Improved PV Performance Modelling by Combining the PV_LIB Toolbox with the Loss Factors Model (LFM)

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Abstract — PV project investments need comprehensive plant monitoring data in order to validate performance and to fulfill expectations. Algorithms from PV-LIB and Loss Factors Model are being combined to quantify their prediction improvements at Gantner Instruments’ Outdoor Test facility at Tempe AZ on multiple Tier 1 technologies. The validation of measured vs. predicted long term performance will be demonstrated to quantify the potential of IV scan monitoring. This will give recommendations on what parameters and methods should be used by investors, test labs, and module producers.

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

I. INTRODUCTION

PV project investments require continuous, accurate and traceable plant monitoring data in order to determine the actual vs. design performance and to fulfill owner/investor expectations.

Algorithms from the “PV Performance Modeling Collaborative” (PVPMC) and “Loss Factors Model” (LFM) are being combined to test out their prediction improvements at Gantner Instruments’ (GI) Outdoor Test facility at Tempe AZ on multiple Tier 1 technologies including c-Si, CdTe and CIGS.

The PV_LIB Toolbox was originally developed at Sandia National Laboratories and has been expanded by contributions from members of the PVPMC [1]. A standard library of PV algorithms includes solar position, irradiance translation, module temperature, and array and inverter performance. PV_LIB is available in MatLab and Python versions [2] [3].

The LFM has been developed and is being used by SRCL and Gantner Instruments to produce optimum PV performance simulation accuracy with determination of performance coefficients, quantification of any instability and fault finding diagnosis [4] [5].

The validation and comparisons of the measured vs. predicted (long term) performance will be demonstrated in this paper to quantify the potential benefits of continuous IV scan monitoring. We will provide recommendations on what parameters and methods should be used by investors, test labs, and module producers. Validated functions are available in the gantner.webportal for advanced utility scale analysis and prediction. Providing more accurate performance analysis, indication of abnormal loss or trends leads to more effective O&M and risk reduction for owners.

II. OUTDOOR MEASUREMENTS

Gantner Instruments’ Outdoor Test facility (OTF) in Tempe, AZ (figure 1) measures IV curves every minute for 24 fixed modules and 6 on a 2D tracker [6]. It has been running since July 2010 with a 98% uptime.

Fig 1. Gantner Instruments OTF in Tempe, Arizona.

Table I lists some of the GI OTF meteorological measurements.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH</td>
<td>Global Horizontal Irradiance</td>
<td>kW/m²</td>
</tr>
<tr>
<td>DH</td>
<td>Diffuse Horizontal Irradiance</td>
<td>kW/m²</td>
</tr>
<tr>
<td>BN</td>
<td>Beam Normal Irradiance</td>
<td>kW/m²</td>
</tr>
<tr>
<td>GI</td>
<td>Global Inclined Irradiance (Pyranometer and c-Si ref cells)</td>
<td>kW/m²</td>
</tr>
<tr>
<td>T_AMB</td>
<td>Ambient Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>T_MOD</td>
<td>Back of Module Temperatures</td>
<td>°C</td>
</tr>
<tr>
<td>WS</td>
<td>Wind Speed</td>
<td>m/s</td>
</tr>
<tr>
<td>WD</td>
<td>Wind Direction</td>
<td>°</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
<td>%</td>
</tr>
<tr>
<td>G(A)</td>
<td>Spectral Irradiance G(350–1050nm)</td>
<td>W/m²/nm</td>
</tr>
</tbody>
</table>
III. VALIDATING PV_LIB AND LFM ALGORITHMS

Using synchronized, 1 minute measured data from a year at the Tempe Site (which is defined by its latitude and longitude; array tilt and azimuth) calculations were made with the PV_LIB routines and checked with existing site calculations (e.g., solar position), actual meteorological measurements (irradiance, temperature, spectrum etc.) and measured PV performance as below (A to F).

A. “GI calculated” vs. PV_LIB Solar Position

The PV_LIB solar elevation and azimuth (calculated using the pvl_spa function) were compared with the predictions from the GI site, which used a less sophisticated algorithm (SUNAE) to calculate sun position. Differences are shown in figure 2. Both azimuth and elevation are mostly within ±2°. These differences are typical, since the pvl_spa model is based on NREL’s Sun Position Algorithm [7] which includes details not addressed by simpler models (e.g., refraction, nutation, etc.).

![Fig 2. Comparing PV_LIB calculations of solar elevation and azimuth with the internal data from GI](image)

B. Predicted Tilted irradiance from diffuse Sky model

PV_LIB contains several methods for estimating tilted global G_t as a function of diffuse horizontal D_D and beam normal B_N (with angle of incidence). Figure 3 shows the correlation between six anisotropic or isotropic diffuse sky models calculated vs. measured G_t. The Perez model is the best with low bias and random errors; the Klucher and King models are nearly as good.

![Fig 3. Comparing calculated vs. measured tilted plane irradiance from six PV_LIB anisotropic or isotropic diffuse sky models (pvl_isotropicsky, pvl_haydavies_1980, pvl_reindl_1990, pvl_perez, pvl_kingdiffuse, and pvl_klucher_1979).](image)

C. Spectral content vs. solar altitude and azimuth

Blue Fraction is defined as “blue light”/”c-Si absorbable light” (1) and is an alternative to the average photon energy (APE) which depends on the lower and upper limits of measured wavelength.

\[
\text{Blue Fraction} = \frac{\sum_{\lambda=350}^{650} G(\lambda)}{\sum_{\lambda=350}^{1050} G(\lambda)}
\]

For AM1.5 the Blue Fraction ~0.52, a higher number comes from a bluer spectrum, a lower value means redder than AM1.5.

At most sites the solar spectrum is not measured but if needed is inferred from solar elevation angles. This may work well under clear sky conditions but not so well under cloudy skies where the clouds absorb more red light than blue. GI use the Blue Fraction as a “rule of thumb” to roughly quantify spectral irradiance.

Figure 4 gives the measured Blue Fraction (y axis) vs. Air Mass (derived just from the solar height - x axis) for different clearness indices (kTh) from 0.2 (mostly obscured) to 1.0 (clear) at the GI Tempe site. Clear skies usually have a kTh~0.8 (meaning 80% of the extraterrrestrial horizontal irradiance reaches the ground, the other 20% is absorbed or reflected by the atmosphere). This is shown in pale green with linear fits from AM1 to AM6. The value at AM1.5 is around 52% and it falls around 2% for each “integer AM” increase. Other clearness indexes follow a similar trend with the overall shift being towards blue rich when the clearness falls.

![Fig 4. Measured Blue Fraction vs. Air Mass (Solar height) for different clearness indices at the GI site at Tempe.](image)
Figure 5 plots the average measured blue fraction vs. solar altitude and azimuth for 1 minute data at the GI Tempe facility (which has predominantly clear skies).

A Blue Fraction of 0.52–AM1.5 is shown in yellow with other colours indicating bluer or redder spectra. In general the higher the solar altitude then the bluer the spectrum and vice versa – also a little bluer (clearer) in the morning than the afternoon. There are two spots of “very blue rich light >0.59” at low solar altitude and azimuths of <80 ENE 1 and >280 WNW 2 when the sun is behind the module so there’s no direct light, only diffuse and hence a bluer than expected spectrum.

There is also a localized spot of blue rich light at 100° azimuth and 10° solar altitude 3 which we will identify in the next section D.

\[ \text{Average measured Blue Fraction vs. solar altitude and azimuth for GI's Tempe facility} \]

D. Isc vs Angle of Incidence and Shading

Figure 6 plots the normalized Isc (2) for a standard c-Si screen print module vs. solar altitude and azimuth at GI Tempe.

\[ n_{\text{Isc}} = \frac{\text{Isc MEASURED}_{\text{STC}}}{\text{Isc REFCELL}} \]

\[ n_{\text{Isc}} \] is smooth over most of the solar positions, becoming a little higher for large azimuths away from south <90 ENE 4 and >270 WNW 5 (presumably the ARC on the c-Si module gives better off-axis reflectivity than the reference cell). However at point 6 (as in figure 3) the current drops 20-30% suggesting it was due to shading. This would filter out some of the red direct light from the low sun making the resultant spectrum go bluer as seen in figure 3.

\[ \text{PVLIB modelled vs. measured module temperature rise above ambient vs. irradiance and windspeed} \]

F. Sensor angle of incidence

Pyranometers tend to have a slightly better angular acceptance response than c-Si reference cells as their domes reflect less light away than a flat plate panel even with antireflective coating. Figure 8 shows the results of comparing the irradiance reported by a plane of array pyranometer versus a plane of array crystalline reference cell vs. horizontal beam fraction and angle of incidence for GI’s Tempe site. This can be used to perform angle-of-incidence (AOI) corrections for flat plate panels with only pyranometer sensors – when c-Si reference cells are used then the angular correction needed is small. Beam fractions are usually between 0.2 (mostly diffuse)
and 0.8 (mostly direct), at the GI Tempe site the angle of incidence only gets below 10° for a short time (spring/autumn equinox at solar noon) also data above 80° AOI has a lot of scatter so the graph does not include some extreme values for clarity. Nevertheless the $G_{c-Si}/G_{PYR}$ approaches 100% for angle of incidence <10° at any beam fraction (as expected from calibrated sensors but note there’s no spectral correction) and falls off as the angle of incidence increases, slightly faster under direct than diffuse conditions. As a rule of thumb the graph suggests a value of about 85% at an AOI of 65° and BF=0.5 meaning the c-Si sensor would predict a 15% better low light coefficient than the pyranometer would suggest under these conditions.

Previously LFM values have been derived by normalizing measurements with a c-Si reference sensor. Fits have been done to “good conditions” i.e. reasonable high irradiance, near noon (so low angle of incidence), unshaded and non-snow covered conditions. Extreme conditions for parameter fitting have been removed by filtering on limits (such as ‘AOI<60 degrees’ or ‘sun height >15°’) to get rid of the “scattered” points that may be hard to fit but filtering gets rid of some good points too. For example if there is a building shading 15 degrees high to the east but a low horizon to the west, filtering ‘sun height>15’ removes some otherwise good low solar height measurements in the west.

PV Voltages depend on the parameters in table III.

**TABLE III. LFM PARAMETERS AFFECTING $V_{OC}, V_{MP}$**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cell Temperature</td>
<td>Estimate from Ambient and Cell Back</td>
</tr>
<tr>
<td>2 Irradiance</td>
<td>Will be affected by previous ~15 minutes weather (thermal capacity)</td>
</tr>
<tr>
<td>3 Wind speed</td>
<td>Will be affected by previous ~15 minutes weather (thermal capacity)</td>
</tr>
<tr>
<td>4 Manufacture</td>
<td>e.g. affects thermal capacity</td>
</tr>
<tr>
<td>5 Mounting</td>
<td>e.g. how close to roof</td>
</tr>
</tbody>
</table>

The LFM is illustrated in figure 9 [4]. It analyses IV curves at different outdoor conditions (irradiance, module temperature, spectrum, angle of incidence etc.) to give six normalized orthogonal parameters (as in Table IV) that characterize a module’s performance and can identify the cause and any rate of change of limiting parameters. The product of these 6 parameters gives the normalized efficiency (also known as the DC performance ratio $PR_{DC}$).

**IV. THE LOSS FACTORS MODEL**

The LFM fits IV curves very well under normal weather conditions [4]. The PV current depends on the following parameters in table II showing the modelled dependence on whether a c-Si reference cell is used or a Pyranometer.

**TABLE II. LFM PARAMETERS AFFECTING $I_{SC}, I_{MP}$**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>c-Si Reference Cell</th>
<th>Pyranometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Shading</td>
<td>Similar near shading if close</td>
<td>Similar near shading if close</td>
</tr>
<tr>
<td>2 Spectrum</td>
<td>Similar if c-Si module</td>
<td>Will be different</td>
</tr>
<tr>
<td>3 Angle of incidence</td>
<td>Similar if same manufacture</td>
<td>Will be different</td>
</tr>
<tr>
<td>4 Soiling</td>
<td>May be similar if coplanar</td>
<td>Different if Glass dome</td>
</tr>
<tr>
<td>5 Snow</td>
<td>May be similar if coplanar</td>
<td>Different if Glass dome</td>
</tr>
<tr>
<td>6 Temperature</td>
<td>Small effect</td>
<td>Small effect</td>
</tr>
</tbody>
</table>

![Chart](https://via.placeholder.com/150)

Fig 8. Average irradiance measured by the POA c-Si reference cell divided by that from a POA pyranometer measured at GI Tempe. No spectral corrections are done.

![Chart](https://via.placeholder.com/150)

Fig 9. Simplified SRCL/Gantner Instruments Loss Factors Model
A. PV Performance vs. Irradiance and Temperature

PV module performance is measured over a period of time at differing meteorological conditions such as irradiance, ambient temperature, angle of incidence and spectrum. The 6 LFM parameters are then characterized by fitting as functions of irradiance and temperature. On line checks of performance can be undertaken by comparing measured with data predicted from the earlier test method.

V. IMPROVEMENTS TO LFM FITS USING EMPIRICAL MODELS OF TOP FRACTION, AOI (AND $T_{\text{MODULE}}$)

Figure 10 shows predicted vs. measured performance of a CdTe module (top) and a c-Si module (bottom) at Tempe for ~750 random data points. For well-behaved modules the five LFM parameters (except $n_{\text{ISC}}$) can usually be fitted to <±1% accuracy shown as the grey horizontal lines (i.e. the coloured dots are usually within the grey lines for a good fit).

The fit for $n_{\text{ISC}}$ is also affected by soiling, snow, angle of incidence reflectivity and spectral response.

It is important to know the $T_{\text{MODULE}}$ for the $n_{\text{VOC}}$ coefficient. If this is not known then it can be calculated from the PV_LIB $pvl\_sapmcell\_temp$

Using some of the previously described empirical fits for spectrum, angle of incidence and module temperature the following improvements are seen

A. $n_{\text{ISC}}$ vs. Spectral content vs. solar altitude and azimuth

Figure 11 shows the $n_{\text{ISC}}$ error for a CdTe module against a c-Si irradiance sensor both without (top) and with (bottom) corrections of the ISC predicted from the blue fraction. The corrected $n_{\text{ISC}}$ has lessened from ~10% (max in summer) to now mostly within ±2% (flat over the year) with only a small ripple around November and December when the sun is lowest and the correction needed greatest and most uncertain.

**TABLE IV. NORMALIZED LFM PARAMETERS**

<table>
<thead>
<tr>
<th>LFM</th>
<th>Performance determining factors include</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{ISC}}$</td>
<td>Spectral mismatch, dirt, snow, beam reflectivity vs. AOI</td>
</tr>
<tr>
<td>$n_{\text{RSC}}$</td>
<td>$R_{\text{SHUNT}}(G)$</td>
</tr>
<tr>
<td>$n_{\text{IMP}}$</td>
<td>$V_{\text{MP}}(G)$ corrected for $R_{\text{SC}}$</td>
</tr>
<tr>
<td>$n_{\text{VMP}}$</td>
<td>$G^2 \cdot R_{\text{SERIES}}(G)$</td>
</tr>
<tr>
<td>$n_{\text{ROC}}$</td>
<td>$V_{\text{OC}}(G) \sim \ln(G/I_{\text{O}})$, $T_{\text{MODULE}}$</td>
</tr>
<tr>
<td>$PR_{\text{ROC}}$</td>
<td>= $(n_{\text{ISC}} \cdot n_{\text{RSC}} \cdot n_{\text{IMP}}) \cdot (n_{\text{VMP}} \cdot n_{\text{ROC}} \cdot n_{\text{VOC}})$</td>
</tr>
</tbody>
</table>

Fig 10. Prediction accuracy for 5 LFM parameters measured (dark dots) vs. calculated (light grey lines ±1%) for a CdTe (top) and c-Si (bottom) for GI Tempe.

Fig 11. Improvement to modelled $n_{\text{ISC}}$ errors from empirical spectral correction (bottom) for a CdTe module at GI Tempe.
B. n\textsubscript{ISC} vs. Sensor type angle of incidence

Figure 12 shows the modelled vs. measured n\textsubscript{ISC} error for a cSi module against a c-Si irradiance sensor and pyranometer

(a) vs. a c-Si reference cell. Most points are within ±1% but there is a degree of scatter

(b) vs. a pyranometer uncorrected for aoi. The best errors are <±1% (when the aoi is low so corrections aren’t needed), when the aoi is high the errors can be worse than -15% (see figure 8 – this loss is expected from an aoi of 75degrees)

(c) vs. a pyranometer empirically corrected for aoi. The average errors are now <±2% but this can probably be improved a little by parameter optimization.

![Graph showing nISC errors vs. time]

VI CONCLUSIONS

- PV_LIB is being integrated into Gantner Instruments measurement data and analysis methods [9]
- LFM is compatible in line with PV_LIB algorithms and will gain further understanding for modelling
- Efficient data filters allow more reliable data analysis and interpretation
- Standardization of algorithms, reduction of site specific impacts allows reliable plant benchmarking within the portfolio
- Empirical modelling with PV_LIB functions enhances LFM fits leading to reduced errors even without spectral information, reference cell or module temperature measurements.
- Gantner Instruments will introduce LFM and PV_LIB to its real time platform (gantner.webportal) which enables more accurate utility scale performance verification, analysis and prediction.
- This provides more accurate performance analysis, indication of abnormal loss or trends leading to more effective O&M and risk reduction for owners on a real time basis.
- Performance guarantees – target versus actual performance – can be validated more reliable as the difference can be linked to the integrated loss stages where optimization potential (in terms of kWh or $) can be identified as well.
- Sandia National Laboratories plans to incorporate the LFM model into the next release of the PV_LIB Toolbox.

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REFERENCES

[8] IEC 61215 - NOCT section 10.5