

# 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.

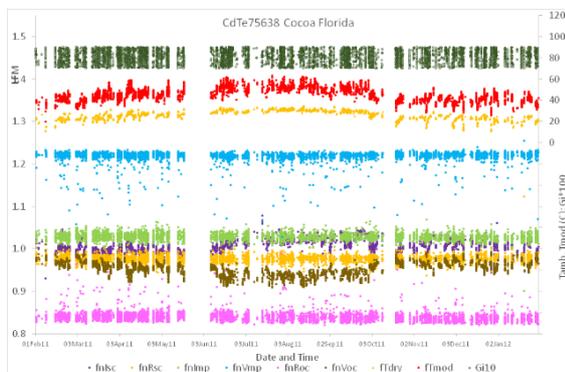
## 1 INTRODUCTION

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 ( $G_i$  kW/m<sup>2</sup>), ambient temperature ( $T_{AMB}$  C) and wind speed (WS ms<sup>-1</sup>).

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.

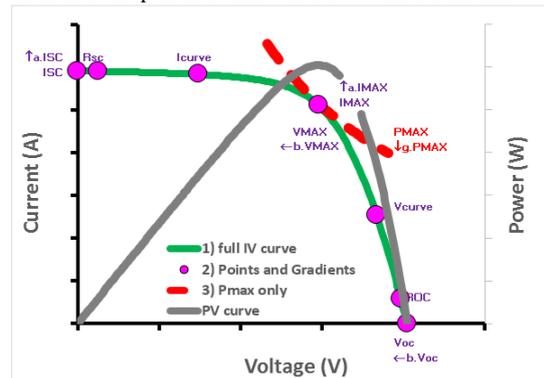
This graph selects data points for a narrow band of irradiance (0.7 to 0.9 kW/m<sup>2</sup>) and moderate module temperatures (30-70C) to enable an easy view of the time distribution and quality of the measurements (i.e. they should be frequent, without long gaps) and also the performance of the module (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<sub>MAX</sub> 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  $V_{MP}/2$  which indicate cell mismatch or shading and a constantly increasing negative slope from  $I_{sc}$  to  $V_{oc}$  (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  $I_{sc}$ ,

$R_{sc}$ ,  $R_{oc}$  and  $V_{oc}$  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  $I_{sc}$ ,  $I_{mp}$ ,  $V_{mp}$  and  $V_{oc}$  points to  $G_i$  and  $T_{MOD}$  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 $P_{MAX}$ or Eff only (Hyperbolic tangent constant $I^*V$ to IV curve)

Examples: Matrix method, IEC 61853[8], PVUSA, Empirical fits.

$I_{sc}$  and  $V_{oc}$  are sometimes analysed too but independently of  $P_{MAX}$ .

Table I shows which parameters can be analysed from the three different model types “Full IV curve”, “Points and Gradients” and “ $P_{MAX}$  only” fits.

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

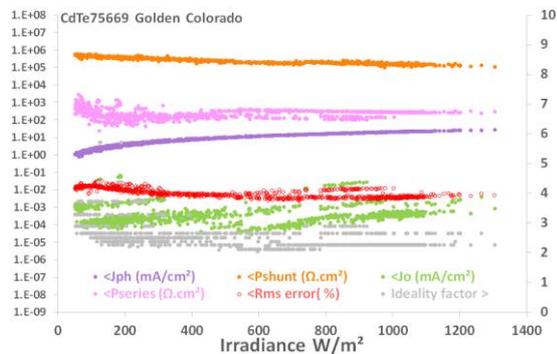
Analysis Reason Parameters to be analysed	Model Type →	2.1 “Full IV Curve”	2.2 “Points + Gradients”	2.3 “ $P_{MAX}$ or Eff only”
<b>Simple “optimum” energy yield</b> i.e. perfect $V_{MPP}$ tracking		Y	Y	Y
<b>Parameter limits</b> $I_{DC}$ limit = Max( $I_{MP}$ ) for fusing $V_{oc}$ limit = Max( $V_{oc}$ ) low temperature for inverter $V_{MP}$ tracking = lowest and highest module Temperatures		Y	Y	N
<b>Performance optimisation, degradation</b> Due to changes in $R_{sc}$ , $R_{oc}$		Y	Y(LFM) N(SAPM)	N
<b>Effect of Mismatch, Shading,</b> Schottky contact degradation		Y	N	N

## 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.

Note that due to some limitations in the fitting method the saturation current density  $J_0$  (green, mA/cm<sup>2</sup>) 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  $P_{SHUNT}$  (orange,  $\Omega$ .cm<sup>2</sup>) and the light current resistivity  $J_{PH}$  (purple, mA/cm<sup>2</sup>) were both fairly smooth and monotonic, the series resistivity  $P_{SERIES}$  (pink,  $\Omega$ .cm<sup>2</sup>) had a minimum value at low light.

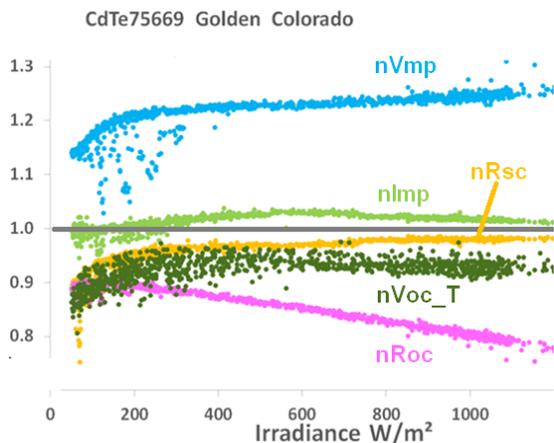
### 3.2 Points and Gradient fits

Figure 4 shows the same module data but fitted with the LFM Points and Gradients type model,

The  $n_{LSC}$  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  $nV_{MP}$  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  $V_{OC,STC}/V_{MP,STC}$ .  $nI_{MP}$  for a good module should be near  $I_{SC,STC}/I_{MP,STC}$ .

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  $nV_{OC,T}$  has been corrected for temperature. Note that as the dc performance ratio  $PR_{DC}$  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  $nR_{SC}$  and  $nV_{OC,T}$  suffer slight drops at lower light levels, the  $nR_{OC}$  suffers a linear drop at increasing light levels (right) due to  $R_{SERIES}$  resistance as  $loss \sim I^2 \cdot R_{SERIES}$ .

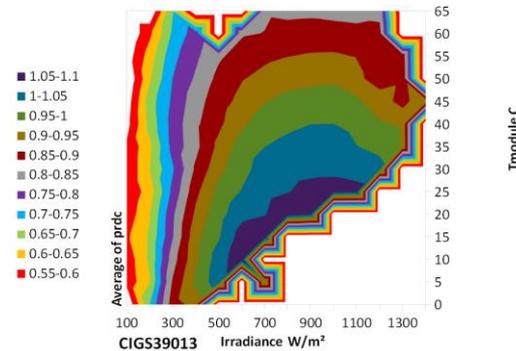


**Figure 4:** LFM points and gradients fits to an NREL measured CdTe module vs. irradiance

### 3.2 P<sub>MAX</sub> OF Efficiency only fits

Figure 5 shows an average Efficiency (~P<sub>MAX</sub>/light level) fits to 1000 IV curves for a poor module which had lower than expected R<sub>SHUNT</sub> and higher than expected R<sub>SERIES</sub> 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:** P<sub>MAX</sub> 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 20C and 800W/m<sup>2</sup> (but presumably still increases at lower temperatures,
- 2) Module Tolerance - What is the efficiency at STC (1000W/m<sup>2</sup> and 25C) – 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/m<sup>2</sup> and a module temperature of 17C, the highest IV trace is at 10:45 when the irradiance was 0.95kW/m<sup>2</sup> and the module temperature was 56C.

### 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 R<sub>SHUNT</sub> and a low R<sub>SERIES</sub> as expected,

Column B is for a “Good” thin film where the R<sub>SC</sub> is approximately as good as that for the c-Si but the R<sub>OC</sub> is somewhat higher (the R<sub>OC</sub> 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 R<sub>SC</sub> and also a poor R<sub>OC</sub>.

Row 0) illustrates the effects that dominate the behaviour of the modules' efficiency vs. irradiance. The V<sub>MP</sub> is affected by the R<sub>OC</sub> at high irradiance and at low irradiance the V<sub>MP</sub> depends on how the R<sub>SC</sub> and V<sub>OC</sub> change with light level. A good low light level response comes from a high R<sub>SC</sub> and a non-declining V<sub>OC</sub>.

### 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/cm<sup>2</sup> for J<sub>0</sub> to 1e+8Ω.cm<sup>2</sup> for P<sub>SHUNT</sub> 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 nR<sub>OC</sub> and nV<sub>MP</sub> which both depend on R<sub>SERIES</sub>. Note how the poor thin film has bad low light nR<sub>SC</sub> and nR<sub>OC</sub> and causes the nI<sub>MP</sub> and nV<sub>MP</sub> to deviate from their usual values of approximately I<sub>SC,STC</sub>/I<sub>MP,STC</sub> and V<sub>OC,STC</sub>/V<sub>MP,STC</sub> 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

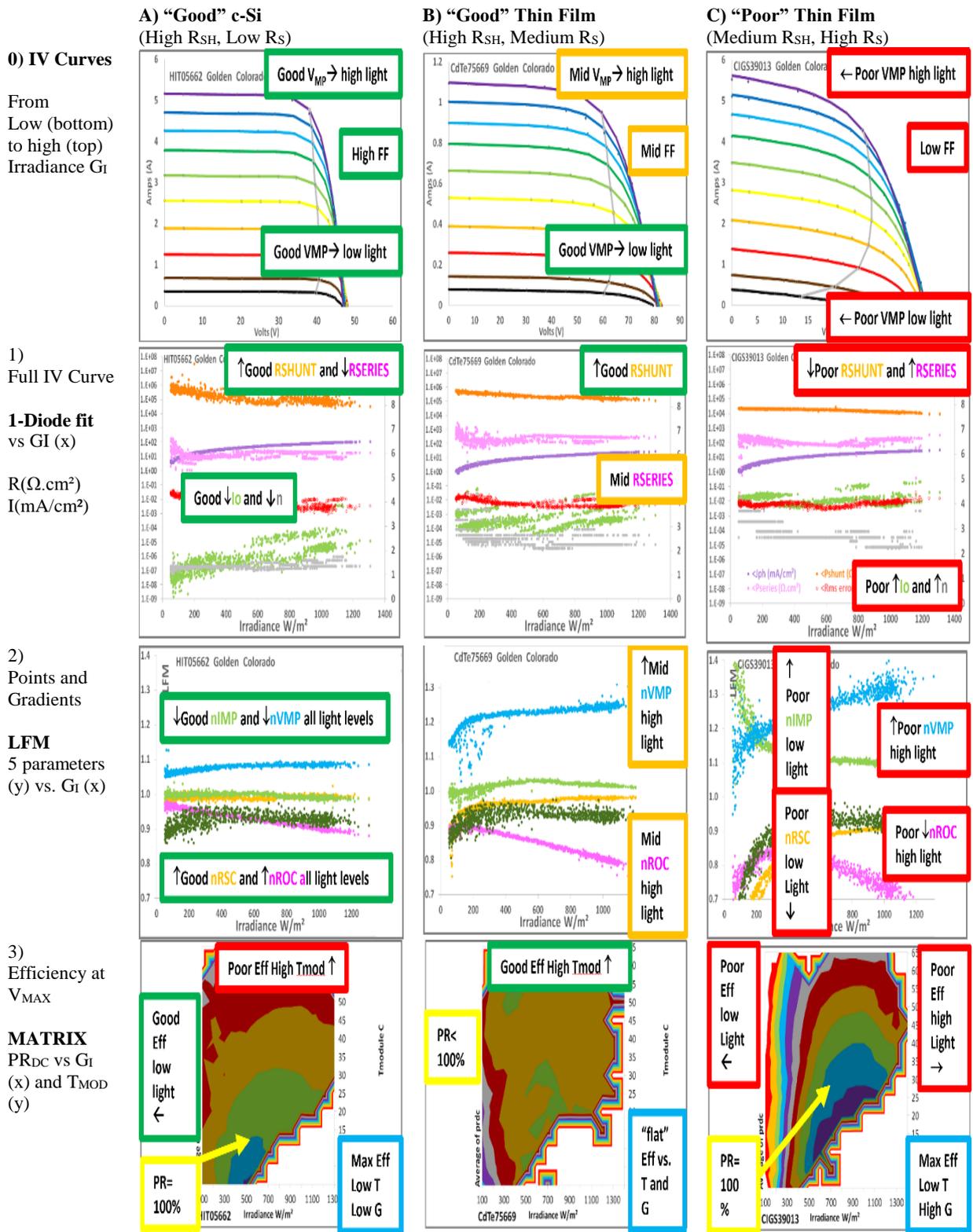
- R<sub>SHUNT</sub> ~ R<sub>SC</sub>
- R<sub>SERIES</sub> ~ R<sub>OC</sub>
- I<sub>0</sub> and n are bad for the poor module

The LFM finds dependencies on

- nI<sub>MP</sub> and nV<sub>MP</sub> (both are related to Fill Factor)
- nR<sub>SC</sub> ( dominated by R<sub>SHUNT</sub>)
- nR<sub>OC</sub> ( dominated by R<sub>SERIES</sub>)

The Matrix method finds dependencies on

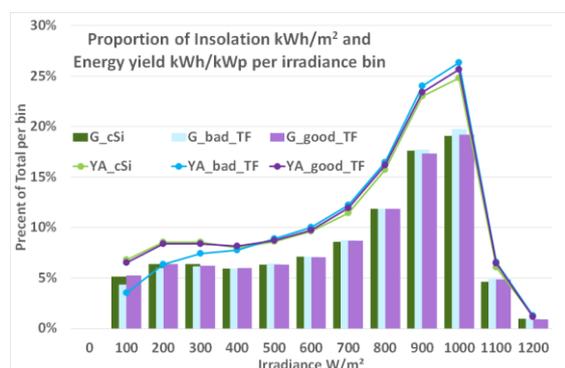
- Efficiency at low or high light
- Efficiency at low or high temperature
- Overall module tolerance P<sub>ACTUAL</sub>/P<sub>PREF</sub>



**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 middle and Red for poor. Row 3 also has a yellow box to show the  $PR_{DC}$  factor for module tolerance ( $P_{ACTUAL}/P_{PREFERENCE}$ ) 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/m<sup>2</sup>/(100 W/m<sup>2</sup> 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/m<sup>2</sup> bin) with almost identical curves for the c-Si and good Thin Film and a much worse generation at low light (< 400 W/m<sup>2</sup>) from the bad thin film.



**Figure 7:** Insolation and energy generated per irradiance bin for three modules.

The energy yield in kWh/m<sup>2</sup>/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/m<sup>2</sup>. 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

	c-Si	Good TF	Bad TF
Pmax.meas (Wp)	217.0	126.7	65.4
Gi (kWh/m <sup>2</sup> )	1480.4	1491.1	1486.2
Energy yield (kWh)	292.2	166.8	89.4
Performance Ratio dc	90.9%	88.3%	92.0%

## 6 CONCLUSIONS

IV curves are dominated by R<sub>oc</sub> at high light, and how V<sub>oc</sub> and R<sub>sc</sub> vary with irradiance at low light.

PV performance with Irradiance and temperature can be differentiated by:

- 1-Diode models:  
R<sub>SHUNT</sub>, R<sub>SERIES</sub> also Ideality n and I<sub>0</sub>.
- Matrix method:  
Max Efficiency vs. Irradiance and T<sub>MODULE</sub> and slopes (but without reasons).
- Loss Factors Model:  
n<sub>IMP</sub> and n<sub>V<sub>MP</sub></sub> with high or low irradiance  
n<sub>RSc</sub> at low light and n<sub>Roc</sub> 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

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