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From IEC 61853 power measurements to PV system simulations

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From IEC 61853 power measurements to PV system simulations

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Abstract

The IEC 61853 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 to existing models—such as the single-diode models and the Sandia Array Performance Model—for calculating system performance.

This report begins by discussing the bilinear interpolation and extrapolation method from IEC 61853-3, and then describes four existing model-based methods that could be used with matrix measurements. Then a new model is developed and all options are compared according to seven objective criteria using the matrix measurements of four PV modules of different technologies. The results show that the new model is an excellent candidate for launching power matrix-based PV system simulations.

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EXECUTIVE SUMMARY

The IEC 61853 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 to existing models—such as the single-diode models and the Sandia Array Performance Model—for calculating system performance.

This report begins by discussing the bilinear interpolation and extrapolation method from IEC 61853-3. It clarifies the approach presented in the IEC standard and describes a simple method to handle undefined corner cases. It also points out important features of efficiency curves for PV cells and modules, such as their concave down shape and that efficiency goes to zero with zero irradiance. The bilinear interpolation and extrapolation methods are especially sensitive to measurement errors in the individual matrix points.

The report goes on to describe four existing model-based methods of calculating efficiency as a function of irradiance and temperature and a new method developed by the first author of this report (ADR). The existing methods include Heydenreich (HEY), MotherPV, PVGIS, and the Mechanistic Performance Model (MPM).

Finally, all five models are fit to measured matrix data measured on four different PV modules representing different cell technologies. These models are compared using seven objective criteria aimed at identifying strengths and weaknesses of each model. These criteria include the following:

1. How well does the model reproduce all measured points in matrix?
2. How well does the model extrapolate to higher irradiance?
3. How well does the model extrapolate to lower irradiance?
4. How well does the model extrapolate lower irradiance and higher temperatures?
5. How well does the model work as irradiance approaches zero?
6. How well does the model work with biased or poorly normalized measurements?
7. How well does the model fit noisy measurements?

Figure E1 show an example of model fits to all of the matrix data (Criterion 1) for one of the test modules. Table E1 summarizes the results for all models and test criteria. Green represents the best result among the models, yellow indicates a clearly visible difference to the best (which may be small or large), and red indicates an area of weakness. Several cells under "Bilinear" are left blank because the metric is not appropriate; the RMSE will always be zero for all given points because no interpolation or extrapolation is actually done in those cases. The ADR model is shown to perform the best in this comparison.

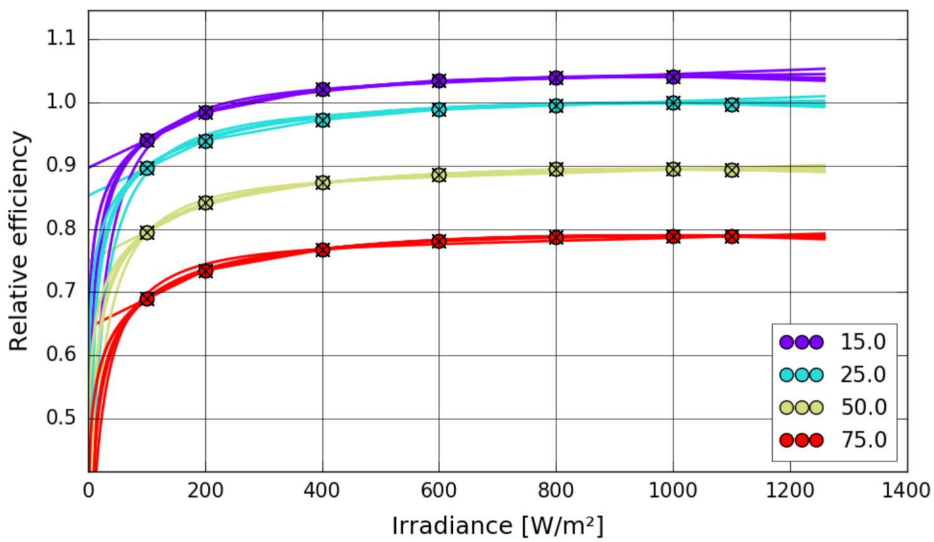

Figure E1: Example of matrix data fit to all of the models. Regions of very high and low irradiance values show the most difference between the models.

Table E1: Qualitative summary and index of test results

#	Fit model to this:	Evaluate this:	Bilinear	HEY	MotherPV	PVGIS	MPM5	MPM6	ADR
1	All points	RMSE all points							
2	Points < 1000 W/m^2	RMSE >= 1000 W/m^2							
3	Points > 200 W/m^2	RMSE <= 200 W/m^2							
4	Points in IEC grid	RMSE outside IEC grid							
5	All points	values at G=0		0.0	nan	nan	−inf.	−inf.	0.0
5	All points	values at G=1 mW/m^2							
5	All plus G=1 mW/m^2	RMSE >= 100 W/m^2							
6	All points + 2%offset	RMSE w.r.t. offset points							
7	All points + 1% noise	RMSE w.r.t. no noise							

NOMENCLATURE

Abbreviation	Definition
G	irradiance
S	normalized irradiance: $S = G / 1000$
T	temperature
dT	difference from reference temperature: $dT = T - 25$
η	efficiency (relative or absolute)
RMSE	root-mean-squared error
IEC	International Electrotechnical Commission
SDM	Single-diode model (for PV cell/module behavior)
SAPM	Sandia Array Performance Model
CSER	Climate-Specific Energy Rating (defined in standard IEC 61853-3)
gamma	Temperature coefficient of power
beta	Temperature coefficient of open-circuit voltage
alpha	Temperature coefficient of short-circuit current
R_s	Series resistance
R_{sh}	Shunt resistance

1. INTRODUCTION

To simulate the performance of a specific PV system one needs to know how the selected PV modules respond to a range of operating conditions, or more specifically, how efficiently they convert available, or effective, irradiance into electrical power at a given operating temperature. The simplest simulation procedure might use a constant efficiency, but more commonly a model-based approach is used such as one of the single-diode models (SDM), the Sandia array performance model (SAPM), or similar. With the appropriate parameters for a specific PV module, the model can predict the efficiency (η) at any combination of irradiance and operating temperature. However, these models can do much more; they can calculate many other useful points on the I-V curves, or even full I-V curves. Consequently, calibration of these models extends beyond parameterization of power or efficiency and is often not a trivial optimization task [6]. In this report we explore a potentially simpler approach enabled by the IEC 61853 measurements and focus on predicting *only* power or efficiency.

Part one of the IEC 61853 energy rating standard [1] requires that module power (as well as other parameters) be measured and reported at 22 different combinations of irradiance and temperature (see Figure 1), covering nearly the full range of operating conditions in all but the most extreme locations. This data is a superb resource for verifying and/or fine-tuning the parameters for existing simulation models; but since the measurements are in a form that can almost be directly used in the simulation process, it also opens the door for alternate approaches. For example, instead of running a complex model to estimate efficiency at a particular combination of irradiance and temperature, the simplest approach would be to use the measured efficiency at the nearest available combination of irradiance and temperature.

Table 2 – I_{sc}, P_{max}, V_{oc} and V_{max} versus irradiance and temperature

Irradiance	Spectrum		Module temperature		
$W \cdot m^{-2}$		15 °C	25 °C	50 °C	75 °C
1 100	AM1,5	NA			
1 000	AM1,5				
800	AM1,5				
600	AM1,5				
400	AM1,5				NA
200	AM1,5			NA	NA
100	AM1,5			NA	NA

Figure 1 Matrix of irradiance and temperature combinations from IEC 61853-1

The foregoing paragraphs mention both power and efficiency. Only power can be directly measured, whereas efficiency is the calculated ratio of input (solar) and output (electrical) powers. Nevertheless, the latter will be referred to as *measured* efficiency in this document. We can convert freely between these measured quantities, but note that some operations are not equivalent when applied to one or the other: linearly interpolated power, for example, is not equal to power calculated from linearly interpolated efficiency.

Part three of the IEC 61853 standard [2] describes the calculation procedure for the climate-specific energy ratings (CSER), which bears a strong resemblance to a system simulation process. It uses bilinear interpolation and extrapolation of the matrix efficiency measurements in order to calculate module efficiency at arbitrary irradiance and temperature combinations. This is, however, only one of many possible approaches.

This report begins by discussing the bilinear interpolation and extrapolation method from IEC 61853-3, and then describes four existing model-based methods that could be used with matrix measurements. Finally, a new model is developed and all options are compared according to seven objective criteria using the matrix measurements of four PV modules of different technologies.

2. BILINEAR INTERPOLATION AND EXTRAPOLATION

Linear interpolation and extrapolation can be used to estimate values for an unknown function of a single variable when the value of that function is known only at certain points. The unknown values are simply presumed to lie on straight lines connecting their two nearest neighbors. For interpolation these neighbors lie on opposing sides of the target, whereas for extrapolation, these neighbors lie on the same side.

Similarly *bilinear* interpolation and extrapolation can be used for unknown functions of *two* variables, where the known values of the function must lie at the vertices of a rectilinear grid of the two variables. The procedure in essence performs linear interpolation (or extrapolation) first for one variable, then for the other; the order is not relevant. Unknown values are determined from four neighboring points that form a grid square (or rectangle); for interpolation, this grid square surrounds the target, whereas for extrapolation, the nearest grid square is used. The interpolated function is continuous at the boundaries of each grid square, but its gradient is usually discontinuous. [3]

In the context of this report, PV module efficiency is an unknown function of the two variables irradiance and temperature. IEC 61853-3 needs efficiency values for many combinations of irradiance and temperature for its energy rating procedure, and stipulates that *bilinear interpolation* should be used within the range of the measurement matrix, and *linear extrapolation* outside this range. Note, however, that the standard also contains the short phrase "or equivalent"…

IEC 61853-3 provides detailed calculations for interpolation and for two cases of extrapolation. The interpolation calculations [Eq. 9-11 in 2] are essentially equivalent to the bilinear interpolation found in many other sources (such as [3]). The first extrapolation case [Eq. 12-14 in 2] is named *linear* extrapolation, but is actually equivalent to standard *bilinear* extrapolation. It is intended for cases where only *one* of the two variables lies outside the range of the measurements, but unfortunately this condition is ambiguous because the rectangular measurement matrix has six positions that are not required to be measured or reported. (See the cells marked "NA" in Figure 1.) The second case of extrapolation applies where *both* variables are outside the range of the measurements. [Eq. 15-17 in 2] differ from standard bilinear extrapolation by forcing the surface that extends from each of the four corners of the measurement matrix to be a flat plane.

Thus, some choices need to be made to turn the directives in the standard into a complete procedure, whether it is to be used for energy rating or for PV system simulation. An open-source bilinear interpolation function was written in python for this report and is available here: https://github.com/adriesse/pvpltools-python.[4]

2.1. Completing the grid

Standard bilinear interpolation/extrapolation requires a rectilinear grid of known values, whereas the IEC measurement rectilinear grid has six empty vertices ("NA"). It might be possible to formulate equations and/or rules to extrapolate from an irregular perimeter, but it is much easier to define how the empty vertices should be filled and then revert to the standard procedure.

The solution we recommend to define the empty grid points is as follows:

- Each of the empty grid points may have a filled neighboring grid point at an adjacent temperature, at an adjacent irradiance, at both, or at neither.
- 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.
- 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.
- Apply this procedure iteratively to fill the grid. The order in which this is done does not influence the end result.

After this simple procedure the completed grid of IEC measurements can be used with the standard bilinear interpolation and extrapolation equations (and program code libraries).

For extrapolating diagonally away from each of the four corners of the completed grid, the two main choices are:

- Apply the IEC 61853-3 equations 15-17 which force a flat extrapolation plane.
- Apply the usual bilinear interpolation/extrapolation equations which may produce a flat or curved extrapolation plane.

We recommend the latter so that there is no special case to consider in the computation.

A typical result of our recommended method is shown in Figure 2.

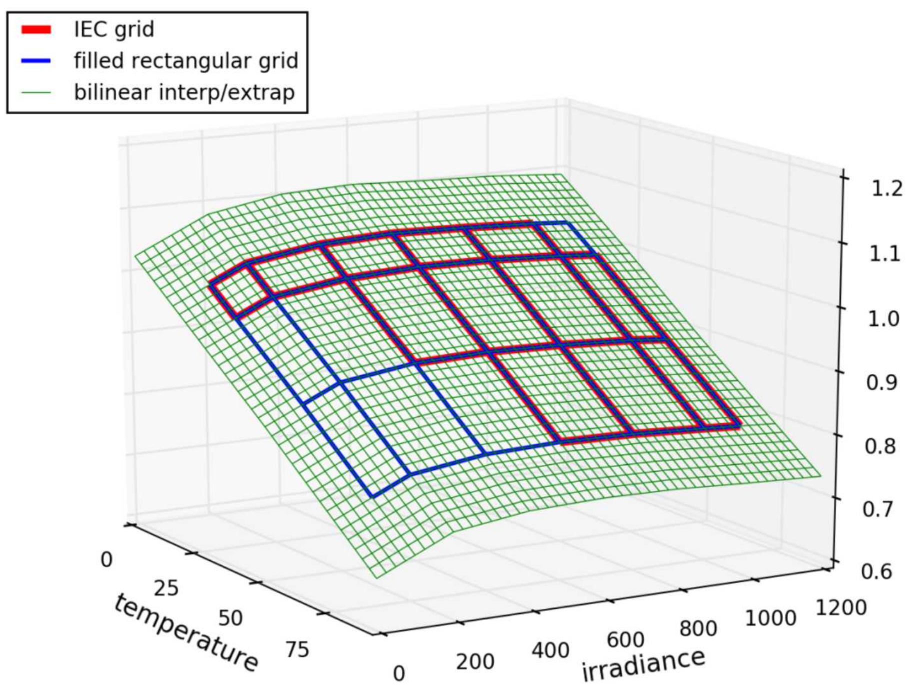

Figure 2 Normalized PV module efficiency as a function of irradiance and temperature with bilinear interpolation and extrapolation

2.2. Concavity and the case of zero irradiance

It is well-known that for real PV cells and modules, efficiency approaches zero as irradiance approaches zero. It would have been rather wasteful to require measurements at zero irradiance, but would it be a good idea to add the zero irradiance values to the matrix of measurements prior to using it for interpolation and extrapolation?

The descent to zero efficiency is most rapid near zero irradiance, therefore a linear descent from the lowest measured irradiance, 100 W/m^2, down to 0 W/m^2 would lead to a strong underestimation of efficiency in that range. On the other hand linear extrapolation from the points at 200 and 100 W/m^2 clearly leads to overestimation. Given the degree of curvature in this region it would certainly be helpful to have an additional measurement at 50 W/m^2 as suggested by the first note accompanying the matrix table in the standard: "To assess nonlinearities, measurements at 300 W/m^2 and 50 W/m^2 can be helpful." [1]

What we observe in this low irradiance region is in fact true over the entire efficiency surface: its curvature is concave down, which means linear interpolation between any two points, especially with different irradiance values, will produce an efficiency value that is less than the value on the curved surface. Thus, bilinear interpolation systematically under-predicts efficiency. And for the same reason of downward concavity, bi-linear *extrapolation* systematically *over*-predicts efficiency.

2.3. Effects of measurement uncertainty and outliers

Bilinear interpolation is very flexible in that it can adapt to any irregularly shaped surface (it does not have to be concave down). So if measurement artifacts cause a wavy surface, this will be seen in the interpolated values; and if there is an outlier, a small pyramid will appear on the interpolated surface. When this occurs in the middle of the matrix, the effect is localized, but if occurs in the perimeter, the effect continues to grow with extrapolation as seen in Figure 3. This problem was first reported and demonstrated in [5].

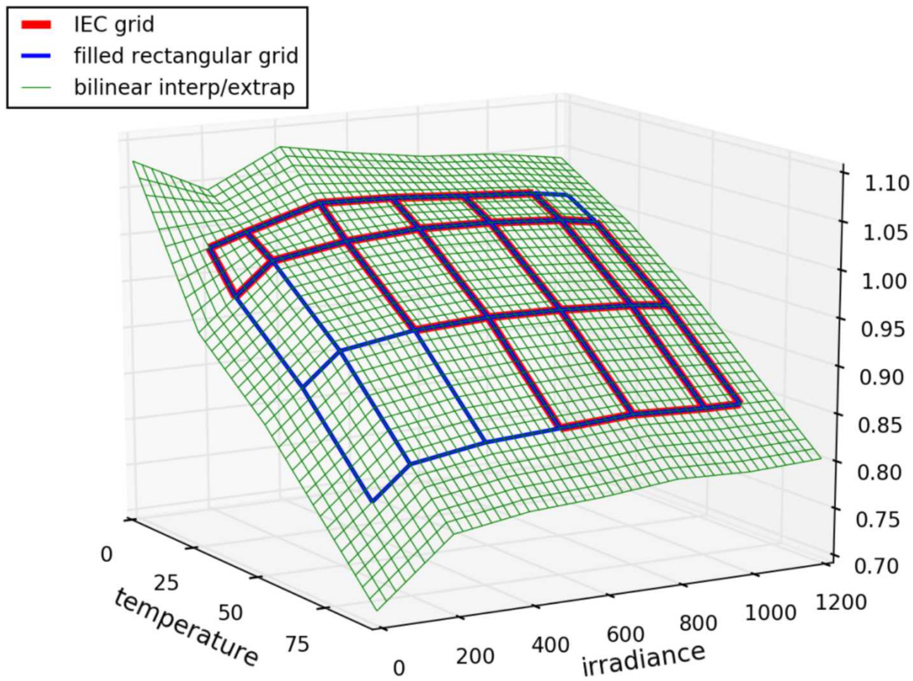

Figure 3 The effect of measurement irregularities on the bilinearly interpolated and extrapolated performance surface

3. MODEL-BASED METHODS

As already mentioned in the introduction, models such as SDM and SAPM can be used to calculate efficiency under any operating conditions provided the correct model coefficients are known. But these models can do much more: they can calculate many other useful points on the I-V curve, or full I-V curves, therefore finding the parameters to accomplish all this is not a trivial optimization task [6].

A potentially simpler approach is to use a model which *only* predicts power or efficiency of the form:

$$\eta = f(G, T) \tag{1}$$

Alternatively it could be expressed in terms of normalized irradiance and temperature deviation from reference conditions:

$$S = \frac{G}{1000} \tag{2}$$

$$dT = (T - 25) \tag{3}$$

$$\eta = f(S, dT) \tag{4}$$

Several such models were proposed in the literature around a decade ago, such as Heydenreich (HEY) in 2008 [7], MotherPV in 2009 [8,9], PVGIS in 2011 [10], but there are also more recent developments on the topic, such as the MPM [11]. The following sections describe these in more detail. The names of the model parameters reflect those of the original authors.

3.1. Heydenreich (HEY)

This model is intuitively constructed as follows, using the same basic building blocks as the single-diode model [6]:

> "The model consists of a current/voltage source and two loss mechanisms, similar to a serial and a parallel resistance. The current I of the current/voltage source is assumed to be linear with irradiation G, while the voltage U is assumed to be proportional to the logarithm of irradiation G. So, the power (P = U I) is proportional to G ln(G). Losses in a serial resistance ($P = R I^2$) are proportional to G^2, and losses in a parallel resistance ($P = U^2 / R$) are proportional to $\ln^2(G)$."[7]

Thus the power can be written as the sum of these three components, weighted by the factors *a*, *b* and *c*. (The authors chose to place the power source between the two loss components in the equation.)

$$P(G) = a\,G^2 + b\,G\ln(G) + c\ln^2(G) \tag{5}$$

This expression can be divided by G to get efficiency:

$$\eta(G) = a\,G + b\ln(G) + c\left[\frac{(\ln^2(G)}{G}\right] \tag{6}$$

Which is further modified to ensure that $\eta(0)=0$:

$$\eta(G) = a\,G + b\ln(G+1) + c\left[\frac{(\ln^2(G+\exp(1))}{(G+1)} - 1\right] \tag{7}$$

The effect of temperature is applied in a second step:

$$\eta(G,T) = \eta(G)\left[1 + \gamma_{pmp}(T - 25)\right] \tag{8}$$

Despite its intuitive development building on the physical components of the single-diode model, the resulting equation does not produce physically meaningful fits. It is not uncommon to find that the power source appears to consume power ($b < 0$) and that the series resistor generates power ($a > 0$).

3.2. MotherPV

This name is an acronym for the phrase: "Meteorological, Optical and Thermal Histories for the Energy Rating of Photovoltaics", which appears to be the umbrella name for a family of different techniques related to data analysis and performance rating as it is used on other contexts. The expression for efficiency proposed in equation 12 of [8] is as follows:

$$\eta_{rel}(S) = 1 + a(S-1) + b\ln(S) + c(S-1)^2 + d\ln^2(S) \tag{9}$$

The development of this expression follows a geometrical rather than 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 [8].

The temperature coefficient γ is applied in a second step just like in Heydenreich, but it is a function of irradiance rather than a constant. This is given in equation 6 and 7 of [9]:

$$\gamma(S) = \gamma_{ref}[1 + a'(S-1) + b'\ln(S)] \tag{10}$$

$$\eta_{rel}(S, dT) = \eta_{rel}(S)[1 + \gamma(S)dT] \tag{11}$$

In contrast to Heydenreich, the MotherPV authors formulated their model to ensure that $\eta_{rel}(1{,}0) = 1$. This means the model can only be used for accurately normalized *relative* efficiencies (PR_{DC}). The authors also claim that the $\eta_{rel}(S \rightarrow 0) = 0$, but this is incorrect.

3.3. PVGIS

The PVGIS model [10] has its origins in the early versions of the Sandia Array Performance Model (SAPM) [12]. In fact, it simply uses the product of the equations for I_{mp} and V_{mp} from [13] (slightly reformulated here):

$$I_{mpp}(S, dT) = c_1 S + \alpha\,dT\,S \tag{12}$$

$$V_{mpp}(S, dT) = c_2 + c_3\log S + c_4(\log S)^2 + \beta dT \tag{13}$$

This product is then divided by irradiance and nominal power to obtain the PVGIS equation for relative efficiency [10]:

$$\eta_{rel}(S, dT) = 1 + k_1 \log S + k_2 (\log S)^2 + k_3 dT + k_4 dT \log S + k_5 dT (\log S)^2 + k_6 dT^2 \quad (14)$$

The above equation for I_{mp} is a simple temperature correction like usually done for I_{sc}, but the derivation of the equation for V_{mpp} is not clear. The author of [13] simply writes that the equation "uses a second order relationship for V_{mp} that implicitly contains the influence of factors such as series resistance (R_s) and non-ideal shunting behavior (R_{sh}, n_2) of cells at low irradiance levels." Yordanov provides a very sophisticated post-analysis of the PVGIS model and its parameters [14], 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 as the equation is an ordinary least squares problem (OLS) which has a unique solution (given enough data points), any other approach should produce the same coefficients.

3.4. MPM

The mechanistic performance model (MPM) [11] comes in two variations, both of which include a term to model the effect of wind. Since wind generally reduces module operating temperature, most performance models do not include the indirect effect of wind in the module performance equations. In any case, the performance matrices are not measured at different wind speeds, therefore we can only consider the MPM without the wind factor(and the equations that follow have one less term than their names imply). The two variations are as follows:

MPM5:

$$\eta(S,dT) = c_1 + c_2 dT + c_3 \log S + c_4 S \quad (15)$$

MPM6:

$$\eta(S,dT) = c_1 + c_2 dT + c_3 \log S + c_4 S + \frac{c_6}{S} \quad (16)$$

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.

3.5. Comments on the existing models

The four models presented above (and also others not discussed here) 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. Having more terms in a linear regression usually leads to closer fits to the data, and the results shown later in this document could be compared to the number of coefficients each model provides. But there is no significant computational cost to having addition terms in the models so this is not in itself an important measure.

More importantly, "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: to estimate efficiency between and beyond the measured points. This is where the choice of terms in the models and, more generally, the form of the model equation play a crucial role by constraining the set of possible solutions to a set of reasonable or plausible ones. The Heydenreich model illustrates this principle by constraining itself to zero efficiency at zero irradiance.

This does not mean that every term in the model equation must be related to a physical explanation. This is seen clearly in the PVGIS model: 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 the PV module. But the simplified term $\log(S)$ is positive for $G > 1000$ W/m^2, negative for $G < 1000$ W/m^2 and tends to very large negative numbers at low irradiance. It appears therefore, that some meaning was lost as this simplification no longer represents the true voltage behavior of the PV module.

Stepping back from the individual terms and looking at the ensemble, we can observe that none of the models have 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 there would not be a unique solution. 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 fit quality because their effects nearly cancel each other out. This is the case with the term $1/S$ in the MPM6, 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 Eq. (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.

In [11] the author claims 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 here.

Naturally after such intense scrutiny of previous work, it is impossible to resist the temptation to develop a new and improved model…

4. DEVELOPMENT OF A NEW MODEL

We develop a new model from a starting point very similar to Heydenreich, positing that we have a generating element composed of a current source (*A*) and diode (*D*), plus two resistive losses, one series (*Rs*) and one parallel (*Rsh*).

$$P = P_{AD} - P_{Rs} - P_{Rsh} \tag{17}$$

Then we say that there is a *representative* current (*I*) and voltage (*V*), such that:

$$P = IV - I^2 R_s - \frac{V^2}{R_{sh}} \tag{18}$$

Where R_s and R_{sh} are the series and shunt resistances respectively. (Note that it is not a proper electrical circuit equation.)

Ignoring the effect of temperature, the current is taken to be proportional to irradiance, or rather normalized irradiance (*S*):

$$I(S) = k_i S \tag{19}$$

where k_i is a constant. With this we can write *P* as a function of *S*.

$$P(S) = k_i S \cdot V(S) - k_i^2 S^2 R_s - \frac{V(S)^2}{R_{sh}} \tag{20}$$

In the single-diode models R_{sh} increases as irradiance decreases, an effect that is approximated by the following equation in the DeSoto model[15]:

$$R_{sh} = \frac{R_{sh,ref}}{S} \tag{21}$$

Incorporating (21) into (20) leads to:

$$P(S) = k_i S \cdot V(S) - k_i^2 S^2 R_s - S\frac{V(S)^2}{R_{sh,ref}} \tag{22}$$

All three terms on the right hand side of this have the factor *S* that conveniently divides out when we calculate efficiency:

$$\eta(S) = \frac{P(S)}{1000\, S\, A} \tag{23}$$

$$\eta(S) = \frac{1}{1000\, A} \cdot \left[k_i V(S) - k_i^2 S R_s - \frac{V(S)^2}{R_{sh,ref}} \right] \tag{24}$$

$$\eta(S) = \frac{k_i}{1000\, A} \cdot \left[V(S) - k_i S R_s - \frac{V(S)^2}{k_i R_{sh,ref}} \right] \tag{25}$$

where A is the module area. Although it seems nice to have constants with physical dimensions (area, resistance, etc.), efficiency is dimensionless and it we prefer to represent modules of different physical dimensions with the same coefficients if they have the same efficiency profiles. So we will replace *V(S)* with a normalized voltage:

$$v(S) = \frac{V(S)}{V(1)} \tag{26}$$

then combine various pairs of constants:

$$\eta(S) = k_a\left[v(S) - k_{rs}S - k_{rsh}v(S)^2\right] \tag{27}$$

and normalize the expression within the square brackets so that the efficiency at reference conditions is k_a:

$$\eta(S) = k_a\left[(1 + k_{rs} + k_{rsh})v(S) - k_{rs}S - k_{rsh}v(S)^2\right] \tag{28}$$

At this point we still need to model *v(S)* and the effect of temperature. Because the effect of temperature on current is an order of magnitude smaller than the effect on voltage *and* we are only concerned about the *combined* effect on power, we will make the simplifying assumption that the effect on power can be approximated by *only* an effect on voltage. Thus:

$$\eta(S,T) = k_a\left[(1 + k_{rs} + k_{rsh})v(S,T) - k_{rs}S - k_{rsh}v(S,T)^2\right] \quad *(29)$$

Now we need to model the voltage, but rather than start with a general statement about logarithmic behavior, we try to use V_{oc} as determined by the single-diode equation. Series resistance does not influence V_{oc} and can be ignored, but shunt resistance makes the equation hard to solve. Fortunately, R_{sh} in commercial modules is usually high enough that its influence on V_{oc} is small, so with this knowledge we also ignore R_{sh} and calculate V_{oc} as:

$$V_{oc} \sim \frac{nkT}{q}\ln\left(\frac{I_L}{I_o} + 1\right) \tag{30}$$

Where nkT/q is the thermal voltage, I_L is the light-generated current, and I_O is the dark saturation current. A temperature dependency has appeared in front of the logarithm (the thermal voltage), but we are going to ignore this because the temperature dependency of the dark saturation current, I_o, is much stronger. Replacing the thermal voltage with a constant k_v, we get the following function for voltage:

$$V(S,T) = k_v\ln\left(\frac{I_L(S)}{I_o(T)} + 1\right) \tag{31}$$

Since I_L is just a scaled version of S, we can use the same factor to create a scaled version of I_o called S_o ("dark irradiance"!) and write:

$$V(S,T) = k_v\ln\left(\frac{S}{S_o(T)} + 1\right) \quad *(32)$$

The temperature dependency of the saturation current I_o is approximated by slightly different equations in the different single-diode models, some of which take into account the temperature dependency of the semiconductor band gap as well. But the special effects are small, and log(I_o)

plotted against temperature is actually not far from a straight line. Therefore we will use a linear dependency in the exponent like this:

$$S_o(T) = 10^{k_d + tc_d(T - 25)} \qquad *(33)$$

The normalized voltage is then:

$$v(S,T) = \frac{V(S,T)}{V(1,25)} \qquad *(34)$$

And with that, the model is complete. It consists of the four equations marked with an asterisk, (29), (32), (33) and (34), and has the five fitting parameters: k_a, k_d, tc_d, k_{rs}, and k_{rsh}. (Several other constants were discarded during the derivation process).

The equations are used as follows to calculate efficiency:

- Calculate $S_o(25)$ and then $V(1, 25)$ using eq. (33) and (32) respectively
- Calculate $S_o(T)$ and then $V(S, T)$ using eq. (33) and (32) respectively
- Calculate the normalized voltage, $v(S,T)$ using eq. (34)
- Calculate the efficiency, $\eta(S,T)$ using eq. (29)

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

- 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.
- k_d is the *dark irradiance* or *diode* coefficient which influences how voltage increases with irradiance.
- 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.
- k_{rs} and k_{rsh} are the series and shunt resistance loss factors. 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 reality, and 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 between data sets for the same module from different sources or times, such as when studying degradation for example.

5. EVALUATION METHOD

An obvious criterion for comparison is to evaluate how well the models can fit measured data, which in the context of IEC 61853 consists of a sparse but regular grid of points. But as previously discussed in the context of bilinear interpolation, it is also very important that the model interpolate and extrapolate accurately and resist the influence of noisy data and outliers. In this chapter we describe several tests we used to evaluate the models, and show how the models differ from one another.

5.1. Fitting procedures

Unfortunately the main emphasis of many publications is on the equations, and the procedures for finding the coefficients are not always explained in great detail. To evaluate and compare these models we used the same method: we determined coefficients by minimizing the sum of the square of the residuals—the residuals being the differences between measured and modeled efficiency. In the case of MPM6 we also imposed the constraint that $C_6 <= 0$ as recommended by the author in private correspondence. As a result MPM6 frequently had C6=0, making it equivalent to MPM5 in those cases.

We used a non-linear least-squares method to find the optimal coefficients for each model and test case. (Specifically, the *curve_fit* function in the python *scipy.optimize* package.) Unfortunately most authors say little about their fitting process, so we hope that any unpublished details were not essential to the use of the models.

We did use constraints on the coefficients for our new model, however these were set to values far beyond any expected solutions primarily to promote convergence of the minimization algorithm:

$0 < k_a < 200$
$-50 < k_d < 0$
$0 < tc_d < 1$
$-10 < k_{rs} < 10$
$-10 < k_{rsh} < 10$

5.2. Data for evaluation

The data used in our model comparison are IEC 61853-1 power matrix data measured on four PV modules, each with a different cell technology (Table 1)

Table 1: Modules tested

Manufacturer	Model	Cell Technology	Measurement Method	Measurement Lab
First Solar	S4V3	CdTe	Indoor flash (Halm) with laminar flow temperature chamber	CFV Labs
Jinko Solar	JKM260P-60	Multi-c-Si	Indoor flash (Halm) with laminar flow temperature chamber	CFV Labs
LG	LG320N1K-A5	n-type mono c-Si	Indoor flash (Halm) with laminar flow temperature chamber	CFV Labs
Panasonic	VBHN325SA16	HIT c-Si	Indoor flash (Halm) with laminar flow temperature chamber	CFV Labs

Note: Measured data is available at: https://pvpmc.sandia.gov/pv-research/pv-lifetime-project/pv-lifetime-modules/

All matrix testing was performed by CFV Labs (formerly CFV Solar), an ISO 17025-accredited test lab, in conformity with IEC 61853-1:2011 § 8.1. The CdTe module was characterized in 2016 under contract with First Solar [14], while the remaining modules were characterized in 2019 under contract to Sandia [15].

The CdTe module was preconditioned in an indoor light soaking chamber kept below 65°C by controlling the air flow through the chamber. The module received more than 30 kWh/m^2 of irradiation dose at an average irradiation of 1100 W/m^2. The c-Si modules were preconditioned by outdoor exposure at open circuit for at least 40 kWh/m^2 of insolation prior to matrix testing.

The test points cover irradiances from 100 to 1100 W/m^2, and temperatures from 15 to 75°C. In addition to the test points defined in IEC 61853-1:2011 § 8.1, measurements were obtained at five additional points at low irradiance/high-temperature combinations (cells marked "NA" in Figure 1). The irradiance was varied by adjusting the voltage applied to the Xenon arc lamp. The spectral match remains class A or better for all irradiances. An integrated thermal chamber varied the module temperature with a laminar air flow, and the module temperature was monitored at 4 points with calibrated RTDs having uncertainties of ± 0.13°C. For each measurement, the max-min temperature spread was less than 1.5°C.

The monitor cell was mounted at a location outside the thermal chamber and was not co-planar with the test module. The monitor cell sensitivity was adjusted to reproduce the Pmp measured at STC on the test module.

5.3. Evaluation Metric

The primary metric for the evaluation is the RMS error (RMSE), i.e. the square root of the sum of the differences between the measured points and the model fits (or predictions) for the same operating conditions. The measured and modeled quantity is normalized efficiency (defined as 1.0 at STC conditions) so the RMSE are directly comparable between modules and models. To gain additional insights, different subsets of the data are used for the fitting process and for the RMSE. And fits are also performed with noise or bias added to the data.

It would be possible to use different, or additional metrics to compare the models, for example mean absolute deviation (MAD), but since the fitting procedures were set to minimize the RMSE, it seemed most fitting to use RMSE to gauge their success.

We have included bilinear interpolation in this evaluation section but in some of the test cases the RMSE metric is not very meaningful since this method always reproduces the measured points precisely!

5.4. Model coefficients

Several of the test cases require model fits to subsets of the data, so multiple sets of coefficients were generated. To make it possible to reproduce our graphs, all coefficients are provided in Appendix A. It is also interesting to observe the ranges, mathematical signs and typical values for each parameter. For example, that the coefficient *b* of the HEY model, which scales the power source, always had a negative value!

6. RESULTS AND OBSERVATIONS

6.1. Reproducing the measured data points

The first test is to simply fit the models to all the available data, and evaluate the resulting RMSE. As shown in Figure 4 below, the RMSE for all the model points is generally below 0.01 (1% relative). Two things stand out somewhat: HEY does not fit quite as well as the others, and all models show higher RMSE with the CdTe module. The latter is in part because the older CdTe data have a little more random scatter, but also in part due to the unique nature of its performance surface and possible meta-stability issues.

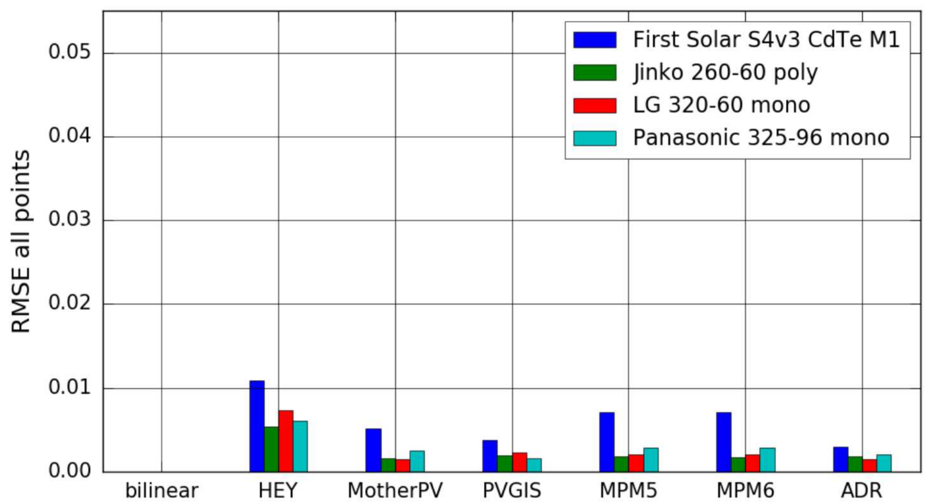

Figure 4 RMSE for all measured points when all points are used to fit the model

Only considering RMSE as the metric suggests that the differences between models are not really all that big. However, this metric only quantifies each model's ability to reproduce the data used to calibrate it. If we look at all the model curves over a larger range of irradiance, we see that there is actually quite a difference in the way each extrapolates beyond the measured points. Figure 5 shows the curves for the Jinko poly-Si module. Despite having the lowest RMSE for all models on the measured points, there is clear disagreement between models when comparing extrapolated conditions. The situation is considerably worse for the CdTe module in Figure 6. Here one of the models (MotherPV) takes a serious turn in the wrong direction below 100 W/m^2.

The next few test cases will try to identify which model might be more reliable at extrapolating.

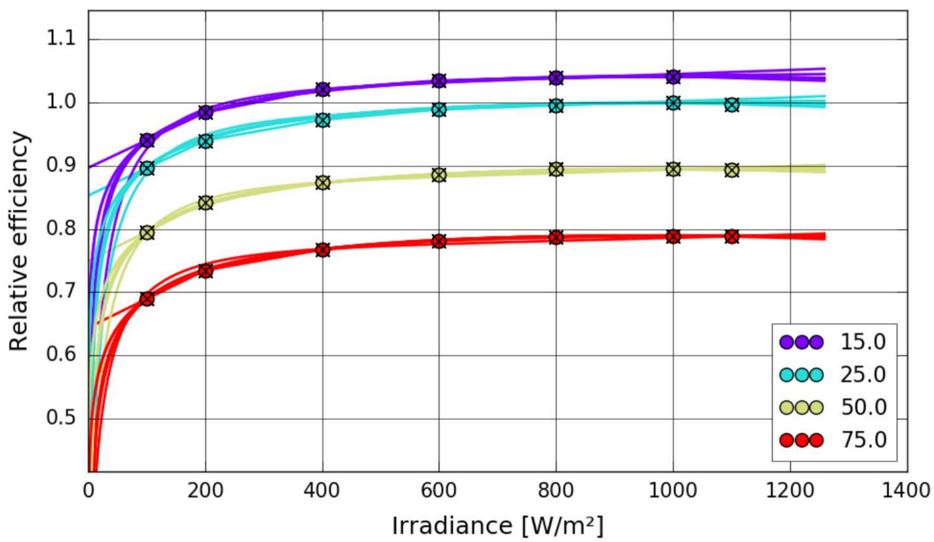

Figure 5 Superposition of all 6 models for the Jinko poly-Si module showing differences in extrapolated regions

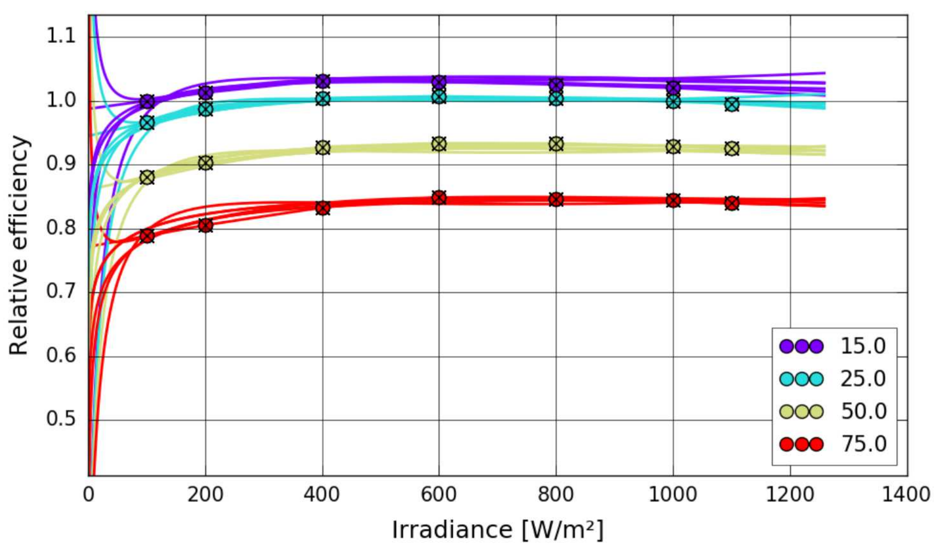

Figure 6 Superposition of all 6 models for the First Solar CdTe module showing extreme differences in extrapolation below 100 W/m²

6.2. Extrapolation to higher irradiance

It impossible to say which model is more accurate when extrapolating beyond 1100 W/m^2 from the above test, so instead we now fit the model to a subset of the data that excludes the points at 1000 and 1100 W/m^2, then compare the extrapolated values to the measured ones again. The HEY model distances itself from the others in this test with much larger RMSE on those extrapolated points (Figure 7) and Figure 8 shows that it has a strong tendency to overestimate efficiency in this region. (HEY does this for the other 3 modules types as well.)

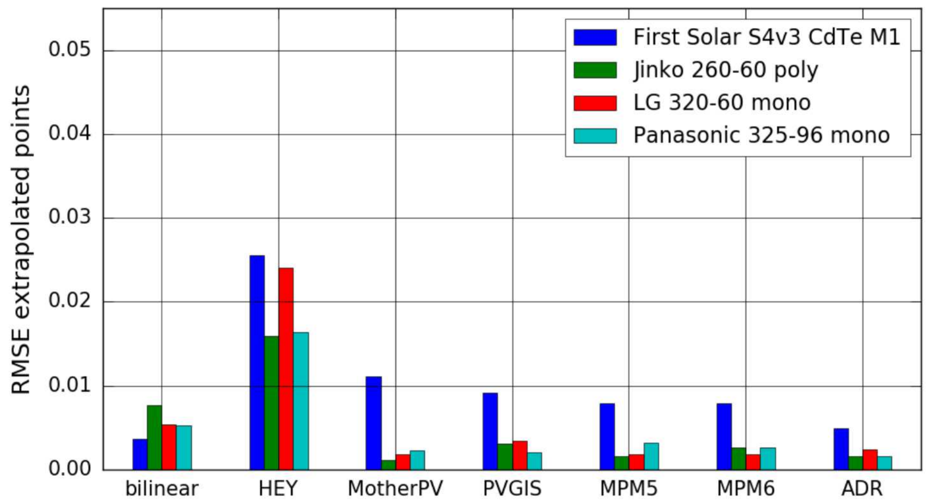

Figure 7 RMSE for points at 1000 and 1100 W/m², when those points are extrapolated from the lower measurements

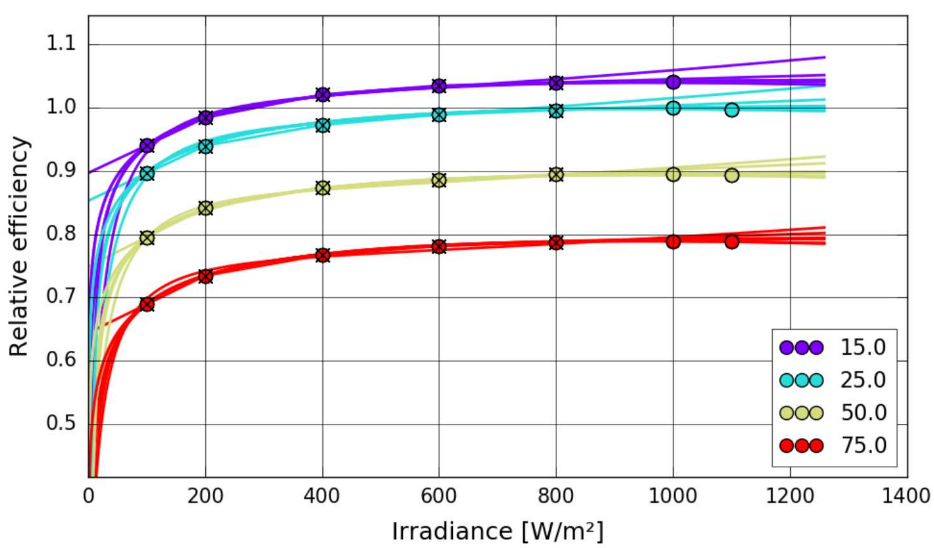

Figure 8 Superposition of 6 models for the Jinko poly-Si module fit to measurements below 1000 W/m² (marked with X)

6.3. Extrapolation to lower irradiance

A much more challenging test is the extrapolation to lower irradiance, where the models are now fit to a subset that excludes 100 and 200 W/m^2. Figure 9 shows a large increase in the RMSE for HEY, PVGIS and especially MotherPV. MPM doesn't work well when the C6 is used except when C6 ends up as zero, which is the case for the mono and poly-Si modules.

The nature of these differences between models is seen more dramatically in Figure 10. This does not answer the important question which model is best at extrapolating below 100 W/m^2, but it gives some indication of which model might *not* be the best.

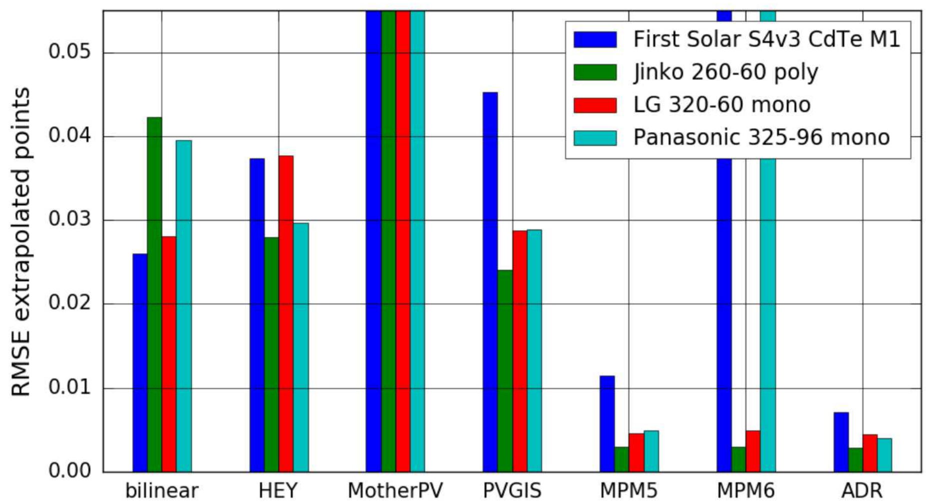

Figure 9 RMSE for points at 100 and 200 W/m², when those points are extrapolated from the higher other measurements

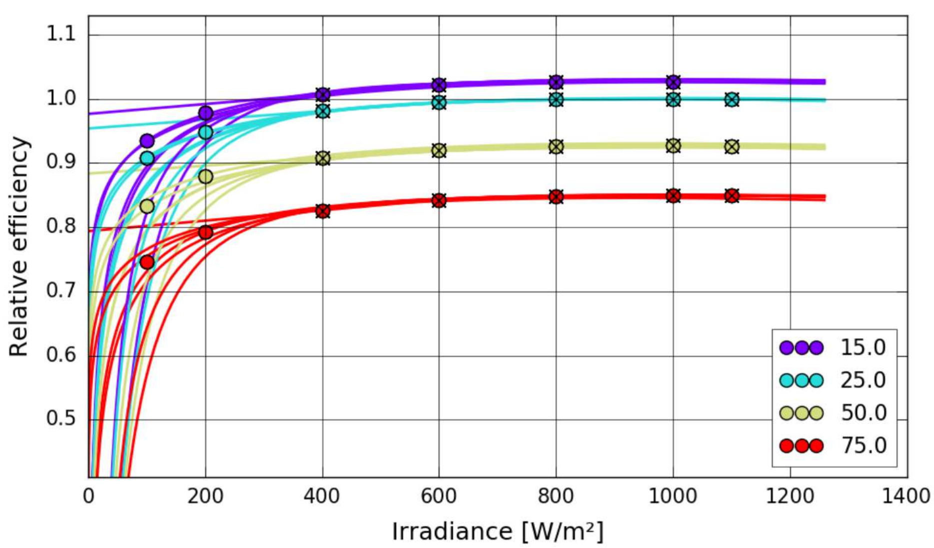

Figure 10 Superposition of 6 models for the Panasonic HIT module fit to measurements above 200 W/m² (marked with X)

6.4. Extrapolation beyond the IEC grid

Our datasets include five measurements at low irradiance and high temperature that go well beyond the requirements of IEC61853-1, so it is possible to evaluate the scenario where only the required IEC matrix points are used for fitting. This is a less challenging test than the previous ones, with fewer extrapolated points, therefore the reduction in RMSE is not so strong (Figure 11). Nevertheless it is clear from the CdTe example in Figure 12 that the reduction in low-irradiance fitting points does make it harder for some of the models to predict those points.

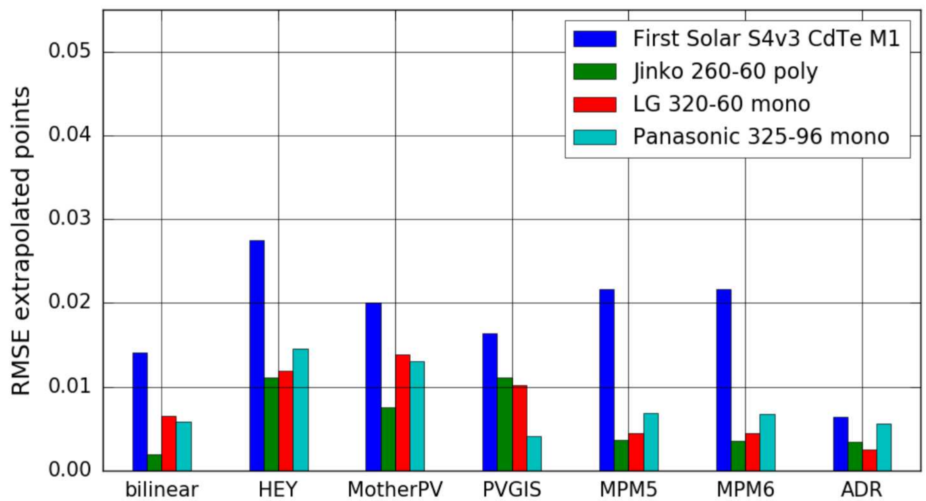

Figure 11 RMSE for extra high-temperature and low-irradiance points when those points are extrapolated from the IEC standard measurements

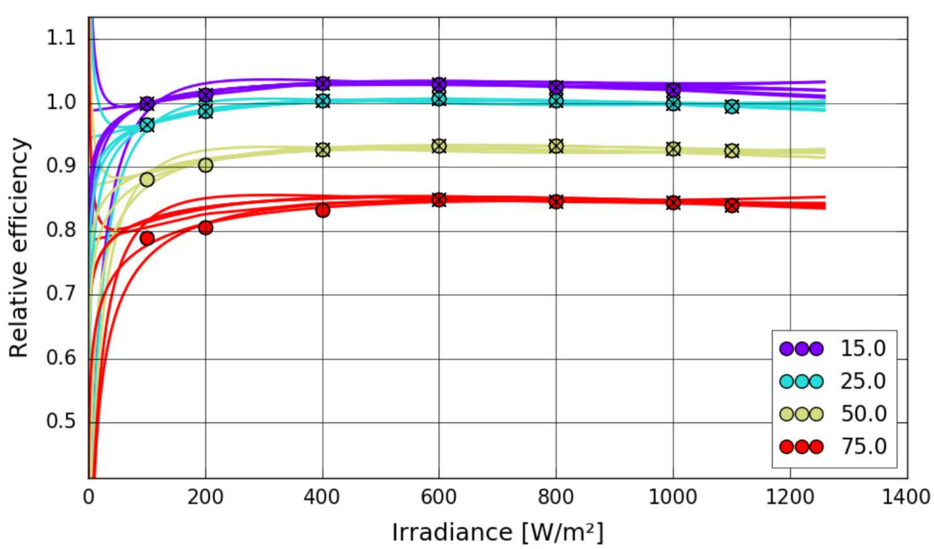

Figure 12 Superposition of 6 models for the First Solar CdTe module fit to IEC standard measurements only (marked with X)

6.5. Efficiency as irradiance approaches zero

The region between 0 and 100 W/m^2 has no measurements. The models do predict quite different curves in this region, but we cannot really say which one is right. We suspect that if a model is better at extrapolating from 200 towards 100, then it's probably also better at extrapolating from 100 down towards zero, but we cannot prove it without additional measurements.

One thing we do know, however, is that as irradiance approaches zero, efficiency must also approach zero, so we could consider this to be an additional measured point for each temperature. The HEY and ADR models were specifically designed to reproduce this behavior, therefore they always produce exactly zero efficiency at zero irradiance whether or not such a measurement is used for fitting. The other four models are mathematically undefined at zero irradiance due to the logarithmic term, but we can instead consider a point close to zero irradiance, such as 1 mW/m².

Figure 13 shows that in many cases, the efficiency values produced near zero irradiance are unrealistic—efficiency between zero and one could be considered realistic, although zero is the required value.

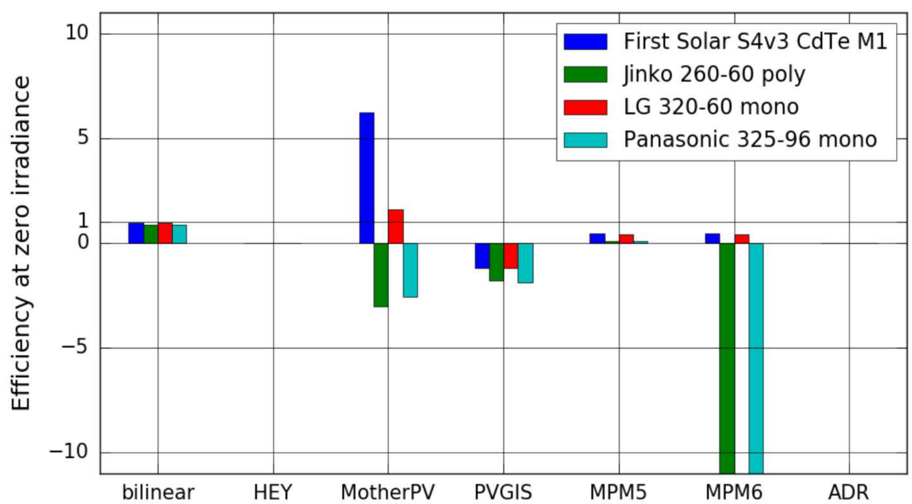

Figure 13 Several models predict unrealistically high or negative efficiencies near zero irradiance (1 mW/m^2)

The next question is whether these four models would perform better if given an additional measurement of zero efficiency at 1 mW/m². Indeed, as Figure 14 shows, this improves the fit at that point a lot, but unfortunately this is to the detriment of the overall RMSE for PVGIS, MPM5 and MPM6 (Compare Figure 15 to Figure 4.).

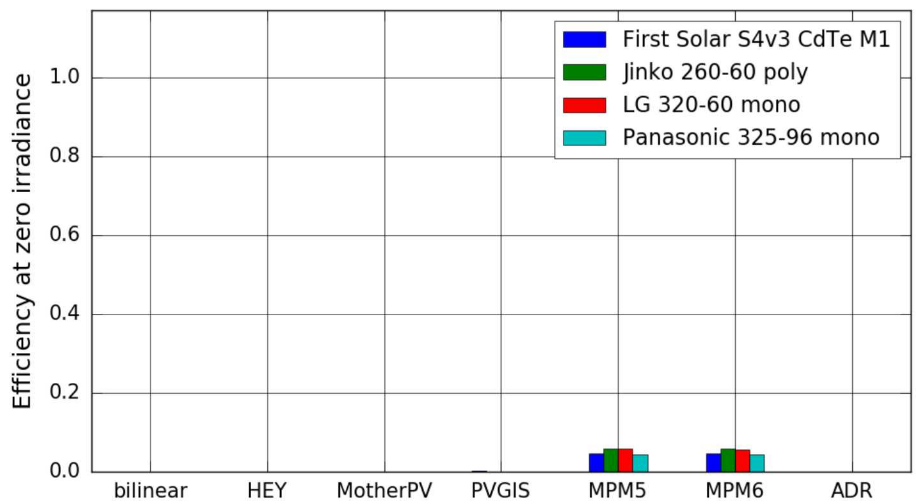

Figure 14 Predicted efficiencies near zero irradiance improve a lot when a "measurement" near zero irradiance is added.

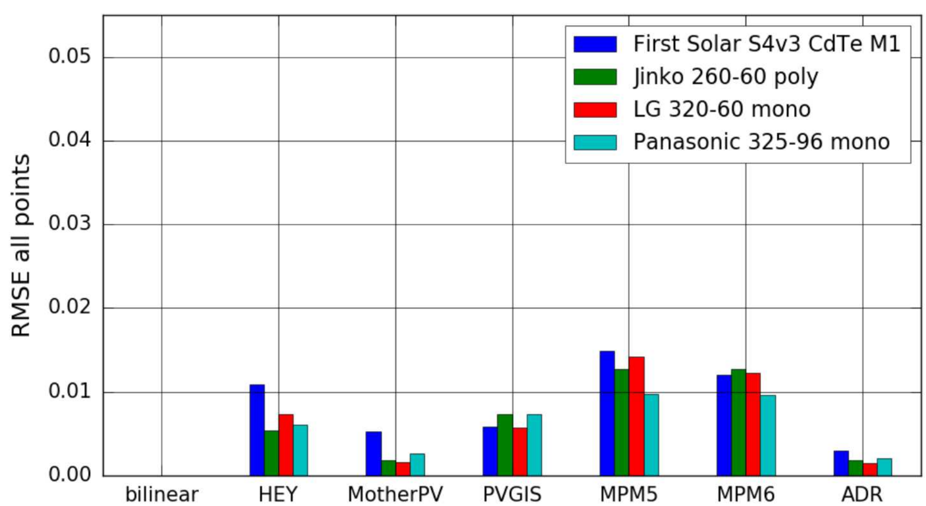

Figure 15 Overall RMSE increases for PVGIS, MPM5 and MPM6 when a "measurement" near zero irradiance is added.

Figure 16 demonstrates that this increase in RMSE is not just caused by errors at that additional point, but indeed that additional point is pulling the curve away from the original points.

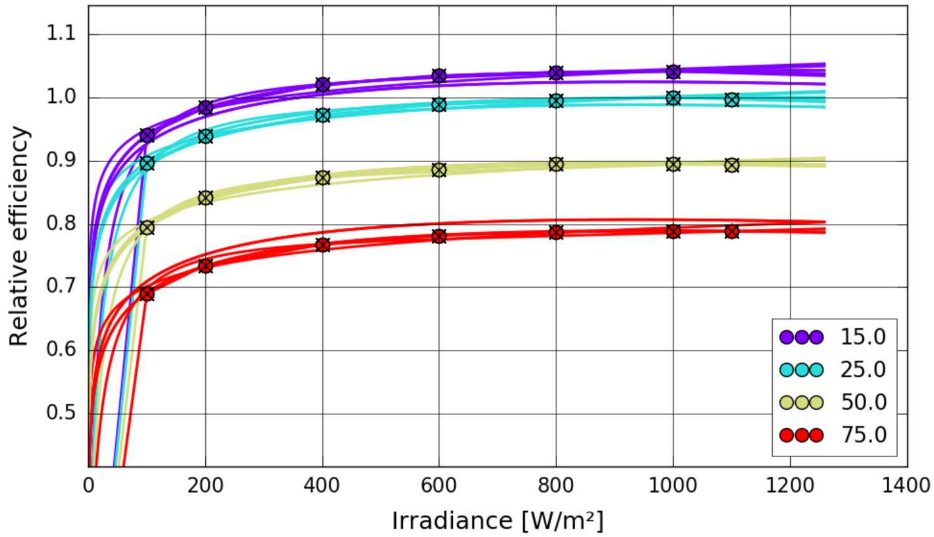

Figure 16 Agreement between models deteriorates over the entire irradiance range when a "measurement" near zero irradiance is added.

6.6. Biased or poorly normalized measurements

Whereas the HEY and ADR models produce zero efficiency at zero irradiance by definition, no matter what parameters are used, the MotherPV and PVGIS models produce 100% or unity relative efficiency at STC conditions. When measurements are normalized by dividing them into the measurement at STC, any measurement error in the latter will produce an offset or bias in the normalized measurements. The MotherPV and PVGIS models do not have the flexibility to follow such a shift, and instead produce a poorer fit with a higher RMSE (Figure 16). The ADR model conveniently extracts the bias value from the data as the first fitting parameter (k_a).

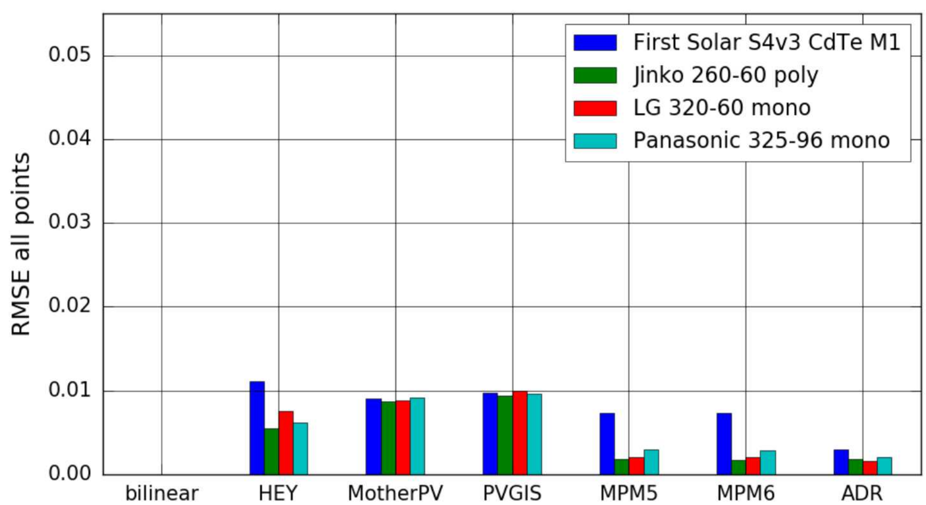

Figure 17 Increase in RMSE for MotherPV and PVGIS as the result of a 2% bias in the normalized measurements.

6.7. Noisy measurements

Random variations in the measurements are particularly troublesome for bilinear interpolation, as discussed earlier. For the efficiency models, fewer parameters means fewer degrees of freedom and naturally greater resistance to noise. We added noise with a standard deviation of 1% to the measurements and observed that all models agreed well with each other in the region 200-1000 W/m^2, but there was a little bit more disagreement toward the extremities of irradiance. (Figure 18).

It is difficult to extract a meaningful RMSE from this test. Comparing the models to the noisy data, the RMSE is dominated by the noise itself, and comparing the models to the original data is not fair either. There are relatively few measurements and the random values frequently conspire together to pull a section of curve one way or another, which the models then quite reasonable try to fit.

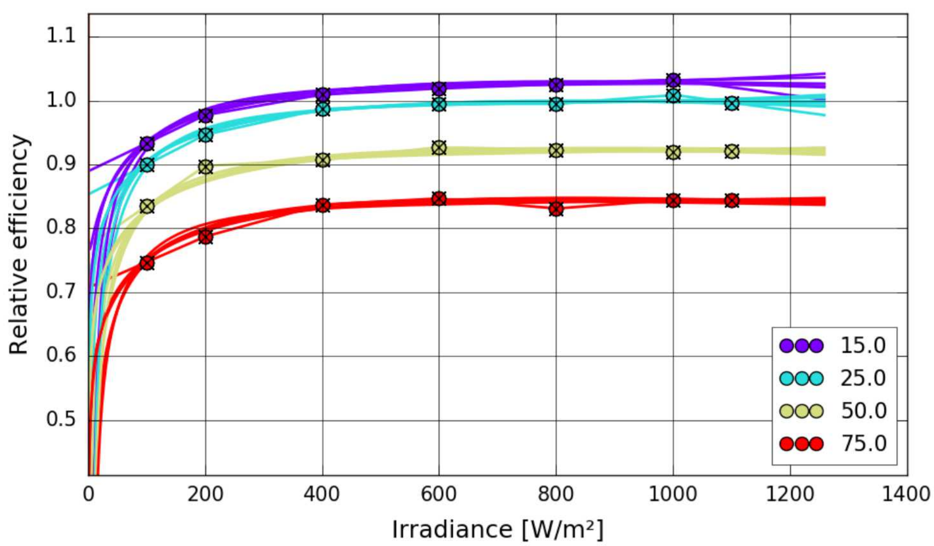

Figure 18 Superposition of all 6 models fit to noisy measurements for the Panasonic HIT module.

6.8. Summary

Condensing the results of the above tests into a single metric or ranking would be both difficult and debatable. Table 1 provides a qualitative comparison as a visual index to the details in the preceding sections. Green represents the best result among the models, yellow indicates a clearly visible difference to the best (which may be small or large), and red indicates an area of weakness. Several cells under "Bilinear" are left blank because the metric is not appropriate; the RMSE will always be zero for all given points because no interpolation or extrapolation is actually done in those cases.

Table 2: Qualitative summary and index of test results

#	Fit model to this:	Evaluate this:	Bilinear	HEY	MotherPV	PVGIS	MPM5	MPM6	ADR
1	All points	RMSE all points							
2	Points < 1000 W/m^2	RMSE >= 1000 W/m^2							
3	Points > 200 W/m^2	RMSE <= 200 W/m^2							
4	Points in IEC grid	RMSE outside IEC grid							
5	All points	values at G=0		0.0	nan	nan	−inf.	−inf.	0.0
5	All points	values at G=1 mW/m^2							
5	All plus G=1 mW/m^2	RMSE >= 100 W/m^2							
6	All points + 2%offset	RMSE w.r.t. offset points							
7	All points + 1% noise	RMSE w.r.t. no noise							

7. CONCLUSIONS

This report has demonstrated in very concrete terms how the IEC 61853 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 good method is needed to interpolate and extrapolate from the matrix measurement conditions to the full range of outdoor operating conditions. This method can be bi-linear inter/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 introduced in this report.

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. We developed multiple test criteria for the methods that incorporate not only the data, but also our overall knowledge of 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 is has a single purpose (to model efficiency) so 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 advantage of the ADR model with respect to other efficiency models are clearly seen in our test results, which collectively show that the new model more closely reproduces the known behavior of PV modules, especially when extrapolating beyond the measurements.

While the new 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 2-D bilinear interpolation, *or equivalent*…"[2] (emphasis added). This implies that the ADR model could be used within the standard energy rating procedure as well.

Of course there is more work to be done. As more and more IEC 61853 data sets are produced—and especially made public—we will be able to carry out broader validation of both new and existing models. Also important is the comparison with outdoor measurements in operating PV systems. In fact the four module types used for this report have been deployed by Sandia for several years already, so the data are impatiently waiting for us to finish writing these conclusions and start analyzing them!

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APPENDIX A. MODEL COEFFICIENTS FOR ALL TESTS

A.1. Heydenreich model

HEY : First Solar S4v3 CdTe M1

	a × 10³	b	c	γ × 10³
fit all	0.1466	-0.2064	-2.396	-3.235
extrap hi	0.2548	-0.2657	-2.735	-3.297
extrap lo	-0.0036	-0.0707	-1.566	-3.078
fit iec	0.1436	-0.2155	-2.46	-2.997
fit zero	0.1466	-0.2064	-2.396	-3.235
fit small	0.1466	-0.2064	-2.396	-3.235
bias	0.1496	-0.2105	-2.444	-3.235
noise	0.1572	-0.2132	-2.439	-3.366

HEY : Jinko 260-60 poly

	a × 10³	b	c	γ × 10³
fit all	0.078	-0.1063	-1.741	-4.304
extrap hi	0.1497	-0.1458	-1.966	-4.329
extrap lo	-0.0339	-0.0022	-1.101	-4.224
fit iec	0.0827	-0.1145	-1.793	-4.21
fit zero	0.078	-0.1063	-1.741	-4.304
fit small	0.078	-0.1063	-1.741	-4.304
bias	0.0795	-0.1084	-1.775	-4.304
noise	0.0862	-0.1117	-1.775	-4.422

HEY : LG 320-60 mono

	a × 10³	b	c	γ × 10³
fit all	0.1319	-0.1891	-2.285	-4.07
extrap hi	0.2406	-0.2488	-2.625	-4.079
extrap lo	-0.0236	-0.0458	-1.406	-3.998
fit iec	0.1315	-0.1935	-2.315	-3.977
fit zero	0.1319	-0.1891	-2.285	-4.07
fit small	0.1319	-0.1891	-2.285	-4.07
bias	0.1345	-0.1929	-2.331	-4.07
noise	0.1409	-0.1951	-2.323	-4.193

HEY : Panasonic 325-96 mono

	a × 10³	b	c	γ × 10³
fit all	0.0872	-0.1194	-1.827	-3.106
extrap hi	0.1579	-0.1582	-2.049	-3.143
extrap lo	-0.0276	-0.0124	-1.169	-3.011
fit iec	0.09	-0.1273	-1.879	-2.978
fit zero	0.0872	-0.1194	-1.827	-3.106
fit small	0.0872	-0.1194	-1.827	-3.106
bias	0.0889	-0.1218	-1.863	-3.106
noise	0.0978	-0.1261	-1.869	-3.235

A.2. MotherPV model

MotherPV : First Solar S4v3 CdTe M1

	a	b	c	d	γ_ref × 10³	a'	b'
fit all	-0.277	0.26	0.1017	0.0442	-3.056	0.1158	-0.1378
extrap hi	-0.432	0.442	0.2356	0.0764	-2.836	-0.1592	-0.0657
extrap lo	3.576	-3.586	-0.9058	-0.9664	-3.043	0.7251	-0.5659
fit iec	-0.226	0.22	0.1087	0.0345	-3.079	0.172	-0.083
fit zero	0	0	0	0	0	0	0
fit small	-0.034	0.001	-0.0432	-0.0051	-3.037	0.0932	-0.1318
bias	-0.667	0.617	0.2722	0.1103	-2.696	-0.3083	-0.0355
noise	-0.029	-0.014	-0.0531	-0.009	-2.988	-0.2572	-0.0255

MotherPV : Jinko 260-60 poly

	a	b	c	d	γ_ref × 10³	a'	b'
fit all	0.05	-0.052	-0.0592	-0.0243	-4.219	0.1108	-0.0839
extrap hi	0.013	-0.01	-0.0318	-0.0167	-4.225	0.1185	-0.0864
extrap lo	2.197	-2.204	-0.6428	-0.5882	-4.204	0.0717	-0.0657
fit iec	-0.022	0.023	-0.0233	-0.0099	-4.22	0.1648	-0.129
fit zero	0	0	0	0	0	0	0
fit small	-0.068	0.074	0.0115	-0.0003	-4.228	0.1182	-0.086
bias	-0.344	0.308	0.1119	0.0424	-3.882	-0.169	-0.011
noise	0.309	-0.339	-0.2233	-0.0797	-4.153	-0.1401	-0.0083

MotherPV : LG 320-60 mono

	a	b	c	d	γ_ref × 10³	a'	b'
fit all	-0.1047	0.0852	0.0111	0.0086	-4.015	0.1485	-0.0925
extrap hi	-0.1133	0.0939	0.0148	0.0104	-4.055	0.1842	-0.1026
extrap lo	0.9098	-0.9343	-0.2766	-0.2551	-4.004	0.0861	-0.0581
fit iec	-0.1338	0.1115	0.0145	0.0151	-4.013	-0.0031	0.0167
fit zero	0	0	0	0	0	0	0
fit small	-0.0431	0.0192	-0.0259	-0.0039	-4.01	0.1444	-0.0914
bias	-0.4988	0.4454	0.183	0.0755	-3.674	-0.144	-0.0169
noise	0.1486	-0.1959	-0.1487	-0.0457	-3.949	-0.1181	-0.0122

MotherPV : Panasonic 325-96 mono

	a	b	c	d	γ_ref × 10³	a'	b'
fit all	0.0318	-0.0343	-0.041	-0.0208	-2.988	0.1346	-0.1201
extrap hi	0.0561	-0.0627	-0.0618	-0.0258	-3.021	0.172	-0.13
extrap lo	0.8547	-0.8543	-0.2202	-0.2514	-2.989	0.1112	-0.1055
fit iec	-0.0193	0.0186	-0.0163	-0.0101	-2.994	0.012	-0.0078
fit zero	0	0	0	0	0	0	0
fit small	-0.0683	0.0727	0.019	-0.0004	-2.996	0.1439	-0.1226
bias	-0.353	0.3168	0.1266	0.0441	-2.627	-0.303	-0.0105
noise	0.2775	-0.3072	-0.1962	-0.0736	-2.92	-0.25	-0.0039

A.3. PVGIS model

PVGIS : First Solar S4v3 CdTe M1

	k1	k2	k3 × 10^3	k4 × 10^3	k5 × 10^3	k6 × 10^3
fit all	-0.01411	-0.01253	-2.498	0.334	0.0374	-0.01207
extrap hi	-0.01366	-0.01234	-2.308	0.734	0.177	-0.01145
extrap lo	-0.0206	-0.01658	-2.463	-0.176	-0.5479	-0.01351
fit iec	-0.01575	-0.01358	-2.511	-0.116	-0.2433	-0.01256
fit zero	0	0	0	0	0	0
fit small	-0.00011	-0.00524	-2.557	0.369	0.0421	-0.00954
bias	-0.04846	-0.02433	-2.208	1.095	0.2953	-0.01009
noise	-0.02377	-0.01608	-2.147	0.951	0.2673	-0.01911

PVGIS : Jinko 260-60 poly

	k1	k2	k3 × 10^3	k4 × 10^3	k5 × 10^3	k6 × 10^6
fit all	0.013	-0.01374	-4.205	-0.0973	-0.0292	-0.428
extrap hi	0.01332	-0.01359	-4.149	0.0132	0.009	-0.318
extrap lo	0.00561	-0.02235	-4.22	-0.122	-0.0724	-0.145
fit iec	0.01284	-0.01429	-4.248	-0.2377	-0.154	0.428
fit zero	0	0	0	0	0	0
fit small	0.03381	-0.00279	-4.176	0.0629	0.0262	1.091
bias	-0.02081	-0.02557	-3.949	0.6549	0.2274	1.786
noise	0.00374	-0.01716	-3.876	0.481	0.1866	-6.994

PVGIS : LG 320-60 mono

	k1	k2	k3 × 10^3	k4 × 10^3	k5 × 10^3	k6 × 10^6
fit all	-0.00667	-0.01199	-3.923	-0.0869	-0.0636	-1.977
extrap hi	-0.00648	-0.01189	-3.842	0.0515	-0.0156	-2.108
extrap lo	-0.01889	-0.02466	-3.926	-0.0383	-0.0272	-2.031
fit iec	-0.00652	-0.01171	-3.983	-0.1731	-0.0427	-0.827
fit zero	0	0	0	0	0	0
fit small	0.00716	-0.00472	-3.89	0.1402	0.0307	-0.794
bias	-0.04088	-0.02378	-3.661	0.6656	0.1923	0.206
noise	-0.01613	-0.01546	-3.585	0.5069	0.1568	-8.728

PVGIS : Panasonic 325-96 mono

	k1	k2	k3 × 10^3	k4 × 10^3	k5 × 10^3	k6 × 10^3
fit all	0.00673	-0.01459	-2.739	0.0382	-0.015	-0.00571
extrap hi	0.00679	-0.01455	-2.68	0.1226	0.0143	-0.00605
extrap lo	-0.0025	-0.02621	-2.788	0.0665	0.0259	-0.00465
fit iec	0.00738	-0.01448	-2.839	-0.0855	-0.0603	-0.0036
fit zero	0	0	0	0	0	0
fit small	0.02848	-0.00318	-2.744	0.1716	0.0275	-0.00344
bias	-0.0272	-0.02643	-2.454	0.7932	0.2418	-0.0036
noise	-0.00273	-0.01808	-2.391	0.6513	0.2145	-0.01266

A.4. MPM5 model

MPM5 : First Solar S4v3 CdTe M1

	c1	c2 × 10^3	c3	c4
fit all	1.064	-3.208	0.04259	-0.0616
extrap hi	1.061	-3.273	0.04114	-0.0563
extrap lo	1.066	-3.079	0.04366	-0.0673
fit iec	1.062	-3.011	0.03822	-0.064
fit zero	1	0	0	0
fit small	1.133	-2.775	0.07864	-0.1432
bias	1.085	-3.272	0.04344	-0.0628
noise	1.06	-3.348	0.04021	-0.0544

MPM5 : Jinko 260-60 poly

	c1	c2 × 10^3	c3	c4
fit all	1.073	-4.175	0.07256	-0.07486
extrap hi	1.075	-4.165	0.07325	-0.07741
extrap lo	1.074	-4.19	0.07356	-0.075
fit iec	1.073	-4.195	0.07324	-0.07447
fit zero	1	0	0	0
fit small	1.066	-3.629	0.07288	-0.07786
bias	1.095	-4.259	0.07401	-0.07636
noise	1.07	-4.304	0.07049	-0.06854

MPM5 : LG 320-60 mono

	c1	c2 × 10^3	c3	c4
fit all	1.068	-4.02	0.04797	-0.0678
extrap hi	1.064	-4.025	0.04665	-0.0632
extrap lo	1.075	-3.997	0.05251	-0.0752
fit iec	1.064	-3.987	0.04558	-0.0647
fit zero	1	0	0	0
fit small	1.12	-3.483	0.07694	-0.1341
bias	1.089	-4.1	0.04893	-0.0691
noise	1.065	-4.154	0.0458	-0.0612

MPM5 : Panasonic 325-96 mono

	c1	c2 × 10^3	c3	c4
fit all	1.074	-3.024	0.07	-0.07428
extrap hi	1.079	-3.041	0.07178	-0.08033
extrap lo	1.072	-2.992	0.06988	-0.07274
fit iec	1.072	-2.975	0.0682	-0.0723
fit zero	1	0	0	0
fit small	1.079	-2.626	0.07501	-0.08703
bias	1.096	-3.084	0.0714	-0.07577
noise	1.071	-3.16	0.06758	-0.06689

A.5. MPM6 model

MPM6 : First Solar S4v3 CdTe M1

	c1	c2 × 10³	c3	c4	c6
fit all	1.064	-3.208	0.0981	-0.06161	-0
extrap hi	1.061	-3.273	0.0947	-0.05629	-0
extrap lo	0.974	-3.081	-0.4216	0.09687	-0.07272
fit iec	1.062	-3.011	0.088	-0.06395	-0
fit zero	1	0	0	0	0
fit small	1.061	-2.788	0.102	-0.06713	-0
bias	1.085	-3.272	0.1	-0.06285	-0
noise	1.06	-3.348	0.0926	-0.05437	-0

MPM6 : Jinko 260-60 poly

	c1	c2 × 10³	c3	c4	c6 × 10³
fit all	1.063	-4.176	0.1435	-0.06276	-1.477
extrap hi	1.051	-4.165	0.123	-0.04822	-2.499
extrap lo	1.074	-4.19	0.1693	-0.07499	-0.004
fit iec	1.073	-4.195	0.1672	-0.07378	-0.092
fit zero	1	0	0	0	0
fit small	1.066	-3.629	0.1678	-0.07786	-0
bias	1.084	-4.26	0.1464	-0.06402	-1.506
noise	1.047	-4.306	0.1086	-0.04097	-3.364

MPM6 : LG 320-60 mono

	c1	c2 × 10³	c3	c4	c6 × 10³
fit all	1.068	-4.02	0.1104	-0.06777	-0
extrap hi	1.064	-4.025	0.1074	-0.06324	-0
extrap lo	1.074	-3.997	0.12	-0.07496	-0.1273
fit iec	1.064	-3.987	0.105	-0.06466	-0
fit zero	1	0	0	0	0
fit small	1.064	-3.493	0.1154	-0.07469	-0.0003
bias	1.089	-4.1	0.1127	-0.06913	-0
noise	1.062	-4.155	0.0983	-0.05748	-0.4503

MPM6 : Panasonic 325-96 mono

	c1	c2 × 10³	c3	c4	c6
fit all	1.058	-3.025	0.1237	-0.05506	-0.00235
extrap hi	1.052	-3.041	0.113	-0.04695	-0.00286
extrap lo	1.036	-2.992	-0.0474	-0.00722	-0.02901
fit iec	1.062	-2.974	0.1354	-0.06174	-0.00141
fit zero	1	0	0	0	0
fit small	1.072	-2.628	0.1649	-0.07949	-0
bias	1.079	-3.086	0.1262	-0.05616	-0.00239
noise	1.04	-3.163	0.0872	-0.03173	-0.00429

A.6. ADR model

ADR : First Solar S4v3 CdTe M1

	k_a	k_d	tc_d	k_rs	k_rsh
fit all	0.999	-7.45	0.03464	0.05671	0.5125
extrap hi	1.002	-7.874	0.03723	0.0455	0.5163
extrap lo	0.998	-6.408	0.03091	0.06757	0.567
fit iec	0.998	-6.76	0.03162	0.06495	0.5371
fit zero	0.999	-7.45	0.03464	0.05671	0.5125
fit small	0.999	-7.45	0.03464	0.05671	0.5125
bias	1.019	-7.45	0.03464	0.05671	0.5125
noise	1.001	-7.277	0.03881	0.0485	0.6169

ADR : Jinko 260-60 poly

	k_a	k_d	tc_d	k_rs	k_rsh
fit all	0.999	-6.525	0.02493	0.07535	-0.026
extrap hi	0.998	-6.435	0.02464	0.07812	-0.0177
extrap lo	0.999	-6.419	0.02475	0.07504	-0.0165
fit iec	0.999	-6.398	0.02488	0.07455	-0.0064
fit zero	0.999	-6.525	0.02493	0.07535	-0.026
fit small	0.999	-6.525	0.02493	0.07535	-0.026
bias	1.019	-6.525	0.02493	0.07535	-0.026
noise	1	-5.957	0.02714	0.06513	0.1742

ADR : LG 320-60 mono

	k_a	k_d	tc_d	k_rs	k_rsh
fit all	0.999	-8.834	0.03661	0.06724	0.1289
extrap hi	1.001	-8.974	0.03794	0.06104	0.1518
extrap lo	0.999	-8.254	0.03307	0.07535	0.0965
fit iec	0.999	-9.429	0.03766	0.06493	0.0806
fit zero	0.999	-8.834	0.03661	0.06724	0.1289
fit small	0.999	-8.834	0.03661	0.06724	0.1289
bias	1.019	-8.834	0.03661	0.06724	0.1289
noise	1.002	-8.065	0.04017	0.05923	0.3202

ADR : Panasonic 325-96 mono

	k_a	k_d	tc_d	k_rs	k_rsh
fit all	0.999	-5.852	0.0194	0.06963	0.2104
extrap hi	0.998	-5.762	0.01919	0.07145	0.2236
extrap lo	0.999	-5.671	0.01957	0.06794	0.2485
fit iec	0.999	-5.591	0.01908	0.07051	0.2399
fit zero	0.999	-5.852	0.0194	0.06963	0.2104
fit small	0.999	-5.852	0.0194	0.06963	0.2104
bias	1.019	-5.852	0.0194	0.06963	0.2104
noise	1.001	-5.483	0.02199	0.05606	0.3801

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