A COMPARISON OF PV PERFORMANCE PREDICTION MODEL TYPES FOR DIFFERENT TECHNOLOGIES FROM OUTDOOR MEASUREMENTS

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ABSTRACT: PV Performance Models should deliver unbiased performance understanding and prediction with best accuracy for optimised project assessments and reduced risk for the asset owner. Therefore the appropriate model should be utilized. PV Performance models derive their coefficients from IV curves at different irradiances and temperatures, fitting either the entire IV curve (e.g. 1-Diode), a selection of points and gradients (e.g. Loss Factors Model) or just modelling the maximum power point (e.g. Matrix method). The performance of a good c-Si, a good thin film and a bad thin film (with poor $R_{SC}$ and $R_{OC}$) measured by NREL has been analysed with all three models. The relative energy yield for Colorado is compared as an example. These models are being studied to be incorporated into Gantner Instruments Web Portal software for optimum performance modelling and understanding.

Keywords: Energy Rating; Energy Performance; Modelling.

1 INTRODUCTION

System energy yield is usually calculated by summing the predicted PV performance from stochastic or measured hourly weather data inputs comprised of tilted plane irradiance (G; kW/m\textsuperscript{2}), ambient temperature (T\textsubscript{Amb}; C) and wind speed (WS m/s\textsuperscript{-1}).

For higher accuracy spectral measurements are used with spectral response calculations; also “Beam/global irradiance fraction vs. angle of incidence” is important for modelling reflectivity losses.

Figure 1 shows typical NREL measured data for weather (top traces right axis – Irradiance (green); ambient (orange) and module (red) temperatures) and the performance of a CdTe module (bottom six Loss Factors Model LFM [1] traces – left axis) at Cocoa beach in Florida for a year. This graph selects data points for a narrow band of irradiance (0.7 to 0.9 kW/m\textsuperscript{2}) and moderate module temperatures (30-70°C) to enable an easy view of the time distribution and quality of the measurements (i.e. they should be frequent, without long gaps) and also the performance of the module (a well performing, optimised, non-degrading module should have almost constant performance factors without too many outliers).

Figure 1: Good data and module quality for a stable CdTe module in Florida for a year NREL Measurements [2]

2 THREE TYPES OF PV MODELLING

There are three types of PV models based on measured IV and PV curves as illustrated in figure 2. Several examples of these models will be discussed.

Figure 2: A “full IV curve” (green), fitted “points and gradients” (purple), “P\textsubscript{MAX} only” (red), temperature coefficients (in brackets).

The following section introduces the three types of models, lists some examples and comments on them.

Note that good quality IV curves (such as those from Gantner Instruments (GI) and NREL) are needed for the best modelling, that is with little noise, no steps around V\textsubscript{MPP} which indicate cell mismatch or shading and a constantly increasing negative slope from I\textsubscript{SC} to V\textsubscript{OC} (otherwise this suggests rollover from a Schottky back contact). Also precision of data acquisition is important, particularly for c-Si modules with high $R_{SC}$.

2.1 Full Curve Fit

a) 1-Diode model 5-7 parameters [3] used in most simulation programmes.

Improvements are needed to match measured low light and temperature coefficients from DeSoto’s original paper. There are several differing models to do this.

b) Karmalkar- Haneefa 4 parameters KH [4].

Does not work well [5] as it often has errors in Fill Factor as 4 parameters aren’t enough to fit it if the I\textsubscript{SC},

$\text{FF = } \text{P_{MAX} / (I_{SC} \times V_{OC}}$
Rsc, ROC and Voc are fitted well. KH model will not be considered further.

2.2 Points + Gradients (not all curve data fitted)
   a) Sandia Array performance model (SAPM) [6].
      Fits Isc, Isr, Vshunt and Voc points to G1 and Tmod
      with 29 coefficients.

   b) Loss Factors Model (LFM) by SRCL/ Gantner
      Instruments [7].
      Fits 6 normalised orthogonal parameters to IV
curve with two curvature parameters.

2.3 PMAX or Eff only (Hyperbolic tangent constant I*V
   to IV curve)
      Examples: Matrix method, IEC 61853[8], PVUSA,
      Empirical fits.
      Isc and Voc are sometimes analysed too but
      independently of PMAX

Table 1: Which different PV parameters can be analysed depending on the type of model used

<table>
<thead>
<tr>
<th>Analysis Reason</th>
<th>2.1</th>
<th>2.2</th>
<th>2.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple “optimum” energy yield</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>i.e. perfect VMP tracking</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parameter limits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isc limit = Max(Imp) for fusing</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Voc limit = Max(Voc) low temperature for inverter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMP tracking = lowest and highest module Temperatures</td>
<td>Y</td>
<td>Y(LFM)</td>
<td>N</td>
</tr>
<tr>
<td>Performance optimisation, degradation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Due to changes in Rsc, ROC</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Effect of Mismatch, Shading,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Schottky contact degradation</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

3 FITTING DATA TO THE THREE MODELS

3.1 1-Diode curve fits
   Care must be taken when fitting IV curves as fits are
   susceptible to “bad data points”; kinks due to cell
   mismatch and non-optimum behaviour such as rollover
due to Schottky back contacts.

   Figure 3 shows 1-Diode parameter fits to 1000 IV
curves for a CdTe module measured by Marion et al,
NREL [2].

   ![Figure 3: 1-Diode full curve fits to an NREL measured CdTe module vs. irradiance.](cde75659_Golden_Colorado)

   Figure 3: 1-Diode full curve fits to an NREL measured CdTe module vs. irradiance.

   Note that due to some limitations in the fitting method
   the saturation current density Jo (green, mA/cm²) and
the ideality factor n (grey) dimensionless suffered
compensating quantisation errors. This means that a good
fit to the curves (rms < 1%) could be achieved by a range
of values for each parameter that could be compensated
by a change in the other, the rms fit error could not
decide between them and the saw tooth effect causing
the values to jump between ranges. The shunt resistivity
Psht (orange, Ω.cm²) and the light current resistivity
Jph (purple, mA/cm²) were both fairly smooth and
monotonic, the series resistivity Pseries (pink, Ω.cm²) had
a minimum value at low light.

3.2 Points and Gradient fits
   Figure 4 shows the same module data but fitted with
the LFM Points and Gradients type model.

   The nIsc parameter is not shown for clarity because
there was insufficient soiling and spectral data to
compensate properly.

   The LFM has 6 normalised and orthogonal
parameters and have values of the order of 1. It can
clearly be seen how smooth most of the points on the
lines are. The nVMP parameter (cyan) has a few “bad data
points” (i.e. off the main trend) at low light levels but for
a good module the trace should be near Voc(STC)/VMP,STC.
nVMP for a good module should be near Isc/STC/Imp,STC.

   The reasons for bad data can usually be traced to
effects such as shading, bad measurements etc. The other
four lines show are quite smooth and will be easy to
model. Only nVoc,STC has been corrected for temperature.
Note that as the dc performance ratio PRdc is the product
of all 6 LFM parameters then any drops can be traced to
the reason and also quantified as to the effect on final
performance. Here nRsc and nVoc,STC suffer slight drops at
lower light levels, the nROC suffers a linear drop at
increasing light levels (right) due to nSeries resistance as
loss ~ I²Rseries.
Figure 4: LFM points and gradients fits to an NREL measured CdTe module vs. irradiance

3.2 PMax or Efficiency only fits

Figure 5 shows an average Efficiency (~Pmax/light level) fits to 1000 IV curves for a poor module which had lower than expected RShunt and higher than expected Rseries measured by Marion et al, NREL.

Whereas figures 3 and 4 show data from individual IV curves figure 5 gives an average in each bin of irradiance (x axis) and module temperature (y axis). It is assumed that a sanity check has been performed to reject bad data but the standard deviation should be checked to ensure that the spread of results isn’t too high – as may be expected under extreme conditions at the edges of the data graph.

Figure 5: Pmax only fits to an NREL measured poor thin film module vs. irradiance

Five main effects can be determined from the graph shape,
1) Where is the maximum efficiency in the measurement data – here it is at 20°C and 800W/m² (but presumably still increases at lower temperatures,
2) Module Tolerance - What is the efficiency at STC (1000W/m² and 25°C) – this module appears to be ~105% of nominal,
3) Change in performance at low light (left) – this module falls fast,
4) Change in performance at high light (right) – this module falls more slowly,
5) Rate of change in performance at higher module temperatures (Gamma),

4 HOW DO IV CURVES DIFFER BETWEEN DIFFERENT PV TECHNOLOGIES AND QUALITY?

Figure 6 row 0 illustrates IV curves for a clear morning from NREL Golden where the lowest IV trace is 06:15 with an irradiance of 0.07kW/m² and a module temperature of 17°C, the highest IV trace is at 10:45 when the irradiance was 0.95kW/m² and the module temperature was 56°C.

4.1 How do IV curves differ between PV technologies and quality?

Figure 6 columns A to C illustrates fits to three different types of modules,
Column A is for a “Good” c-Si module with a high RShunt and a low Rseries as expected,
Column B is for a “Good” thin film where the Rsc is approximately as good as that for the c-Si but the ROC is somewhat higher (the ROC of a c-Si is dominated by the tabbing material; that of a thin film module is limited by the TCO sheet resistivity).
Column C gives the traces for a “Poor” thin film that had poorer than expected Rsc and also a poor ROC.

Row 0) illustrates the effects that dominate the behaviour of the modules’ efficiency vs. irradiance. The Vmp is affected by the ROC at high irradiance and at low irradiance the Vmp depends on how the Rsc and Voc change with light level. A good low light level response comes from a high Rsc and a non-declining Voc.

4.2 How do they appear for different models?

Row 1 shows how the 1-Diode model fits the different modules, row 2 is for the points and gradients LFM and row 3) is the Efficiency only matrix.

The differences in the traces for the 1-Diode model are hard to spot. Because they have very different magnitudes from 1e-9 A/cm² for J0 to 1e+8Ω.cm² for Pshunt there are 17 orders of magnitude on the y axis.

The LFM is normalized and its y axis only ranges from 0.7 to 1.3. Clear differences can be seen between the traces – easily identifying the good c-Si from the good thin film in terms of nRsc and nVmp which both depend on Rseries. Note how the poor thin film has bad low light nRsc and nRoc and causes the nVmp and nVmp to deviate from their usual values of approximately ISC.STC/IMP.STC and VOC.STC/VMP.STC respectively.

4.3 Which model parameters cause these effects?

Rows 1 to 3 identify which parameters cause the changes in IV parameters and are summarized below.

The 1-Diode model finds dependencies on
- Rshunt ~ Rsc
- Rseries ~ Roc
- J0 and n are bad for the poor module

The LFM finds dependencies on
- nIMP and nVmp (both are related to Fill Factor)
- nRsc (dominated by Rshunt)
- nRoc (dominated by Rseries)

The Matrix method finds dependencies on
- Efficiency at low or high light
- Efficiency at low or high temperature
- Overall module tolerance Pactual/Pref
Figure 6 Comparison of IV curves (top row) and performance from different models (other rows) for three PV modules - “Good c-Si” (left), “Good Thin Film” (centre) and “Poor Thin Film” (right). The boxes are outlined in Green for Good, orange for medium and Red for poor. Row 3 also has a yellow box to show the PRDC factor for module tolerance (PACTIVE/PREFERENCE) and the blue box highlights the overall shape of the array.
5 ENERGY YIELD DEPENDENCY FROM MODULE PERFORMANCE

Figure 7 illustrates the irradiance and energy generated distributions by the three modules from August 2012 to September 2013 (they would have slightly different measurement, down times and/or missing data). The columns show the insolation distribution in kWh/m²/(100 W/m² bin) which are almost identical indicating there’s not much of a systematic error between them. The lines show the corresponding energy generated in kWh/kWp/(100 W/m² bin) with almost identical curves for the c-Si and good Thin Film and a much worse generation at low light (< 400 W/m²) from the bad thin film.

The energy yield in kWh/m²/year from a poor low light response will depend on the fraction of insolation occurring at low light levels. Colorado has a relatively good climate so only has ~17% of insolation below 300W/m². The relative difference in performance can be seen by the Performance ratios, the good thin film is about 1% higher than the c-Si (presumably due to spectral and temperature effects), the bad thin film is 3% worse.

This low light loss would be worse for a lower insolation site with higher insolation percentages at low light such as in Northern Europe.

Table II: Summary of dc performance of the three modules at Golden Colorado

<table>
<thead>
<tr>
<th></th>
<th>c-Si</th>
<th>Good TF</th>
<th>Bad TF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pmax.meas (Wp)</td>
<td>217.0</td>
<td>126.7</td>
<td>65.4</td>
</tr>
<tr>
<td>Gi (kWh/m²)</td>
<td>1480.4</td>
<td>1491.1</td>
<td>1486.2</td>
</tr>
<tr>
<td>Energy yield (kWh)</td>
<td>292.2</td>
<td>166.8</td>
<td>89.4</td>
</tr>
<tr>
<td>Performance Ratio dc</td>
<td>90.9%</td>
<td>88.3%</td>
<td>92.0%</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

IV curves are dominated by Voc at high light, and how Voc and RsC vary with irradiance at low light.

PV performance with Irradiance and temperature can be differentiated by:

- 1-Diode models: RsHUNT, RsSERIES also Ideality n and Io.
- Matrix method: Max Efficiency vs. Irradiance and T_MODULE and slopes (but without reasons).
- Loss Factors Model: nLMF and nVMF with high or low irradiance nRsc at low light and nRoc at high light

Recommendations:

PV Monitoring solutions and concepts have to reflect the PV Performance Modelling needs and improve their functionalities to allow unbiased performance understanding and risk reduction for the PV asset owner.

For simple kWh/kWp calculations on optimum sites Efficiency only model may be enough.

For a fast inline check, degradation/ non-optimum “points+gradients” models better.

For the ultimate understanding the full weighted point IV curves should be studied (actual and over time).

7 REFERENCES

[1] Sutterlueti et al “SBV.2.18 Using the Loss Factors Model to Improve PV Performance Modelling for Industrial Needs ” 29th PVSEC 2014 Amsterdam
[8] Photovoltaic (PV) module performance testing and energy rating IEC 61853