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Understanding Outdoor PV Performance Measurements

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Introduction

Many PV arrays around the world are continually monitored (measurements are often logged every few minutes) and the yearly energy yield is usually quoted in terms of kWh/kWp or an average performance ratio (PR) for the customer or owner [1][2][3].

However calculating just one total or average performance figure for a year does not give much information as to exactly how the array is behaving as many different faults or problems could all give the same underperformance value, whereas miscalibrations of module power or under sensitive irradiance sensors would tend to suggest a higher output than expected.

Sometimes these effects can cancel each other out – for example an underperforming array and an under sensitive irradiance meter might erroneously suggest a reasonable performance figure.

kWh/kWp and Performance Ratio

The most often used values in the PV industry to compare and contrast arrays are ac energy yield YF (kWh/kWp) and performance ratio PR (dimensionless).

These are defined as :-

STC : Tmodule=25C, Spectrum=AM1.5G, Angle of Incidence=0°, Wind speed=0ms^{-1} and Direct/Global irradiance=1.
kWp : Nominal power of array using manufacturer's STC rating.
kWh : AC energy (usually /year).
YR : Plane of array insolation (kWh/m²/y)
YF : kWh/kWp (1)
PR : YF/YR (2)

Note that the area and efficiency of modules cancel out to make the PR dimensionless. For example if there were two arrays and the second had half the efficiency of a first it would need twice the area to get the same kWp; it would also impinge on twice the incident insolation (kWh/m²).

Table 1 shows how different parts of the industry use kWh/kWp figures

Table 1: kWh/kWp use by industry sector

Section of industry	kWh/kWp relevance
Manufacturers	Claim high performance
Indoor testers	Measure relevant parameters
Sizing programs (simulation models)	Claim accurate predictions
Customers	Expect high values
Financial	Demand guaranteed values over lifetime
3rd party outdoor comparisons	Different rankings for each technology

It has been shown by several studies that kWh/kWp values are similar for correctly defined and well measured stable modules; the biggest variabilities are the apparent/nominal Wp, also down time and degradation.

In production lines modules are rated at STC conditions whereas in real systems modules experience real world weather conditions.

The following list shows the advantages and disadvantages of outdoor measurements with respect to indoor ones :-

Advantages of outdoor vs. indoor data

- real measurements
- fewer corrections/assumptions to understand performance
- also tests packaging, thermal stresses etc.

Disadvantages of outdoor vs. indoor data

- not as repeatable
- stabilisation due to exposure slower than light soak - may have several months without full sun say in climates like N Europe
- harder to quantify degradation
- May be site specific.

Normalising values to ease comparisons and validate data

When comparing small scale samples with individual modules, strings or complete arrays it is useful to normalise the data to their nominal STC values, this also helps check the data is valid.

Equations (3) and (4) are used to normalise the current and voltage, (5) defines the dc performance factor (PF) from Idn and Vdm.

Vdm = Vdc / Vmax.stc (3)
Idn = Idc / Imax.stc / Irradiance (4)
PF = Efficiency dc/ Efficiency.stc
= Vdm * Idn (5)

Normalising measurements helps to establish limits to remove bad data points (e.g. if the normalised current or voltage aren't in the range 80-110% then it is likely that the data accuracy is poor).

Also ignore data when the clearness index (kT = "measured / extraterrestrial" horizontal plane irradiance) is outside sensible limits (mostly this is between 0.2 for a very overcast sky and 0.8 for a very clear sky).

Temperature measurements should also be within site specific limits, for example faults or bad sensors mean that temperature data that isn't feasible e.g. <-20C or >70C should be removed - local knowledge of a site might reduce this range still further.

When there is redundant data check that all the measurements are feasible – for example with a given plane of array irradiance, ambient temperature, wind speed and module type and known mounting method (e.g. ventilated back, solar slate etc.) estimate the module temperature from equation (6).

Tmod = Tamb + Irrad/0.8*(NOCT – 20)
– fn (Wind speed) (6)

If Tmod is also measured perform a sanity check – i.e. compare measured module temperature with that expected from measured irradiance and ambient temperature. NOCT will be on the module specification sheet and will usually be between approximately 45 and 50C for a PV laminate or framed module and maybe 65C for a solar slate.

The function of wind speed will be mounting method and module type specific and may be approximately -3.5C/(ms^{-1}) for low wind speeds saturating at high winds so that Tmodule >= Tamb.

Figure 1 shows some measured meteorological and electrical measurements for a dc module in Germany, note the coloured bars at the side indicate the normal sensible limits (for example the Idn should usually be between 0.8 and 1.1). The apparent NOCT (calculated as above) is shown and for the majority of the data points it appears to be between 40 and 55C.

Further accuracy improvements can be done by smoothing out transient input data and also considering the recent measurements as the thermal mass of the module means it would take ~15 minutes to stabilise temperature after a step change in irradiance or wind speed.

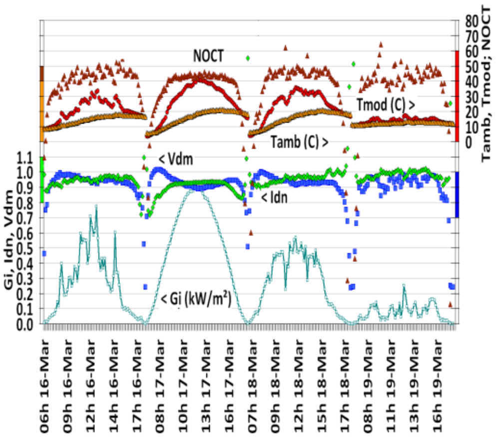

Figure 1: Normalised current and voltage vs. meteorological parameters showing sensible limits (left and right axes).

Correlated weather values

Indoor tests will often attempt to extract device performance parameters by applying them orthogonally, i.e. varying one at a time while maintaining all the others constant. For example to measure the power temperature coefficient gamma (γ = 1/Pmax * dPmax/dT) the other STC conditions are kept constant while just the temperature is varied.

However in real outdoor conditions all weather parameters are correlated.

Table 2 shows the parameters and their indoor or STC rated value. Outdoors there are two columns showing "worse weather" and "better weather" and descriptions on how they tend to vary with each other. For example if a user tried to extract data by monitoring performance between low and high irradiance they would also find that at the high irradiance condition the temperature, spectrum, angle of incidence and direct fraction would all tend to have changed which could have affected the results.

Table 2: How all weather parameters are correlated.

	Indoor	**Outdoor**	
Parameter	STC	**Worse weather**	**Better weather**
Irradiance	1 kW /m²	Lower	Higher
Module temperature	25 C	Colder	Warmer
Spectrum	AM 1.5 G	Redder	Bluer
Angle of incidence	0° normal	Away from normal	Nearer normal
Direct : Diffuse	All Direct	Mostly diffuse	Mostly direct

This has the effect that modelling data by deriving orthogonal coefficients of irradiance, temperature etc will give the wrong performance result.

Figure 2 shows attempts at finding the current and voltage temperature coefficients for a c-Si module in Germany. The data had to be heavily filtered to get this good fit – any points with low irradiance, temperature, times not close to noon or having a high diffuse content had to be excluded otherwise the scatter would be too great. Even so there are some bad points for Voltage around Tmodule=31C. Fits for c-Si can usually be close to indoor measurements however for thin film the correlated spectral effects can dominate temperature performance.

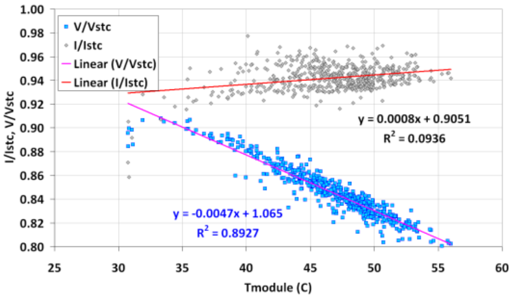

Figure 2: Extracting temperature coefficients from outdoor data

Analyse performance and compare with standard modules

Plotting module temperature and normalised current and voltage and P/Pmax give traces similar to figure 3 for most PV technologies. New modules on test should be compared with these shapes to confirm correct behaviour and to identify any differences.

The normalised V parameter will usually tend to be highest from 0.2-0.4kW/m², falling at low light levels and also falling slightly above this range. The slope at high light levels and the spread at a given irradiance depend on the temperature coefficient.

The normalised I parameter will tend to be flat at highest Irradiance, at low values it will split into two – a lower falling curve (bright sky at high angles of incidence) and a higher triangle shape (diffuse sky).

The heights of the V and I lines indicates the rating accuracy and performance of the module, ideally the peak of the V and the flat part of the I curves should be close to 1.

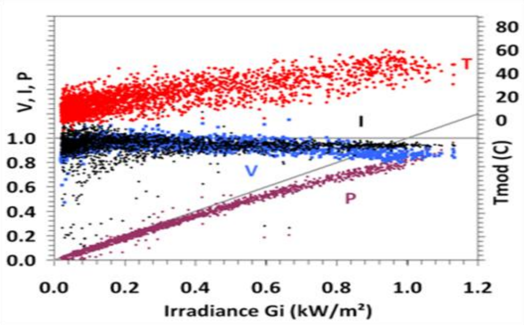

Figure 3: Module temperature, normalised I, V and Pmax vs. irradiance for a c-Si module in Germany.

Checking for Shading

To check if the array is shaded the maximum irradiance per hour and month can be plotted as in Figure 4. This plot shows fairly symmetrical concentric rings which indicate a good unshaded array. Any shading would show as vertical strips of lower than expected maximum irradiance.

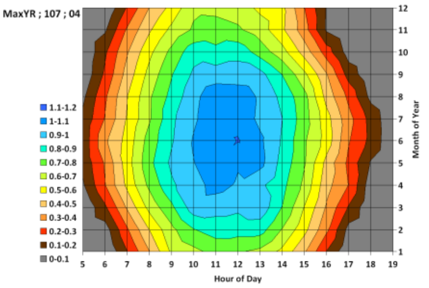

Figure 4: Maximum Irradiance per hour of the day and month of the year at site in USA.

Checking for inverter saturation and temperature effects.

Figure 5 plots the maximum ac yield by hour and month for a thin film array in the US. Again the plot is mostly of concentric rings (i.e. good performance). Saturation or temperature effects would usually show as asymmetries particularly later in the day and in the summer. It can be seen that the August (month=8) performance is slightly better than June (month=6), possibly due to thermal annealing.

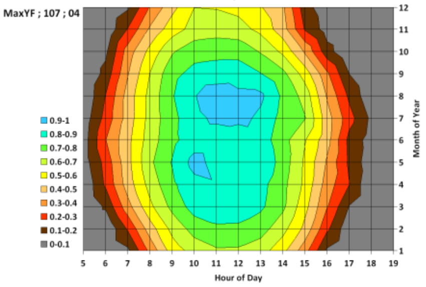

Figure 5: Maximum ac yield per hour of the day and month of the year at site in USA.

Array performance

To check the performance of arrays we should compare the PR and YF of a dc module with an ac array. The balance of systems such as the inverter will reduce the power overall due to its efficiency, mismatch will reduce the overall power a little more and the low light level performance may be limited by the inverter's poor efficiency at low input power.

Figures 6 (Thin film) and 7 (c-Si) show the PR and AC Yield of large arrays in the US vs. irradiance.

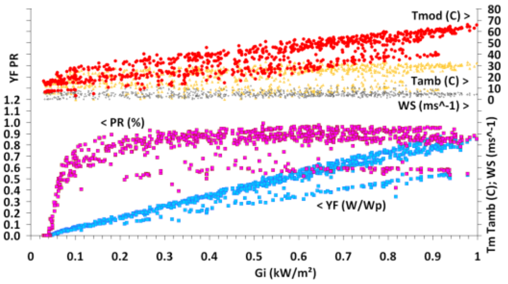

Figure 6: PR and AC Yield vs. Irradiance for a thin film array in the USA

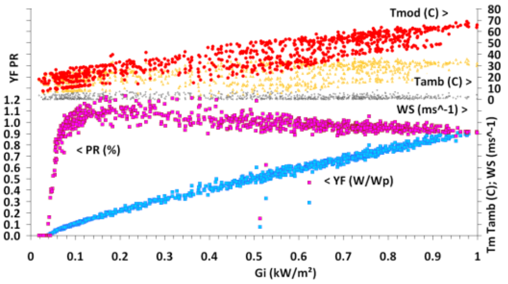

Figure 7: PR and AC Yield vs. Irradiance for a crystalline Silicon array in the USA

Other details which can be identified on these graphs are that there was a period of bad performance with the TF array (see some of the PR points are lower than expected).

The kWh/kWp of the arrays would be dominated by the average PR with irradiance. Note that with these measurements the c-Si and the TF both have PR ~80% at high light level (high temperature) but this c-Si will win out due to its higher temperature coefficient and better performance at low light levels

Conclusions

- Sophisticated outdoor testing has been used on c-Si and thin film devices.
- Plots of performance vs. time of day and month can give useful information
- Normalisation of data makes it easier to do error checking for bad measurements when these are outside narrow ranges.
- Calculations and checks with redundant data also enable sanity checks on the data to be performed.
- Checking of the raw data enables a large number of faults, limits and weather effects to be analysed.

Acknowledgements

Peter Funtan, ISET for the dc data.

References

This paper will be available in colour as well as all the references below at http://www.steveransome.com

[1] "Analysing array performance" Invited paper International Workshop on PV System Monitoring and Performance Assessment - 30-31 Oct 2008 Nice France
[2] "4DO.9.6 A Review of kWh/kWp Measurements, Analysis and Modelling" Valencia 2008 23rd European PVSEC
[3] "4BV.1.58 Array Performance Analysis Using Imperfect or Incomplete Input Data" Valencia 2008 23rd European PVSEC