IMPROVING AND UNDERSTANDING kWh/kWp SIMULATIONS

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ABSTRACT:

Discrepancies have been found between the models used in PV simulation programs and outdoor measurements.

3rd party PV kWh/kWp measurement reports sometimes show insufficient data to understand their results and often make incorrect assumptions as to the cause and importance of the results (which often differ in ranking).

Suggestions are made on how to improve the modelling of PV arrays and comparisons with measured data.

A new "Loss Factors Model" has been developed with Oerlikon Solar which can model outdoor IV curves for different PV technologies at different sites under different weather conditions.

Keywords: Energy performance, Modelling, System performance, Energy rating

1 INTRODUCTION

Independent comparisons of kWh/kWp from different technologies often find values of kWh/kWp within experimental error of each other and much less variability than some manufacturers' claims[1][2][3][4].

Discrepancies have previously been found between the 1-diode models used in several commercial PV simulation programs (**PVSP)** and measured outdoor performance [5][6] - differences have been found in their assumptions of R_{SHUNT} as a function of irradiance (this is not on the manufacturers' datasheets [7] and will vary for each module type).

Modules are also graded in manufacture into finite width bins (e.g. ±2Wp) and the distribution of modules within these bins must be taken into account in modelling.

2 SIMULATION PROGRAM IV CURVE DISCREPANCIES

Figures 1 and 2 show predicted IV curves at both 1000 and 200W/m² for a commercial Thin Film and a c-Si module respectively [6] from four different PVSPs.

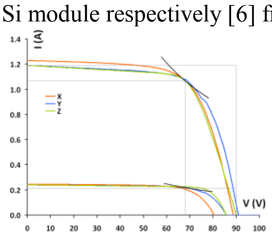

Figure 1: PVSP predicted thin film IV curves @ 1000 and 200W/m²

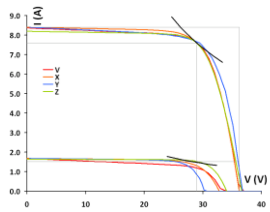

Figure 2: PVSP predicted c-Si IV curves @ 1000 and 200W/m²

Grey lines plot the I_{SC}, V_{OC}, I_{MP} and V_{MP} from the manufacturer's datasheets at 1000W/m² and 200W/m² scaled by irradiance, black curves give the lines of constant P_{MAX} at 1000W/m² and the manufacturers' measured values at 200W/m².

Modelled I_{SC} and V_{OC} values differ at 1000W/m² although the programs predict the I_{MP} and V_{MP} similarly at 1000W/m². At 200W/m² they all predict similar I_{SC} but the curves near V_{MP} and V_{OC} are very different. The R_{SHUNT} for c-Si are modelled differently. P_{MAX} at 200W/m² for program Z is much higher than program X.

Figure 3 shows the PVSP predicted IV curves and P_{MAX} points (brown dotted line) with irradiance (200 to 1000W/m²) for the thin film module in Figure 1. The R_{SC} value vs. Irradiance (black line upper x, right y axes) shows more than a 2:1 variation between the highest (X) and lowest (Z) model. Measurements of R_{SC} vs. G_I were performed outdoors by Oerlikon Solar on micromorph [6] and indoors by BP Solar on c-Si [6] confirming similar approximate shapes of the R_{SC} vs. G_I curve but the magnitude will be module and technology dependent and in PVSPs is just guessed value.

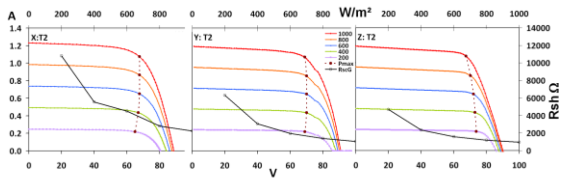

Figure 3: IV curves (colours - lower and left axes) of a thin film module with R_{SC} vs. irradiance (black - right and upper axes) from 3 PVSPs X, Y and Z

These discrepancies between the modelled IV curves under different irradiances and temperatures dominate the kWh/kWp predicted by different PVSPs.

3 ELECTRICAL VARIABILITIES ON MANUFACTURER DATA SHEETS

PVSPs programs assume the modelled performance will be due to values from just one IV curve from their model without any allowances for module variability and uncertainty.

There will be site dependent variability (microclimate, yearly weather variation) plus uncertainties in both the calibration module and the manufacturer's flash tester [6].

Module manufacturers very rarely produce publically available data for the expected variability in performance between all modules in one bin (for example 200-210Wp) but a minimum estimate of the uncertainty can be taken from the datasheet values of I_{SC}, I_{MP}, V_{MP}, FF and V_{OC} per P_{MAX} bin.

Figures 4 and 5 show a manufacturer's defined values increase over the lowest P_{MAX} bin on the sheet. As $P_{MAX} = I_{MP}*V_{MP} = I_{SC}*V_{OC}*FF$ then stacked bar graphs of $\Delta I_{SC}+\Delta V_{OC}+\Delta FF$ and $\Delta I_{MP}+\Delta V_{MP}$ will show the proportion of improvement in Pmax due to each of these parameters.

Figure 4 shows the proportion of improvement from a c-Si cell manufacturer with approximately 2.4% P_{MAX} bin widths. This graph (which may not apply to all c-Si) shows that approximately 1/3 of the improvement is due to each of I_{SC}, FF and V_{OC} and slightly more due to V_{MP} than I_{MP}. This means that for each 2.4% wide P_{MAX} bin there must be at the very least 0.8% variation due to I_{SC}, FF and V_{OC} and about 1.3% due to V_{MP} and 1.1% due to I_{MP} differences.

Figure 5 shows values for a CdTe manufacturer (which may not be the same for all CdTe or thin Film). Here the P_{MAX} bins are >4% apart and there is very little improvement in I_{SC}, mostly it is due to FF and V_{MP} more than V_{OC} or I_{MP} (indicating that the parameter which determines the P_{MAX} is likely to be R_S which affects V_{MP} and FF more than others). Over half of the P_{MAX} change is then due to FF and two thirds due to V_{MP}. This means that at the very least there will be something like 2.5% V_{MP} and 3% FF variation between bins.

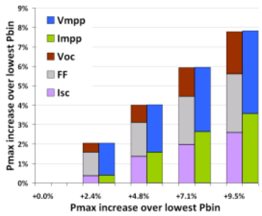

Figure 4: c-Si bin values from manufacturer's datasheet

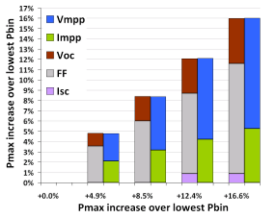

Figure 5: CdTe bin values from manufacturer's datasheet

However these are absolute minima and would only apply if there was perfect correlation between parameters. In reality there are likely to be (higher I_{SC}, lower V_{OC}) and (lower I_{SC}, higher V_{OC}) modules in the same P_{MAX} bins so the expected distributions of each parameter will be higher.

Purchasers of large numbers of modules from the same P_{MAX} bin with lists of measured IV curve values can calculate how much higher these are.

4 A NEW PV "LOSS FACTORS MODEL"

Several 3rd party PVSP models have too many non independent modelling parameters, which may be unphysical and/or not normalised making comparisons and results harder to understand.

A new "Loss Factors Model" (**LFM**) has been developed [8] to study the performance of different technologies by looking at their outdoor IV curves as represented in figure 6 at different sites.

Five different loss factors and two corrections in the LFM were chosen such that they are all independent and the performance factor <001> is the product of all of the loss factors <002>.

$$PF = PR_{DC} = \frac{\text{dc Eff}_{\text{MEASURED}}}{\text{dc Eff}_{\text{NAMEPLATE}}} \quad \text{<001>}$$

$$PF = nI_{SC.G} * nR_{SC} * nFF_R * nR_{OC} * nV_{OC.T} \quad \text{<002>}$$

where $nI_{SC.G} = (MMF * nI_{SC})$ and $nV_{OC.T} = (T_{CORR} * nV_{OC})$.

These are illustrated in figure 6 and are explained further in table 1.

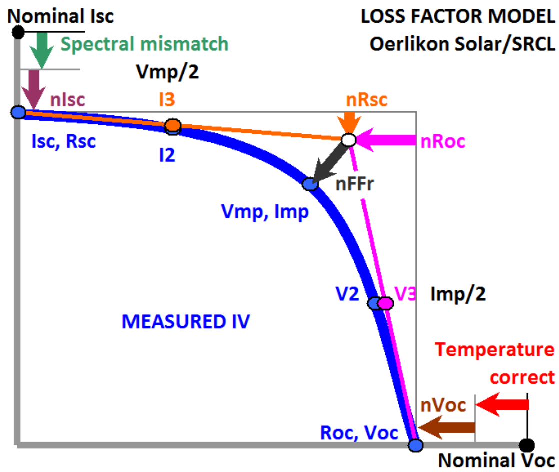

Figure 6: Identifying the 7 independent normalised coefficients that determine the performance factor in the LFM.

Table 1: Definitions and calculations for the LFM

r* = Reference absolute value e.g. STC (A,W etc.))
m* = Measured absolute outdoor value (A,W etc)
n* = Normalised to reference – (dimensionless)

Parameter	**Comments**
G_I	Global POA irradiance (kW/m²) depends on spectral response and AOI of sensor
rFF	reference Fill Factor $= (rI_{MP} * rV_{MP}) / (rI_{SC} * rV_{OC})$
Correction factors :	
MMF	Spectral mismatch factor IEC 60904-7 applied to current only
T_{CORR}	Voltage temperature correction $= (1+\beta_{VOC}*(25\text{-}TMOD))$
Normalised loss factors :	
$nI_{SC.G}$	"I_{SC} loss (spectrally corrected)" $= mI_{SC} / rI_{SC} / G_I * MMF$
nR_{SC}	"R_{SC} loss" (depends on R_{SHUNT} and mismatch) = "slope" of IV @ I_{SC}
nFF_R	"FF loss" independent of R_{SC} and R_{OC} $= mFF / (nR_{OC} * nR_{SC}) / rFF$
nR_{OC}	"R_{OC} loss" (depends on R_{SERIES} and exponential I terms)="slope" of IV@V_{OC}
$nV_{OC.T}$	"V_{OC} loss (temperature corrected)" $= mV_{OC}/rV_{OC} * T_{CORR}$
Resultant performance factor :	
PF	= dc measured/STC efficiency = mEff/rEff **$= nI_{SC.G} * nR_{SC} * nFF_R * nR_{OC} * nV_{OC.T}$**
IV curvature checks on shape	
I_C	I curvature factor $= I_2/I_3$ @$V_{MP}/2$
V_C	V curvature factor$= V_2/V_3$ @$I_{MP}/2$

The "curvature factors" I_C and V_C are useful in checking whether there are losses due to non ideal curves from cell mismatch, breakages or schottky back contacts.

For most well behaved modules tested so far (i.e. without appreciable cell mismatch and Schottky back contacts) these come out to be 100±2% whereas deviations outside this narrow range indicates problems and/or degradation.

When fitting LFM coefficients to measured data it has been found useful to divide measurements into several weather types as shown in figure 7. This differentiates the performance under diffuse or clear sky conditions so that separate Angle of Incidence and Beam Fraction coefficients do not need to be added to the seven coefficients above [9].

Clear skies are defined as “when the clearness index kTh > 0.5”, morning/evening are separated from noon when the time is >±3 hours from solar noon.

Low light levels can occur either during “clear mornings or evenings (with high AOI, high beam fraction, low sun height and redder skies)” or “diffuse noons (low beam fraction and bluer skies)”.

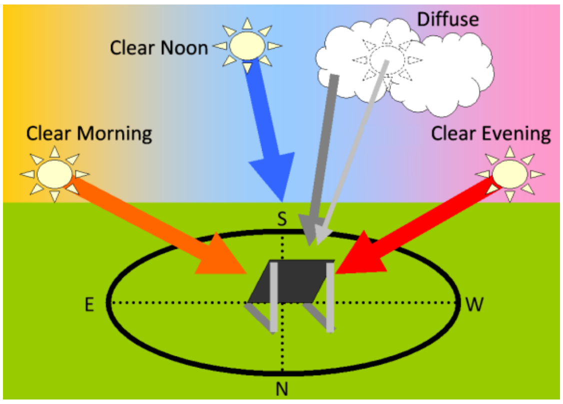

Figure 7: Different weather types used in this analysis (and colours for later figures)

The LFM diffuse fits differ from the clear sky fits particularly when the irradiance sensor differs from the PV technology (for example when using a pyranometer). Figure 8 shows how well the loss factors model fits the 5 different parameters for two similar a-Si:uc-Si modules at two Oerlikon Solar Outdoor test facilities (OTF) in very different climates - Arizona (OTF4-AZ left) and Switzerland (OTF1-CH right). The shapes and values of the curves are almost identical apart from the low light $nI_{SC.G}$ which depends on the differences between the spectral and angle of incidence responses between the PV and the irradiance sensors.

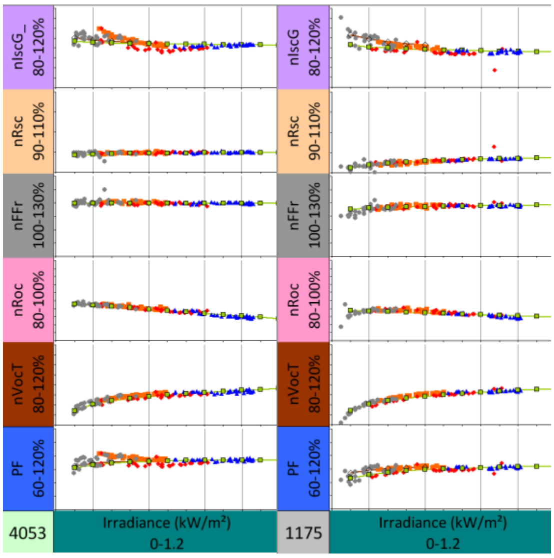

Figure 8: LFM fits to an a-Si/uc-Si module vs. Irradiance at OTF4-AZ (left 4053) and OTF1-CH (right 1175).

Figure 9 shows the temperature and spectrum corrected energy yield measured vs. predicted for a c-Si module in Arizona. The top traces (right axis) show the 5 minute energy yields ($W_{MEASURED}/W_{NOMINAL}$) for 6 days in April, the first two are variable diffuse weather and the right 4 are clear sky.

The bottom traces show the module mismatch factor (here it is 0 because the reference cell and module are both c-Si) and the percentage error of the yield, mostly <±2% apart from the diffuse sky days when the weather was changing erratically.

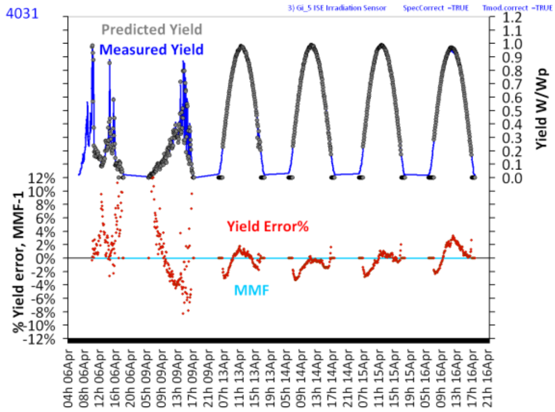

Figure 9: Energy yield LFM fits to a c-Si module at OTF4-AZ right

Figure 10 plots 4 traces for an a-Si:uc-Si module in Arizona. The left column are not temperature corrected, the right hand column are. The top row aren’t spectrally corrected, the bottom row are.

Note the best fit (~<1%) for the a-Si:uc-Si module when both corrections are on for the clear sky days, the diffuse days are still a few % out – this may be due to erratic weather causing temperatures to fluctuate and will be checked in steady diffuse conditions.

These are only initial energy yield simulations with the current status of the model which will be further enhanced for even better correlation with measured performance soon.

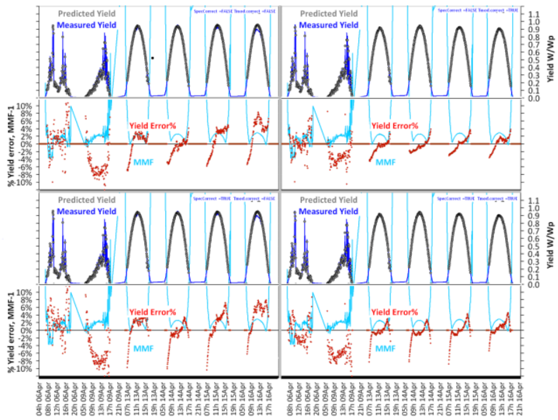

Figure 10: Energy yield LFM fits to an a-Si:uc-Si module at OTF4-AZ – temperature correction (left=no, right=yes); spectral correction (upper=no, lower = yes)

5 BETTER REPORTING IS NEEDED

Many 3rd party comparative energy yield studies worldwide only quote the total derived kWh produced by the modules over the year. This sum does not show how the results are affected due to any errors such as

- poor measurements
- incorrect setup (perhaps inverter matching)
- shading on some or all modules
- poor V_{MP} tracking
- atypical modules (e.g. shunted or cracked cells)
- corrections for missing or poor data
- inverter and BOS losses
- other yield affecting problems.

Listed below are many factors that should be taken into account when reporting measurement and modelling data.

Simple graphs to prove PV performance claims

Manufacturers often make claims for extra energy yield for their products vs. their competitors for several reasons but rarely do they show enough monitored data which is easy to represent in the graphs identified below in table 2.

Table 2: Types of improved performance claimed by manufacturers and graphs they should use to prove or disprove the claim.

Claimed better performance at	Graph to show
low light levels due to - good R_{SHUNT} - good diffuse spectrum	PF vs. G_I - and IV vs. irradiance - and diffuse fraction
high light levels due to - low I^2R loss - blue spectrum	PF vs. G_I - and IV showing R_{SERIES} - and APE
high temperatures	PF vs. Tmodule

Weather correlations need to be corrected for

All weather parameters are correlated with each other (high irradiance tends to occur with high temperatures, in summer with low AOI and under clear blue skies etc.).

Figures 11 and 12 show the correlation of weather parameters. Each of the 8 axes of the graph represent a different parameter, normalised and scaled so that a value identified with a high irradiance appears at the outside of the graph and that associated with a low irradiance towards the inside. Correlation between weather parameters is seen when there are many almost parallel lines between the axes, few crossovers or scatter.

Three of the weather types from figure 7 are shown, clear noon, clear evening and diffuse (clear morning isn't shown for clarity but it's similar to clear morning with a little higher temperature). ~30 random measurements in April are plotted for each type. The clear noon and clear evening show high T_{MODULE}, $T_{AMBIENT}$ and Beam Fraction plus low AOI are associated with high irradiance at both sites. The clear evening shows lower temperatures and beam fractions plus higher AOI than the clear noon.

The diffuse measurements show lower temperatures, varied AOI, higher blue fraction and very low beam fractions than the clear conditions.

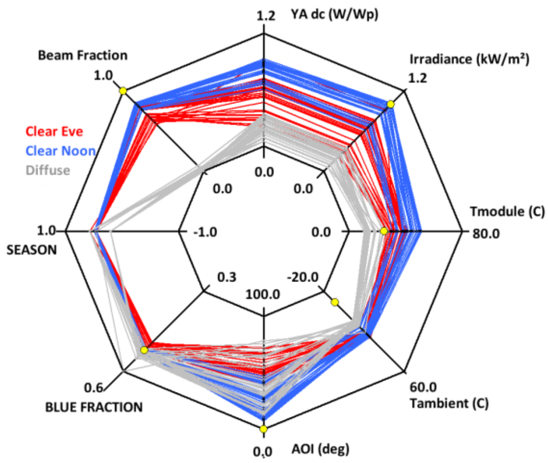

Figure 11: Correlations in April OTF1-CH weather.

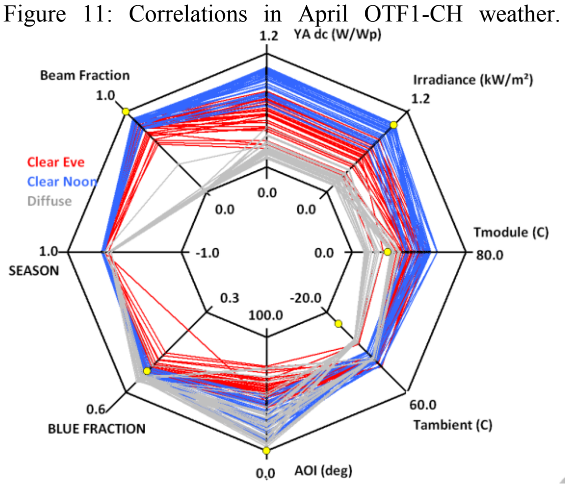

Figure 12: Correlations in April OTF4-AZ weather.

When calculating outdoor temperature coefficients for spectrally sensitive devices such as a-Si or CdTe (which absorb more in the bluer end of the spectrum than irradiance sensors of c-Si or pyranometers these correlations are important.

Because module temperatures tend to be higher under blue skies, the spectrum needs to be corrected for otherwise wrong temperature coefficients are found. Also seasonal annealing gives higher performance after hotter weather so for longer term studies the effect is greater.

Uncertainty limits on measured side by side comparisons

Modules of different technologies are measured under the same conditions over a year – then the total sums of kWh/kWp compared. Sometimes modules are measured on their own flash testers and the kWh divided by the kWp flash tested rather than use the manufacturer's nominal ratings.

Modules are then ranked from highest to lowest kWh/kWp but the uncertainty of the flash test measurements (usually > ±2.5% even from test houses to international standards) is often ignored.

kWh/kWp variations of <5% from best to worst aren't statistically significant.

Simulation programs will predict one IV curve per time period (usually hourly) i.e. irradiance, temperature and any other modelled input. However as the input values for I_{SC}, P_{MAX} and FF are known to vary as in figure 4 and 5 then allowance for these variations should be made.

User defined input uncertainty

At a 2010 workshop at Sandia in Albuquerque Stein [10] analysed the results from many designers using a variety of different commercial and internal simulation programs to model the same systems and found :-

- *Large variation seen in model results*
- *Variation not entirely consistent across systems*
- *Uncertainty in assigning derates*
- *Discomfort when components are not included in database.*

Closest fit - modelled vs. measured kWh/kWp studies

Table 3 discusses a hypothetical study where a user models a system that measured 1000kWh/kWp with 4 different simulation programs A-D with default derates as in row 1. Simulation program D would appear to give an exact fit. Now suppose that the dirt derate had to be raised by 2% - the apparent modelled output would fall 2% for each program as in row 2 and model C would now be the best match. Suppose the customer found the average P_{MAX} of the modules supplied was at the low end of the bin at 2% below average then the predictions would fall another 2% as in row 3. It might be that the shading wasn't allowed for and including a 2% value would result in another fall in row 4.

There is obviously a limit in the number and amount of additions to the nominal derates before the designed output falls to substandard levels but it shows that the "best match" of simulation program to measured data relies on the input derates – many of which are not known exactly.

Table 3: Hypothetical measured vs. predicted kWh/kWp with different derating factors.

Hypothetical measured kWh/kWp		1000		
Simulation Program Predicted kWh/kWp	A	B	C	D
1) Default derates	1060	1040	1020	**1000**
2) 2% more dirt	1040	1020	**1000**	980
3) 2% lower Pmax/Pnom	1020	**1000**	980	960
4) 2% more shading	**1000**	980	960	940

Correlation does not imply causation

Claims are often made with yearly tests when a module claimed to perform well under certain weather conditions (e.g. diffuse skies or high temperatures) when tested in a specific climate type (i.e. high diffuse content or high yearly ambient temperature) that performance differences are due to this effect alone.

For example a module claimed to work well under high diffuse and measured at a low insolation site with plenty of diffuse radiation might perform better than expected if its $P_{MAX.ACTUAL}/P_{MAX.NOMINAL}$ was higher than expected, perhaps from being underrated or pre degradation at the start of a test.

The only way to tell if a module is performing better under high diffuse radiation is to plot vs. the diffuse fraction and correct out for all other parameters such as irradiance and temperature.

It's also important to see how much difference this is worth in terms of energy yield – for example a 10% better diffuse light performance under the 20% of insolation of highest diffuse is only worth 10% * 20% = 2% in terms of energy yield.

The fact that many independent tests of energy yield worldwide come out with <±5% values each site, and that the ranking between best to worst performing technologies varies between these sites proves that kWh/kWp does not vary as much as some manufacturers claims and is limited by measurement accuracy and random performance variations.

How wide can kWh/kWp variations ever be ?

The majority of "mature technology" (c-Si and 2nd Generation thin films) have quite similar looking PF vs. irradiance and temperature curves under outdoor conditions. This means that these technologies will have a similar kWh/kWp$_{.ACTUAL}$ to each other. Claims for very large differences in kWh/kWp can only come if there are large losses near STC conditions (i.e. high irradiance and current).

A module with a high R_{SERIES} will experience a high $I^2 R_{SERIES}$ loss near STC and because its high irradiance P_{MAX} has been lowered more than its low irradiance value it might appear to have a slightly higher efficiency at low light level. However reducing the R_{SERIES} will bring up the efficiency at high light level and will improve the $P_{MAX.STC}$ and kWh/year dramatically even if the kWh/kWp falls a little (as the kWp now increases).

Some manufacturers have claimed 30% better kWh/kWp for their products – recently a claim for 55% extra performance has been made – but the performance factor PV vs. irradiance and temperature as in figures 8 and 9 show remarkably similar shapes for different sites and technologies.

This indicates that there can't be large kWh/kWp variations as the modules are quite linear to irradiance and temperature variations site to site.

Apparent measured low light performance depends on irradiance sensor choice

When characterising low light level performance of modules it is essential to consider both the spectral and the angle of incidence differences between the sensor and the PV module.

Figure 13 shows the irradiance values measured by pyranometers vs. corrected ISE sensors on both tilted plane and a 2D tracker for a good irradiance day in April at Oerlikon Solar's OTF4-AZ. (These traces were corrected to allow for manufacturer's tolerances by multiplying the irradiance of the ISE sensors to match that seen by the pyranometer only at AM1.5 when blue fraction = 0.52). The lower part of the graph (left y-axis) shows the raw irradiances on the tracker and the tilted plane (and the diffuse horizontal for comparison).

At the top and right of the graph are shown the values of $G_{.PYR}/G_{.ISE.CORR}$ for the two locations. The apparent $G/_{PYR}/G_{.ISE.CORR}$ on the fixed tilted plane rises away from solar noon due to the combined effects of "angle of incidence" and "solar spectral response" differences between the pyranometer and the ISE sensor. When the sensors are tracked there is a much more linear response just due to the spectrum as the angle of incidence is now 0°.

The vertical line shows when the morning irradiance was around 200W/m² (clear sky, high angle of incidence, spectrum redder than AM1.5). The $G_{I.PYR}/G_{I.ISE.}$TILT is approximately 118% - meaning that under these conditions the Pyranometer reads 18% higher G_I than the ISE sensor – this makes a large difference to the "apparent low light level response" under clear sky conditions – it is essential to quote which type of irradiance sensor is used under which weather conditions when measuring outdoor low light level coefficients.

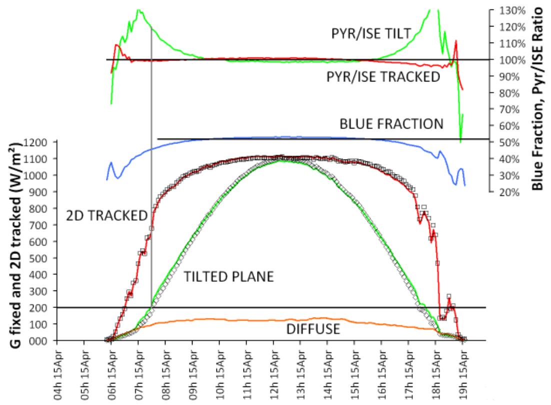

Figure 13: Irradiance from a pyranometer vs. corrected @AM1.5 ISE sensor, tilted plane vs. 2D tracked for a good irradiance day in April at Oerlikon Solar's OTF4-AZ

Figure 14 replots the data from figure 13 for a c-Si module at OTF4-AZ against irradiance. It shows the raw performance ratio (without spectral or thermal corrections) of two similar c-Si modules in the fixed plane and on the 2D tracker for a clear day in April versus the ISE and Pyranometer scaled so their irradiances match at AM1.5.

The lower plot shows the non temperature corrected performance factor at low light deviating by the 18% error found in figure 13 – meaning that using an ISE reference sensor the PF would appear 18% better than with the pyranometer at 200W/m² under clear skies but high AOI and red rich spectrum.

The upper plot shows very little difference at any light level between the ISE and the Pyranometer on the 2D tracker meaning that most of the deviation is due to the sensor/module angle of incidence differences (corrected out on the 2D tracker) rather than spectrum.

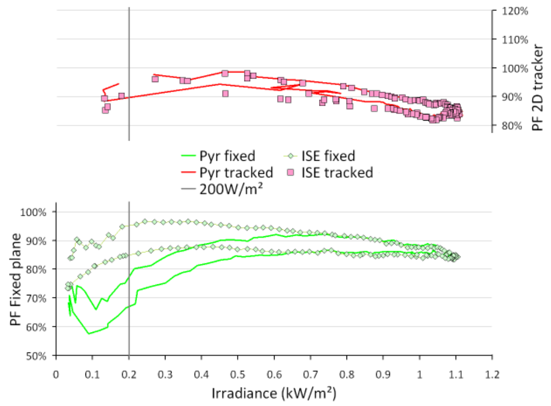

Figure 14: Apparent change in low light behaviour due to sensor choice for a c-Si at Oerlikon Solar's OTF4_AZ

7 CONCLUSIONS

Many 3rd party tests only provide kWh/kWp data which is insufficient to differentiate the results – low kWh/kWp may be due to downtime, shading etc., not poor module performance

Many suggestions have been made for improving the understanding of kWh/kWp measurements

Apparent performance at low light level has been shown to depend on whether it's diffuse sky or clear with high aoi; also it depends on the irradiance sensor used as pyranometers have a different performance at high aoi.
The "Loss Factors Model" has fitted s all technologies tested at two different sites

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