UNDERSTANDING PV MODULE PERFORMANCE: FURTHER VALIDATION OF THE NOVEL LOSS FACTORS MODEL AND ITS EXTENSION TO AC ARRAYS

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ABSTRACT: The Loss Factors Model (LFM) has been introduced as a tool to better understand PV module performance under outdoor conditions. It is based on outdoor IV curves compared with its reference values to find six independent and normalized coefficients which when multiplied result in the DC Performance Factor. The Loss Factors Model thus allows us to easily monitor any changes in module efficiency and determines which IV parameters is responsible for changes. In this paper we show how the model can be used to extract outdoor temperature coefficients, low irradiance behavior and how seasonal variations can be distinguished from effects such as degradation or soiling. We compare different PV technologies such as Thin Film or crystalline Silicon at different climatic conditions and show how the Loss Factors Model can be used as a basis for quick benchmarking and prediction of PV performance. The DC-only Loss Factors Model then has been extended to model AC systems. Two a-Si power plants, with similar PV Modules (a-Si) and different inverter topologies (transformer, transformerless) have been modeled based at one year of data from a single a-Si module, seasonal annealing has been added and the model predicts well the power plant performance when it is working optimally and shows underperformance due to broken modules or snow cover. The setup also shows no impact on long term degradation as expected due to transformerless inverters.

Keywords: Modeling, Outdoor Testing, Characterization, PV System

1 INTRODUCTION

The performance of Photovoltaic (PV) power plants depends on the outdoor performance of its individual PV modules, the stringing and mismatch of PV modules and the performance characteristics of its inverters with limits on the input Power (wake up and clipping) and Vmp tracking.

Energy yield and Performance Factor (PF) are used to characterize the performance of PV power plants but their usefulness is limited due to the known variability of modules from production lines, the uncertainty of measurements (especially irradiance) and the unknown Pmpp calibration used by the manufacturer [1].

For characterization of the individual PV modules a method based on IV parameters is essential to help distinguish performance losses (for example falling Imp could be caused by overall falling shunt resistance or cell mismatch, monitoring just Imp could not tell which one is happening). A model which normalizes measured outdoor IV data to reference data such that losses can be separated in current and voltage losses was presented at the 26th EUPVSEC 2011 [2] as Loss Factors Model (LFM). An enhancement of the model (LFM-B) was then presented on the 38th IEEE PVSC conference 2012 [3].

In this paper we compare amorphous Silicon (a-Si), micromorph^{TM} (a-Si/uc-Si) and crystalline Silicon (c-Si) PV modules at OTF1-CH (Switzerland) and OTF4-AZ (Arizona/USA) using the LFM-B. The PV modules were randomly selected. For normalization we used the IV parameters from the data sheets. Thus the absolute difference between modules depends on the module binning widths – for example comparing two 100Wp modules in bin widths of 100-102Wp means an absolute difference of <4% is not statistically significant. The behavior of single modules analyzed with LFM-B is then compared to the performance of Test PV power plants (T-PVPP) at the same location.

2 LOSS FACTORS MODEL

The Loss Factors Model allows PV modules of any technology to be characterized by six normalized, independent and physically significant coefficients plus correction factors for module temperature and spectral mismatch. These normalized coefficients (prefix “n”) are calculated from measured outdoor IV parameters (prefix “m”) and from reference IV parameters (prefix “r”) as for example indoor flash measurements at standard test conditions (STC) or from name plate values. The Loss Factor parameters are defined in Figure 1 and Table I.

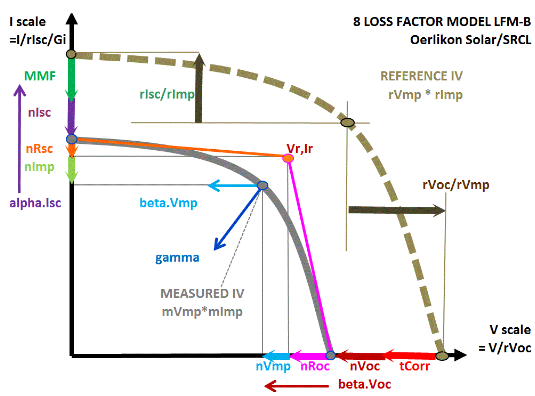


Figure 1: Graphical derivation of LFM-B parameters.

The magnitudes of LFM-B parameters at high irradiance levels extrapolate to the STC values while at low irradiance levels the low light behavior (LLB) can be studied. The gradients of LFM-B coefficients versus module temperature determine the temperature coefficients alpha, beta, gamma, etc. It can be useful to define two more coefficients namely nIdc and nVdc which refer to the maximum power point when complete

IV curves are not available (see lower part of Table I).

The Performance Factor (DC-Efficiency.measured / Efficiency.STC) can be expressed as the product of the Loss Factor coefficients:

$$PF = [MMF \cdot (nIsc \cdot tCorr.Isc) \cdot nRsc \cdot nImp] \cdot [nVmp\, nRoc\, (nVoc \cdot tCorr.Voc)] = [nIdc] \cdot [nVdc] \quad \text{<1>}$$

Table I: LFM-B equations
The intersection of Rsc and Roc is at (Vr, Ir).

Description	formula
MMF	spectral mismatch factor
nIsc	mIsc / rIsc / Gi
nRsc	%Pmax loss due to Rsc
nImp	mImpp / Ir * rIsc / rImp
tCorr.Isc	1+alpha.isc*(25-Tmod)
nVmp	mVmpp / Vr *rVoc / rVmp
nRoc	%Pmax loss due to Roc
nVoc	mVoc / rVoc
tCorr.Voc	1+beta.voc*(25-Tmod)
nIdc	mImp / rImp / Gi
	= mmf * nIsc * nRsc * nImp * tcorr.Isc
nVdc	mVmp / rVmp
	= nVmp * nRoc * nVoc * tCorr.Voc

3 SINGLE MODULE CHARACTERIZATION

3.1 Outdoor Test Facility (OTF)

The Outdoor Test Facilities (OTF) are located in Switzerland (OTF1-CH) and Arizona (OTF4-AZ). Modules are oriented South with a tilt angle of 25° at OTF1-CH and a tilt angle of 33° at OTF4-AZ. At OTF1-CH a total number of 48 modules can be installed and tested simultaneously. At OTF4-AZ 24 modules can be tested at fixed orientation and 6 modules can be mounted on a 2D Tracker. For each individual module IV scans are measured with a calibrated DC load every minute and logged together with averaged environmental data measured during the period of each IV scan.

The OTFs are equipped with measuring tools to continuously collect environmental data of high accuracy. Pyranometers (CMP22, secondary standard) are installed for in-plane (Gi), global (Go) and diffuse irradiance measurements, a Pyrheliometer (CHP1) mounted on a sun tracker is measuring direct irradiance, a calibrated Spectroradiometer (MS700) measures the solar spectrum each minute to allow for spectral corrections. Various unfiltered and spectrally filtered c-Si reference cells are mounted for reference measurements. Module temperature is measured with PT100 temperature sensors on the back side of the PV module, ambient temperature, wind speed, wind direction and humidity are other parameters which are logged every minute to characterize the outdoor conditions under which the modules are being tested. From the measured solar spectrum and the spectral response of each module the spectral mismatch factor (MMF) is calculated automatically to allow for spectral correction.

For calculation of the Loss Factor parameters and the temperature corrections datasheet values of each module are used.

The LFM-B coefficients can be calculated from each set of outdoor IV parameters using the equations in Table I. The Loss Factors can then be analyzed as a function of irradiance (Gi), as a function of temperature (using non-temperature corrected data) and as a function of time.

3.1 Analysis of LFM-B parameters versus temperature

The slope of linear fits to spectrally and non-temperature corrected LFM-B parameters versus module temperature can be used to determine the temperature coefficients (TC) alpha, beta, gamma etc.

The result of such analysis is shown in Figure 2 for a c-Si PV module located in OTF1-CH. Data from one clear day every third month from September 2010 to March 2012 were taken for the analysis.

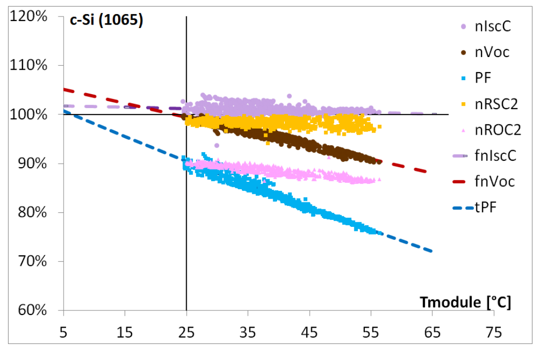


Figure 2: LFM-B coefficients and their gradients versus module temperature for a c-Si PV module at OTF1-CH.

This fitting procedure can also be done for shorter periods of time (e.g. monthly) to analyze long-term or seasonal variations of TC. Such a study was done for PV modules of different technologies in [3].

3.2 Analysis of LFM-B parameters versus irradiance

Figure 3 shows the variation of LFM-B parameters for a-Si, a-Si/uc-Si and c-Si PV modules with (in-plane) irradiance (Gi) at OTF1-CH from August 2009 to August 2012.

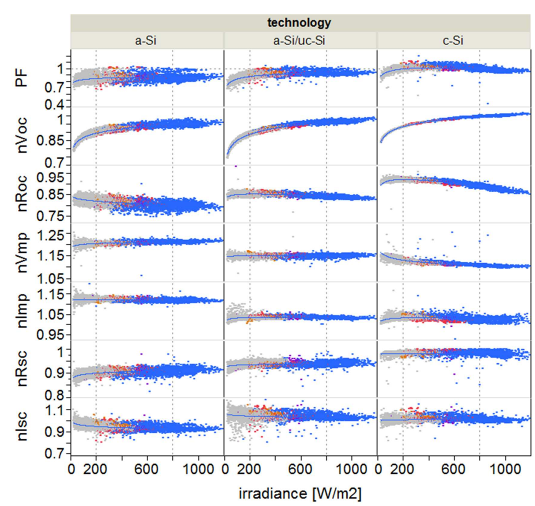


Figure 3: Performance factor (PF=mEff/rEff) and LFM parameters as a function of irradiance (Gi) for a-Si, a-Si/uc-Si and c-Si PV modules at OTF1-CH from 08/2009-08/2012.

Logarithmic/linear fits to the LFM-B data points can be used to model the behavior of these modules as a function of irradiance.

The color code in Figure 3 indicates clear morning (orange), clear noon (blue), clear evening (red) and diffuse (grey) weather conditions. Categorizing each data point based on environmental data allows to distinguish different module behavior in different weather situations. For example, low light situations may occur at clear morning and clear evening situation but low irradiance levels will also be faced under diffuse weather conditions in the middle of the day but with completely different spectral conditions and different angle of incidence (AOI) situations. So, working with different weather types allows to fit LFM-B parameters by these categories which in turn allows to investigate these situations in much more detail – this often causes differences in nIsc at low light between clear sky/high AOI and diffuse sky, particularly for multi-junction devices.

From Figure 3 we can see that the crystalline Silicon module has good low light performance with losses only starting for irradiances smaller 200W/m^2. For all three technologies performance losses at low irradiance levels are mostly due to losses in nVoc. The a-Si and micromorph^{TM} PV modules seem to gain current at low light levels while nIsc of c-Si is rather flat. The c-Si has highest nRoc and nRsc which is inherent for the technology. Because this data is over a long period (August 2009 to August 2012) the widths of the traces are wider due to thermal annealing, degradation or other effects. The a-Si module shows a relatively wide scattering of its LFM-B parameters (some more than others) compared to the micromorph module or the crystalline PV module which shows the least scattering, i.e. variation over this long period.

If LFM-B parameters are fitted separately over shorter periods of time instead of fitting over the full period of outdoor testing then effects such as degradation, seasonal annealing etc. can be analyzed in more detail.

3.3 Analysis of LFM-B parameters versus time

Testing PV modules for just enough days to cover the range of low to high irradiance levels with a statistically sufficient number of data points would then allow to determine the module behavior as a function of irradiance. However, it is clear that if only few days are analyzed the prediction from these data has only limited validity. Long term degradation and seasonal variation may not be reflected from a few days of monitoring. On the other hand if a long period is taken for the analysis then the data points in such a plot may scatter more (due to annealing, dirt etc.) and therefore the quality of fit and thus the quality of the model is less accurate.

In Figure 4 the same PV modules from Figure 3 were now analyzed for each month separately for a period from October 2009 to July 2012. For better visibility only quarterly data are shown.

Such an analysis of LFM-B parameters versus irradiance may quickly become impractical when more modules are to be compared or shorter but more periods are studied as in Figure 4. For quick analysis we may then simply use the values of each fit to the LFM-B parameters at low (200W/m^2) and high light (800W/m^2) levels (indicated as grey dotted vertical lines in Figure 3).

In Figure 5 such an analysis was done for the PV modules shown in Figure 4 from OTF1-CH but also for similar modules at OTF4-AZ. Similar here means that the PV modules with the same nominal rating were purchased anonymously and after comparison of flash measurements and electroluminescence (EL) pictures two modules with similar performance were selected for the two OTFs.

The first six months at OTF1-CH show somehow higher nIsc and PF. This might be related to some irradiance sensor issues but could not be tracked back entirely. This has to be considered for the following graphs.

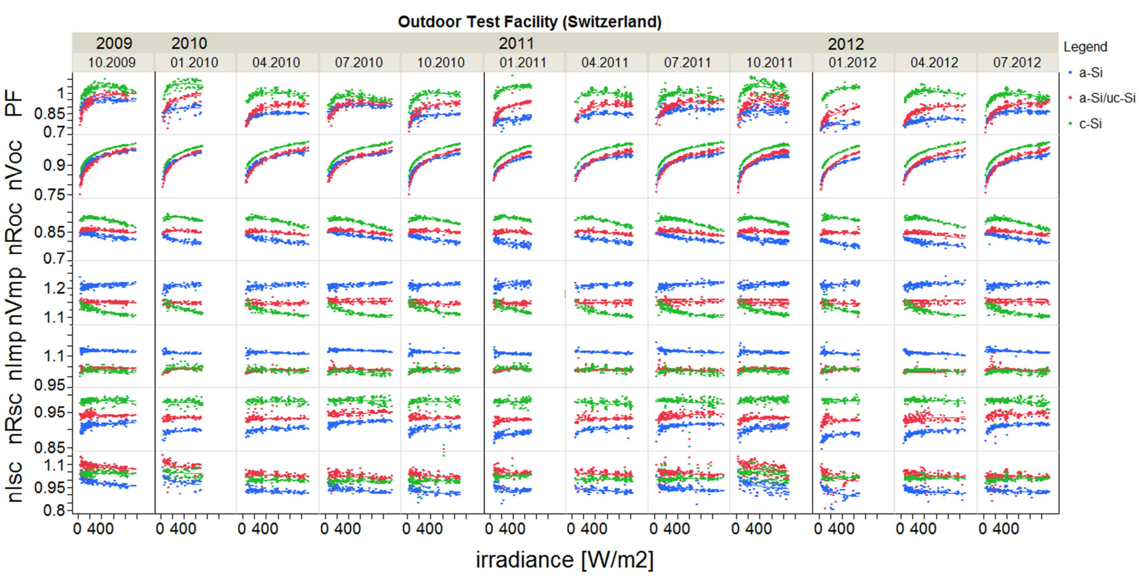


Figure 4: LFM-B parameters and PF versus irradiance for quarterly data from 10/2009 to 07/2012 for a-Si, a-Si/uc-Si and c-Si PV modules at OTF1-CH.

Figure 5 (a) shows a-Si, (b) a-Si/uc-Si and (c) c-Si PV modules. OTF4-AZ data are plotted on the left and OTF1-CH data are plotted on the right side of each figure. Data for each month have been fitted and values of LFM-B parameters at low irradiance levels (200W/m^2) are plotted as black circles and the values at high irradiance levels (800W/m^2) are shown as colored circles.

With the low and high irradiance behavior for each LFM-B parameter and each month as shown in Figure 5 long term variations can be studied more easily.

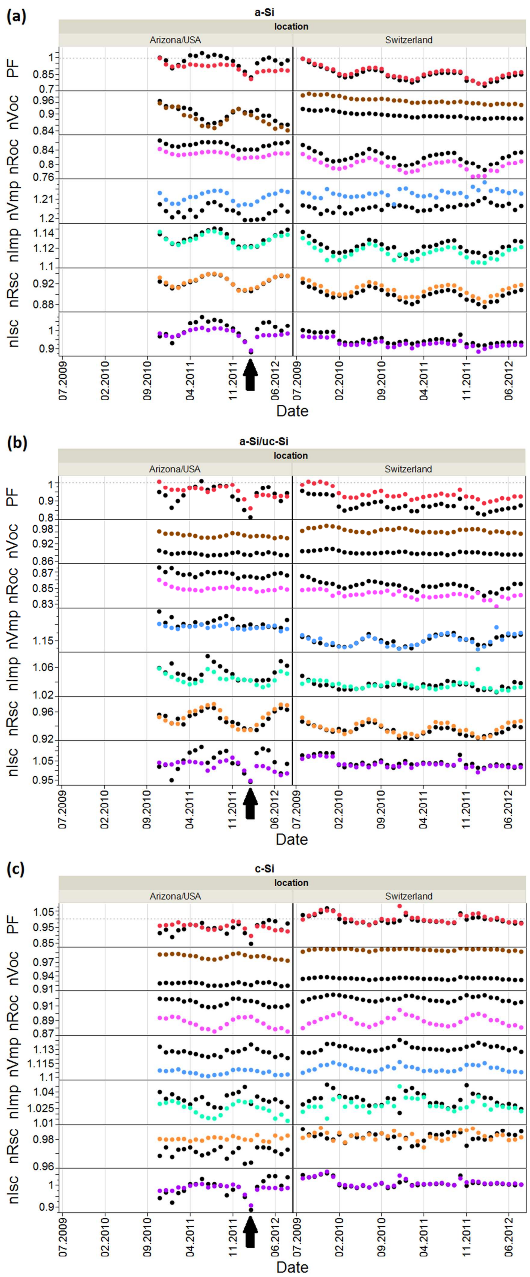


Figure 5: LFM-B parameters and PF at low (200W/m^2, black circles) and high (800W/m^2, colored circles) irradiances every second month from 08/2009 to 08/2012 for (a) a-Si, (b) a-Si/uc-Si and (c) c-Si PV modules at OTF4-AZ (left) and OTF1-CH (right).

The dip in nIsc and PF at OTF4-AZ around 01/-02/2012 (indicated by the arrow) is due to strong soiling of all PV modules after a sandstorm. After cleaning of the PV modules nIsc and PF recover to the values before.

The comparison of each module at OTF1-CH with similar modules at OTF4-AZ shows that different climatic conditions have some quite significant impact.

The crystalline PV modules at both OTFs show only a small variation over the year with a decrease in PF and LFM-B parameters in summer periods when temperatures are high. For c-Si modules at OTF4-AZ some parameters vary more and seem to be on a lower level than the c-Si module at OTF1-CH. The crystalline PV modules measured at OTF1-CH show higher PF in Switzerland than in the hot and dry climate of Arizona.

Amorphous and micromorph PV modules show stronger variation over the year both with their maximum in PF and nIsc in summer and their minima in winter (opposite to the behavior of the c-Si module). The effect seems more pronounced in Switzerland than in Arizona (which has a more blue shifted spectrum) and micromorph shows less variation than amorphous Silicon thin film as expected. For the micromorph module some variation may come from spectral correction errors since spectral response was only measured for the initial matching state of the module and not for various spectral conditions. This will be presented in a forthcoming paper.

Note that OTF4-AZ has a flat horizon and therefore a higher fraction of red light at low sun elevations but higher blue fraction than OTF1-CH (which has mountains east and west) during clear days. The clearer skies and lower latitude lead to higher sun elevations.

3.4 LFM prediction

The shapes of any changes of LFM-B parameters with time offers another possibility to gather information on module performance (and potential losses). Since nIsc is spectrally corrected it is expected to be almost flat. As Voc~ln(Gi) the shape of nVoc is expected to be concave. Deviations of LFM-B parameters from the model may result from seasonal annealing, degradation, soiling, angle of incidence effect (AOI) or other non-modeled effects.

Figure 6 shows temperature corrected nVoc, nIsc (spectrally corrected), PF, in-plane irradiance (Gi in kW/m^2 scaled by a factor 100), ambient temperature (Tamb) and module temperature (Tmod) for c-Si, a-Si and a-Si/uc-Si PV modules for one clear day each month from September 2010 to April 2012. Furthermore, fits of nVoc and nIsc resulting from LFM-B versus irradiance analysis are now plotted over time. Data from OTF1-CH are plotted in (a) and data from OTF4-AZ are plotted in (b). The measured irradiance Gi is used to determine the LFM-B parameters from derived Loss Factors vs. irradiance fits as was done in Figure 4. The spikes in some graphs are due to sunrise/sunset effects.

To avoid effects due to dust or dirt as in Figure 5 we used the crystalline module at OTF1-CH and OTF4-AZ as an irradiance reference assuming that all modules of one location are exposed to similar soiling.

The predictions of nIsc and nVoc (small symbols) as extracted from fits to these LFM-B parameters versus irradiance show good agreement with the measured values.

The PF in Figure 6 (blue line) is temperature and spectrally corrected and therefore cannot be used for energy yield analysis. PV performance depends on external influences including temperature and spectrum. When modeling performance these effects are corrected with coefficients such as gamma and MMF so that it can be determined if modules are performing according to the model or whether there is degradation or deviation from the model. The Energy Yield (EY) produced by a module does not use corrected data (apart from downtime for a given module where interpolated data is used to compare against other modules) so Energy Yield predictions need to be "uncorrected from the model".

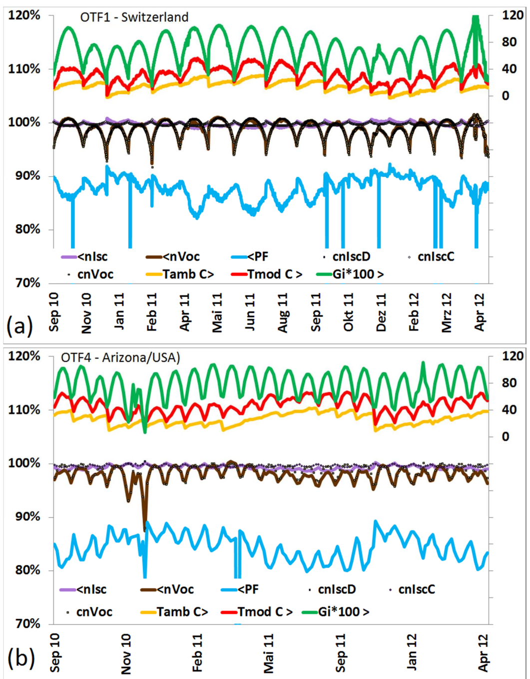


Figure 6: Irradiance (Gi), ambient and module temperatures, PF, LFM-B parameters nIsc, nVoc and their fits over time for similar c-Si PV modules at OTF1-CH and OTF4-AZ (09/2010-04/2012).

The first part of this paper focused on the characterization of individual PV modules under outdoor conditions and at different climatic conditions. A more detailed analysis including more technologies can be found in [3]. In the following section we try to model the AC performance of PV power plants based on LFM-B characterizations of a similar individual PV module.

5 EXTENSION TO AC ARRAYS

Modeling AC performance is not quite so straight forward as modeling DC as there are inverter limitations on the V_{DC} input (where it has to be within the V_{mpp} tracking window), on the I_{DC} (less than a design maximum) and also on P_{DC} (again less than a given manufacturer design limit). The efficiency of the AC output over the DC input will depend on both P_{IN} and V_{DC}.

The number of modules in series and parallel are chosen versus the inverter's design characteristics to match the V_{DC}, I_{SC} and P_{DC} under the extreme weather conditions such as lowest or highest module temperature at the highest irradiance expected. The modeled value of PR is then calculated by:

$$PR_{AC} = PF_{DC} * fI_{DC} * fV_{DC} * fP_{DC} * Inv_{eff}(V_{DC}, P_{DC}) \quad \langle 2 \rangle$$

Where the PF_{DC} can be calculated by the LFM-B coefficients and methodology. fI_{DC} and fP_{DC} model the output as filter functions of the input conditions and may look like "low pass" (for P or I) or "band pass" (V_{MPP} tracking).

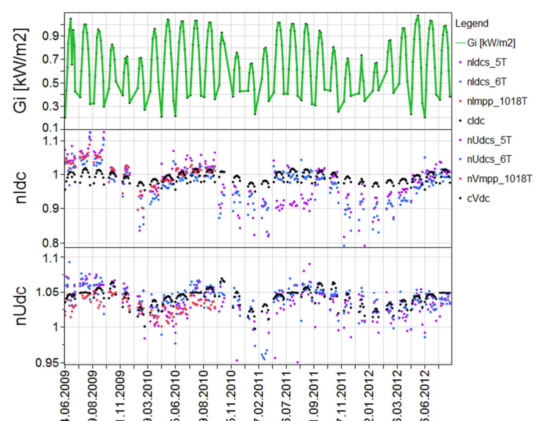
At the OTF1-CH site in Switzerland the individual DC IV traced modules are side by side with arrays of modules feeding power into grid connected inverters as specified in Table II.

Table II: Test PV power plants in Switzerland.

PVPP ID	type	strings	modules per string	inverter	Pnom [W]
5	a-Si	6	4	no transformer	1802
6	a-Si	11	4	transformer	3325

Inverter	**Variables**	**Values**
	Vin.max	550V
	Vmp.	175-440V
	Iin.max	15A
	Pin.max	4200W
Modules a-Si		
	Vmp	93V
	Imp	0.81A

The performance of two a-Si power plants (PP 5 and 6, different inverter topologies) is shown in Figure 7 (Imp and Vmp) compared with the measured performance of a similar individual a-Si module (1018, red).



Figures 7: Stabilization of the a-Si arrays over 3 years with seasonal annealing of (a) nIdc and a smaller change in (b) nVdc (hourly data).

The PV modules at PP5 and PP6 are from the same module manufacturer and same production batch so that results of the two power plants are comparable.

There was a single module of exactly the same type and vintage on individual IV scan test for the first year which was used to derive its LFM-B parameters (as in Figure 5) which were then used to compare with the array performance. These parameters were extracted from a monthly dataset (using hourly data) – this allows seasonal annealing effects on nIdc and nVdc to be modeled as indicated by the black dots in Figures 7.

The nIdc (current) in Figure 7 shows a good fit when the plants are performing optimally. There are three discrepancies, the first two months the measured nIdc was higher than modeled due to stabilization, late 2010 to Sept 2011 there was a broken module in PP5 (meaning only 10/11 strings were working and the nIdc was therefore about 9% lower than expected) and in the mid winters there may well be snow cover affecting current but the summers of 2010-2012 all show good agreement meaning a good modeled fit and very small degradation.

The nVdc (voltage) in Figure 7 shows an even better fit – there is a little stabilization at the beginning and a few excursions around November 2010 – the reason is not known but for the final year the fit is excellent.

The LFM-B parameters from the individual module data in Figure 8 were multiplied by the other parameters from equation <2> modeling the I_{DC}, V_{DC} and P_{DC} limits and a simple model for the inverter efficiency were used to estimate the predicted performance ratio of the power plants.

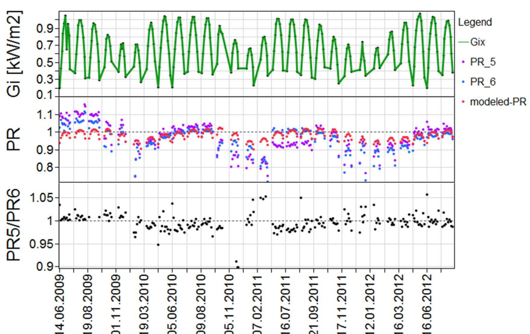


Figure 8: Comparison of Performance Ratio of plants 5 (pink) and 6 (blue) versus model (red) and ratio of PR5/PR6 (hourly data).

It shows Performance Ratio data for clear sky days (approximately one per month) for over 3 years. There is some initial stabilization to August 2009 then there was underperformance from January to July 2011 of PR_5 due to broken module taking out 1 of the 6 strings as discussed in Figure 7. The a-Si shows a decline in performance in wintertime (due to thermal annealing and snow cover) and improved performance in Summer as modeled by the seasonal annealed LFM-B fits. The graph shows the a-Si array climbing back to the same PR values in late summer 2010-2012 indicating good stability.

There is a small difference between PR_5 and PR_6 so if we normalize the performance ratios of both power plants to their initial value their ratio (grey line in Figure 8) is mostly constant over 3 years. The two power plants have the same PV modules and number of modules per string. Only the number of strings varies and the inverters are different. The inverter for power plant 5 has no transformer while the one for power plant 6 has a transformer. Supposed that the number of strings does not have a significant impact on the tracking and PV modules in both power plants degrade similarly then the ratio of PR of both power plants (normalized to their initial values) should show the degradation due to the inverters, i.e. potential induced degradation and TCO corrosion in the case of the transformer less inverter [4]. So far none of the two effects is observed and the power plant with transformerless inverter does not show any degradation.

6 CONCLUSIONS

We demonstrated how PV modules of different technologies can be studied with the Loss Factors Model. The performance losses of modules were assigned to the IV parameters responsible and effects such as seasonal annealing or degradation were distinguished. Previously the energy yield losses due to Rsc and Roc were hard to quantify due to their correlation with fill factor. Now, due to the normalization by the Loss Factors Model these parameters can be analyzed easily to give quick feedback on any cell or module improvements. Furthermore, the Loss Factors Model offers a simple way to analyze temperature coefficients, performance at standard test conditions and low light.

Fits to the Loss Factor parameters versus irradiance allows predictions of their behavior as a simple function of irradiance. Since the Performance Factor is the product of all six Loss Factors prediction of Energy Yield from the non-corrected Loss factors (spectrum, temperature) is possible.

Previously [1,2] and in this paper the LFM-B model has been used to fit individual module DC IV data for many different technologies and at different sites. LFM-B has been extended to model variability in performance due to seasonal annealing and other time dependent effects to be able to understand metastable behavior better.

Furthermore, the LFM-B has been extended by several more functions (Idc, Vdc, Pdc and Inverter Efficiency) to model AC power plants of multiple modules.

Thin film Silicon modules in combination with transformerless inverter topologies do not show any specific degradation nor TCO corrosion after three years of operation.

7 REFERENCES

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