A 4 year study of kWh/kWp modelling of different technologies at more than 50 sites worldwide

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Abstract: BP Solar is involved in long term studies[1][2][3] on grid connect, maximum power point tracking or IV swept arrays at more than 50 sites worldwide (Figure 1). Modules include both BP Solar and competitors products. Technologies studied include Laser Grooved Buried Grid, mono and multicrystalline Silicon; single, double and triple junction amorphous Si and CdTe. Different monitoring sites include Independent test houses, 3rd party collaboration, BP Solar factories, downloads from the Internet and Petrol station roofs.

This study shows that kWh/kWp differences between correctly measured different technologies is small and differences depend more on incorrect declaration of power, variability within a Pmax range, BOS losses (e.g. Inverter loss, incorrect Vmax tracking, curved arrays etc.), thin film degradation and downtime.

Empirical formulae have been used to predict array performance, identify faults and check for satisfactory installation.

1 ARRAY MEASUREMENTS AND DEFINITIONS

The frequency of Monitoring of these arrays at the more than 50 sites is between every 15secs and every 15 minutes. Some of the Parameters logged and/or calculated are shown in Table 1.

	NAME	UNITS	MEASURE-MENT TYPE	NORMALISATION	
MEASURED					
Date+Time			ALL		
Gi	POA Irradiance	(kW/m²)	ALL	-	
Tam	Ambient Temperature.	(°C)	ALL	-	
Pac (at Vdc)	Output Power	(W)	AC	Pac/Pmax.stc	
Idc	Module Current	(A)	DC	Idc/Imax.stc/Gi	Idn
Vdc	Module Voltage	(V)	DC	Vdc/Vmax.stc	Vdm
Isc	Short circuit Current	(A)	SWEPT	Isc/Imax.stc/Gi	Isn
Voc	Open circuit Voltage	(V)	SWEPT	Voc/Voc.stc	Von
WS	Wind Speed	($m\ s^{-1}$)	OPTIONAL	-	
CALCULATED					
YR	POA Insolation = ΣGi	(kWh/m²)	ALL	-	
YF	AC Yield = ΣPac/ΣGi	(kWh/kWp)	AC	-	
PRac	AC Performance Ratio = ΣYF/ΣYR	#	AC	-	
YA	DC Yield = ΣPdc/ΣGi	(kWh/kWp)	DC	-	
PRdc	DC Performance Ratio = ΣYA/ΣYR	#	DC	-	
IE	Inverter Efficiency	%	DC and AC	-	
FF	Fill Factor	#	SWEPT	-	
Rshunt	dV/dI @ Isc	(Ohms)	SWEPT	Rsh/(Vmax/Imax)	Rshn
Rseries	dV/dI @ Voc	(Ohms)	SWEPT	1/Rse(Vmax/Imax)	Ssen
Vhi	Min(V) where P>0.9*Pmax	(V)	SWEPT	Vhi/Vmax-1	Vmhi
Vlo	Max(V) where P>0.9*Pmax	(V)	SWEPT	1-Vlo/Vmax	Vmlo

Table 1. Some of the Measured, calculated and Normalised Parameters analysed at the different sites.

(Some of these parameters can be normalised by dividing by the nominal STC values to make comparisons between different types and sizes of arrays easier).

Other parameters such as Isc, Fill Factor and Series resistance are available at sites with IV Sweeping. Spectral measurements are not generally available.

Calculated parameters (see IEC 61724 [4]) include ac final yield (YF kWh/kWp) and ac Performance Ratio ($PR_{AC} = \Sigma YF / \Sigma GI$).

2 MET DATA

It is not the fraction of time at each light level that is important but the fraction of irradiant energy. One hour at 1000W/m² contains ten times the incident energy as one hour at 100W/m².

Figure 2 shows the cumulative Energy available above an Irradiance vs. Irradiance for six sites listed in Table 2. Note that the worst sites (UK and Germany) only have 25 to 30% of the energy below 300W/m², all of the others are from 13 to 19%, therefore the energy output from systems at these locations will not be dominated by low irradiances.

	Site	City	Country	Yearly KWh/m²	Latitude °	Tilt °	Measurement Frequency	Meter	Comments
1	EDG	Cape Town	ZA	1783	34S	20N	10 min	Pyr	4 year average
2	TISO		CH	1498	46N	45S	1 min	Pyr	No data <50W/m²
3	MD	Germantown	USA	1459	39N	55S	30 min	Pyr	High Tilt
4	TN	Nashville	USA	1284	36N	10S	15 min	Pyr	Low Tilt
5	ISET	Kassel	D	1106	52N	30S	10 min	Pyr	4 year average
6	CREST	Loughborough	UK	808	52N	52S	10 min	Spec Rad	Some high Spikes

Table 2. Locations of Met Data sites detailed in Figure 2. Note : CREST figures have some erroneous readings at high Irradiances

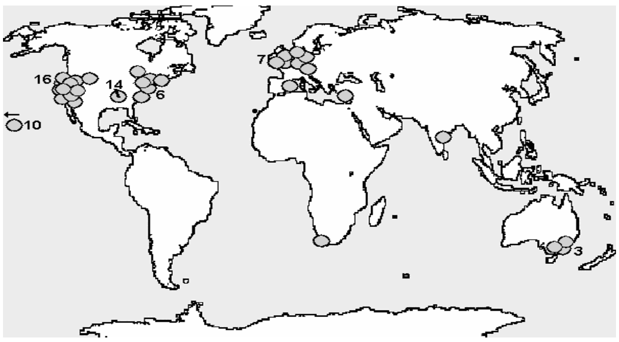

Figure 1: Locations of some of the 50+ PV sites studied

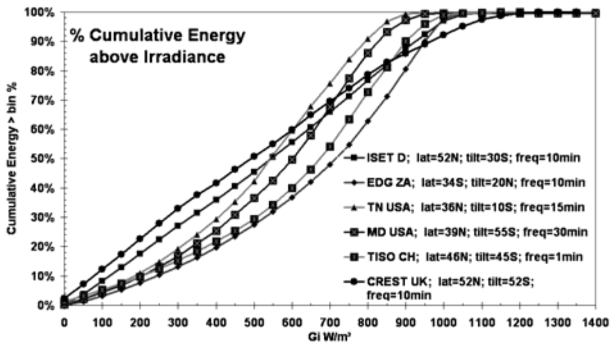

Figure 2 : Cumulative Energy above Irradiance vs. Irradiance for 6 sites detailed in Table 2. Some sites do not report Irradiances below 50W/m².

3 kWh/kWp PREDICTIONS – MATRIX METHODS and EMPIRICAL FORMULAE

Studies can be performed showing the average final Yield produced by the array at each irradiance (~50W/m²) and Tambient (~5C) bin. This will usually be a smooth surface and will show how the array performs under extreme conditions such as low light level, high temperatures etc. Figure 3.

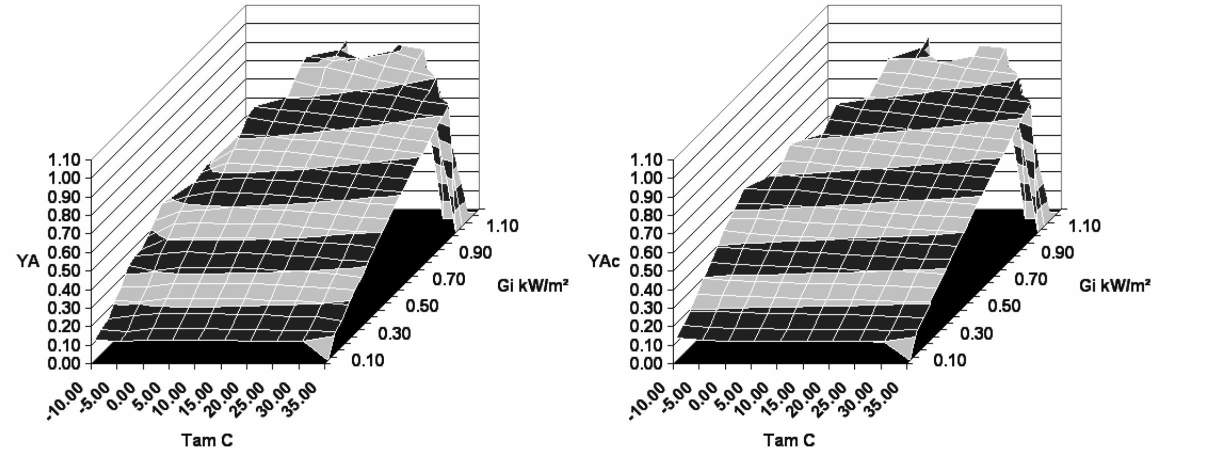

Figure 3 : Measured (left) against Modelled (right) dc Yield YA versus Ambient Temperature Tam and Irradiance Gi for Saturn in Germany

Sub hourly measurements include effects like Angle of incidence and spectrum; low light levels often correspond to high angle of incidence (hence higher reflective losses) or high Air Mass (hence possible spectral losses).

Equation <1> is an empirical formula used to predict dc or ac Yield as a function of plane of array irradiance, ambient temperature and wind speed. This will approximate to the surface from the matrix shown in Figure 3 (left) A best fit to logged data is obtained by minimising rms errors <3> varying the parameters A (the dominant total system performance figure), B(non linearity), C(Temperature derating), D(wind speed sensitivity if known) and E (a BOS related constant loss figure).

"A" determines to first order the system performance and will be a product of the factors in equation <2>

Equations for both T_{MODULE} <4>and V_{DM} <5> as functions of YR and WS are plotted in Figure 4.

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

<2> $A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}*A_{STABIL'N}(\text{exposure})*A_{SPECTRUM}(\text{time of year})$

<3> $YF_{ERR} = [\Sigma(YF_{MEASURED}-YF_{CALC})^2]^{0.5}$

<4> $T_M = C'*T_{AM} + \Sigma GI*(A' + D'*WS) + E'$

<5> $V_A = A''*LOG10(\Sigma GI) + C''*TM + D''*WS + E''$

Table 3. Some Empirical Equations used in this work

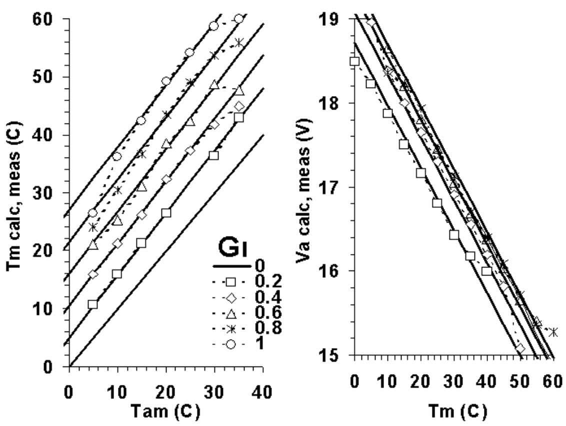

Figure 4 : Mono Si module.
Array Temperature Calculated lines<4> and measured points (Left)
Array Voltage Calculated lines <5> and measured points (Right) vs. Irradiance G_I (suns) in Germany.

The value of kWh/kWp from different climates can be estimated by multiplying the expected array energy at each Irradiance and Tambient bin by the distribution of bins in the climate to be modelled.

Because there is a wide spread of irradiances from 0 to 1000W/m² at all climates then the kWh/kWp dependencies of technologies at different light levels is lessened and actual values of kWh/kWp depend more on Wp declaration, measurement errors and BOS losses than on technology.

4 MEASURED PERFORMANCE – Daily and Sub Hourly averages

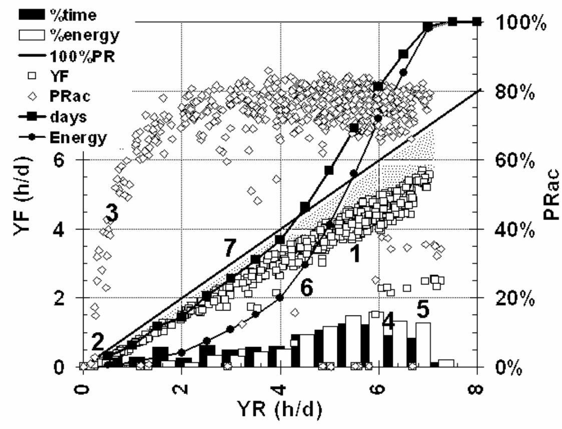

Figure 5 : Daily AC array measurements vs. irradiance

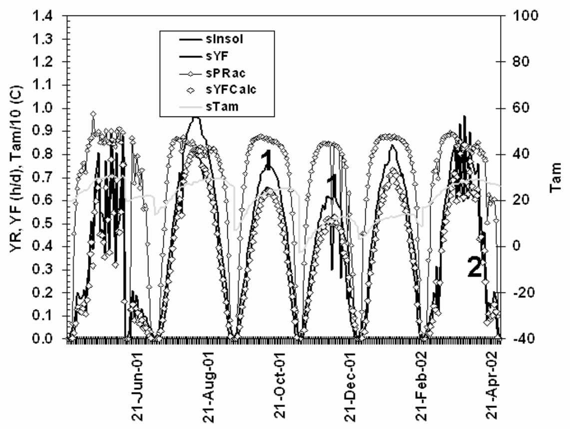

Figure 6 : Sub Hourly AC array YF and calculations YF_{CALC} vs. time for several days - good a-Si Apr 2001–Apr 2002

Figure 5 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. %Time shows the percentage of days each ½h YR bin (here %Time has a flat number of days from ½-4h/d, then a small peak from 5-7h/d)
5. %Energy shows the % of YR energy available for each bin of ½h/d, there is a large peak around 6 h/d. %Energy is more important than %Time 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 6 shows STABILITY, looking for any change in the performance with time of AC a-Si array in TN, USA. The final yield for one day every two months is plotted as YF. An empirical fit was done at the beginning of the measurements (YF_{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 Insolation {1} were clearly lower than the other days but the empirical model was a good fit to all the days YF vs. YF_{CALC} {2} showing the array is stable over this period.

5 kWh/kWp due to Technology

Many teams measure different modules and arrays and report kWh/kWp values as if they were the only indicator of the system's performance. This paper suggests other factors such as BOS performance and measurement errors are significant systems performance predictors.

- The raw data should be scrutinised before any kWh/kWp differences can be attributed solely to the module technology.
- kWh/kWp values are not the only important factor distinguishing technologies; kWh/m² or kWh over the lifetime of the system might be more relevant comparisons.
- The choice of Tilt and Azimuth angle, mounting method (e.g. BIPV vs. Free Back), amount of Shadowing and choice of BOS components will affect technologies differently.
- Systems kWh/kWp is a complex subject. Table 4 shows some of the effects that need to be considered before publishing kWh/kWp figures.

MODULE	STRING	MET DATA	BOS	V TRACKING	INVERTER	MEASUREMENT
Pmax variations within band	Mismatch/ sorting	Shadowing	Localised or overall dirt	**Vmax accuracy**	Efficiency vs. Light level	Instantaneous vs. Averaged values
Rsh variation between modules	Connections/ wiring	Irradiance calibration	**Downtime**	Parasitic losses		Av(P) <> Av(I)*Av(V)
Pmax nameplate declaration	Worst module in a string limits	T_{AM}	Fixing/ replacing during test	Turn on in morning or staying at a constant value, not tracking.		**Inaccuracies/ drifts**
Allowance for stabilisation	High or low band sampling	Spectrum	Free back/ insulated mounting	Particular BOS performance may match some technologies better than others		Clock Offsets prevent simultaneous comparisons
Variability in power drops due to stabilisation	Modules with similar irradiance and temperatures	Wind speed	Cleaning		**Inaccurate Inverter Power measurements**	Irradiance meter spectral sensitivity
		Angle of Incidence		BOS component variability		Irradiance meter drift

Table 4. Some of the factors affecting kWh/kWp measurements that are not just due to the module technology showing what are considered to be the **Most important** and Next most important factors.

6 CONCLUSIONS

A 4 year study of different technologies at more than 50 sites world wide has shown that measured kWh/kWp differences can depend to a large extent on incorrect declaration of power, BOS losses and downtime as listed in Table 4. Empirical formulae have been used to predict array performance, identify faults and check for satisfactory installation.

7 REFERENCES

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