PV technology differences and discrepancies in modelling between simulation programs and measurements

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***Abstract* — Side by side comparisons of kWh/kWp from individual dc modules are usually < ±5% when correctly measured. Some PV simulation programs give biases towards certain technologies mainly due to the limitations in the 1-diode model [1] which predicts incorrect Pmax - temperature and low light efficiency coefficients [2].**

The distribution of plane of array insolation vs. irradiance is affected by averaging by time [3]. PV low light efficiency often differs between clear dawn/dusk and diffuse conditions which is not modelled. The spectral response and angle of incidence dependence between the PV technology and the irradiance sensor (particularly with pyranometers) differ.

Some thin film devices are also susceptible to seasonal annealing (improving after hot weather periods i.e. better in autumn than spring). These discrepancies are discussed further and a new PV model (LFM-B) is introduced which was developed with Oerlikon Solar to lessen these limitations and errors[4].

Index Terms — Modeling, Simulation, Photovoltaic systems, Energy, power, Meteorology.

I. INTRODUCTION

Most PV simulation programs (PVSPs) fit a 1-diode model [1] to one STC IV curve from a flash tester or inferred from a datasheet (which is not the same for all modules of the same type). This fit forces values of the Pmax temperature coefficient Gamma (= $1/P_{MAX} * dP_{MAX}/dT$) and the Low Light Efficiency Change LLEC (= [Eff@200W/m²]/[Eff@1000W/m²]-1) which often differ from measurements according to IEC standards[2].

The Energy yield predicted by a PVSP depends on the modelled Gamma and LLEC, discrepancies up to 16% [2] have been seen. Many PVSPs simulate weather hourly but this averages transient weather (with low and high irradiance periods) into a medium light level thus overestimating the fraction of insolation at lower irradiance and over predicting Energy Yield errors from LLEC discrepancies [3].

The apparent value of LLEC is irradiance sensor dependent – it appears better with a c-Si reference cell than a pyranometer (as the latter collects more off axis light than a flat sensor thus implying a higher irradiance for any given PV module performance) [2].

A fit to a measured kWh/kWp is not validation of a model, it can be fitted in numerous ways with sufficient unknowns (dirt, Pmax.meas / Pmax.nom etc.). Seasonal annealing, degradation and the spectral response of a module can have an effect on yield which isn't always modelled well if at all.

A new "Loss Factors Model Version B" (LFM-B) [4] is being developed with Oerlikon Solar to get around many of the problems with the 1-diode model. This will improve the characterization to a more reproducible level. The LFM-B Analysis of different PV devices will find the real unbiased source of module changes (e.g. seasonal vs. degradation trends) which has not been possible previously.

II. ENERGY YIELD PREDICTION UNKNOWNS

Table I lists some of the uncertainties for kWh/kWp measurements. As the overall uncertainty is given by (1)

$$U^2 = (u_1^{\,2} + u_2^{\,2} \ldots + u_n^{\,2}) \qquad (1)$$

Then just taking reference sensor and module calibration, manufacturer tolerance and degradation ("*" in Table I and correcting for the other uncertainties) gives an uncertainty of ±4% 2σ which is approximately equal to the range of differences in kWh/kWp found by several international tests.

TABLE I.
kWh/kWP UNCERTAINTIES

	Variability or Uncertainty	(±%)
Measured plane of array insolation kW/m²/y	Yearly variability Microclimate Reference Sensor Calibration(*) Reference Sensor Stability	(±4%?) (±?) (±2.5%) (±0.5%)
Actual PV power	Reference Module Calibration(*) Tolerance P_{MEAS}/P_{NOM} (*) Spectral Response, annealing Degradation (*)	(>±2.5%) (±2.5%/bin) (?) (±0.5%/y)
Self;Near;Horizon shading	Varies across site, depends on stringing	(?)
Dirt, Soiling	Wash off rate, distribution	(~2%?)
Inverter	Eff(P_{IN}, V_{IN}), V_{MP} tracking	(?)

III. FACTORS AFFECTING DIFFERENT PV TECHNOLOGIES.

Several parameters that affect the modelling of kWh/kWp differently for the various PV technologies are listed in Table II (yellow). Some factors such as seasonal annealing and spectral response affect Thin film modelling more than c-Si and so needs to consider more input parameters than c-Si.

TABLE II.
KWH/KWP DETERMINING FACTORS AFFECTING DIFFERENT PV TECHNOLOGIES

	c-Si Hi Eff	c-Si Std	1-J Thin Film	Multi-J Thin Film	Modelled ?
Gamma %/K	-0.40	-0.45	-0.25 to -0.35%/K		Use the correct value
Low light efficiency	~95%		~95%(> high R_{SERIES})		Use the correct value
Initial Deg-radation	small	~3%	Allowance by manufacturer		Simple initial drop
Linear Deg-radation	-0.5 to -1%/year ? (If 80%@25y guarantee)				Linear fall
Best sensor	c-Si		Filtered c-Si Ref. cell	Two Filter c-Si	Often ignored ?
Angle of Incidence	More similar to c-Si ref cell than pyranometer; changes with ARC				Curve vs. beam fraction
Spectral response	350-1050nm		350-650~1050?	350-650; 650-1050	Need SR/ spectrometer
Seasonal anneal	No		Some technol better in autumn		Not done ?

IV. THE 1-DIODE MODEL AND ITS LIMITATIONS

Most PV simulation programs use a 1-diode model (2) to fit an IV curve with 4 constraints. As there are five unknowns a 5th constraint is needed and this is taken to be R_{SC} =-1/(dI/dV)@V=0. This parameter is not listed on manufacturer datasheets and may vary for each module. Its value in the 1-diode model is guessed as is its behaviour with respect to irradiance and any other parameters (such as temperature)

$$I = I_L - Io\left(e^{q(V+I.Rs)/nkT} - 1\right) - \frac{V+I.Rs}{Rsh} \qquad (2)$$

Two other equations (3) and (4) in the 1-diode model are used to calculate values for both Gamma (instead of measuring with IEC 61215 or 61646) and Low light efficiency (instead of using the procedure in EN 50380).

$$a = \frac{q}{nkT}\,;\ \frac{a}{a_{ref}} = \frac{T_c}{T_{c.ref}} \qquad (3)$$

$$\frac{Io}{Io{,}ref} = \left[\frac{Tc}{Tc{,}ref}\right]^3 e^{\frac{\varepsilon\, Ns}{a_{ref}}}\left(1 - \frac{Tc{,}ref}{Tc}\right) \qquad (4)$$

The Gamma and Low light efficiency from 1-diode models should agree with IEC standard measurements otherwise incorrect efficiency will be predicted. Fig 1 shows typical predicted curves of efficiency vs. irradiance (x axis) for different module temperatures (lines) from a 1-diode model. Shown are the graphical representation of Gamma (separation of blue diamonds) and Low light efficiency (red dot) coefficients.

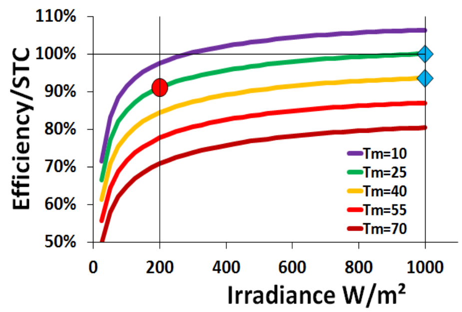


Fig 1. Graphical definition of Gamma and LLEC from PV efficiency/nominal (PF) vs. irradiance and module temperature (Tmod) for a typical device.

A. Variability of simulation programs fitting typical datasheet STC IV curves

Fig 2 shows the attempts of four different PVSPs simulating the IV curve of the same c-Si module type at 1000W/m² and also their predictions of performance at 200W/m².

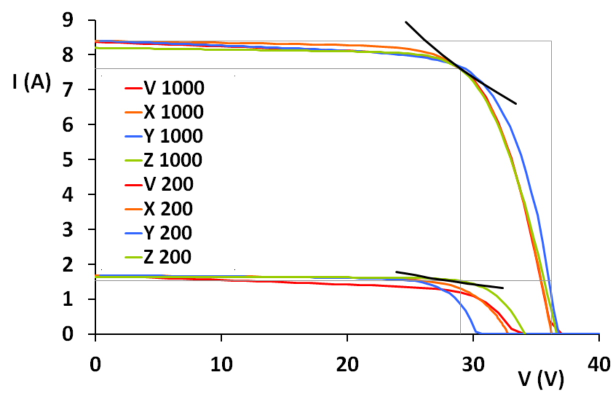


Fig 2. Four different PVSPs simulating the IV curve of the same c-Si module type at both 1000 and predictions for 200 W/m².

Note that there are small discrepancies in the 1000W/m² STC trace (I_{SC}, R_{SC}, R_{OC} and V_{OC}) but larger discrepancies particularly near V_{OC} at 200W/m², these differences will dominate the energy yield predicted at low insolation sites.

Fig 3 plots LLEC values from different manufacturers datasheets (black bars) vs. 5 simulation programs (coloured dots) for 13 different PV modules.

Most manufacturers suggest an LLEC of around -5% but simulation programs predict anything from -30% to +20%.

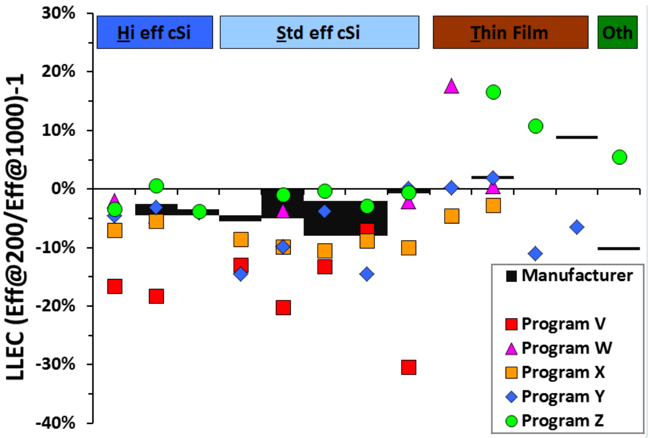


Fig 3. Manufacturers declared LLEC vs. PVSP modelled for 13 modules of varying technologies.

B. kWh/kWp sensitivity to modelling errors

Simulating the energy yields with these magnitudes of discrepancies in LLEC as in fig 3 and also in Gamma gives resultant kWh/kWp errors as plotted in fig 4.

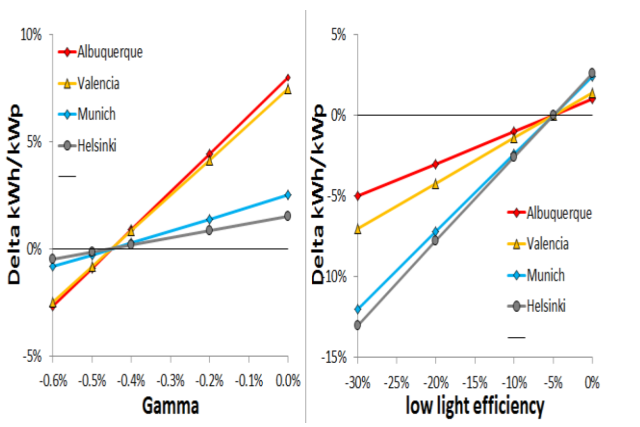


Fig 4. Change in predicted kWh/kWp vs. Gamma (left) and LLEC (right) errors at different sites from Albuquerque (red) to Helsinki (grey).

The differences in kWh/kWp to errors in Gamma and LLEC are summarised in table III for the most extreme weather sites.

TABLE III.
kWh/kWP SENSITIVITY TO ERRORS IN GAMMA AND LLEC

Coefficient	Low light	Gamma
Maximum error seen	30%	0.15%/K
Site; Lat °; YR kWh/m²/y	Predicted kWh/kWp change	
Helsinki; 60°N; 1150	16%	1.5%
Albuquerque; 35°N; 2300	6%	3%

C. Simulation program fits to IV curves for different Pmax bins

The PVSP module performance databases usually contain a fit to just one measurement of each module type.

Fig 5 shows how modules in P_{MAX} bins (65, 67, 70, 72 and 75W$_P$) from a typical thin film manufacturer were fitted. These traces appear to be from individual random samples as the different P_{MAX} bin curves have nonlinear I_{SC}, V_{OC}, I_{MP}, V_{MP} and non-*constant* R_{SC} and R_{OC} (see the zoomed inserts near I_{SC} and V_{OC})

Low R_{SC} modules will have lower predicted kWh/kWp in low insolation climates whereas high R_{OC} modules have lower predicted kWh/kWp in high insolation climates.

The predicted kWh/kWp will therefore tend to vary between P_{MAX} bins due to the manufacturer using random modules in the database rather than averaged interpolations.

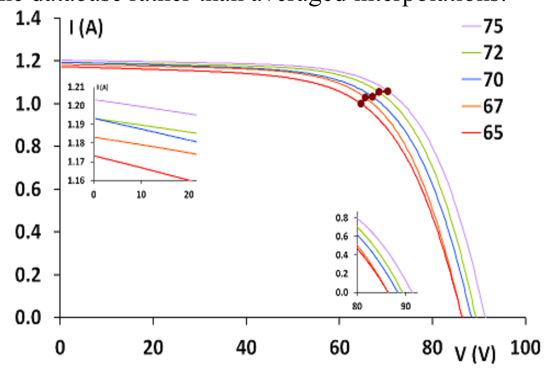


Fig 5. 1-diode model fits for a series of modules from a thin film manufacturer's datasheet showing random variations.

V. OTHER EFFECTS THAT NEED TO BE MODELLED

A. The effect of averaging irradiance by time

Fig 6 shows how pyranometer tilted plane insolation (kWh/m²/bin) vs. irradiance bin (W/m²) change distribution as the irradiance values are averaged from every minute to every hour (Oerlikon Solar Test Site in CH). Periods of variable cloud cover (i.e. sunny with bright reflective clouds then overcast a few minutes later) will be averaged into intermediate irradiance conditions. This will affect the modelled kWh/kWp of any module with a non-constant efficiency vs. irradiance. It also shows the distribution from a commercial weather simulation program (grey) which suggests a higher irradiance at lower light levels than occurs.

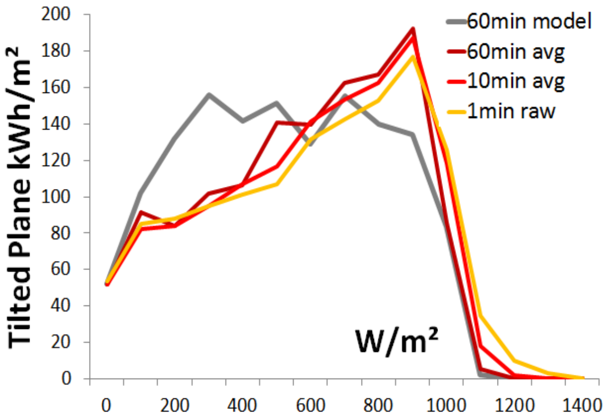


Fig 6. Modelled hourly and "measured minute to averaged hourly" POA insolation vs. irradiance at Oerlikon Solar's OTF1 in Switzerland (CH), data: Aug-10 to Aug-11

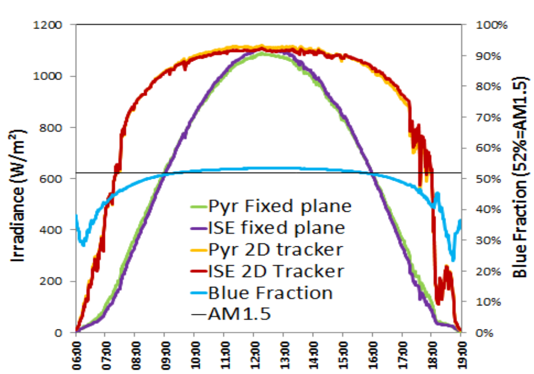
B. Measured low light efficiency vs. irradiance sensor type

The measured apparent low light efficiency depends on the irradiance sensor type – not just as the spectral responses may vary but more importantly due to the angular response as pyranometers collect more off axis light than flat plate sensors.

Fig 7 (top) shows irradiances (Pyranometers vs. c-Si ISE reference cells on Fixed plane and 2D tracker) measured on a clear day from 06:00 to 19:00 (x axis) at Oerlikon Solar's OTF 4 in Arizona AZ (corrected so that measured irradiance was the same at AM1.5=Blue fraction 52% on the 2D tracker (5)).

$$\text{Blue Fraction BF} = \frac{\text{Gi(350..650nm)}}{\text{Gi(350..1050nm)}} \qquad (5)$$

Fig 7 (bottom) plots the irradiance ratio (ISE c-Si type reference sensor / pyranometer) and blue fraction vs. irradiance. There is little difference in the irradiances on the 2D tracker with an angle of incidence (AOI) of 0°. However on the fixed plane the apparent irradiance is 18% lower on the ISE reference cell at 200W/m² (due to AOI effects in collecting more off axis light). Therefore any PV low light module performance (Pmax/irradiance) will appear to be 18% worse compared with a pyranometer compared with an ISE reference sensor.



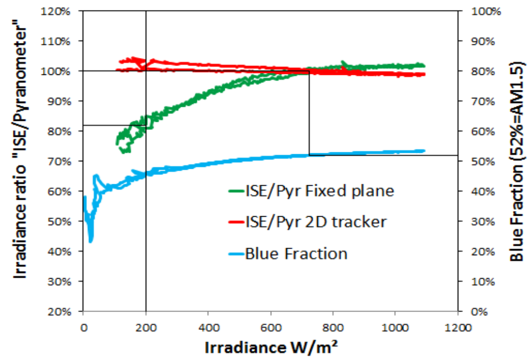


Fig 7. Clear day Irradiances in Arizona : 2D tracker vs. fixed plane (top) and difference in irradiances vs. light level (bottom) day.

C. Measured outdoor low light efficiency vs. irradiance is site specific (IWES Kassel Germany)

Outdoor low light irradiance of 200W/m² can occur under different conditions, either "diffuse sky + blue rich" or "Clear sky morning/evening + red rich + high AOI". PV Modules may have different performance due to their spectral and AOI dependencies under these conditions so the Efficiency vs. Irradiance curves in Fig 8 differ at low light. (The IEC 61853 matrix method has just a single efficiency at each irradiance and temperature). When measured outdoor the "average Efficiency vs. Irradiance" (as highlighted in pink on graph 8) will depend on the relative proportions of clear sky vs. diffuse – i.e. in desert locations the apparent low light is dominated by red rich off axis light performance (and be lower nearer the red line) but under low insolation sites it will depend more on diffuse, blue rich performance (and be relatively higher, nearer the blue line).

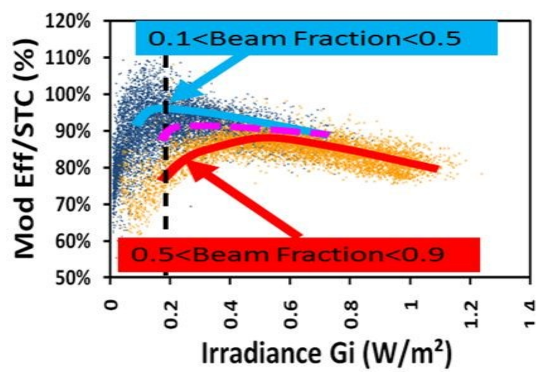


Fig 8. Dc module efficiency / STC vs. irradiance for a c-Si module at IWES in Germany for clear sky (red) and diffuse (blue) conditions

D. R_{SC} vs. Irradiance

The low light level P_{MAX} performance predicted by the 1-diode model is determined by how the R_{SC} varies with irradiance. Fig 9 plots the "normalised Rsc" (6) where

$$R_{SC.R} = \frac{Rsc}{\left[{Voc_{STC}}/{Isc_{STC}}\right]} \quad (6)$$

Note that $R_{SC.R}$ varies exponentially for all four Thin Film modules shown with their ID numbers. (c-Si also follows same shape but the scatter is higher and so is not shown for clarity). These curves need to be characterised for modelling.

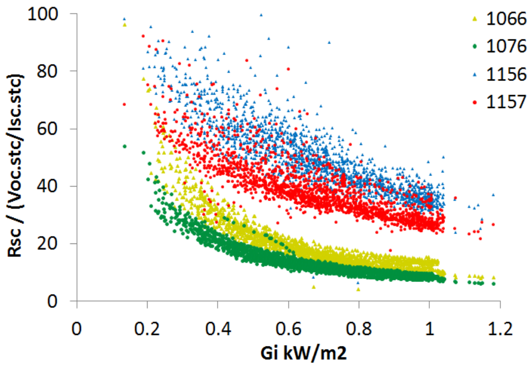


Fig 9. Measured normalised R_{SC} vs. Irradiance for four third party thin film modules at Oerlikon Solar's OTF in Switzerland.

E. Seasonal or thermal annealing

Seasonal or thermal annealing (usually better performance after high temperature conditions in the autumn) are known to apply to some thin film technologies but not c-Si. Before modelling, much more information needs to be gathered to answer these questions before attempting to model

- What is the time constant ? (does annealing happen in a morning, a week or a month ?)
- Does the module anneal faster with higher temperatures or is just a threshold temperature needed ?
- Is annealing faster with continuous (e.g. light soak) or pulsed (e.g. daily) high temperatures
- Is annealing perfectly reproducible and/or reversible ?
- Which factor(s) are affected e.g. Isc, Voc, FF ?
- Do all modules of the same type behave in the same way ?

F. Spectral changes from shading by high horizons

Fig 10 plots the relative % of irradiance in each 100nm bin (350-1050) and total irradiance vs. time. It shows how on a clear day at Oerlikon Solar's Test location in Switzerland (CH left) the morning and evening gave much lower red light fraction than expected when the sun was behind a high horizon such as a mountain compared with the Arizona test site (AZ right) with a low horizon. Sites with high horizons will be giving more apparent kWh/kWp to blue sensitive technologies

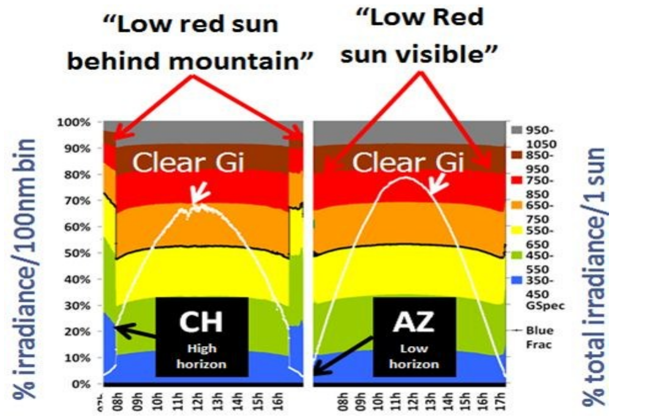


Fig 10. Lowered red irradiance fraction from high horizon site (left, CH) than low horizon (right, AZ) (Oerlikon Solar data)

G. Spectral modelling

When modelling devices with different spectral responses from that of the irradiance sensor we need to know Spectral distribution = f(Gi, Tmodule). Fig 11 plots the spectral distribution in terms of Blue Fraction (5) (where Blue Fraction@AM1.5 = 52%) vs. module temperature and irradiance in Switzerland and Arizona where Bluer dots <AM1.5, Grey=AM1.5, Redder dots>AM1.5.

At low light levels this is Site specific, less so at high light where "high irradiance and temperature" come from a blue rich sky. Table IV highlights the reasons for the differences.

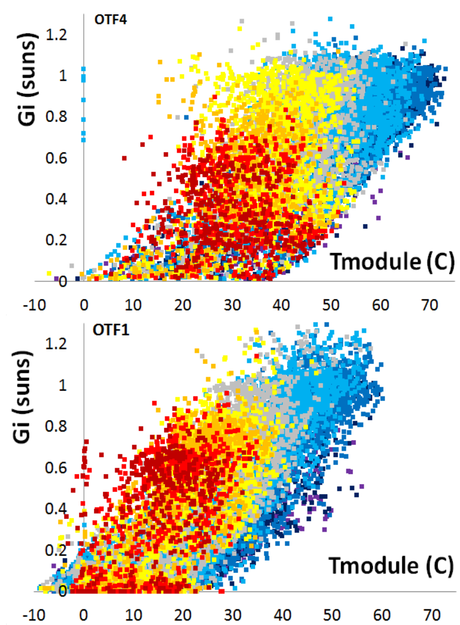


Fig 11. "Blue Fraction" vs. Tmodule and Irradiance at Test Oerlikon Solar sites in Arizona (top) and Switzerland (bottom) where grey=AM1.5 .

TABLE IV.

IRRADIANCE COLOUR AT HIGH AND LOW LIGHT, IN CH VS. AZ (OERLIKON SOLAR TEST SITES)

	CH		AZ	
High Gi	Low red fraction	High blue fraction	Low red fraction	High blue fraction
Low Gi	Low red (shading from mountain)	High blue (a lot of diffuse in CH)	High red (clear dawn and dusk)	Low blue (not much diffuse in AZ)

VI. A NEW "LOSS FACTORS MODEL" (LFM-B)

To overcome many of these limitations with the 1-diode model a new "Loss Factors Model"[3] has been developed with Oerlikon Solar to understand how modules of different technologies work outdoors at different locations.

This model allows module variability, temperature coefficients, seasonal annealing, degradation and performance validation to be understood by creating 6 normalised, orthogonal and physically understandable coefficients with a thermal and a spectral correction as shown in Fig 12.

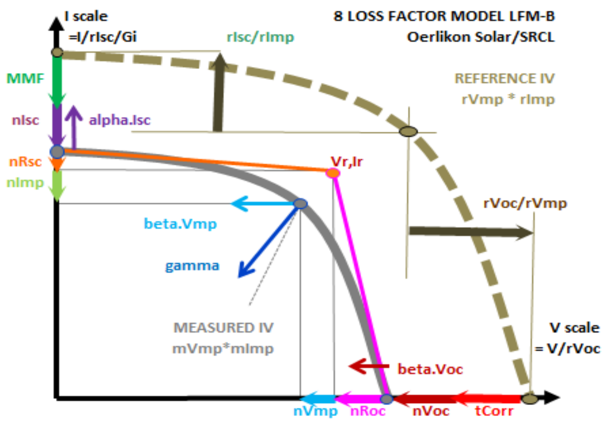


Fig 12. The Loss Factors Model – 6 normalized, orthogonal and physically understandable coefficients (acknowledgements PV Systems Group, Oerlikon Solar)

The Performance factor PF is the product of the normalised, orthogonal coefficients with temperature and spectral correction as in equation (7).

$$PF = [nISC.G * nRSC * nImp] * [nVmp * nROC * nVOC.T] \qquad (7)$$

This model gives a good simulation to measured performance at all weather conditions and at all times.

Fig 13 illustrates the modelled and measured performance for good and bad weather days in Arizona for a typical thin film module. There is much more detailed information in the paper from Sellner et al; "Advanced PV module performance characterization and validation using the novel Loss Factors Model", this conference.

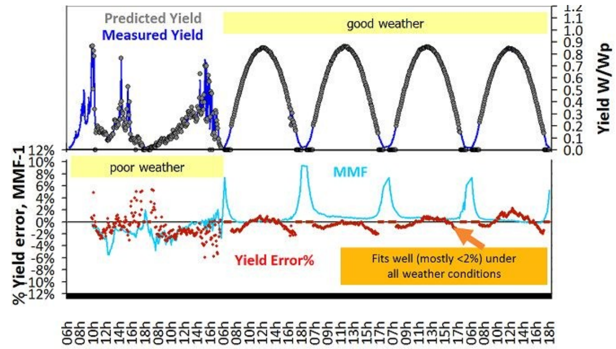


Fig 13. LFM Energy yield prediction on different weather days (data: PV Systems Group, Oerlikon Solar)

VII. CONCLUSIONS

There are too many uncertainties to be able to predict very accurate energy yields (<4% kWh/kWp) for every location and module type.

The 1-diode model can result in simulation programs having incorrect gamma and low light efficiency errors <16% kWh/kWp

Rsc vs. Irradiance affects the low light efficiency – Rsc is not on the datasheets and not regularly measured

For the best modelling we need improved studies of

- understanding of average module binning
- spectral measurements
- spectral response
- irradiance averaging frequency
- seasonal annealing
- horizon at site
- irradiance sensor type
- low light vs. clear and diffuse sky etc.

A new Loss Factors Model [4] is being developed with Oerlikon Solar to understand the real performance of PV modules including spectral, seasonal annealing and degradation effects plus module variability. This will lead to lower uncertainty and more accurate characterization for further technology improvements.

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[3] Ransome et al. "Why Hourly Averaged Measurement Data Insufficient to Model PV System Performance Accurately", *20th PVSEC Barcelona 2005*

[4] Sellner et al., "Advanced PV module performance characterization and validation using the novel Loss Factors Model", *38th PVSC Austin 2012*

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