CAN GRID TIED PV SYSTEMS BE CHARACTERISED WITH ONLY MONTHLY AVERAGE VALUES OF PR?

S J Ransome
BP Solar,
Building B, Chertsey Road,
Sunbury on Thames, TW16 7XA,
UK
Tel: +44 (0) 1932 775711
Fax: +44 (0) 1932 762686
Email: ransomsj@bp.com

J H Wohlgemuth
BP Solar,
630 Solarex Court,
Frederick, MD 21703
USA
Tel: +1 301 698 4375
Fax: +1 301 698 4201
Email: wohlgej@bp.com

S Poropat and Rhys Morgan
BP Solar Australia,
2 Australia Ave,
Sydney Olympic Park,
NSW 2127, Australia
Tel. +61 (0) 2 8762 5765 / 5745,
Fax. +61 (0) 2 8762 5788
Email: poropas@az1.bp.com
rhys.morgan@az1.bp.com

ABSTRACT: Many grid connected PV Systems worldwide are monitored and analysed to calculate ac Performance Ratio (PR) and kWh/kWp figures. Monthly average PR values are often compared to show how well systems are working. This paper shows how monthly average PR values are insufficient to identify and quantify different losses. Better understanding can be gained by analysing daily or hourly data to maximise output Energy and reduce ¢/kWh cost.
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1 INTRODUCTION

Many Grid connect arrays are designed using simple commercially available "Sizing" programs. These store weather data (often in the format of monthly average horizontal plane or Typical Reference Year format – taken by choosing real data from periods in different years where the averages and spreads of this sequence correspond to a normal "typical" year). The program will then transpose irradiances to the tilted plane using algorithms to find the solar position and its incidence angle with respect to the array, partitions the irradiance into direct, diffuse and reflected components and uses an anisotropic diffuse model for example [1] to estimate the irradiance impinging on the array.

Sizing Programs attempt to estimate the module power at different irradiances and module temperatures using simple models. Listed below are three examples known of the data stored in the program's PV component databases and approaches used for their calculations of module power.

1) Store V_{MAX} and I_{MAX} values at "low" and "high" irradiance values. Predict a family of curves for all relevant temperatures and irradiances from just two points.
2) Store $V_{MAX\cdot STC}$ and $I_{MAX\cdot STC}$ values. Assume linear changes with Irradiance and Temperature.
3) Store an IV curve at STC (often from flash testing). Use an IV translation model e.g. IEC891, Blaesser or Anderson.

Many of these commercial programs studied use either characterized data from one module in a test lab or they copy the electrical values from the manufacturer's data sheet.

Characteristics for Inverters (Inverter Efficiency vs P_{INPUT}) and Ohmic losses for the wiring are used to predict output performance.

Often no modelling is performed for Actual/Nameplate P_{MAX}, Light Induced Degradation (LID), Angle of Incidence dependency, Module Mismatch, Spectrum, Stability, non-optimum V_{MAX} tracking or Dirt. Experience shows that the output predicted, although of the "right" magnitude often 75-80% Performance Ratio (PR = kWh_{AC} / $kWp_{\cdot STC}$ /Plane of Array Insolation kWh/m²) depends more on the assumptions of the device models than anything else.

Low light levels do not dominate performance of well oriented, Grid Connected arrays for anywhere sunnier than Northern Europe where up to 30% of the irradiance is <300W/m^2 compared with 12-19% for sunnier sites [2]. In addition inverter inefficiencies reduce the amount of power produced at low light levels so module technologies with rising efficiency as the light level falls are in effect losing energy at the more productive higher light levels.

If the monthly average Performance Ratio of real logged systems produce a close match to the Sizing program's output, it is often taken as validation of the program and as an indication that the array is working correctly.

A simple analysis of IV curves and Inverter efficiencies will often give a predicted PR that is too high, loss figures then get added into the program for parameters such as I^2R loss, Mismatch, and V_{MAX} mistracking to bring the output down to the expected value without necessarily being realistic. For example if Angle of Incidence effects (i.e. Reflectivity vs Beam angle normal to the module) aren't modelled then adding the loss expected from AOI to one of the other parameters may still give a believable result.

This paper analyses some of the real effects that can change the output of an array and how these can't be modelled by looking at simple monthly averages of array performance.

2 EXAMPLE RESULTS FROM A LARGE mc-Si ARRAY

The example data below is taken from one system selected from more than 80 sites studied on 5 continents around the world. It is a 200kWp retrofit close spaced roof top array in Australia using 1328 x BP SX 150 multicrystalline modules and 83 x SMA 1700 Inverters. Figure 1 shows the average monthly PR_{AC} for two halves of the array varied between 77 and 80% for the initial four months after June 2003. This is a high value and it indicates that overall the array is working well. Studies were made to identify the drop in PR in the summer months. Figure 2 shows how the daily PR varies with Insolation, on days ~ 2.5kWh/m² the PR averages 80% but with a spread ±5%.

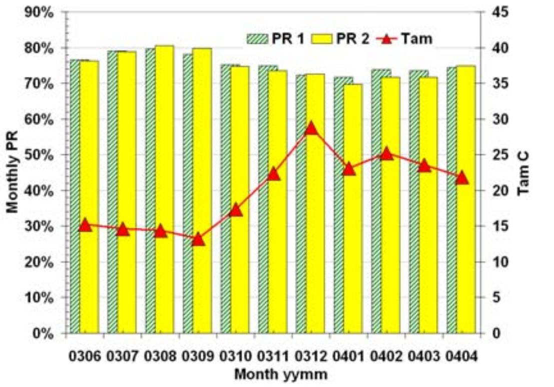

Figure 1: Monthly average PR from two halves of the array PR1, PR2 and Tambient vs Month for a well performing mc-Si array in Australia.

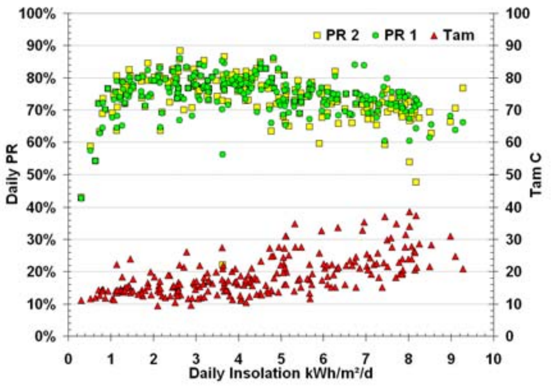

Figure 2: Daily average PR and Tambient vs Insolation for a mc-Si array showing PR~80% at lower insolation days falling slightly as the Insolation and hence the Tambient rises.

For the first three months the performance ratio of the Array in figure 1 was averaging 79%. This was in the Southern hemisphere winter when the Tambient was relatively cool at 15C. Studying the hourly data through the year showed that as this was a close spaced retrofit, the module temperature rose faster than that expected from a free back mounted array and the performance ratio fell at the higher insolations. Shadowing could be seen to fall from winter to summer as the sun's elevation rose. These effects (which could not have been identified and characterised from Monthly PRs) reduced the measured Performance ratio averaged over the year to 74%.

3 LOSS MECHANISMS FOR ARRAYS

There are many loss mechanisms (some are listed in TABLE 1) which can be present from quantities of 0 (e.g. shading for an unshaded site) or a minimal value (e.g. series resistance of wires in a well designed system) up to an effect large enough to be influential. Any effects of these mechanisms cannot be distinguished by simple analysis of monthly values of Performance ratios.

Empirical equations can be used to predict expected performance from measured parameters - values of the empirical coefficients will depend on the BOS and PV technology [3] used. Three useful empirical equations for Yield, Module Temperature and Optimum dc Voltage are given below <1> to <3> :-

<1> $Y_{CALC} = \Sigma G_I*(A+[B*\Sigma G_I]+[C*T_{AM}]+[D*WS])-E$

<2> $T_{MOD} = C'*T_{AM} + \Sigma G_I*(A' + D'*WS) + E'$

<3> $V_{OPTIMUM} = A''*LOG_{10}(\Sigma G_I) + C''*T_{MOD} + D''*WS + E''$

These can be used by the analysis of for example hourly data to calculate the expected Performance Ratio and help determine reasons like shading or high temperatures when this value is not achieved.

TABLE 1 : Some loss mechanisms that can affect the average PR.

Problem and Comments	**Graphical means of finding problem**
Downtime Will have more impact during summer months as a higher percentage of Yearly kWh occurs per summer day.	"Random" drop outs in Daily PR vs Time of Year. Will reduce monthly PR by approximately fraction of Irradiance not utilised.
Mistracking of Array DC Voltage (Fig 3) Estimate $V_{OPTIMUM}$ from Irradiance and $T_{AMBIENT}$	Hourly PR vs $V_{OPTIMUM,}$ drops may occur above or below Voltage limits – Plateaus in the V vs hour plot indicate tracking may not be taking place
Stability (particularly Thin Film modules) TF often experience a stabilisation fall off for a period of up to 3 months	Performance Ratio of high Irradiance days vs time will decrease initially
Inverter Loss High if incorrect or poor quality component selection	Non-linear dependence of Hourly PR on Light level
High Module Temperature effects Estimate T_{MODULE} from Irradiance and $T_{AMBIENT}$. Performance Ratio will fall ~ -0.45%/deg C as Modules heat up.	PR vs Irradiance and $T_{AMBIENT}$ Can ventilation to module backs be improved ?
Wiring I^2R Loss Should be <2% for well designed systems. Estimate Current from Irradiance and T_{MODULE}	PR vs light level, drop off at high irradiance irrespective of T_{MODULE}
Module Mismatch Should be <2% for well selected systems	Will appear as a poorer PR at all light levels

Obstacle or Horizon Shading (Fig 5) From objects on the horizon or nearby obstacles not part of the array. The effect of deciduous Trees may be seasonal.	PR vs Time of day and month, worst for high Irradiance as light in the shadows is from the lower diffuse component. At low irradiances (i.e.cloudy periods) shadowing will not be as important as the diffuse fraction is larger.
Self or Row-to-Row Shading (Fig 6) Shading from other parts of the array (self shading)	PR vs Time of day and month, worst for high Irradiance as above. Look at clearness index
BOS low light level performance Some BOS components have constant loss and may not have a disconnect at night giving a power drain.	PR vs light level at low Irradiance may appear negative at night
Saturation, Turn on Clipping at high power, Turn on problems if poor components chosen	PR vs Irradiance may show saturation above a given P_{OUT} or drop to zero below a given P_{OUT}
Underperforming Strings on large systems (Fig 4) Small numbers of poorer strings on large systems will just appear as a small drop in performance of the whole array.	Fraction of Total Energy per string vs Time and Irradiance. (Shows importance of having individual string data)
Dirt Will be seasonally dependent, particularly in dry, dusty regions, less after heavy rain	PR vs Time of Year. Look for slow falls with high irradiance days then sudden rises after periods of low irradiance (maybe indicating rain)
Snow Losses can be high in some sites	Tends to occur in lowest irradiance months. Worse with lower tilt angles. Solar tracking may tip snow off.

4 SOME EXAMPLES OF ARRAY PROBLEMS

Below are some graphs exhibiting effects found in some of the systems studied.

4.1 VOLTAGE MISTRACKING

Fig 3 shows Voltage Mistracking on a shaded string. Usually the normalised dc Voltage $V_{DM} = V_{DC}/V_{MAX.STC}$ for most PV technologies should be between around 0.8 and 1.0 depending on Temperature. On this array the only mistracked strings were those suffering from shading.

On clear days the Irradiance YR ranged up to 0.7 kW/m², The $T_{AMBIENT}$ varied from 5 to 20C.

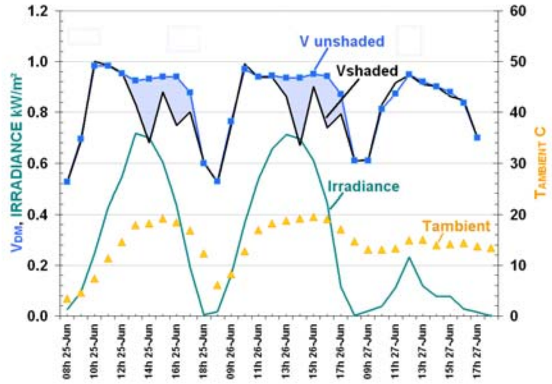

Figure 3: Tambient (right axis), Irradiance and V_{DM} (left axis) for unshaded substrings and an afternoon shaded string of a large system in Australia. Note the loss in the voltage compared to the average for unshaded strings, there is little effect on the cloudy day (right)

4.2 UNDERPERFORMING STRINGS

For a system all equal sized, unshaded, planar strings should contribute almost equal fractions of the energy at all times. Figure 4 shows the fraction of each of four strings in an array for two days of clear sunshine (left) and a cloudy day (right). Also shown is the Insolation (versus right hand scale).

For the right hand (cloudiest day) all sub arrays are contributing almost equal amounts. On the two clear days, the sub-arrays contribute equally until noon after which the top array declines with time indicating shading. There is little difference between the arrays on the cloudy day (right)

Changes in relative fraction of power with time may indicate non-parallel arrays or shading, with light level it might indicate a poor module or BOS component on one string [4].

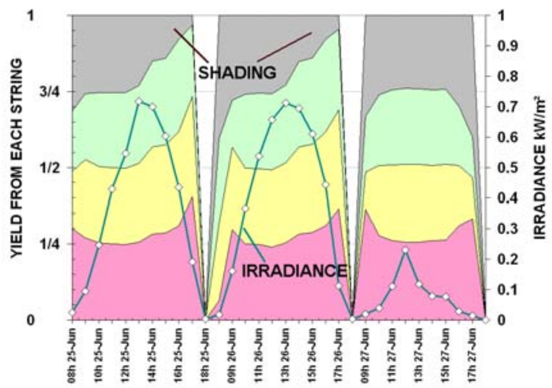

Figure 4: Irradiance (right axis) and percentage of total energy (left axis) for 3 unshaded and 1 afternoon shaded substrings of a large system in Australia.

4.3 HORIZON OR OBSTACLE SHADING

Rooftop arrays, particularly retrofit systems will often experience shading from nearby obstacles or perhaps chimneys, piping and air conditioning on the same building (see 4.4 for study of self shading).

Figure 5 shows the I_{DM} (= DC current / $I_{MAX.STC}$) of the average for 40 paralleled unshaded strings, plus a string shaded in the afternoon on two successive clear days and a cloudy day in Australia (repeated fall off of performance at the same times of the day implies shading). (If DC currents are not available then analysing the YF versus time will give similar results as long as the Voltage tracking is good).

Analysis of the relative positions of six poorer strings in the array shows them to be in positions that imply external shading – morning shaded strings are along the east edge, the afternoon shaded ones are along the west edge and two underperforming (due to a "diffuse shadow") are right at the front (nearest the equator)

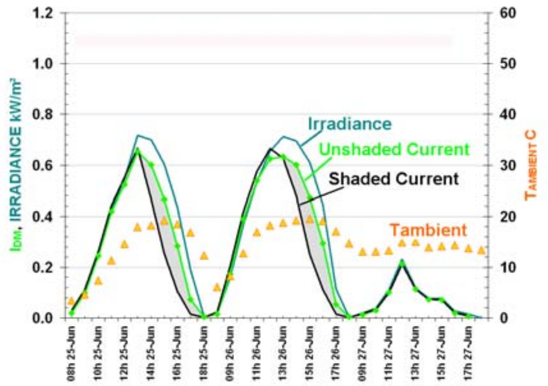

Figure 5: Tambient (right axis), Irradiance and I_{DM} (left axis) for unshaded substrings and an afternoon shaded string of a large system in Australia. Note the loss in the Current as the shaded string drops below the performance of the unshaded strings, there is little effect on the cloudy day (right)

4.4 SELF SHADING

Figure 6 shows a typical arrangement with 4 close spaced arrays facing South on a roof in the Northern Europe. When mounting tilted arrays if they are too close together then all of the arrays (except A - nearest the equator) could shade each other when the sun is low and particularly when the sky is clear.

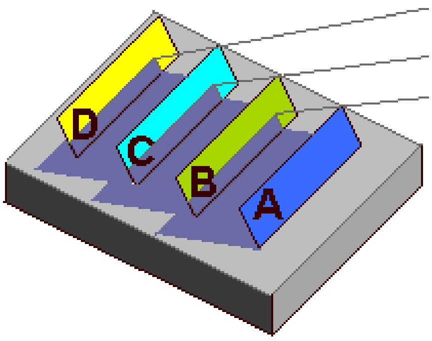

Figure 6: Sketch showing four sub arrays on a roof demonstrating self shading on the rear three arrays.

A simple graph of fraction of total power per array versus day is shown in Figure 7 – at this site Insolation t recorded so the total energy of the array is also shown as this will be approximately proportional to the insolation. Note that all the 4 arrays contributed approximately 25% of the Energy up until early November when the front (unshaded) array started to contribute proportionally more as the sun was lower (closer to the shortest day 21st Dec) and the Insolation was highest.

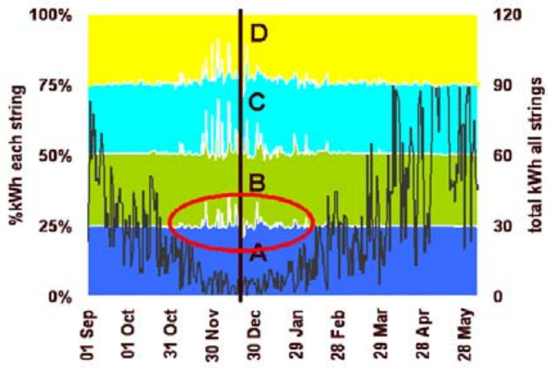

Figure 7: Fraction of energy per day (left axis) contributed by each of the arrays in figure 6 and the total power contributed by all four arrays (right). Mid winter (21 Dec) is indicated by the vertical bar. On bright days near mid winter the front array (bottom section) contributes proportionally more than 25% due to self shading on the other arrays (seen in the ellipse).

5 CONCLUSIONS

This analysis shows that Monthly average Performance Ratios (even if they are high) are not sufficient to characterise a large array, nor can a value of PR be predicted from a PV technology without considering all possible losses. More frequent PR data for each string analysed against time of day, irradiance or module temperature can help to identify underperformance or faults.

Some of the main factors affecting calculated PR figures are :-

1) Actual/nameplate P_{MAX}
2) Measurement accuracy including Irradiance and AC Power meters
3) Downtime
4) BOS losses

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