Advanced PV module performance characterization and validation using the novel Loss Factors Model

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***Abstract* — The Loss Factors Model (LFM) [1] allows PV modules of any technology to be characterized by outdoor IV measurements into six normalized, independent and physically significant coefficients plus correction factors for module temperature and spectral mismatch. These fitted coefficients allow the prediction and validation of PV module performance under any weather conditions. Their magnitudes at higher irradiance levels extrapolate to the STC values to be compared with flash test or datasheet values, values at lower irradiance give the low light performance (LLEC), their gradients vs. module temperature determine temperature coefficients alpha, beta, gamma etc. Differences of the individual LFM coefficients can be seen between single or double junction thin film vs. crystalline silicon technologies with the latter having lower resistance losses. The shapes of any changes with time allow the seasonal annealing or degradation of performance to be distinguished and evaluated.**

***Index Terms* — Modeling, characterization, Photovoltaic systems, Energy, Power**

I. Introduction

For realistic estimation of Photovoltaic (PV) power plant performance it is necessary to know how PV modules perform under specific outdoor conditions as the irradiance, spectrum, angle of incidence and module temperature vary continuously during the course of a day and during a year for each location in contrast to Standard Test Conditions (STC).

Simply comparing the cumulative energy produced from each PV module within the analysis period has only a limited validity due to the known variability in modules from production lines, the uncertainty in measurements (especially irradiance) and the unknown Pmpp calibration that the manufacturer used [2].

From the modelers, PV module developers or producers perspective a more detailed characterization of module performance on the level of IV-parameters is essential. Being able to assign performance losses to the individual IV-parameters allows optimization of the cell design which in turn would result in improvements of Energy Yield (EY) [3].

Such a Loss Factors Model (LFM) [1] was introduced recently and its benefits for module characterization were shown.

In this paper we further validate the Loss Factors Model for different PV technologies at Oerlikon Solar Outdoor Test Facilities (OTF) in Arizona (OTF4-AZ) and Switzerland (OTF1-CH). We show how seasonal effects can be distinguished from long term degradation and how LFM can be used to study single junction technologies as well as multi junction cells.

II. Loss Factor Model

The following definitions and parameters (see Figure 1 and Table 1) are used in the LFM-B model which is an enhancement over the LFM model presented at the 26th EUPVSEC conference 2011 (now referred to as LFM-A) [1]. The changes are that the earlier FFr (fill factor corrected for Rsc and Roc losses) has become the product of independent [nImp*(rIsc/rImp)] and [nVmp*(rVoc/rVmp)] losses such that current and voltage related effects can be separated.

To distinguish between measured, reference and normalized IV data the following prefixes are introduced: n=normalized, r=reference, m=measured and f=fitted.

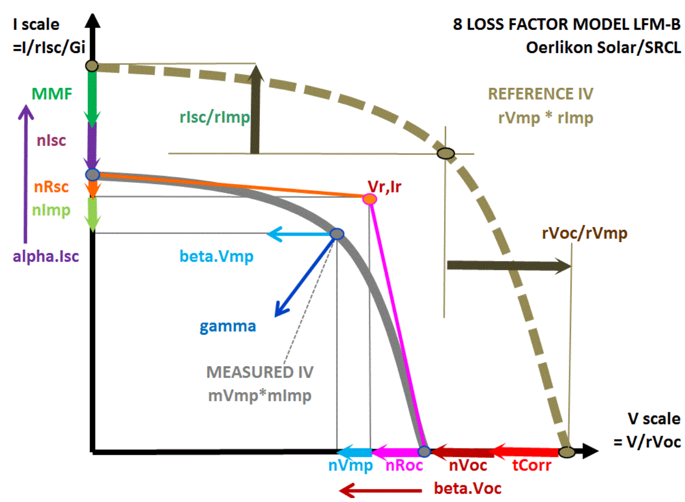

Fig. 1. Graphical derivation of LFM-B parameters.

All the LFM parameters are normalized (currents are divided by $I_{SC.STC}/G_I$(suns) and voltages by $V_{OC.STC}$) so that cross-comparison of different modules or technologies can be done more easily. The existing R_{SERIES}, R_{SHUNT} and Fill Factor FF= (Imp*Vmp)/(Isc*Voc) parameters (their absolute values depend on irradiance and technology) are replaced by the four normalized parameters nRoc, nRsc, nImp and nVmp representing the percentage of power losses due to finite series and shunt resistances and the roundness of the Fill Factor (FF) (corrected for drops caused by the Rsc and Roc).

TABLE I

LFM-B EQUATIONS. THE INTERSECTION OF RSC AND ROC LINES IS AT (VR, IR)

MMF	Spectral mismatch factor
nIsc	mIsc / rIsc / Gi
nRsc	%Pmax loss due to Rsc intersection with Roc
nImp	Impp / Ir*[rIsc/rImp]
nIscT	nIsc *(1+alpha.isc*(25-Tmod))
nVmp	Vmpp / Vr*[rVoc/rVmp]
nRoc	%Pmax loss due to Roc intersection with Rsc
nVoc	mVoc / rVoc
nVocT	nVoc*(1+beta.voc*(25-Tmod))

The spectral mismatch factor (MMF ref IEC 60904-7) of the short circuit current Isc is calculated for each minute, based on the measured spectrum and the spectral response characteristics of the device under test.

So the performance factor (PF=dc Efficiency.measured/ Efficiency.STC) can be expressed as:

$$PF = [MMF * nIscT * nRsc * nImp] * [nVmp * nRoc * nVocT] \quad (1)$$

These fitted coefficients allow the prediction and validation of PV module performance under any weather condition. Their magnitudes at higher light levels extrapolate to the STC values to be compared with flash test or datasheet values. Values at lower light give the low light performance, their gradient vs. module temperature determines temperature coefficients alpha, beta, gamma etc.

Note that the shown LFM-B values are for relative comparison. For absolute values we use accurate indoor STC data from external institutes (not shown in this paper). This also allows indoor versus outdoor data analysis.

III. OUTDOOR TEST FACILITIES

In this paper we investigate randomly selected PV modules of different technologies (c-Si, a-Si, CdTe, CIGS and micromorph) in different climatic regions. Similar ("twin") PV modules of each type are mounted at our Outdoor Test Facilities (OTF) OTF1-CH and OTF4-AZ. For each analysis we investigate the same PV modules.

Each Outdoor Test Facility is equipped with the following measurement tools to continuously collect high accuracy environmental data. Pyranometers (CMP22, secondary standard) are installed for in-plane (Gi), global (Go) and diffuse irradiance measurements. Direct irradiance is measured by a Pyrheliometer (CHP1) on a sun tracker. A calibrated Spectroradiometer (Type 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. Furthermore ambient temperature, wind speed and wind direction are also measured.

Synchronized I-V scans taking one second each are measured every minute for each PV module with a calibrated DC load. For the period of I-V scan environmental data are averaged and logged such that the exact environmental conditions during each I-V scan are known.

For each PV module the module temperature is measured with PT100 elements fixed to the backside of each PV module.

At OTF1-CH PV modules are mounted in South direction with a tilt angle of 25° while at OTF4-AZ the PV modules are mounted with a tilt angle of 33°. For further details see reference [4].

With the spectral response of each module the spectral mismatch factor (MMF) can be calculated to allow spectral correction. Nameplate values are used for calculation of the Loss Factors and for thermal corrections.

IV. RESULTS AND ANALYSIS

In this section we present analysis results based on the Loss Factors Model. We will show how information on the different irradiance levels and temperature behavior of PV modules can be easily extracted from the Loss Factors.

A. Dependency on irradiance

For each module under investigation spectrally and thermally corrected Loss Factors are calculated from I-V parameters according to Table 1. Figure 2 shows LFM-B coefficients vs. irradiance for a single junction thin film device compared with a c-Si ISE reference cell for clear days of every third month between September 2010 and April 2012 at OTF1-CH. The smooth curves (fnVoc and fnIsc) show fits to the calculated Loss Factors nVoc and nIsc (the others were omitted for better visibility).

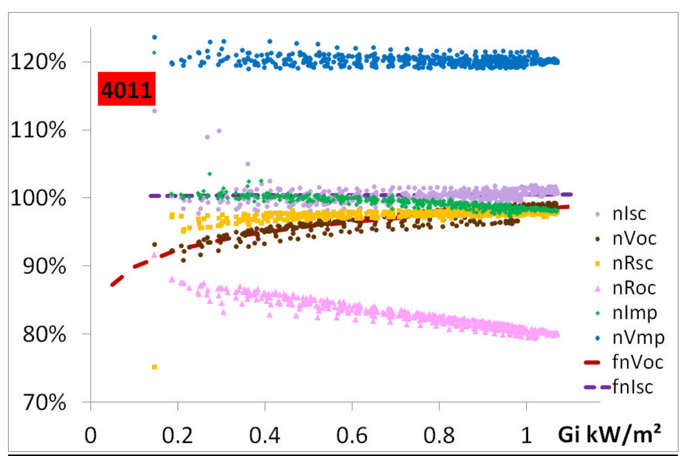

Fig. 2. LFM-B coefficients (clear days) vs. irradiance and fits (fnIsc, fnVoc) for nIsc and nVoc.

The values down to low light levels (e.g. 0.2kW/m^2) can be seen. Note, the PF is calculated from spectrally and temperature corrected values and thus cannot be used for Energy Yield analysis.

This procedure was done for twin modules of different technologies every third month from September 2010 (1009) to March 2012 (1203) for the Outdoor Test Facilities OTF1-CH and OTF4-AZ. Fitting LFM-B data for different periods (e.g., each month) allows to study monthly variations. Figure 3 shows fitted LFM-B coefficients at low (200W/m^2, black bars) and high (800W/m^2, colored bars) irradiance levels. The yellow bars in PF indicate mid-summer. The high and low limits of each LFM-B parameter are shown on the left of the graph – e.g OTF1-CH the top red row PF is scaled from 70% (min) to 110% (max).

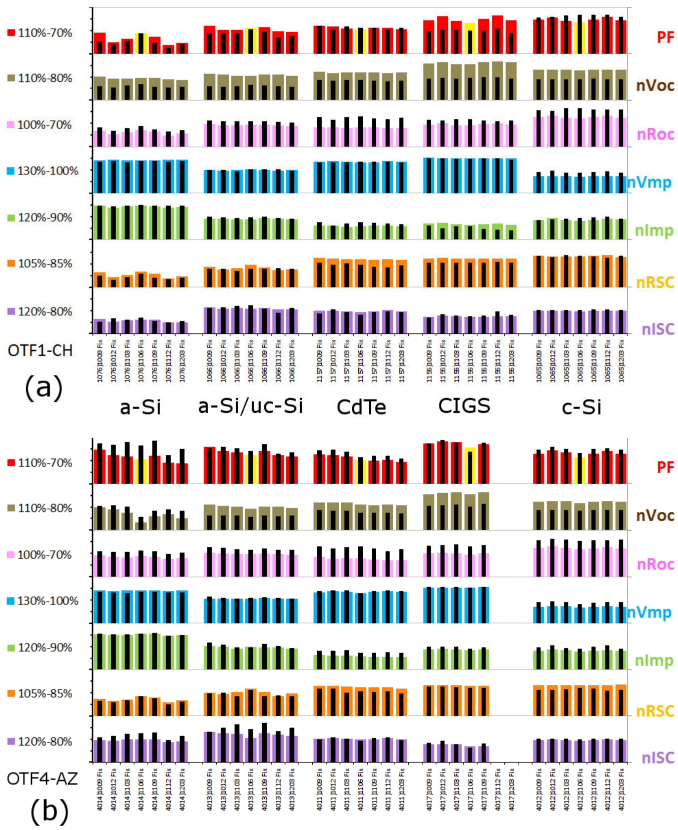

Fig. 3. LFM-B coefficients for "twin" PV modules of different technologies for low (200W/m^2, **black** bars) and high irradiance behavior (800W/m^2, colored bars) at (a) OTF1-CH and OTF4-AZ.

These data are based on individual modules, these might be atypical examples as there will be a manufacturing performance spread in all technologies.

Generally, since Loss Factors are corrected for spectrum and temperature we would expect to see only small variation during a year and for the different technologies. Deviations of the Loss Factors or Performance Factor from the model are due to other effects as for example soiling, degradation, annealing and low light level performance. To avoid effects due to dirt/dust we used the crystalline module at each location as an irradiance reference assuming that all modules of one location are exposed to similar soiling.

For some modules in Figure 3 we observe stronger variations over the year and stronger differences between the two locations (a) OTF1-CH and (b) OTF4-AZ than for others. The c-Si and CdTe PV modules show good low light behavior on both locations for all LFM-B parameters except for nVoc while for Thin Film Si PV modules it depends on the location, due to e.g. spectral effects caused by different horizons (see Ransome et al. this conference [5]).

The amorphous and micromorph modules show higher PF at OTF4-AZ. Since current and voltage are already corrected for temperature the better temperature coefficient of Thin Film Si cannot explain this difference. At higher module temperatures the LID is lower [6] and thin films can also anneal to higher efficiencies which might explain the higher PF at OTF4-AZ. Furthermore, the spectral response of the micromorph module was determined for a specific matching state under AM1.5 (top cell current/ bottom cell current) which does change with spectrum and season due to the different absorption characteristics of top and bottom cells. Therefore, varying spectral conditions might lead to different matching states and spectral corrections might introduce higher uncertainties.

Slight degradation of PF is observed for CdTe modules at both locations. Especially at OTF4-AZ the degradation can be attributed to losses in nVoc, nRoc, nImp and nRsc. The Thin Film Si modules also show some degradation at OTF4-AZ mostly due to nVoc. Crystalline PV modules show the best nRoc due to low series resistance dominated by the tabbing compared to the higher resistance of the contact and window layers as used in thin film technologies.

B. Dependency on temperature

Figure 4 shows how plotting non-temperature corrected Loss Factors versus module temperature allows the temperature coefficients (TC) of the corresponding IV parameters to be determined, alpha (Isc), beta (Voc), gamma (Pmpp), etc.

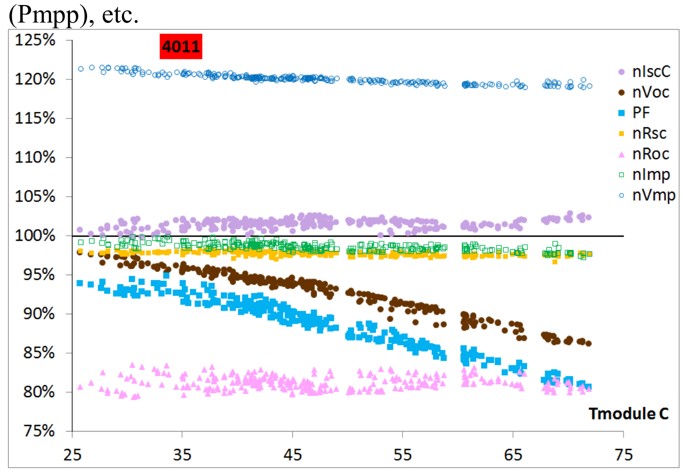

Fig. 4. Fitted LFM-B coefficients vs. module temperature (n=normalized data) from OTF1-CH. nIscC is nIsc for clear days.

Automated curve fitting procedures are used to determine the normalized LFM-B parameters and the outdoor temperature coefficients for any time periods (e.g. yearly or monthly). This allows for example to study variations of the TCs over the year. This was done in Figure 5 for PV modules of different technologies at OTF1-CH. The temperature coefficients taken from the nameplate (module data sheet) are shown as dots while the measured temperature coefficients are plotted as bars.

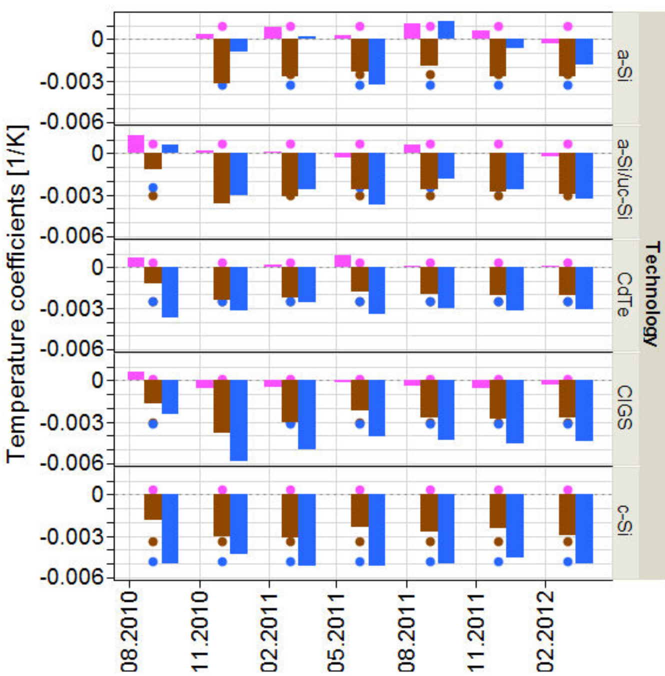

Fig. 5. Temperature coefficients (dots: data sheet, bars: measured) for different technologies from 08.2010 to 03.2012 every three months at OTF1-CH. Purple: alpha Isc, brown: beta Voc, blue: gamma Pmpp.

The measured gamma for the CIGS PV module is mostly higher compared to the nameplate TC throughout the year while for the c-Si module the monthly averaged measured temperature coefficients usually correspond to the data sheet values or are even slightly better. Micromorph and amorphous PV modules show the lowest temperature coefficients. Note that the alpha coefficients have the highest uncertainties (which also affect gamma). Although these data are spectrally corrected dirt factors (e.g. cleaner on cooler/wet days vs. dirtier on drier/hotter days) may come across as a correlated effect.

C. Variation with time

The shapes of any changes of LFM-B parameters with time allow any seasonal annealing or degradation of performance to be distinguished and evaluated. Typical shapes are explained in Table 2.

Figure 6 shows spectrally and temperature corrected nIsc and nVoc respectively with other LFM-B parameters, irradiance (Gi), ambient temperature (Tamb) and module temperature (Tmod) for one clear day each month from September 2010 to April 2012 for the five different technologies at OTF1-CH (left side, a-e) and their "twin" modules at OTF4-AZ (right side, f-j). In Figure 6(g) the predictions for nIsc and nVoc are also shown. The measured irradiance (Gi) is used to determine the LFM-B parameters from the derived Loss Factors vs. irradiance fits from Figure 2. The CIGS module at OTF4-AZ was removed after May 2011 therefore less data are available. The spikes in some graphs are due to sunrise/sunset effects.

Crystalline PV modules show only a small variation over the year with a decrease in PF, nVoc and nIsc in summer periods when temperatures are high (TC differs slightly between summer and winter see Figure 5). PF varies more at OTF4-AZ than OTF1-CH. The crystalline PV modules measured here show higher PF in the colder Switzerland than in the hot Arizona. The nIsc has a "concave up" shape indicating slightly better performance than the reference cell and correction factors at high Angle of Incidence (AOI) conditions.

The CdTe module in Arizona shows some degradation in PF which is due to a gradual decline in nVoc. At OTF1-CH the degradation is not as strong as at OTF4-AZ. In contrast to the c-Si module the nIsc of the CdTe module shows some "concave down" shape indicating worse than expected Isc at high AOI. The predictions of nVoc and nIsc are plotted with black dots in the same graph at OTF4-AZ (Fig.6,g) and show good agreement with the measured LFM-B values. Deviations are due to dirt, soiling, non-modeled degradation effects etc.

The CIGS modules also show higher PF in cooler winter months (already concluded from Figure 3) which can be attributed to higher nVoc in winter. The shape of nIsc is rather flat over the entire period of investigation.

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. The effect seems more pronounced in Switzerland than in Arizona (which has a 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.

The Performance Factor PF (cyan line) in Figure 6 cannot be used for Energy Yield analysis for the following reason. 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.

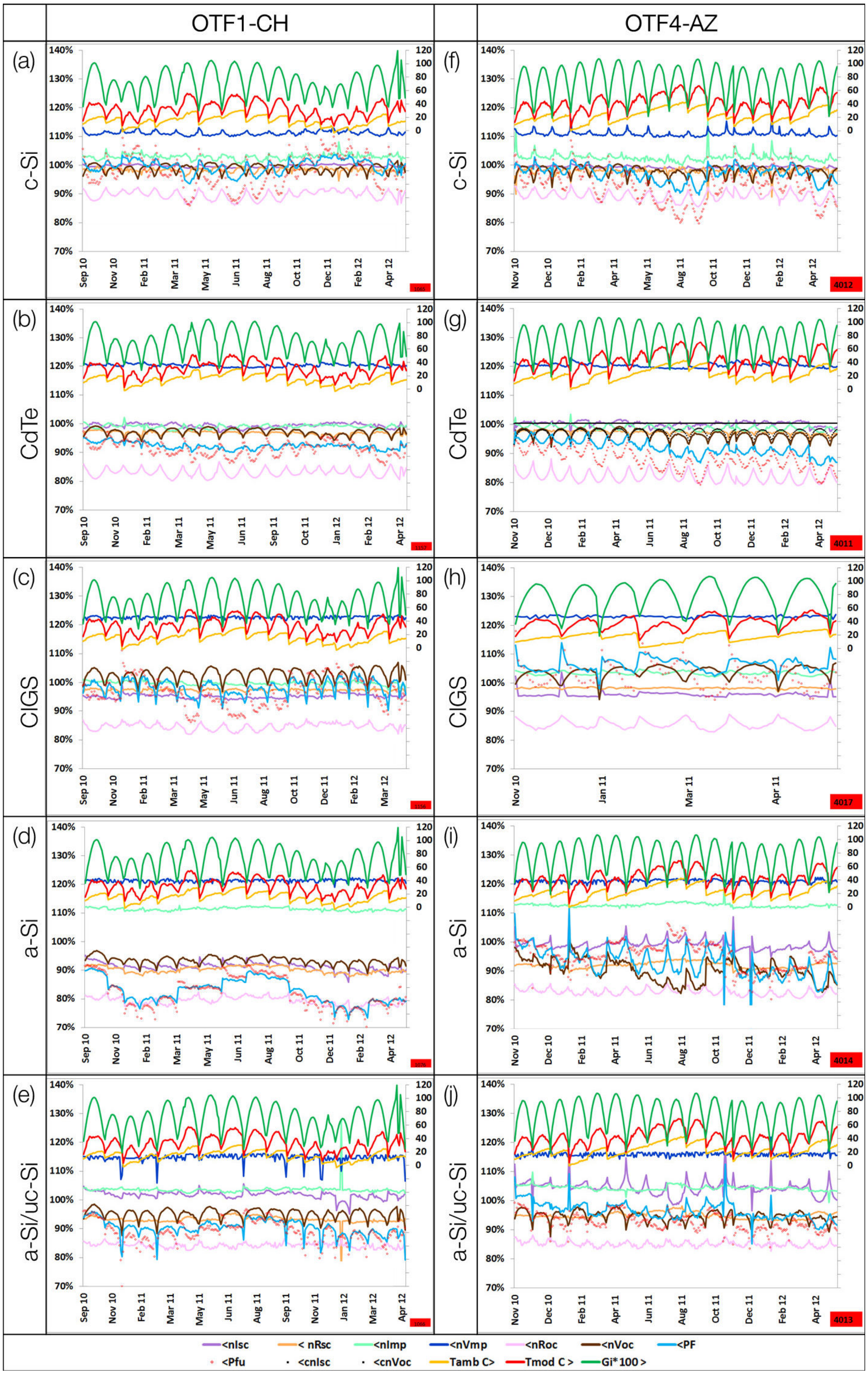

Fig. 6. Measured LFM-B coefficients vs. time for c-Si, CdTe, CIGS, a-Si and micromorph PV modules at OTF1-CH (left side) and OTF4-AZ (right side). (g) shows additionally predictions cnIsc and cnVoc. One clear day every month from September 2010 to April 2012.

TABLE 2

EXPLANATION OF EXPECTED SHAPE OF SPECTRALLY AND TEMPERATURE CORRECTED LFM-B PARAMETERS WITH TIME.

Parameter (correction)	Expected shape vs. time	Reason	Comment
Gi (vs. right y-axis)	Concave down, or flat low	High or low insolation day	
Tm (vs. right y-axis)	Concave down	Tm follows Gi with time lag (higher in afternoon)	Higher for high Gi
nIsc (corrected MMF)	"Almost flat"	Corrected for MMF	Deviations, Dirt/degradation
nRsc	Concave down	Rshunt loss is less noticeable at high Gi, worse at low light	Higher amplitude means worse at low light
nImp	Low curvature up or down	Slight dependence on Gi	being studied
nVmp	Low curvature up or down	Slight dependence on Gi	being studied
nRoc	Concave down	I²R loss is higher at high Gi	Higher amplitude = worse I²R loss at high light
nVocT (corrected Tmod)	Concave down	Voc~ln(Gi)	Slope depends on I_0

The energy yield produced by a module does not use corrected data (apart maybe from downtime for a given module where interpolated data is used to compare against other modules).

As an example consider two stable modules X and Y, where X has a worse temperature coefficient than Y. Under very hot conditions module X would be expected to produce less energy as the sum of the uncorrected Pmax figures would be lower. However as both modules are stable they would appear to have the expected efficiency when corrected back to STC using the temperature coefficients.

Calculating an uncorrected Performance Factor (PFu, see red dots in Figure 6) allows to study Energy yield of the different technologies.

V. CONCLUSION

In this paper we have shown how PV module performance at different light levels can be studied and how temperature coefficients and long-term trends can be better analyzed with the Loss Factors Model. From the shape of LFM-B coefficients over time further information can be obtained and from analyzing monthly averaged Loss Factor coefficients of low and high light performance we will be able to distinguish seasonal effects from degradation which was not possible so far.

Previously the energy yield losses due to Rsc and Roc were hard to quantify, now through normalization they can be analyzed easily and the value of improvements can be estimated.

We have shown that from fits to the individual Loss Factors versus irradiance prediction of Loss Factors and thus prediction of Performance Factor as a function of irradiance is possible. This will allow to better estimate Energy production and to optimize production quality which in turn will allow to improve PV module production quality, to better estimate realistic lifetime expectations, to quickly validate R&D improvements and in the end to increase confidence for energy yield harvest and performance prediction.

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