CHARACTERISING PV MODULES UNDER OUTDOOR CONDITIONS: WHAT'S MOST IMPORTANT FOR ENERGY YIELD

J. Sutterlueti[1]*, S. Ransome[2], R. Kravets[1], L. Schreier[1]
[1] Oerlikon Solar, PV Systems Group, Hauptstrasse 1a, 9477 Truebbach, Switzerland
*phone +41 81 784 6449; juergen.sutterlueti@oerlikon.com
[2] SRCL (Steve Ransome Consulting Ltd) UK, +44 7515 565010, steve@steveransome.com)

ABSTRACT:

Standard parameters in Photovoltaic (PV) such as Final Energy Yield (YF) or Performance Ratio (PR) (IEC 61724) are simply calculated as sums (YF) or averages (PR) of the PV device performance over the measurement period and therefore do not allow for correlations with parameters such as irradiance, temperature or downtime.

For a better characterisation and prediction of PV module performance under outdoor conditions detailed studies on the level of I-V parameters would be desirable. However, algorithms as used in commercial simulation programs were found to be of limited use [1].

Therefore a new **"Loss factors model" (LFM)** has been developed which determines a module's performance from its I-V curve simply as the product of five physically significant and independent normalized "loss factors" as well as spectral and temperature corrections. The benefits of such a Loss Factors Model will be shown in this paper. It allows validation of technology improvements, also performance distributions in mass production can be checked by quantifying initial losses and separating them from any long term changes. It also benchmarks different modules, production series or technologies at sites with different climates and can be used for Energy yield and Performance predictions. Differences at low light behaviour and temperature coefficients can be checked and validated with the LFM and seasonal changes can be distinguished from module degradation. Previously, the effect of energy yield losses due to R_{SC} and R_{OC} were hard to quantify, now they can be determined easily and the value of improvements can be estimated.

In the present paper the LFM has been verified for different PV module technologies (c-Si, HIT, a-Si, CIGS, CdTe and a-Si/uc-Si) in two different climatic conditions (Switzerland and Arizona)[3]. Good fits to module performance (I_{SC}, R_{SC}, FF, R_{OC} and V_{OC} and hence P_{MAX} or efficiency) were obtained under a wide variety of weather conditions.

Keywords: Modelling, Energy rating, Outdoor Testing, Characterization

1 PV PERFORMANCE MODELLING AND CHARACTERISATION STATUS

Standard PV parameters like Final Energy Yield (YF) or Performance Ratio (PR) (IEC 61724) are simple sums (YF) or averages (PR) of the PV device performance during the measurement period and so do not allow detailed correlations with parameters such as irradiance, temperature or downtime.

Many present PV performance models [4] are not ideal at modelling PV for the following reasons:

1) Too many correlated parameters – models cannot distinguish between "identical effects" such as P_{MAX} changes with "P_{MEAS}/P_{NOM}" or dirt.

2) Models use unphysical parameters e.g. "AirMass[4]". All parameters should be associated with some measurable physical quantity (e.g. I_{SC}, FF, dP/dT).

3) Models are not normalized to STC values. It is hard to compare absolute values of current or voltage between different technologies or module vs. array; and it is difficult to tell which are "good" values without comparing against the nominal values.

4) Some effects are not considered – most models do not take into account effects which may be important such as spectrum, seasonal changes or thermal annealing.

5) Nominal parameters (such as STC or NOCT values) are modelled from only one module or datasheet values – they do not account for variability in manufacturing and bin widths.

6) Models are often based on indoor measurements only – some are measured at conditions which can never occur outdoors such as 200W/m² AM1.5 at 0° AOI and 55°C (IEC 61853-1).

2 A NEW "LOSS FACTORS MODEL"

A new "loss factors" model (**LFM**) has been developed which fits measured outdoor IV curves and then apportions loss values to five independent normalized parameters (associated with I_{SC}, R_{SC}, FF, R_{OC} and V_{OC}) plus temperature and spectral corrections (for better fits) as shown in figure 1 (see also [2]).

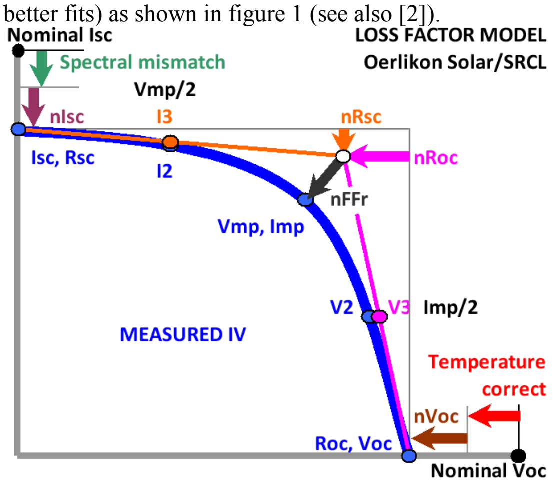

Figure 1: Determining the normalised independent loss factors (nI_{SC}, nR_{SC}, nFF_R, nR_{OC} and nV_{OC}) with two corrections (spectral mismatch and temperature) from a measured IV curve.

The benefits of the LFM include:

1) It can monitor relative changes in efficiency based on tracking the main IV parameters and can identify causes (e.g. either a fall in R_{SHUNT} or a rise in R_{SERIES}).

2) All parameters are normalized to their nominal values, so benchmarking of different modules or technologies can be done more easily.
3) It identifies how much loss is due to “previously not normalized parameters” such as R_{SHUNT} and R_{SERIES} (i.e. illustrating how much benefit to P_{MAX} and energy yield is available if manufacturers could improve these values. Reference [5] showed energy yield drops of 10% in 2004 when R_{SHUNT} were often well below minimum accepted levels in 2011.
4) It easily shows differences between nominally identical modules (mass production performance distributions) or compares different technologies.
5) It can compare module measurements from different weather sites as good weather at a low insolation site might be similar to poor weather at a high insolation site as there is no need to correct to STC (or other standard) conditions.
6) Use for Energy yield & Performance prediction.
7) Validation of R&D improvements and long term behaviour.

Sometimes non ideal “curved” shapes can be seen in the IV trace which can be due to cracked, broken, shunted or mismatched cells (to the left of the P_{MAX} knee) or Schottky/non Ohmic back contacts (to the right of the knee). Values of $I_2/I_3@V_{MP}/2$ and $V_2/V_3@I_{MP}/2$ from figure 1 can then be used to check any mismatch or non Ohmic contact problems but for a good IV module and measurement these values will usually be (100 ± <2)%.

Table 1 gives further details and definitions of the loss factors model. Note that spectral mismatch corrections need only be applied to I and β_{VOC} temperature corrections need only be applied to V to give good fits.

Table 1: Loss Factors Model (LFM) definitions, calculations and colours in later figures.

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 $= (1+\beta_{VOC}*(25-T_{MODULE}))$
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 **$= nI_{SC.G}*nR_{SC}*nFF_R*nR_{OC}*nV_{OC.T}$ <1>**
IV curvature checks on shape	
I_C	I curvature factor $= I_2/I_3 @V_{MP}/2$
V_C	V curvature factor$= V_2/V_3 @I_{MP}/2$

3 ANGULAR AND SPECTRAL DEPENDENCIES

Oerlikon Solar presently measure outdoor performance of their own, customers’ and competitors’ modules at several sites around the world, Table 2 details two locations discussed in this work in central Europe and in South Western USA.

Table 2: Details of two Oerlikon Solar Outdoor Test Facilities (OTF)

OTF Number	OTF1-CH	OTF4-AZ
Site	Trubbach, CH	Arizona, USA
Location	47°N, 10°E	34°N, 112°W
Fixed orientation	25° tilt South	33° tilt South
2D tracker?	No	Yes (6 mods.)
Module Measurement Channels	48	24
Start year	2008	2010
Horizontal/Tilted Insolation kWh/m²	~1200/~1400	~2100/~2400
Module IDs	1000-1999	4000-4999

PV data measured under clear sky conditions are often used to determine performance parameters such as low light efficiency and thermal coefficients. However all of the parameter values such as angle of incidence (AOI), air mass etc. are correlated with the tilted plane irradiance each day and these vary seasonally [1].

Blue fraction (BF) <2> measures the “blueness” of light compared with the overall spectrum and is particularly useful for a-Si/uc-Si modules as the wavebands correspond to the absorption of the blue and red junctions.

$$\text{Blue Fraction} = \frac{G_I(350-650\text{nm})}{G_I(350-1050\text{nm})} \qquad <2>$$

Note: The Blue Fraction at AM1.5 = 0.52 and bluer light has correspondingly a higher value. It serves the same purpose as Average Photon Energy (APE) and Useful Fraction (UF) in quickly quantifying the relative colour of the spectrum i.e. the insolation in the red vs. the blue.

Figure 2 shows how the solar height, AOI and Blue Fraction vary with the plane of array irradiance for a clear sky day each month from winter (December) to summer (June) at OTF4-AZ. There is a clear seasonal effect with all these parameters having a higher magnitude in summer than in winter. The blue fraction will be higher in the summer at 200W/m² than the winter as the sun will be higher at this tilted plane irradiance (also higher AOI).

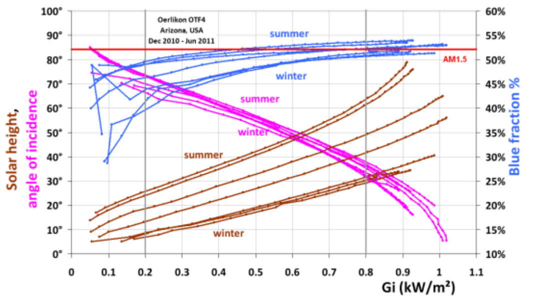

Figure 2: Blue fraction, AOI and Solar height vs. irradiance each month for clear sky days at OTF4-AZ.

Figure 3 shows similar data from OTF1-CH.

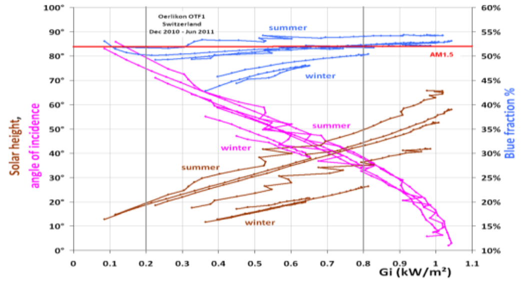

Figure 3: Blue fraction, AOI and Solar height vs. irradiance each month for clear sky days at OTF1-CH.

These parameters have a strong interdependence, especially at lower light intensity and these do vary by month. Some differences between the sites are:

1) Smoothness of data: Switzerland has more scatter as the irradiance in a clear sky seems to vary more than in Arizona – (this can also be seen in the right hand plots of figures 6a and 6b).

2) Low light data: The site in Switzerland is surrounded by mountains and therefore has a higher horizon in the east and west while the site in Arizona has a low horizon.

3) Absolute solar height: Arizona has a higher solar height as the site is closer to the equator (the height at noon in midsummer will be "90 + 23.45° - latitude" outside the tropics) so will be 13° higher.

4) Weather: Arizona has significantly more days with clear sky than Switzerland and the clearness also tends to be higher.

5) AOI : In the winter the sun will rise south of east and set south of west i.e. "in front of the module", meaning the module "sees" high air mass red light if there is a low horizon. In the summer the sun rises north of east and sets north of west i.e. "behind the module" with an AOI >90° so there will be a sudden change in irradiance where the redder direct radiation cuts out and the module only sees diffuse blue skies.

6) Blue fraction – this rises with irradiance at both sites reaching AM1.5 at the equinox at 0.8 sun, bluer in the summer and redder in the winter. At low light levels (down to 0.2sun) it becomes progressively redder, particularly in the winter.

4 REAL WORLD TEMPERATURE COEFFICIENTS

IEC standards 61215 and 61646 detail how to measure temperature coefficients by using an indoor measurement system. Several authors including [6] suggest that indoor temperature coefficients may vary with both irradiance and temperature.

A method has been developed further [7] to measure real world temperature coefficients i.e. involving non-normal angles of incidence, diffuse skies, seasonal changes etc.

A selection of data that satisfied several measurement criteria were taken and the spectrally corrected values of $nI_{SC.G}$, nV_{OC} and PF vs. (T_{MODULE}-25°C) were plotted to calculate the alpha, beta and gamma values, respectively.

Example data from these selections are shown for a c-Si module (top) and thin film (bottom) at an Oerlikon Solar OTF.

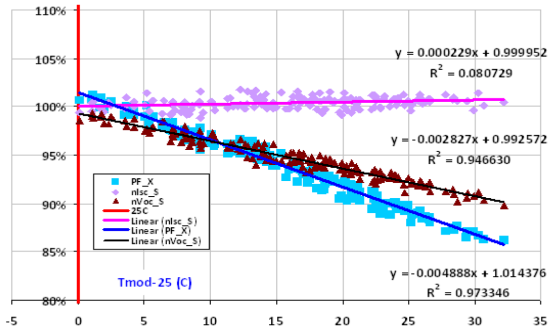

Figure 4a: Outdoor temperature performance of $nI_{SC.G}$, nV_{OC} and PF vs. temperature (T_{MODULE}-25°C) for c-Si.

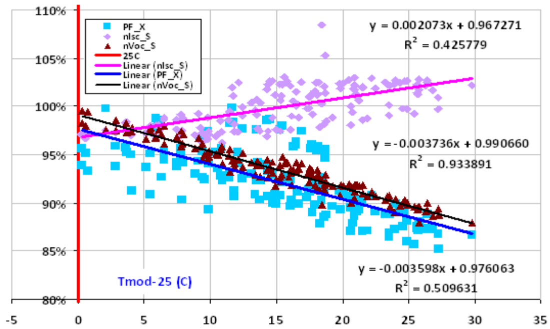

Figure 4b: Outdoor temperature performance of $nI_{SC.G}$, nV_{OC} and PF vs. temperature (T_{MODULE}-25°C) for a Thin Film.

Linear regression fits to the spectrally corrected data vs. temperature were used to find the three temperature coefficients by dividing the gradients of the fits by the intercepts to get relative coefficients at 25°C for different modules as shown in figures 5a and 5b.

$$\text{alpha} = \frac{1}{nI_{SC.G.STC}} * \frac{\partial\, nI_{SC.G}}{\partial T_{MOD}}$$

$$\text{beta} = \frac{1}{nV_{OC.G.STC}} * \frac{\partial\, nV_{OC}}{\partial T_{MOD}}$$

$$\text{gamma} = \frac{1}{PF_{STC}} * \frac{\partial\, PF}{\partial T_{MOD}}$$

Figure 5a illustrates the temperature coefficients measured in a fixed plane, the four technologies in figure 5b in the fixed plane (left) are also characterized on the 2D tracker (right) and give consistent values compared with their twin modules on fixed plane.

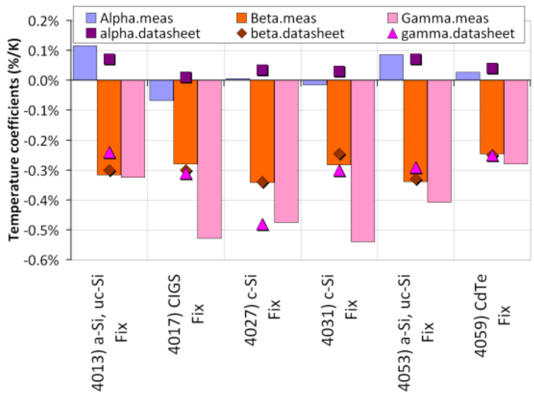

Figure 5a: Measured outdoor temperature coefficients vs. nominal datasheet values for six different PV modules under real weather conditions at OTF4-AZ.

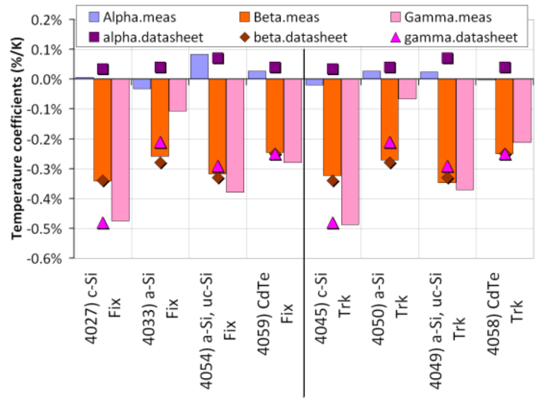

Figure 5b: Measured outdoor temperature coefficients vs. nominal datasheet values for different PV modules under real weather conditions at OTF4-AZ – left are fixed plane, right are 2D tracked equivalents.

There is some scatter in the alpha coefficients (including dirt, spectral mismatch and AOI) but the beta and gamma are close to the datasheet values – mostly <±0.05%/K.

Note, some Thin Film Modules experience seasonal annealing of the I_{SC} which causes alpha to appear more positive and makes a better gamma. For Thin Film Modules with this effect it is better to analyse temperature coefficients at shorter periods (e.g. <1 month) to avoid influence from seasonal variations.

5 SPECTRAL CORRECTIONS FOR CURRENT

Figure 6a shows detailed 100nm spectrum bins measured on a cloudy and a clear day in Arizona (5 min intervals), the blue fraction is represented as the black line and it shows monotonic falls to very low light levels. Also shown in white is the apparent irradiance (/1000W/m²) from the tilted spectroradiometer between 350-1050nm.

Figure 6b plots the effect in Switzerland, clear jumps upwards in Blue Fraction are seen at the lowest light levels on clear days as the sun sets behind the mountains (note glitches in the spectrum and Gspec line) as only diffuse bluer light is seen by the modules when the sun is above a flat horizon but is behind the mountains.

All currents are corrected by spectral mismatch factor (MMF) based on the actual measured spectrum and its corresponding spectral response.

6 VALIDATION OF THE LOSS FACTORS MODEL

The LFM has been validated based on data from OTF1-CH and OTF4-AZ [3] in two different climates with identical PV modules with fixed orientation and on a 2D tracker in AZ only.

Four different "weather types" [8] (as defined in table 3) were used to analyse the data.

Shown below are the results of LFM fitting to data points for different weather conditions for a CdTe module (figure 7), a CIGS device (figure 8) and 2 x micromorph (figures 9 and 10).

Clear ness kTh	Irradiance W/m²	Time		
		<09:00	09:00 -15:00	>15:00
>0.6	>200	Clear Morn -ing	Clear Noon	Clear Even -ing
		Other Clearness values		
<0.5	<500	DiFfuse		

Quite good agreement is seen for the pairs of modules at the two different sites (i.e. the left and right parts are similar).

Differences between the PV technologies can be seen by the values of each coefficient.

The overall Performance Factor is indicated by the height of the lowest of the 6 lines.

Low light level performance is estimated by the drops in performance at 0.2 vs. 1.0suns.

The CdTe modules appear to have a lower nR_{OC} value (hence a higher R_{SERIES}) than the others due to their slope at high irradiance. The CIGS modules appear to have a worse low light because of a falling nV_{OC}.

The Micromorph modules have more scatter in the $nI_{SC.G}$ and they show different behaviour for diffuse and clear skies because of their 2 junctions.

Note all these graphs are spectrally and temperature corrected to fit the model, the actual performance depends on the uncorrected data which can be replotted with the corrections reversed but this will be shown in upcoming publications.

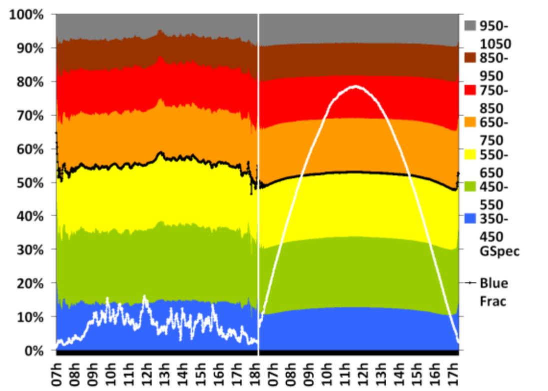

Figure 6a: Diffuse day and clear day spectra at OTF4-AZ 21 and 23 Mar 2011.

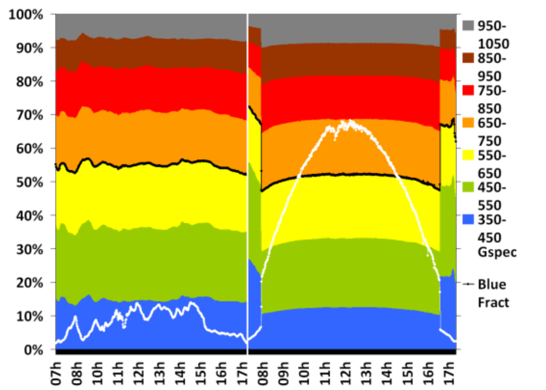

Figure 6b: Diffuse day and clear day spectra at OTF1-CH 19 and 20 Mar 2011.

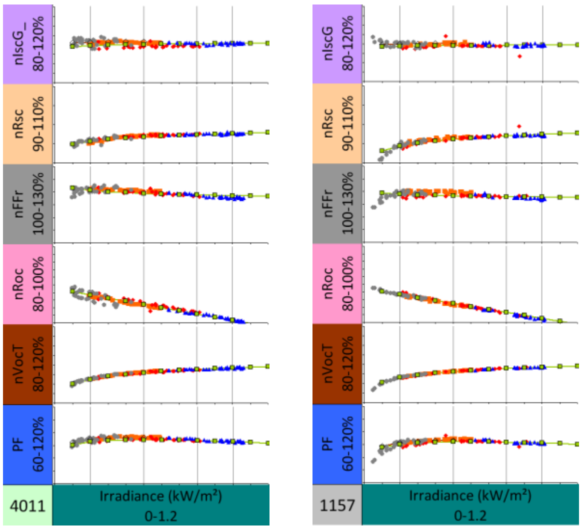

Figure 7: LFM fits to a CdTe module vs. Irradiance at OTF4-AZ (left 4011) and OTF1-CH (right 1157).

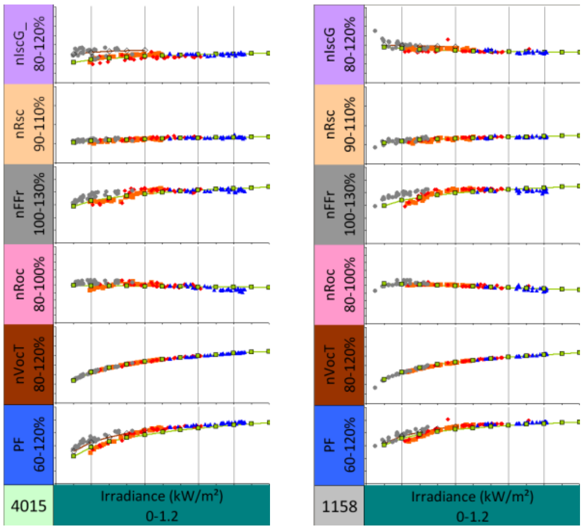

Figure 8: LFM fits to a CIGS module vs. Irradiance at OTF4-AZ (left 4015) and OTF1-CH (right 1158).

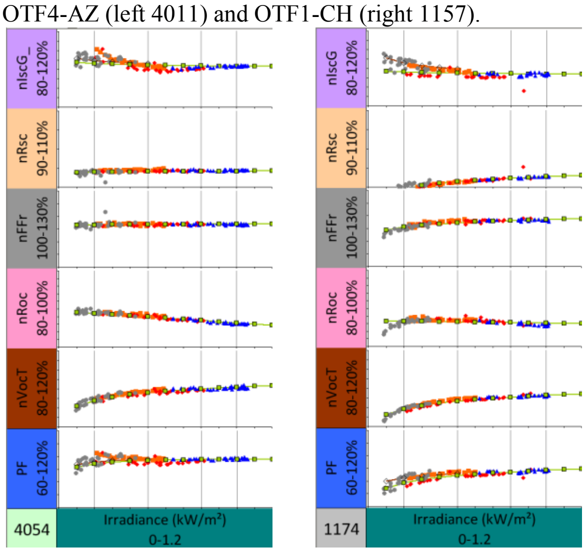

Figure 9: LFM fits to an a-Si/uc-Si module vs. Irradiance at OTF4-AZ (left 4054) and OTF1-CH (right 1174).

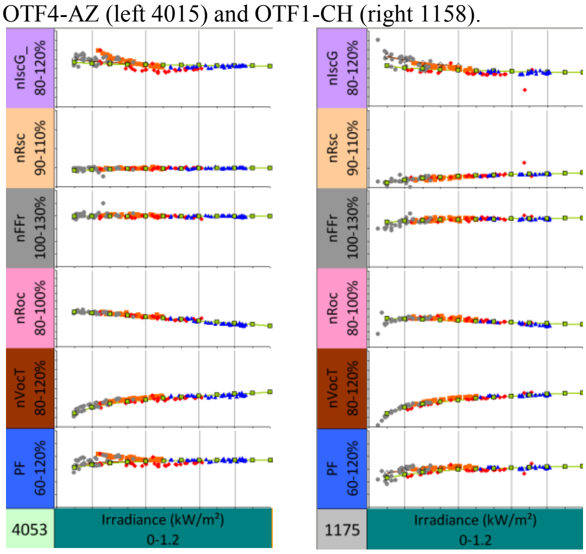

Figure 10: LFM fits to an a-Si/uc-Si module vs. Irradiance at OTF4-AZ (left 4053) and OTF1-CH (right 1175).

7 LOSS FACTOR ANALYSIS

Figure 11 compares the 5 fitted loss factor coefficients (green lines in figures 7 to 11) for spectrally and thermally corrected measurements from 6 different modules at OTF4-AZ at high light levels (800W/m², coloured bars) and low light levels (200W/m², black bars).

The Performance Factor is plotted in the top chart of Figure 11 in blue colour. It is the product of all of the 5 readings below it.

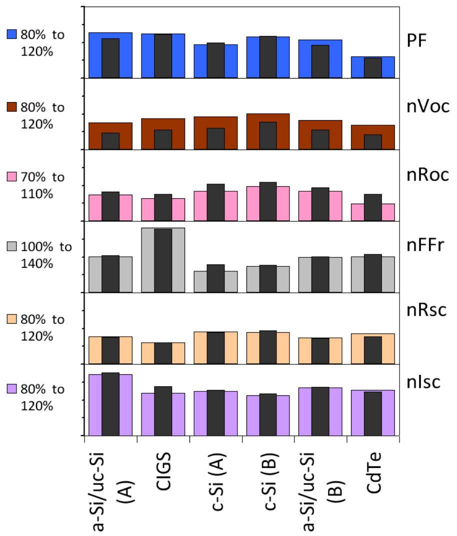

Figure 11: Five fitted loss factor coefficients for various modules at OTF4-AZ

The overall energy yield of the modules will be dominated by the PF values at low and high light levels; however it is also useful to look at the 5 individual loss values to see how they differ and how the performance may be improved. Note, they all depend on the random process variations and the $P_{MAX.ACTUAL}/P_{MAX.NOMINAL}$.

1) $nV_{OC.T}$ will always be worse at low light levels than high – the best modules have $nV_{OC.T}$ near 100% at high light levels – 2 modules are a little lower.
2) nR_{OC} (which depends on R_{SERIES}) is best for the c-Si modules as may be expected (for c-Si it may be dominated by the cell tabbing at something like 0.5Ω/module but for a thin film it will be dominated by the TCO at around 10Ω/square and will therefore be much higher).
3) nFF_R (FF independent of R_{SC} and R_{OC}) varies 25% between the modules and is best for the CIGS module.
4) nR_{SC} (dominated by R_{SHUNT}) is similar but slightly better for c-Si, worst for the CIGS.
5) $nI_{SC.G}$ has the highest uncertainty due to dirt, spectral corrections and AOI dependency. The best value is for the a-Si/uc-Si and the worst is the CIGS but this parameter will depend on module manufacture variability.
6) PF is the product of the 5 other LFM values.

8 MEASURED vs. MODELLED PERFORMANCE

Once these modelled parameters have been found, they can be folded into the weather data to predict the performance under different weather conditions to check past, present or predict future performance.

Figure 12 shows the accuracy of a modelling for a thin film module at OTF4-AZ for a cloudy and a clear day.

At the top (right axis) of the graph are the irradiance, and module temperatures. To the left axis are measured vs. modelled nR_{SC}, $nI_{SC.G}$, $nV_{OC.T}$, nR_{OC} and nFF_R.

For clear sky conditions good fits have been found with all parameters at higher irradiances, there is a little scatter around otherwise good fits at low light/diffuse conditions and this is being studied further.

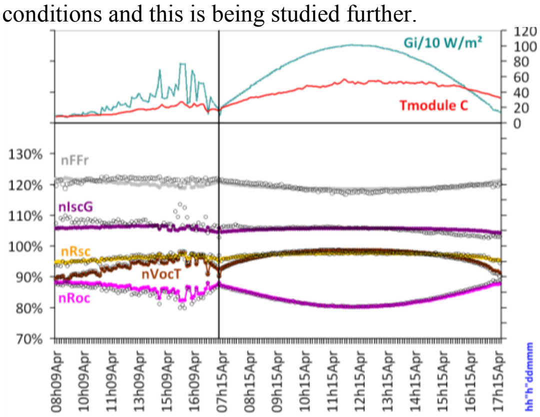

Figure 12: Fitted (colour) vs. measured (black) loss factor parameters and weather data for a thin film module measured at OTF4-AZ showing good agreement for a diffuse and a clear day in April

9 TRACKED MODULES vs. FIXED ORIENTATION

For a module with fixed orientation there is a correlation between parameters such as AOI, irradiance and solar height as shown in figures 2 and 3, for example the reddest skies must always be associated with high angles of incidence and low light levels. OTF4-AZ has a 6 module 2D tracker – this can be used to keep the AOI at 0° so that the spectral and AOI dependencies can be studied separately.

Figure 13 compares the performance of two similar c-Si modules at OTF4-AZ on a fixed array (left) vs. a 2D tracker (right). For modules mounted on the tracker there will be much higher irradiance in clear morning and evening conditions compared to modules at fixed plane. It can be seen that the biggest difference is in the increased irradiance values of the clear morning (orange) and evening (red) measurements due to the tracker – however the shapes and values of the curve fitting to the 5 loss factors is quite similar between the two modules.

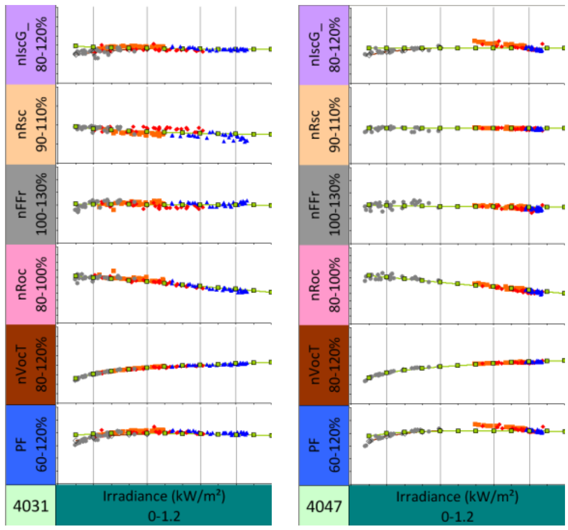

Figure 13: c-Si module at OTF4-AZ, Fixed plane (left 4031) vs. Tracker (right vs. 4047)

Figure 14 compares the performance of two different micromorph modules. There is more of a deviation in low light clear vs. diffuse than in figure 13.

The LFM works well for single junction modules while for multi junction modules some refinement might be necessary to obtain the same accuracy.

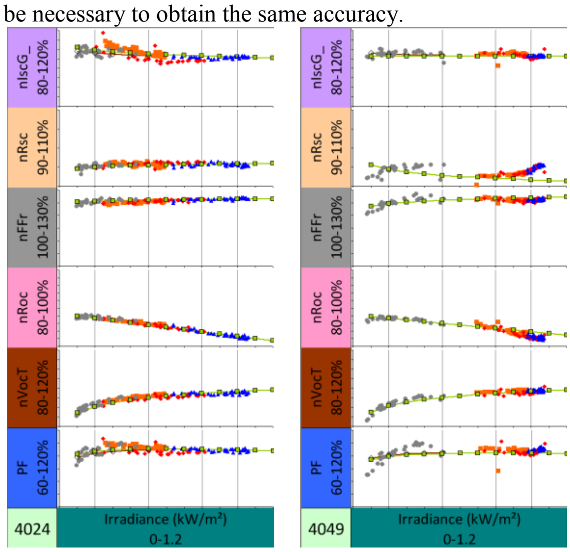

Figure 14: Micromorph modules at OTF4-AZ, Fixed plane (left 4024) vs. Tracker (right vs. 4049).

10 IMPORTANCE FOR ENERGY YIELD

Energy Yields (in kWh/kWp) are important in the design and validation of a PV System as well as for its levelised cost of electricity (LCoE).

The kWp is the nominal value of the array and it is defined by the manufacturer nameplate rating. This value is limited in accuracy by the value of the calibrated reference module, random flash tester error, module bin width and nominal Wp rating which includes also the allowance of future long term degradation until the end of lifetime guarantee.

Energy yields can be different due to technical and commercial reasons.

The technical way to ensure a high energy yield is to optimise the combination of loss factors as in table 4:

Table 4: – Key parameters for maximising energy yield kWh/kWp

Parameter	Comments
$P_{MAX.NOMINAL}$ / $P_{MAX.NAMEPLATE}$	High from positive binning tolerances from manufacturers
Site selection	High insolation site (kWh/m²/y)
Good array orientation	Tilt near latitude towards equator for best yields
Low T_{MODULE} with proper ventilation	From better thermal module design and/or free ventilation
Minimal shadowing	Try for no shading in spring to autumn day hours, if impossible string array to minimize total loss
Good module stability	Many guarantees are <20% drop P_{MAX} in 25 years. Predictable (long term) degradation during lifetime.
Clean modules	Minimise soiling but compare the cost of cleaning and possible damage vs. lost energy yield
Electrical parameters	
PF (high and low irradiance)	High values fitted from LFM
nI_{SC}	Low dirt value, good AR coating
nR_{SC} (~Rshunt)	Good high R_{SHUNT} will minimize losses at low light levels nR_{SC}>90%
nFF_R	>110% (c-Si), >120% (TF)
nR_{OC} (~Rseries)	Good low R_{SERIES} will minimize losses at high light levels nR_{OC}>85%
nV_{OC}	Good β coefficient, low T_{MODULE}
Spectral correction	Maximise absorption of each junction and match multi-junctions for best site specific yield
Other	Proper Monitoring equipment and field performance validation

11 CONCLUSIONS

The LFM described in this paper has fitted all PV technologies tested under clear and diffuse weather conditions (in central Europe and SW USA) for both fixed plane and 2D tracker.

Differences at low light behaviour and temperature coefficients can be checked and validated with the LFM.

Seasonal changes can be distinguished from degradation.

Previously the effect of loss of energy yields due to R_{SC} and R_{OC} were hard to quantify, now they can be determined easily and the value of improvements can be estimated.

Future R&D improvements can be validated quickly and accurately.

PV Module manufacturers can focus and optimize on all electrical LFM parameters for their mass produced modules. This can ensure high production quality, realistic lifetime expectations and better energy yield harvest and performance prediction.

System Developers and Investors will be able to reduce their financial risks with well characterized PV devices leading to lower uncertainties and better understanding of the PV Power Plant performance.

The LFM can be compared with indoor measurements and characterization such as the IEC 61853-1 "ENERGY rating".

12 REFERENCES

[1] S. Ransome: "Recent Studies of PV Performance Models", Invited talk Sandia PV modelling workshop, 2010

[2] S. Ransome: "Improving and Understanding kWh/kWp Simulations", 26th EUPVSEC Hamburg, 2011

[3] J. Sutterlueti et al.: "Energy Yield Optimization and Seasonal Behaviour of Micromorph Thin Film Modules", 25th EUPVSEC, Valencia, 2010

[4] S. Ransome: "Comparing PV simulation models and methods with outdoor measurements", PVSC Hawaii, 2010

[5] Grunow et al: "Weak light performance and annual yields of PV modules and systems as a result of the basic parameter set of industrial solar cells", 19th PVSEC, Paris, 2004

[6] U. Jahn et al.: "Comparison of Different Thin-Film Technologies - Performance Characteristics Obtained from Laboratory and Field Tests", 25th EUPVSEC, Valencia, 2010

[7] J. Sutterlueti et al.: "Outdoor Characterisation and Modelling of Thin-Film Modules and Technology Benchmarking", 24th EUPVSEC, Hamburg, 2009

[8] S. Ransome "How kWh/kWp Modelling and Measurement Comparisons Depend on Uncertainty and Variability" 37th PVSC; Seattle 2011