Checking the new IEC 61853.1-4 with high quality 3rd party data to benchmark its practical relevance in energy yield prediction

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***Abstract* —IEC 61853 1-4 [1-4] (International Electrotechnical Commission) define measurements, procedures and equations intended to characterise PV module performance against weather parameters (irradiance, temperature, windspeed, angle of incidence, spectrum) to enable energy rating predictions from reference climate data. Gantner Instruments (GI) have been making high quality IV measurements with a wide variety of module technologies (c-Si; HIT; ABC; thin film) at Outdoor Test Facilities (OTF) worldwide including a site in Arizona which has been continuously measured since 2010 [5]. The IEC 61853 equations are being checked against the GI measurements and models such as the Mechanistic Performance Model/Loss Factors Model (MPM/LFM) [6] for example performance matrices vs. irradiance and temperature.**

Index Terms **— energy, modeling, photovoltaic systems, power, simulation, degradation.**

I. Introduction

This paper evaluates some of the Energy rating approaches in IEC 61853 and compares them with high quality measurements from Gantner Instruments' OTF in Tempe AZ as shown in figure 1 where Module IV measurements are taken every minute and the data validated in real time and stored in a high-performance database.

Fig. 1. Gantner Instruments OTF at Tempe, AZ

OTF Measurement data is listed in Table I

TABLE I
Measurements and Calculations from Gantner Instruments' OTF

Date Time	Calculated solar position, angle of incidence, clearness index etc.
Met Data	Wind Speed (ms^{-1}), Wind Direction (deg), $T_{AMBIENT}$ (C), Relative humidity (%)
Inclined Irradiance	Pyranometers Gi, reference cells cSi unfiltered, cSi KG3 (kW/m^2)
Horizontal Irradiance	Global Gh and Diffuse Dh Pyranometers (kW/m^2)
2 D track normal	Beam pyrheliometer Bn; Pyranometer Gn; reference cells cSi, cSi KG3 (kW/m^2)
Spectrum	G(350–1050nm) @ 3.3nm (kW/m^2)
Each Module	Measure Tmod and IV curve every minute, derive Isc, Rsc, Imp, Vmp, Roc, Voc, PRdc+

In this study the following six fixed tilt modules installed in from 2010 (at 33 deg tilt due south) were investigated for 2013.

TABLE II
Six Modules Used in This Study

Module ID	Module Technology	Nominal Eff_{STC}	$Wp._{STC}$	Comment
#10	a-Si: uc-Si	9.6%	105	Matched junctions
#11	CdTe	11.4%	75	Faulty, low Rshunt
#12	c-Si	15.3%	220	OK
#13	a-Si: uc-Si	8.5%	85	Blue limited
#14	a-Si	6.0%	60	OK
#15	CIGS	7.5%	75	Degrading a little

The flowchart in figure 2 details some of the measurements and methodology used in IEC 61853 1-4. Several equations/datasets (highlighted in purple) will be compared with GI techniques, these are marked 1) Climate, 2) Reflectivity vs. angle of incidence, 3) Spectral response 4) Module temperature rise and 5) PV performance matrix. (Note that the D_{CORR} equation cannot be checked presently).

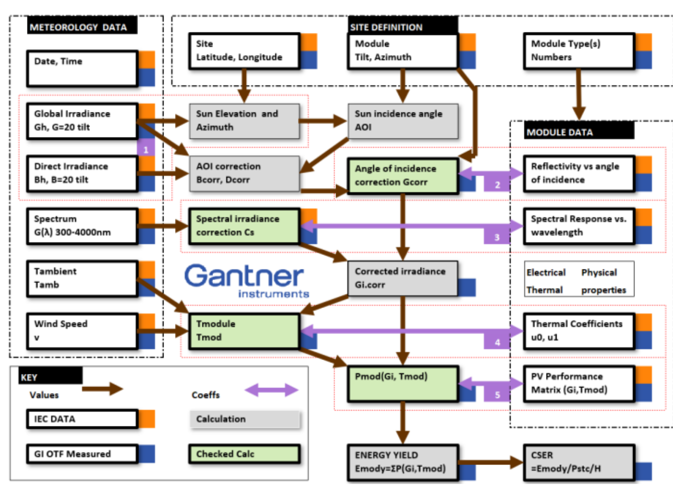


Fig. 2. Flowchart of process to generate an energy yield with data checks marked in purple

A. Climate data in IEC 61853-4 vs. GI measurements

IEC 61853-4 provides 6 hourly datasets for different climates. Figure 3 plots the fraction of the yearly insolation in each 0.05 kW/m^2 irradiance and 5C T_{MODULE} bins (assuming typical thermal values from equation (5)) for six 61853 sites vs. two GI OTF Sites. The centre 61853 site #2 is equivalent to the centre top GI #7 and the data looks similar. Three of the sites differ in climate from the others (high elevation, temperate coastal and tropical humid) and the reasons are highlighted and given.

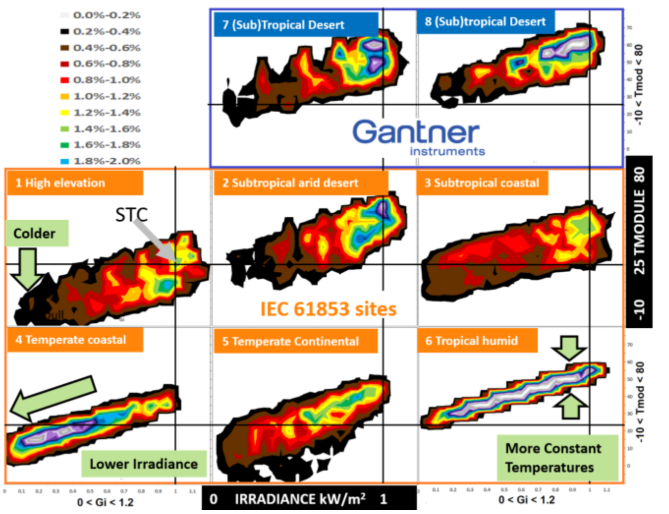


Fig. 3. Percentage of total yearly insolation (colours) per irradiance bin (0 to 1.2 kW/m^2 x-axis) and temperature bin (-10 to 80C y-axis) for different sites where #1-6 61853 vs. GI (top row) are #7 Tempe AZ and #8 Middle East.

B. Reflectivity vs. Angle of incidence response

The Gantner OTF includes tilted plane reference cells both unfiltered (for cSi) and KG3 filtered (for CdTe). This had allowed previous analysis to be done without the need for spectral or angle of incidence calculations for cSi and CdTe as the cells matched these modules well enough.

However, when using a pyranometer for the irradiance measurements both angle of incidence vs. beam fraction and spectral corrections must be performed to match the module.

61853-2 details how to make AOI measurements indoors with direct beam radiation or outdoors (when beam fraction > 85%).

As modules at test sites may not have had this done a method has been developed to derive the reflectivity data comparing the normalised module nI_{SC_T} with both reference cell and pyranometer readings using GI's OTF.

Figure 4 plots the normalised nI_{SC_T} as in equation (1) (%, y-axis) vs. Beam fraction and AOI at Air Masses close to 1.5 to simplify the analysis.

$$nI_{SC\_T} = \frac{meas.I_{SC}}{ref.I_{SC} * G_I} \times (1 - \alpha_{ISC} \times (T_{MOD} - 25)) \qquad (1)$$

(For example, a module with an $I_{SC.STC}$ of 10A reading 4.5A at G_I=0.5kW/m^2 at 25C has an nI_{SC_T} of 4.5/10/0.5=90%).

Data seems similar to Riedel et al's round robin [7].

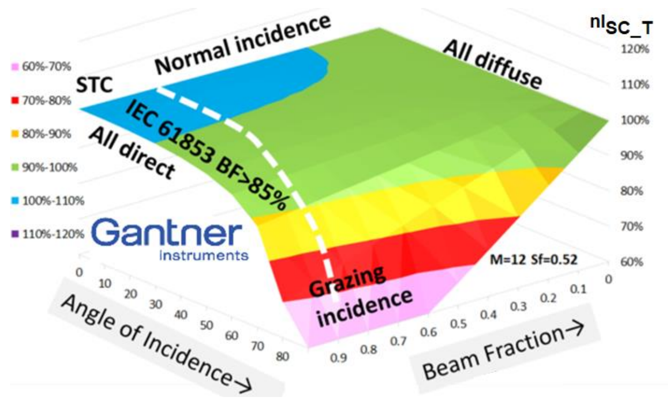


Fig. 4. GI OTF measurements for reflectivity vs. Beam fraction & AOI

C. Spectral measurements

The GI OTF measures spectra with a spectroradiometer presently from 350 to 1050nm every 3.3nm every minute.

GI use a parameter called Spectral fraction (SF) (previously known as Top Fraction or Blue fraction) defined in equation (2) as the ratio of "bluer / total" irradiance as absorbed by common PV technologies from 350 to 1050nm. It's easier to understand than APE which varies depending on wavelengths measured.

$$SF = \sum G_{350...650nm} \Big/ \sum G_{350...1050nm} \qquad (2)$$

61853-3 takes its spectral measurements from satellite data and defines its spectral bands with non-uniform widths as shown by vertical black lines in figure 5 (to cover the atmospheric absorption bands from H_2O etc.).

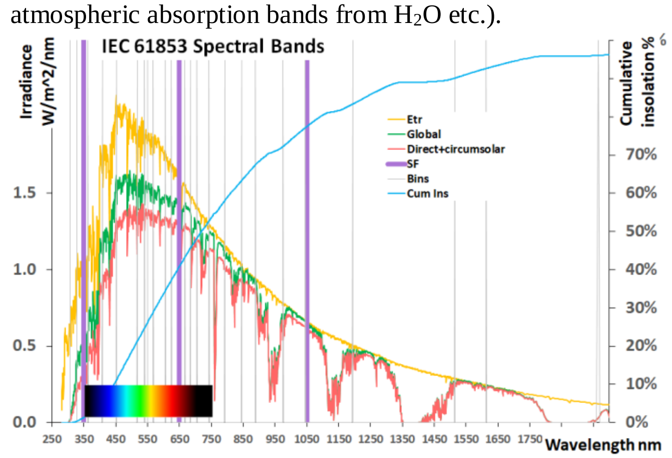


Fig. 5. IEC 61853-3 spectral bin widths vs. ASTM G173-03 spectra and SF limits of 350,650 and 1050nm [8].

Figure 6 shows the total irradiance G_I (white) vs. the relative proportion of irradiance in the different IEC 61853-3 bands from 350-1050nm coloured approximately correctly in the visible bands (with browns and greys for IR) for two days "clear" (left 19-Mar) and "variable" (right 23-Mar) around the equinox.

On the clear day the sky is bluer around noon, getting redder in the morning and evening with a bluer sky close to dawn and dusk as the red sun rises and sets in the plane of the module which then only sees the blue diffuse sky.

The five glitches each band around 7am "(1)" are when the sun rises behind transmission lines (top right of figure 1) hiding some of the red sun making it become a little bluer than expected. Spectral fraction also rises during brief cloudy periods (2).

The Spectral Fraction is the border between the red G_0646 and pink G_0675 curves marked "SF" which is about 52% near noon, around AM1.5.

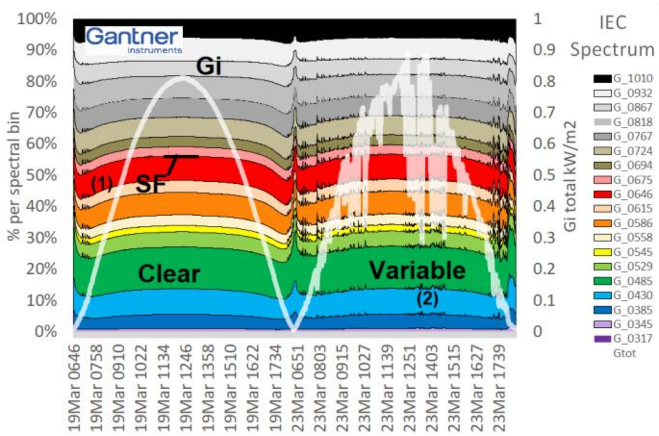


Fig. 6. Gantner Instruments' measurements of spectrum bands as defined in 61853-3 for clear and variable days in Tempe, AZ.

61853 gives a method of spectrally correcting modules with known spectral responses by weighting them by the measured and reference curves as in equation (3).

$$C_{s,j} = \frac{1000 \int_{\lambda_s}^{\lambda_e} S(\lambda) R_{corr,AOI,j}(\lambda) d\lambda}{G_{corr,AOI,j} \int_{\lambda_s}^{\lambda_e} S(\lambda) R_{STC}(\lambda) d\lambda} \quad (3)$$

Because spectral response measurements might not have been made on test modules the GI OTF has a method for measuring nIsc_T (5) against SF for any device then making a smooth fit which gives a spectral correction factor vs. spectral fraction curve as in figure 7 for six modules of differing technologies in table II.

When correcting performance, the measured I_{SC} should be divided by this factor.

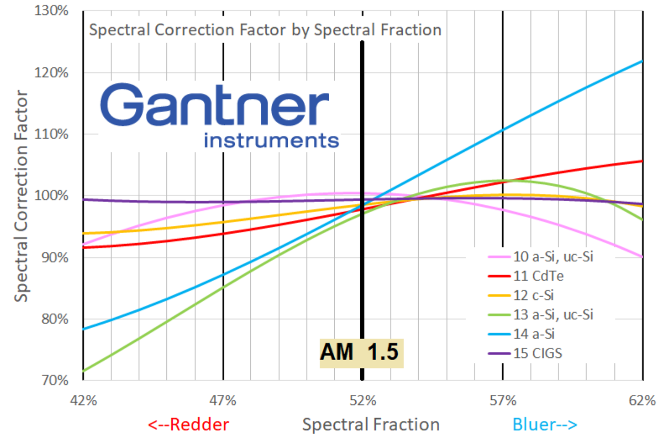


Fig. 7. Simplified spectral correction factor vs. spectral fraction from a smooth fit to measured GI OTF data.

Equation 4 is being used to spectrally and angle of incidence correct the MPM/LFM for outdoor use with pyranometers, where cSFM, cSF, cAOI and cBF are empirical coefficients.

$$nI_{SC\_T,SPEC,AOI} = nI_{SC\_T} * (1 + cSF_M * (SF - cSF)) * ((1 - BF*cAOI * (1/Cos(AOI)-1)) + cBF*BF) \quad (4)$$

In figure 8 we plot the spectral and Angle of incidence correction to a Silicon reference cell for 3 days each quarter compared with a pyranometer and the fit is seen to be good, usually within ±1%. There may have been some soiling in the winter and spring, in the summer the AOI correction is high as the sun is still above the horizon when it is behind the module at AOI>90. In the winter the sun will rise and set in front of the module (i.e. SE to SW in the northern hemisphere) so AOI correction is lower.

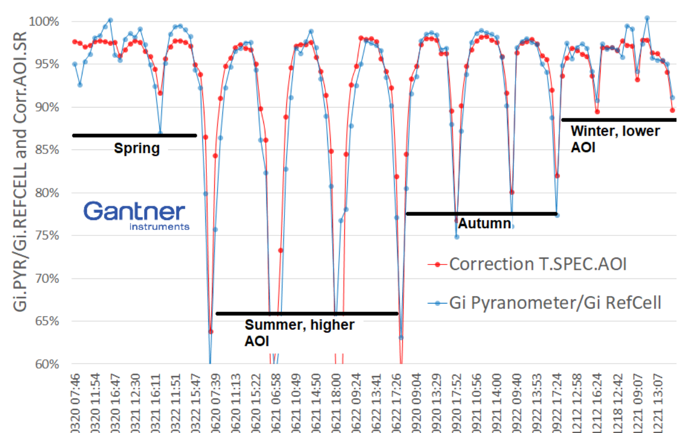


Fig. 8. Spectral and Angle of incidence correction to a Silicon reference cell compared with a pyranometer.

D. $T_{RISE} = T_{MODULE} - T_{AMBIENT} = fn$(Irradiance, Wind speed)

IEC 61853 uses equation (5) to predict the rise in module temperature above ambient temperature as functions of corrected irradiance and windspeed

$$T_{RISE} = T_{MOD} - T_{AMB} = \frac{G_{CORR.AOI}}{U_0 + U_1.W_S} \qquad (5)$$

Figure 9 plots T_{RISE} by windspeed and irradiance bins for an example thin film module #13 (left) measured by GI in Tempe for 1 year and (centre) the best fit using equation (5). The fit deviates at lowest light levels where the module can be a few degrees cooler than the ambient temperature due to radiative cooling to the sky. A better fit was made by adding a 3rd coefficient as in equation (6) and this is illustrated (right).

$$T_{RISE} = T_{MOD} - T_{AMB} = \frac{G_{CORR.AOI}}{U_0 + U_1.W_S} + U_2 \qquad (6)$$

However this is not expected to have a great effect on yield predictions as most energy is generated at high light levels.

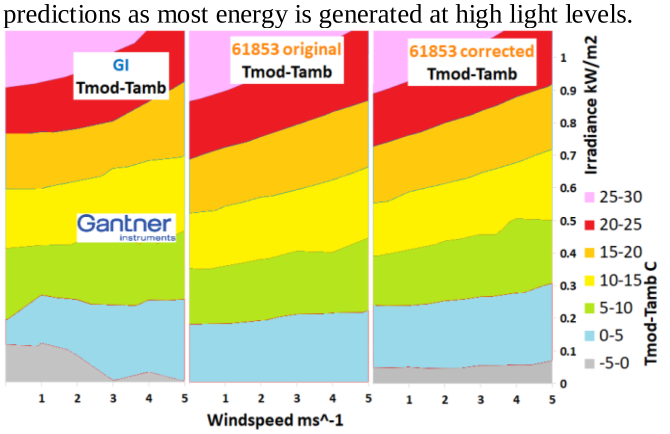


Fig. 9. T_{RISE} vs. Windspeed and measured Irradiance (left to right) measured (GI OTF), 61853 fitted (4) and 61853 corrected (5)

Higher efficiency modules should be cooler than lower efficiency ones under the same weather conditions, also glass-glass may be hotter than single glass. Ranges of U_0, U_1 and U_2 values should be investigated further [9].

E. Matrix performance

IEC 61853-1 defines 23 different (G_I, T_{MOD}) conditions to measure performance where G_I values are 0.1-1.1kW/m^2 and T_{MOD} is 15-75C but measurements investigated have varying numbers of points and ranges of irradiance and temperature.

Figure 10 illustrates as an example of good indoor measurements made at CREST in the UK with a smooth curve fit with the MPM (6).

$$PR_{DC} = C_{1\_TOL} + C_{2\_TC} \times dT_{MOD} + C_{3\_LL} \times Log_{10}(G_I) + C_{4\_HL} \times G_I + C_{5\_WS} \times WS \qquad (6)$$

(where $dT_{MOD} = (T_{MOD}-25)$ C and G_I =irradiance kW/m^2)

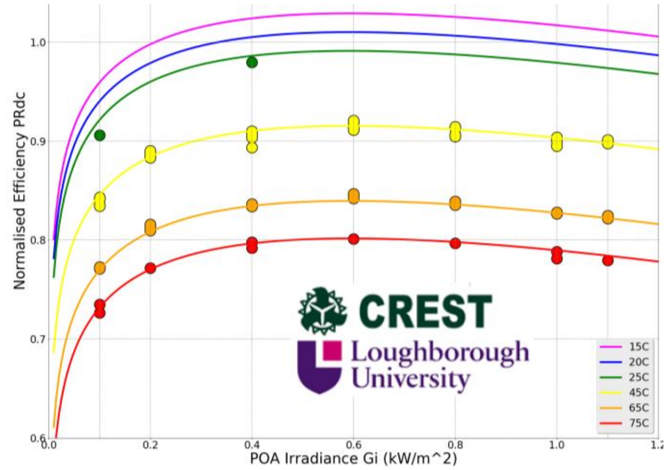


Fig. 10. CREST [10] indoor matrix measurements (dots) for a typical c-Si module. Smooth lines show the fit from the MPM/LFM model with an rms error of 0.23%

61853 suggests using linear interpolation and extrapolation to derive performance values at other irradiances. However best fitted curves to data points are not linear. There are several existing empirical or mechanistic models particularly the MPM which can be used to fit points already. Table III summarises some of the reasons why using a mechanistic model is better than linear interpolation and extrapolation. Subsequent graphs have all been fitted using the MPM [6] algorithms in equation (7) to give smooth curves for predictions at any irradiance and temperature.

Figure 11 illustrates a matrix approach from GI ORTF outdoor measurements for a year in AZ. The average performance in bins of 0.05kW/m^2 irradiance and 15C T_{MODULE} was taken and then temperature corrected to the nearest 15C line. Note that scatter is only a little worse than indoor measurements in figure 1, despite not yet being corrected for spectral response, angle of incidence or soiling and the smooth fits from the MPM/LFM are still good.

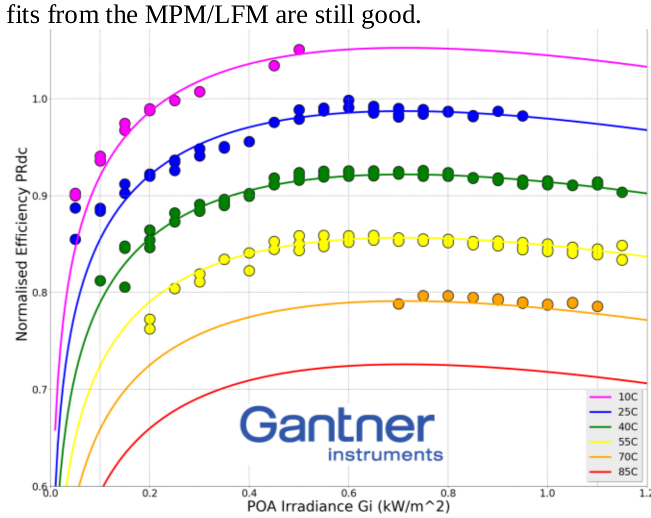


Fig. 11. GI OTF average matrix measurements (dots) for #12 c-Si module. Smooth lines show the fit from the MPM/LFM model with an rms error of ~0.5%

Figure 12 shows temperature corrected raw data (averaged, but not yet spec and aoi corrected) but still good fits can be obtained with MPM.

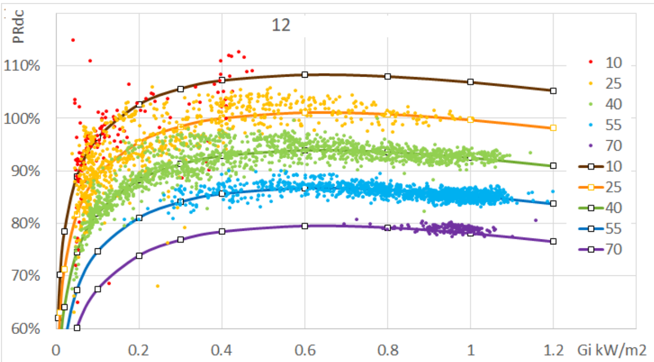


Fig. 12. GI temperature corrected outdoor raw measurements (dots) for a cSi module, fitted with MPM

Figure 13 shows an example of a poor quality indoor measurement when there was a temperature measurement and uniformity problem. The MPM fits the points well (shown by the curved lines) but the linear interpolation/extrapolation would have been poor as points have up to about a 3% error and even cross over at 0.6kW/m^2 and >65C.

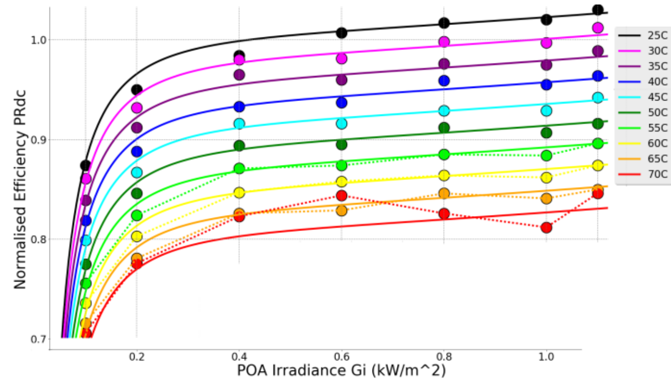
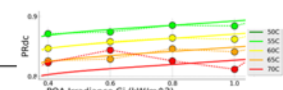
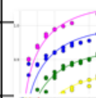
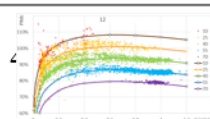
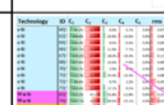
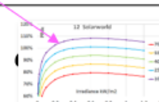
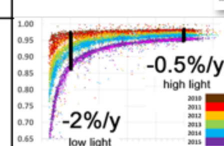


Fig. 13. MPM fit (smooth line) and linear interpolation (dotted) for a poor quality indoor matrix measurement of a cSi module,

Table III lists reasons why a mechanistic fit is better than a linear interpolation.

TABLE III

MECHANISTIC MODEL VS LINEAR INTERPOLATION/EXTRAPOLATION FOR FITTING MATRIX MEASUREMENTS

Effect	Linear Interpolation 61853	Mechanistic model GI MPM	Examples
1) Points with wrong values?	☒ Nearby interpolated and extrapolated values badly affected	☑ "Sanity check" easily finds them Erase, correct or remeasure!	1,2 
2) Noisy Data?	☒ No noise reduction	☑ Robust fit, noise averages out	
3) Missing Points?	☒ Affects extrapolations	☑ Can still can get good fits	 3)
4) Reduced or outdoor data (points<>23)	☒ Can't easily interpolate too few or too many points	☑ Can fit any number of points, weighted if needed	
5) Useful Coefficients to analyse ?	☒ No coefficients from analysis	☑ Yes, useful normalised orthogonal coefficients for a database	 5)
6) Data storage	☒ Every point needs to be stored	☑ Only 5-6 coefficients stored +rmse	
7) Module variability or degradation Binning	☒ Hard to compare datasets without coefficients	☑ Normalised coefficients can determine rates and causes ☑ Pmax binning → C1?	 7)

Simulation programs have been predicting energy yields vs. Technology, climate, temperature coefficients, spectral effects etc. well enough for manufacturers, investors etc. for many years.

Binning of module Pmax (±2.5%?), manufacturing variability and irradiance sensor tolerance may limit the accuracy of any energy rating validation

A "cookie cutter approach" is often used to guarantee performance by making similar new sites to old ones that are known to work

How useful is this 61853 method?

Will it duplicate existing predictions/measurements or differ?

2. CONCLUSIONS

In comparison GI OTF with IEC 61853

1) Hourly climate data - OTF similar data.

2) Reflectivity/Angle of incidence - OTF similar results.

3) Spectral response
If **61853 SR** is not available then a simpler OTF method has been suggested, (more complicated for multi junctions but will be presented soon).

4) Module temperature rise vs. Gi and WS
GI OTF suggests a correctable offset at low Gi, then similar results

5) Matrix performance vs. Irradiance, Temperature fitting
61853 – defines bilinear extrapolation and interpolation.
☒ Poor, particularly when data values are noisy or missing

GI OTF – suggests a mechanistic model **MPM**
☑ meaningful, orthogonal, robust, normalised
☑ validated on data from many test institutes
☑ technology and site independent

Further work

In subsequent work we will show more results in the use of the MPM to curve fit matrix points, further work on spectral and aoi corrections and also improved modelling of real outdoor data using IEC 61853 methods or improvements to them including Bifacial, 1D or 2D tracker and also to power plants.

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