it has a single purpose (to model efficiency) and therefore, determining the parameters is comparatively easy. By contrast the single-diode model is expected to reproduce entire *IV* curves, so the fitting process is more complex and accuracy in efficiency may be sacrificed for accuracy on other points on the *IV* curve. The advantages of the ADR model compared with other efficiency models are clearly seen in the presented test results, which collectively show that the new model reproduces more closely the known behavior of PV modules, especially when extrapolating beyond the measurements.

While the ADR model's main target application is PV system simulation, the process of fitting the model to a set of efficiency measurements (which may be a full or partial matrix of indoor measurements or data collected outdoors) can lead to useful insights as well, such as identifying possible outliers, or assessing whether there is a bias. And last—but certainly not least—IEC 61853-3 states that "in general, it is necessary to perform a two-dimensional bilinear interpolation, *or equivalent …*" (emphasis added). This implies that the ADR model could be used in conformity with the standard energy rating procedure as well.

As more and more IEC 61853 data sets are produced—and especially made public (e.g., PV Lifetime project)—broader validation of both new and existing models will be made possible. Also important is the comparison with outdoor measurements in operating PV systems. In fact, the four module types examined in this article have been deployed by Sandia National Laboratories in Albuquerque, New Mexico, USA, for several years already. Future work will compare models to this field performance data.

ACKNOWLEDGMENT

AUTHOR CONTRIBUTION

Anton Driesse: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Marios Theristis**: Visualization, Writing – review & editing. **Joshua S. Stein**: Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

REFERENCES

[1] *Crystalline Silicon Terrestrial Photovoltaic (Pv) Modules – Design Qualification and Type Approval*, Standard IEC 61215, Geneva, Switzerland, 2016.

[2] *Photovoltaic (PV) Module Performance Testing and Energy Rating—Part 1: Irradiance and Temperature Performance Measurements and Power Rating*, Standard IEC 61853-1, Geneva, Switzerland, 2011.

[3] *Photovoltaic (PV) Module Performance Testing and Energy Rating - Part 2: Spectral Responsivity, Incidence Angle and Module Operating Temperature Measurements*, Standard IEC 61853-2, Geneva, Switzerland, 2016.

[4] *Photovoltaic (PV) Module Performance Testing and Energy Rating - Part 3: Energy Rating of PV Modules*, Standard IEC 61853-3, Geneva, Switzerland, 2018.

[5] *Photovoltaic (PV) Module Performance Testing and Energy Rating - Part 4: Standard Reference Climatic Profiles*, Standard IEC 61853-4, Geneva, Switzerland, 2018.

[6] C. Monokroussos *et al.*, "Energy rating of c-Si and mc-Si commercial PV-Modules in accordance with IEC 61853–1,-2,-3 and impact on the annual yield," in *Proc. 33rd Eur. Photovolt. Sol. Energy Conf.*, 2017, pp. 1438–1444.

[7] D. S. Chan and J. C. Phang, "Analytical methods for the extraction of solar-cell single-and double-diode model parameters from IV characteristics," *IEEE Trans. Electron. Devices*, vol. ED-34, no. 2, pp. 286–293, Feb. 1987.

[8] D. L. King *et al.*, "Photovoltaic array performance model," Sandia Rep. No. SAND 2004-3535, Sandia National Laboratories, Albuquerque, NM, 2004.

[9] C. W. Hansen, "Parameter estimation for single diode models of photovoltaic modules," Sandia Rep. No. SAND2015- 2065, Sandia National Laboratories, Albuquerque, NM, 2015.

[10] W. Heydenreich *et al.*, "Describing the world with three parameters: A new approach to PV module power modelling," in *Proc. 23rd Eur. Photovolt. Sol. Energy Conf. Exhib.*, 2008, pp. 2786–2789.

[11] A. G. de Montgareuil *et al.*, "A new tool for the MotherPV method: Modelling of the irradiance coefficient of photovoltaic modules," in *Proc. 24th Eur. Photovolt. Sol. Energy Conf.*, 2009, pp. 21–25.

[12] T. Huld *et al.*, "A power-rating model for crystalline silicon PV modules," *Sol. Energy Materials Sol. Cells*, vol. 95, no. 12, pp. 3359–3369, 2011.

[13] S. Ransome and J. Sutterlueti, "How to choose the best empirical model for optimum energy yield predictions," in *Proc. 44th IEEE Photovolt. Specialist Conf.*, 2017, pp. 652–657.

[14] A. Livera *et al.*, "Optimal development of location and technology independent machine learning photovoltaic performance predictive models," in *Proc. 46th IEEE Photovolt. Specialists Conf.*, 2019, pp. 1270–1275.

[15] A. Driesse. *PV Performance Labs Tools for Python*. Accessed: Nov. 27, 2020. [Online]. Available: https://github.com/adriesse/pvpltools-python

[16] A. G. de Montgareuil *et al.*, "First results of the application of the MotherPV method to CIS modules," in *Proc. 24th Eur. Photovolt. Sol. Energy Conf. Exhib.*, 2009, pp. 3451–3455.

[17] D. L. King *et al.*, "Field experience with a new performance characterization procedure for photovoltaic arrays," Sandia Rep. No. SAND-98-3147C, Sandia National Laboratories, Albuquerque, NM, 1998.

[18] G. H. Yordanov, "Relative efficiency revealed: Equations for k 1–k 6 of the PVGIS model," in *Proc. 40th IEEE Photovolt. Specialist Conf.*, 2014, pp. 1393–1398.

[19] W. De Soto *et al.*, "Improvement and validation of a model for photovoltaic array performance," *Sol. Energy*, vol. 80, no. 1, pp. 78–88, 2006.

[20] S. R. Wenham *et al.*, *Applied Photovoltaics*. Sydney, Australia: Centre for Photovoltaic Devices and Systems, 1994.

[21] "System Advisor Model Version 2020.2.29," Nat. Renew. Energy Lab., Golden, CO, USA.

[22] P. Singh and N. M. Ravindra, "Temperature dependence of solar cell performance—An analysis," *Sol. Energy Materials Sol. Cells*, vol. 101, pp. 36–45, 2012.

[23] First Solar, "Third party validation of first solar PAN files," Tech. Rep. PD-5-500, rev. 2.0, 2016.

[24] *PV Performance Modeling Collaborative,* Sandia National Laboratories, Accessed: Sep. 3, 2020. [Online]. Available: https://pvpmc.sandia.gov/pv-research/pv-lifetime-project/pv-lifetime-modules/

[25] A. Driesse and J. S. Stein, "From IEC 61853 power measurements to PV system simulations," Sandia Rep. No. SAND2020-3877, Sandia National Laboratories, Albuquerque, NM, 2020.