# ARRAY PERFORMANCE ANALYSIS USING IMPERFECT OR INCOMPLETE INPUT DATA

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ABSTRACT: For the analysis of outdoor monitored PV data it is important to have both good quality and complete inputs including setup data, date and time, plane of array irradiance, module and ambient temperatures, wind speed, string dc voltage and current (if available), inverter ac power – all at least once an hour.

However for various reasons some of these values might be missing or incorrect. Summing energy yield each measurement into yearly kWh/kWp figures means that these errors may not be noticed. Consequently, models developed to analyse output data from correct and complete input data will be invalid. This paper describes how to analyse data if some of the inputs are missing and shows how to correct performance.

Keywords: Energy Performance, Modelling, System Performance.

## 1   INTRODUCTION

Monitored data from outdoor PV systems can be used to model the performance of PV modules at DC, to model and understand the energy output of complete PV systems (including inverters and other BOS components) and to help with performance guarantee calculations [1]-[7].

However the data gathered in not always perfect, for example data may be missing (e.g. system or monitoring downtime or perhaps just lost data) or be "wrong" (examples are errors in the setup, clock synchronization or accuracy of sensors). Glitches can occur (sudden extremely high or low erroneous numbers or steps in the data stream as an error randomly occurs).

kWh/kWp outputs are usually obtained by summing the energy generated each time step to give an overall energy yield. This means that many of these errors may then not be noticed as they become averaged in with plausible data and have a smaller effect on the output. This will decrease their accuracy (errors must be removed as they are generated) and wrong conclusions could be reached (for example just one high erroneous value could change the energy sum significantly).

## 2   IMPROVING DATA COLLECTION

The accuracy of data as generated can be improved by performing sanity checks to confirm all the points are within sensible limits and that the average values are reasonable. If the erroneous data is removed then gaps can be interpolated for modelling or just ignored for energy yield.

To perform these sanity checks calculations can be made as follows :

From the clock date and time and details of the site location and array orientation calculate:-
- earth-sun distance (Sol.dist)
- solar position (Sol.Ht and Sol.Azi)
- extraterrestrial beam radiance ($X_B$)
- extraterrestrial horizontal plane radiance ($X_H$)
- sun-array angle of incidence (AOI)
- extraterrestrial tilted plane radiance ($X_I$).

From measured tilted plane radiance ($G_I$) and $X_I$ we can calculate clearness index $kT_I = G_I / X_I$

The accuracy of the clock can be checked by the modelled and measured times of dawn and dusk on the array (either instantaneously on a clear day or perhaps the average insolation with time over a month). Figure 1 shows how the extraterrestrial and global tilted irradiance have the same dawn and dusk when the clock is synchronized and calculations are correct for three days of variable weather at ISET in Germany. Also shown is the clearness index $kT_I = G_I/X_I$ which will usually be ~0.7 to 0.8 for bright conditions. If there are times when $G_I > X_I$ and the $kT_I$ for clear days appear non flat then it suggests that there are clock calibration errors.
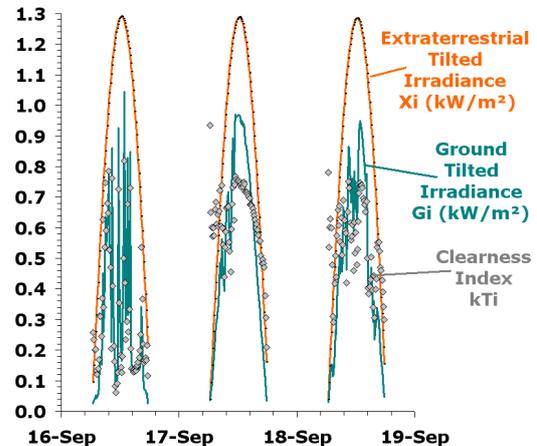


Figure 1: Extraterrestrial tilted plane irradiance $X_I$, global tilted irradiance $G_I$ and clearness index $kT_I$ for three days of variable weather at ISET in Germany.

## 3   DEFINITIONS

From the array setup (i.e. module types, nominal current and power) the normalized currents and voltages can be calculated as in table 1

Table 1. Definitions and graph colours used for measured and normalized parameters.

| Abbr. | Formula | Unit | Comment |
|---|---|---|---|
| $G_I$ | $G_{I.MEAS}/G_{I.STC}$ | kW/m$^2$ | Normalised Tilted plane Irradiance |
| $T_{AMB}$ | (air temperature) | C | Measured ambient Temperature |
| $T_{MOD}$ | (back of module temperature) | C | Measured module Temperature |
| WS | (wind speed) | ms$^{-1}$ | Measured wind speed |
| V | $V_{DM}= V_{DC} / V_{MAX.STC}$ | Dimensionless | Normalised $V_{MAX}$ |
| I | $I_{DN}= I_{DC} / I_{MAX.STC}/G_I$ | Dimensionless | Normalised $I_{MAX}$ |
| PF | $= V_{DM} * I_{DN}$ $=EFF_{DC}/EFF._{STC}$ | Dimensionless | Performance Factor |
| P | $= P_{DC} / P_{MAX.STC}$ $= PF * GI$ | Dimensionless | DC Power |

## 4  USING "REDUNDANT" or CHECK DATA

Further checks of data can be done by checking "redundant" measurements. For example the tilted plane irradiance Gi, ambient and module temperatures $T_{AMB}$ and T (respectively) and the wind speed WS should all be linked together via the NOCT formula <1> where the irradiance $G_{I.NOCT} = 0.8$ kW/m² (Global AM1.5), the ambient temperature $T_{AMB.NOCT}=20C$ and the wind speed is 1ms$^{-1}$.

$$T_{MOD} = T_{AMB} + G_I/G_{I.NOCT}*(T_{NOCT} - T_{AMB.NOCT}) \quad \textbf{<1>}$$

$T_{NOCT}$ for most modules is ~47C for free back devices and somewhat higher for roof tiling.

As we do not necessarily have free ventilation and the wind speed in general is not equal to 1ms$^{-1}$ then we have in equation <2> :-

$$T_{MOD} = T_{AMB} + G_I/G_{I.NOCT}*(T_{NOCT} - T_{AMB.NOCT} - fn(WS)) \quad \textbf{<2>}$$

(where fn(WS) = some system/pv dependent/wind direction function which depends on the mounting details and has the magnitude ~-3.5K/(1kW/m²) for a low wind speed for a free freely ventilated back, less for higher wind speeds and/or close mount).

Rearranging the formula gives equation <3>

$$T_{NOCT} = (T_{MOD} - T_{AMB}) * G_{I.NOCT} / G_I + T_{AMB.NOCT} + fn(WS) \quad \textbf{<3>}$$

We can plot this apparent $T_{NOCT}$ and check that is of a sensible value and is smooth, if any data is missing it can be interpolated as to what would give a sensible $T_{NOCT}$. Figure 2 plots the apparent $T_{NOCT}$ of a module in Germany for five variable weather days – Note that the apparent $T_{NOCT}$ is ~40C with only erratic excursions away from this (coinciding with intermittent irradiance). So it would appear that a calculated $T_{NOCT}$ of ~40C

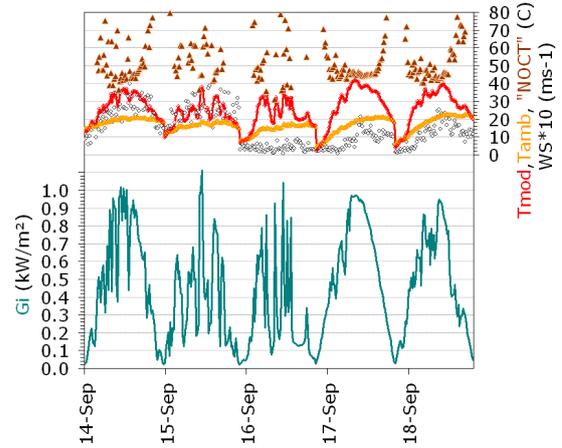shows good measurement of the other values.



Figure 2: Apparent $T_{NOCT}$ of a module in Germany for five variable weather days.

## 5  "USUAL" DC DATA

Figure 3 shows a graph of normalized I, V and P (from table 1) vs. irradiance from a well behaved module at ISET. Note that most of the data points are on quite well defined curves, The V and I values are generally 0.8 to 1 (i.e. they are between 80% and 100% of nominal). Data points outside these ranges are generally bad measurements, extremes of climate or other errors. The values of P mostly appear on a smooth curve with a gradient near 1:1 at low light levels and falling a little at higher light as the temperature rises and I$^2$R losses become significant.
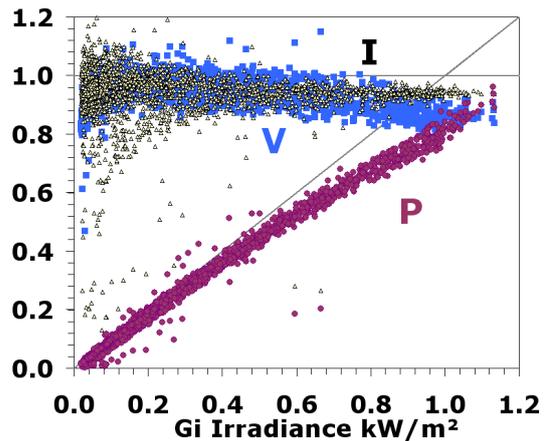


Figure 3: Normalized I, V and P vs. Irradiance from a well behaved module at ISET.

## 6  EMPIRICAL MODELLING

Equations <4> to <6> can be used to model temperature, voltage and power to predict good performance and identify outliers.

Empirical coefficients $A_X$ to $E_X$ (where X denotes the parameter being calculated) transform the performance

values as they depend on temperature, irradiance and wind speed.

$$T_{MOD.CALC} = C_{TM}*T_{AMB} + Gi*(A_{TM} + D_{TM}*WS) + E_{TM} \qquad <4>$$

$$V_{DM.CALC} = A_{VDM}*LOG_{10}(Gi) + B_{VDM}/Gi + C_{VDM}*T + D_{VDM}*WS + E_{VDM} \qquad <5>$$

$$YA_{CALC} = Gi*(A_{YA} + B_{YA}*Gi + C_{YA}*T + D_{YA}*WS) - E_{YA} \qquad <6>$$

RMS errors of <3C are usually found for the $T_{MOD.CALC}$; usually <2% for $V_{DM}$ and ~1% for $YA_{CALC}$ (often within the spread in errors of the measurements themselves). Good fits to typical data are shown in figure 4.
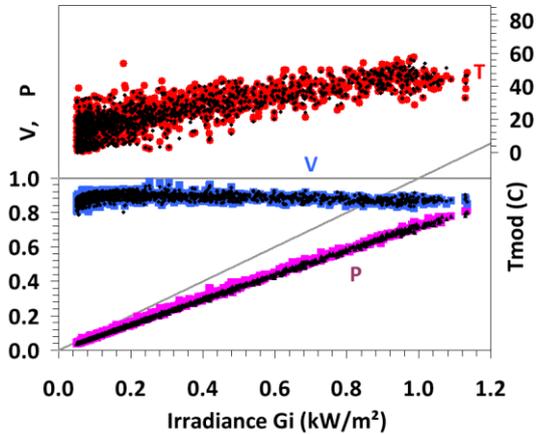


Figure 4: Good fits (black) to measured values of temperature, normalized voltage and power (coloured dots) for a module in ISET.

## 7 DATA vs. SOLAR POSITION

Shading can be a problem for some sites and can be identified by calculating the sum or average irradiance and pv performance for each sun position in (bins of solar altitude and azimuth).

Figure 5 illustrates the yearly total global tilted plane irradiance versus solar altitude and azimuth in 10° increments. The horizontal banding increasing with solar altitude shows a good array location without shading. If there were shading it would appear as low values vs. azimuth (perhaps buildings or trees) or at low solar elevations (horizon shading).

Compare this with the graph of dc yield in figure 6. This has a very similar shape indicating there are no shading limitations here.
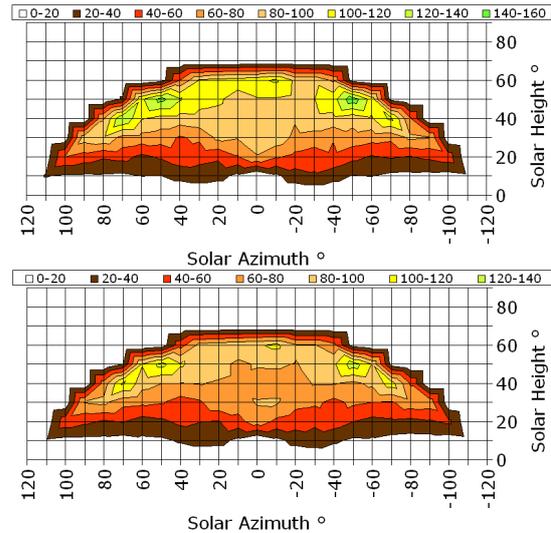


Figure 5 (top): Total global tilted plane irradiance (kW/m²) versus solar altitude and azimuth in 10° increments for Kassel Germany

Figure 6 (bottom) : dc Yield (kWh/kWp) vs. solar altitude and azimuth in 10° increments for Kassel Germany

## 8 DATA vs. DATE and TIME

Downtime can be identified by plotting the sum irradiance, energy yield or the average voltage and current vs. hour of day (vertical) and day or month (horizontal axis) as in figures 7 and 8.

Vertical lines of low performance indicate downtime (see all day 6th and early 7th and 10th March).

The current in Figure 8 should be flat and near 1 for good performance – horizontal bands of low performance could indicate shading or perhaps inverter turn on problems.
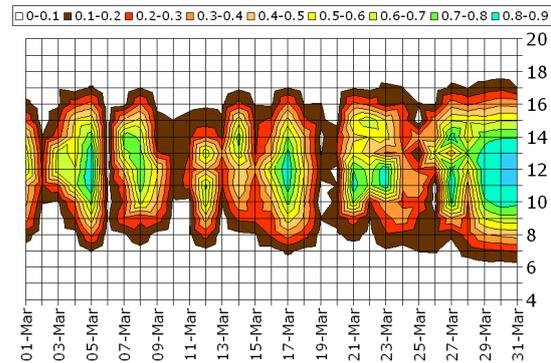


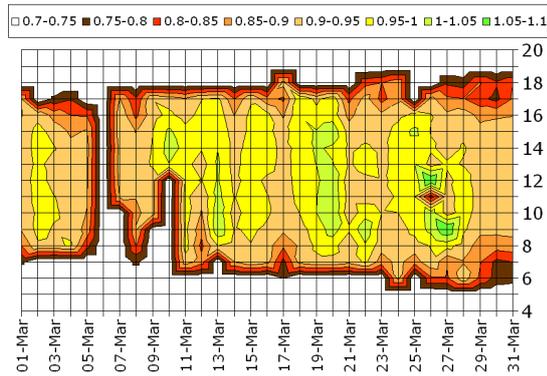Figure 7: Average Irradiance vs. day (horizontal) and hour (vertical axes)

Figure 8: Average normalised current vs. day (horizontal) and hour (vertical axes).

As performance data builds up over a year then shading can be investigated by plotting the maximum irradiance each month and hour. A good system is given in figure 9 – if there were shading problems then there would be localized dips superimposed on what is shown here which is essentially a symmetrical 2 dimensional Gaussian shape.
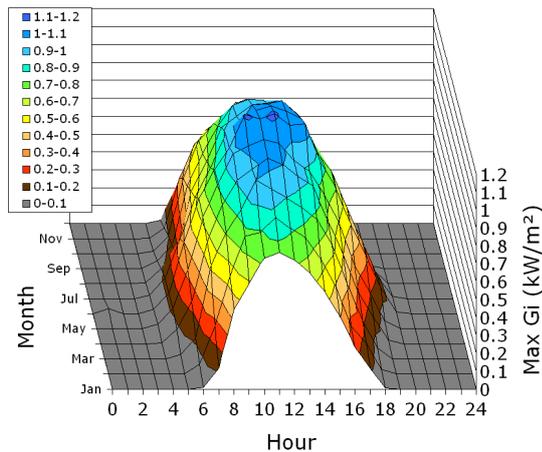


Figure 9: Maximum irradiance vs. hour (horizontal) and month (vertical axes) measured every 15 minutes.

## 9    VALIDATING DATA

Once the empirical coefficients from equations, <4> to <6> have been derived they can be used to validate each measurement. If any of the inputs ($G_I$ Irradiance, $T_{AMB}$, $T_M$ or Wind speed) or outputs (normalized Voltage, Current or Power, Performance Factor or Ratio) are wrong or missing then the measured output will differ from that predicted. Figure 10 compares the measured with predicted performance ratio of an AC system in the USA just using 15 minute averaged $T_{AMB}$ and Irradiance $G_I$ input data on a sunny day, there were four measurements in the middle of the day that were much lower than expected.
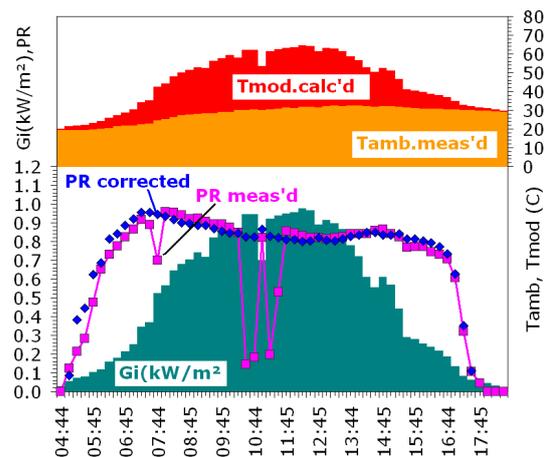


Figure 10: Corrected vs. Measured performance ratio for a PV system in the US on a bright day.

Figure 11 contrasts the daily average measured figures with the predicted, now as the data is the sum of many input values (for example 12 hours day length * 4 measurements per hour at the equinox ) the errors will only be large when an appreciable fraction of a day is in error. The two points marked in different colours (15th and 18th Oct) were the largest errors in this time series of about 10% PR.
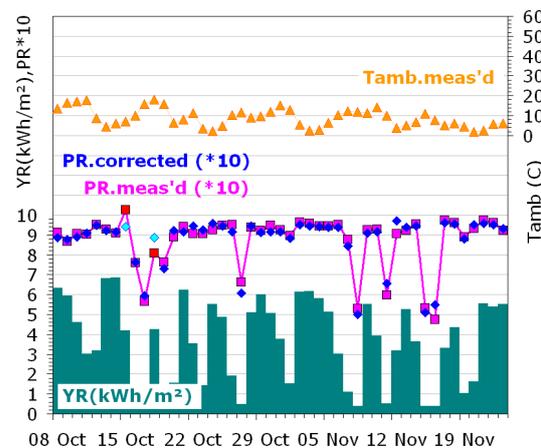


Figure 11: Corrected vs. Measured daily performance ratio for a PV system in the US for October and November

## 10 CONCLUSIONS

- Methods have been shown to improve the accuracy of monitoring data
- Corrections and validation can be taken at the measurement stage
- Historical data can be analysed to determine the effect of any downtime or shading.
- Empirical equations are shown to be useful in studying module or array performance

## 11   ACKNOWLEDGEMENTS

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