UNDERSTANDING AND CORRECTING kWh/kWp MEASUREMENTS

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ABSTRACT: Several teams worldwide monitor grid tied PV arrays or V_{MAX} tracked modules to calculate kWh/kWp. Results published show differences between module technologies from "very close" [1][2][3][4] to "up to 40% difference"[5]. This paper suggests many of the variations that have been reported are due to measurement errors, incorrect P_{MAX} declarations (because of stabilisation and incorrect declaration of power) and BOS limitations (like Inverter efficiency and V_{MAX} tracking accuracy). It shows graphical techniques for analysing instantaneous or averaged array data to determine when arrays are not performing optimally and shows how to help identify what is causing the loss. Empirical equations are introduced to help determine what Power the system should be producing during each measurement.
Keywords: Monitoring - 1: Performance - 2: Modelling – 3: PV System

1 INTRODUCTION

A standard database and graphical reporting format have been designed at BP Solar to allow modules and arrays of different technologies to be compared and contrasted. It has been used on over 1 GB of raw data from over 37 sites worldwide. Faults and poor performance can be determined by checking measured against predicted performance (using Empirical coefficients) in real time and likely reasons suggested.

2 MEASUREMENTS AND DEFINITIONS

Parameters measured and derived are listed in Table I. In this paper prefixes to the Parameter indicate measurement frequency, "s"=measurement, "h"=hour, "d"=day and "m"=month. The postfix "calc" is used to show a fit to measured data e.g. sYFcalc is a value fitted to every individual measurement of YF (usually every 5-15 minutes)

3 STANDARD GRAPHS

Standard XY scatter graph formats were developed (Figs 1-6) to enable results from monitored modules and arrays to be compared. Hourly or more frequent data parameters are averaged by hour so that graphs of different measurement frequencies can be compared. All normalised parameters (except Temperature and Windspeed) will usually be within the same range of 0 to 1.4. Daily data is shown averaged by day; most normalised parameters will be between 0 and 14. For both datasets the temperature right hand y-axis is –40 to 100C.

Using this method all graphs can be compared and only erroneous data should be off the scale.

Table I : Explanation of measured and calculated Parameters (see also IEC 67124 [7])

Parameter	Name	Definition	Units	Legend	Line/Point Colour
YR	Reference Yield (=POA Irradiance)	$\int G_I \, dt / G_{STC}$	kW/m²		Teal/Green
T_{AM}	Ambient Temperature		°C		Orange/Orange
T_{MOD}	Module Temperature		°C		Red/Yellow
WS	Average Wind speed		ms^{-1}		Black/White
YA	DC Array Yield	E_A / P_0	kWh/kWp		Mauve/Pink
YF	AC Final Yield	$E_{USE,PV} / P_0$	kWh/kWp		Blue/Cyan
PR_{DC}	DC Performance Ratio	ΣYA / ΣYR	%		Grey/Grey
PR_{AC}	AC Performance Ratio	ΣYF / ΣYR	%		Magenta/Pink
InvEff	Inverter Efficiency	ΣYF / ΣYA	%		Grey/Black
V_{DM}	DC voltage/ STC V_{MAX}	$V_{MOD,DC} / V_{MAX.STC}$	%		Cyan/Blue
I_{DM}	DC current / STC I_{MAX}	$I_{MOD,DC} / I_{MAX.STC}$	%		Green/Dark Green
cumYR	Cumulative YR with time	ΣYR	kWh/m²		Red/Yellow
cumYA	Cumulative YA with time	ΣYA	kWh/kWp		Black/White
cumYF	Cumulative YF with time	ΣYF	kWh/kWp		Brown/Yellow
MaxIns	Maximum Irradiance / time period	Max(YR)	kW/m²		Teal/Yellow
pcTime	Percentage of time in YR bin	YR_n<%(YR)<YR_{n+1}	%		Brown/White
pcEnergy	Percentage of Energy in YR bin	YR_n<%(Energy)<YR_{n+1}	%		Blue/White

3.1 HOURLY DATA vs. TIME FOR A DAY

Figure 1 shows a good DC performance from a c-Si module with MPPT versus time. For correct measurements of good performance the following may be observed :-

1. Double humped PR_{DC} and V_{DM}. The noon dip is due to the higher temperatures; the afternoon peak is lower than the morning as T_{MOD} is higher for the same T_{AM}.
2. V_{DM} tracking should be smooth (i.e. not limited by end stops, flat or with glitches)
3. Sky lightening predawn/post dusk can be seen
4. There should be zero yield and current at night, i.e. YA=0 and I_{DM}=0 when YR=0.
5. Night time temperatures should be the same T_{AM}~T_{MOD} when YR=0
6. If NOCT~46 then (T_{MOD}–T_{AM})~32deg C when YR=1.
7. Glitches in PR_{DC} (low light) performance are unimportant as there is little energy available.
8. DC kWh/kWp loss LC=YR-YA, shown shaded on this and other graphs. Loss around noon (almost 0.2) is higher than at dawn or dusk indicating more energy is lost under high irradiations than low which is mostly due to thermal effects.

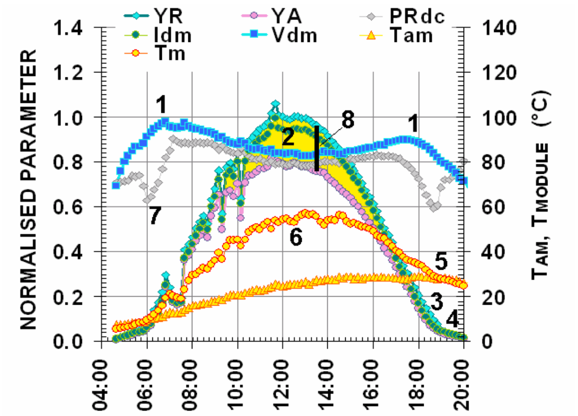

Figure 1 : Hourly DC module measurements vs. time for a good c-Si module on a sunny day in Germany

3.2 HOURLY DATA vs. IRRADIANCE FOR A DAY

Figure 2 shows the performance of the same c-Si module against irradiance (x-axis). kWh/kWp is the sum of the YA values. Measurements at high YR dominate because there is more available energy at high light levels (see also fig 4). Note :-

1. A linear device with no thermal losses would have its YA on the "100%PR" line (where YA=YR)
2. V_{DM} is normally 0.8–1 falling at very low and also high irradiance (due to high module temperatures).
3. I_{DM} should be near the 100%PR line (this shows correct V_{DM} tracking and little current degradation)
4. There is usually hysteresis (due to thermal lag).
5. On this module there is a constant loss in YA at low light levels due to the BOS.
6. The gradient of YA will lessen at high Irradiances due to the modules running hotter. (This change should be smaller for a-Si as the $\gamma = dP/dT$ factors will be lower).
7. The DC loss of kWh/kWp at each point LC=YR-YA and is proportional to the height of area 7 shown shaded.

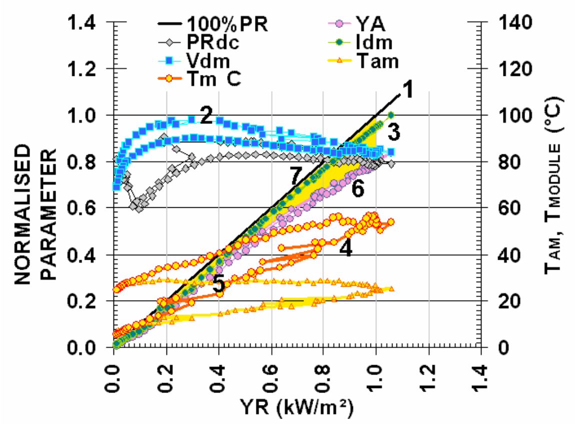

Figure 2 : Hourly DC module vs. irradiance, good c-Si

3.3 DAILY DATA vs. DATE

Figure 3 shows daily AC measurements for an a-Si array with MPPT in TN, USA [6]. Note :-

1. PR_{AC} seasonal effects (due to T_{AM} or Irr) are the difference in values between the summer and winter.
2. Any stabilisation/degradation would show as a PR_{AC} change (allowing for 1) at the same time each year (avg PR_{AC} for days around 1st May are highlighted.
3. Weather or measurement drifts would show from the MaxIns trace which should be constant year to year. (MaxIns is the max value of YR during the time period. Summer peaks should be near 100% (i.e. one sun), less in winter due to a lower solar height. If the Irradiance meter is changing there will be a slope, (allowing for the seasonal changes).

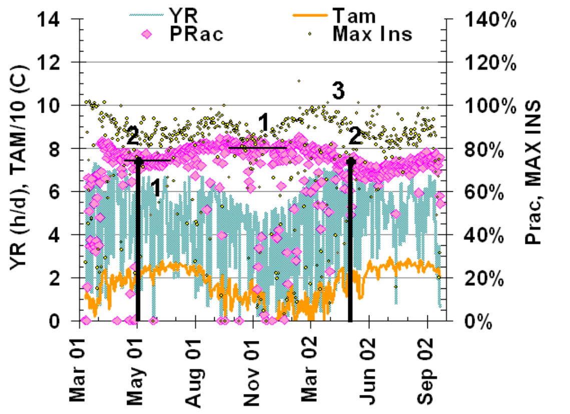

Figure 3 : Daily AC array measurements vs. time

3.4 DAILY DATA vs. IRRADIANCE

Figure 4 shows daily AC measurements for an a-Si array with MPPT and Inverter in TN, USA. Note

1. YF varies almost linearly with the irradiance.
2. At this site there is a constant loss for the YF around 0.25h/d (see the intersection with the X-axis at {2} there is no output for an irradiance of 0.25h/d or less)
3. PR_{AC} appears to fall under low light due to the constant loss in 2 as PR_{AC} = YF/YR
4. pcTime shows %days each ½h YR bin (here pcTime has a flat number of days from ½-4h/d, then a small peak from 5-7h/d)
5. pcEnergy shows the % of YR energy available for each bin of ½h/d, there is a large peak around 6 h/d. pcEnergy is more important than pcTime as a day of high YR produces more energy than a day of low YR.

6. cumEnergy is the cumulative Energy available above each bin, here over 50% of the energy is from days of > 5 h/d and only 10% of the energy is from days of <2.5 h/d.
7. Loss in kWh/kWp LC+LS=YR-YF as shown shaded.

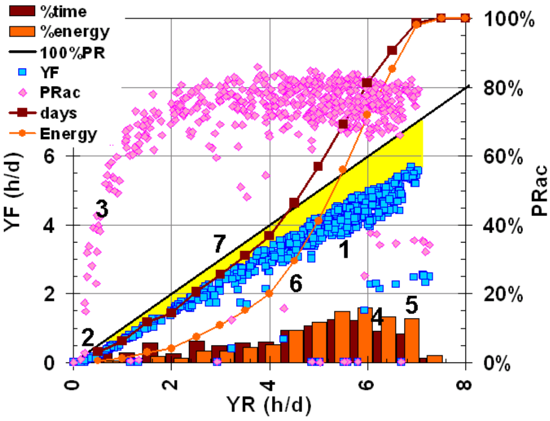

Figure 4 : Daily AC array measurements vs. irradiance

3.5 PERCENTAGE ENERGY PER ARRAY vs. DATE

Figure 5 shows how self shading (e.g. by parallel sub arrays on a roof) can be studied without any YR or T_{AM} measurements, by plotting a stacked area graph of the kWh from strings under test, then superimposing a curve showing the sum of the kWh out on the right hand axis. Four parallel roof mounted c-Si sub arrays are measured on a petrol station in Holland. Four areas show the proportion of energy of the four sub strings {A}-{D}; {E} is the total kWh on the right axis. Clear deviations from the expected 25% per string are seen centred in December {1} when the sun is lowest whereas little deviation is seen before November or after February when the sun is higher.

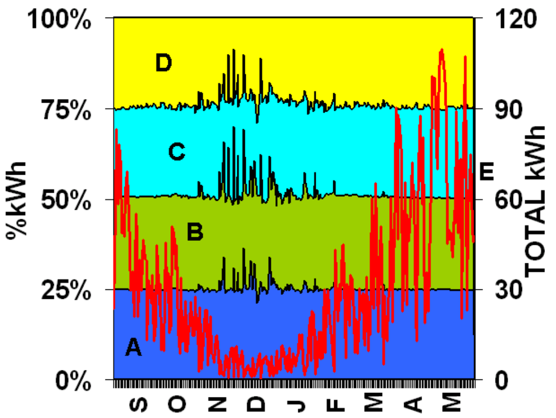

Figure 5 : Proportion of output energy per array and total energy to study the effects of self shading.

4 ANALYSING NON OPTIMUM PERFORMANCE

Many system and module faults can give rise to non-optimum performance. The following graphs and methods show how to check for specific problems.

For **STABILITY**, measure the maximum value of PR (high Irradiance days) allowing for any seasonal effects as in Fig 3 or for any change in the performance with time as in Figure 6 (an AC a-Si array in TN, USA). The final yield for one day every two months is plotted as sYF. An empirical fit was done at the beginning of the measurements (sYF_{CALC}) and this was then extrapolated to subsequent data – if the initial fit was good and the array stable then later data should be predicted well. The October and December Irradiances sInsol {1} were clearly lower than the other days but the empirical model was a good fit to all the days sYF vs. sYF_{CALC} {2} showing the array is stable over this period.

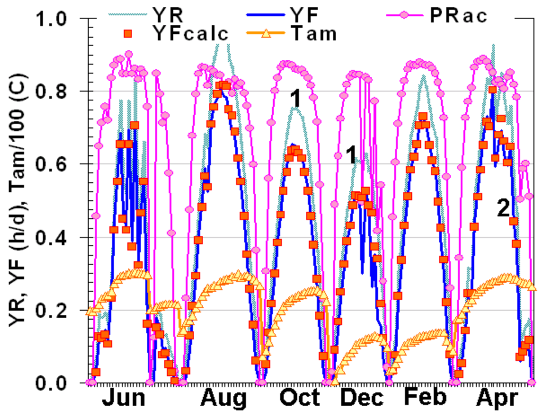

Figure 6 : Hourly AC array sYF and calculations sYF_{CALC} vs. time for several days - good a-Si Apr 2001–Apr 2002

SHADOWING BY EXTERNAL OBJECTS appears as a regular fall at a similar time each sunny day but maybe with a seasonal dependence with a drop in YF and PR, strongest when the Direct Irradiance is highest. Multiple arrays may see the problem at slightly different times or depths of drop as shadows move across the strings.

POOR VMAX TRACKING: V_{MAX} must be tracked constantly for optimum performance. The following are descriptions of some faults seen in non-optimum V_{MAX} tracking behaviour.

i) Wrong values (should normally be 0.8 to 0.9)
ii) "Turn on" (not starting until a threshold YR is reached)
iii) "Sticking" (staying at a fixed voltage)
iv) Glitches as the system hunts for the correct V_{MAX}
v) Limiting at extreme conditions, an upper V limit (cool) or lower V limit (hot).

Figure 7 shows 5 arrays at the same site with poor V_{DM} tracking. {1} and {2} are too low (~0.7), although {1} is varying {2} is constant. {3}-{5} are too high (0.95-1.15) and {5} has severe glitches.

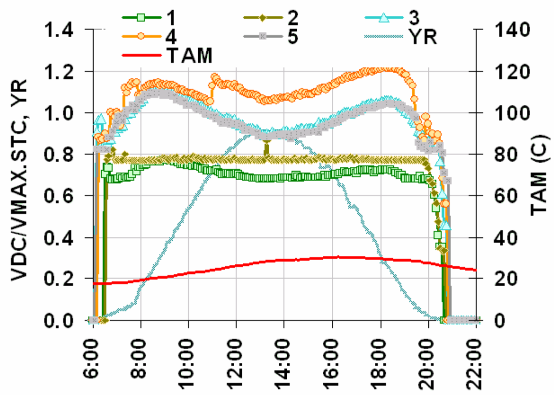

Figure 7 : Poor V_{DM} tracking of 5 arrays.

On systems with multiple inverters and/or strings **PARTIAL FAULTS** occur when one or more of the parts of the array are not functioning. Figure 8 shows multiple lines of YF of fractions of the gradient expected .

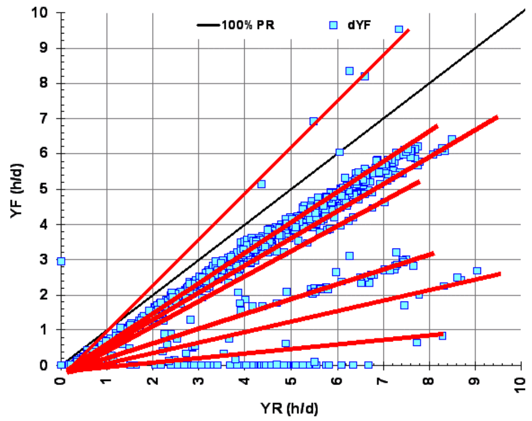

Figure 8 : Daily Varying YF:YR gradients

The number of points on each line show the times measured, the relative gradients of these versus the expected line {1} may be due to either a fraction of the array working (if part of the array is not functioning) or the relative performance of the faulty array with respect to the optimum.

PARASITIC LOSSES in BOS components show when YA or YF intersects the x-axis not at the origin as in {2} in figure 4. Some Inverters don't turn on before a certain threshold; this constant loss may therefore be related to a dissipation within an Inverter. Losses at high YR may be thermal in nature, whereas resistive losses would be proportional to current and light level and would show deviation from the YR=YF line as YR increases.

SEASONAL EFFECTS due to YR or T_{AM} have a periodicity of yearly (for optimum tilt) or perhaps twice yearly (for non optimum tilts) (see fig 4). Spectral effects will normally be only yearly as the sun's spectrum depends on the solar height. Multi junction devices suffer larger spectral effects as the junctions are in series. If there are 3 junctions peaking in the red, green and blue, then the current is limited by the cell with the poorest match to the sun's spectrum..

INCORRECT PMAX DEFINITIONS are most common in Thin Films where the power of the module is incorrectly stated because of the allowance for stabilisation. The value of Power at PTC can be estimated by fitting YF vs. YR and T_{AM}, then interpolating to PTC (Irr=1, T_{AM}=20). This may then be estimated at STC (Irr=1, T_{MOD}=25) by using γ (dPmax/dT) (assuming linear derating) in Table 2

<1> $T_{MOD}(IRR,TAM)-T_{AM} = (NOCT-25)*IRR/0.8$

<2> $T_{MOD}(1,20) = 20+(NOCT-25)*1/0.8$

<3> $P_{PTC}/P_{STC} = 1+\gamma*(T_{MOD}(1,20)-25)$

Table II : Estimates of P_{STC}/P_{PTC} for a-Si and c-Si

	a-Si	c-Si
NOCT	46 C	46 C
$T_{MOD}(1,20)$	46.25 C	46.25 C
γ dPmax/dT	-0.25%/deg C	-0.5%/deg C
P_{PTC}/P_{STC}	~95%	~90%

5 AUTOMATED PERFORMANCE CHECKING

At each measurement the actual performance can be checked against that predicted using Empirical Equations [1] with parameters derived from characterising previous installations. (Note that these are Technology and BOS dependent). Equation <4> gives the Calculated YF as a function of YR, T_{AM} and WS. (A to.E are derived by minimising YF_{ERR} in <5>).

<4> $YF_{CALC} = \Sigma G_I*(A+B*\Sigma G_I+C*T_{AM}+D*WS)-E$

<5> $YF_{ERR} = [\Sigma(YF_{MEASURED}-YF_{CALC})^2]^{0.5}$

Good fits can be obtained to either sub hourly or daily data but values of A to E will not be the same. Sub hourly measurements include effects like Angle of incidence and spectrum; low light levels often correspond to high angle of incidence (hence reflective losses) or high Air Mass (hence spectral losses).

"A" determines to first order the system performance and will be a product of the factors in equation <6> [3]:-

<6> $A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}*A_{STABIL'N}(\text{exposure})*A_{SPECTRUM}(\text{time of year})$

Equations for both T_{MODULE} and V_{DM} as functions of YR and WS are shown[1].

<7> $T_{MODULE} = C'*T_{AM} + \Sigma G_I*(A' + D'*WS) + E'$

<8> $V_{DM} = A''*LOG_{10}(\Sigma G_I) + C''*T_M + D''*WS + E''$

Studies can be undertaken for each technology and acceptable bounds found for the V_{DM} and the YF_{CALC} as functions of YR, T_{AM} and WS. For each point measured V_{DM} and YF can be compared with those predicted. If they are outside the limits then an error can be flagged. Pattern matching to graphs in section 4 can often determine the failure mode.

6 CONCLUSIONS

•All Systems studied have at least some kWh/kWp loss attributable to BOS performance limitations. •BOS faults mean that logged kWh/kWp differences aren't always indicative of the module technology.

•Several BOS problems have been illustrated and differentiated graphically

•These quick diagnostics should result in better uptime, improved performance and a lower energy cost per kWh

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