Preprint of Poster 7P-B3-03 to be presented at WCPEC-3, Osaka, Japan, 13 May 2003

AN OVERVIEW OF 4 YEARS OF kWh/kW$_P$ MONITORING AT 67 SITES WORLDWIDE

Steve Ransome[1] and John Wohlgemuth[2]
BP Solar
[1] 12 Brooklands Close, Sunbury, TW16 7DX, UK
[2] 630 Solarex Court, Frederick, MD 21703 USA

ABSTRACT

BP Solar is involved in long term studies on IV swept, Maximum power point tracked or grid connected arrays at currently 67 sites worldwide (see figure 1). Modules tested are from both BP Solar and competitors products. Technologies studied include Laser Grooved buried Contact (Saturn) "LGBC", screen printed 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 different PV systems depend strongly on module power tolerance, mismatch between series connected modules, BOS losses and downtime.

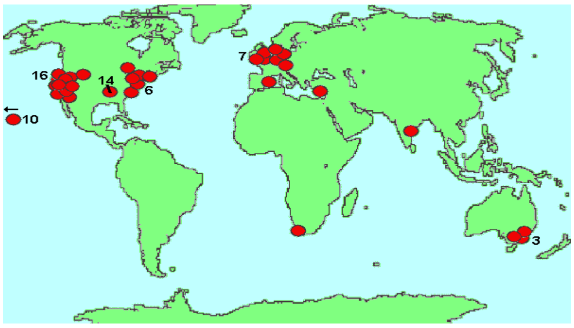

Fig 1. Location of the 67+ sites studied by BP Solar.

1. PRESENT STATUS

Many teams around the world [1][2][3][4][5] now are reporting kWh/kW$_{P.ACTUAL}$ differences due to module technology of <±5% (less than the probable measurement and calculation uncertainties) when correctly measured and with respect to the actual W$_P$ of the module.

Many reasons have been found [6] for problems in measurements, definitions, BOS losses etc. that can appear to give differences due to inaccurate kWh/kW$_P$ calculations.

2. ARRAY MEASUREMENTS AND DEFINITIONS

This paper summarises some of the findings from analysing data from at 67 sites worldwide.

Monitoring of the arrays at the different sites is performed between every 15secs - 30 minutes and some of the important parameters are shown in Table I.

Some sites sweep the Voltage to find the $V_{OPTIMUM}$ value to maximise the power. These traces can be used to derive the I_{SC} and V_{OC}, then the R_{SHUNT}, R_{SERIES} and Fill factor can be calculated.

Other sites either use MPPTs to attempt to find the $V_{OPTIMUM}$ on single modules, or larger arrays will use Inverters with MPPTs to set the voltage on strings of modules.

Data comes from a large variety of formats and a database has been written to convert it into a common definition for easy comparison [7].

Table I. Some of the important parameters measured and calculated See also IEC 61724 [8]

Abbreviation	Parameter Name	Unit	Range or Normalisation
G_I	Irradiance	kW/m²	0 to 1.4
T_{AM}	T Ambient	C	-40 to 100
T_M	T Module	C	-40 to 100
WS	Wind Speed	ms^{-1}	0 to ?
YR	Insolation	kWh/m²	$= \Sigma G_I$
V_{DM}	DC Voltage		$= V_{DC}/V_{MAX.STC}$
I_{DM}	DC current		$= I_{DC}/I_{MAX.STC}$
I_{DN}	Normalised DC current		$= I_{DM}/G_I$
YA	DC yield	Wh/Wp	$= P_{DC}/P_{MAX.STC}$
YF	AC yield	Wh/Wp	$= P_{AC}/P_{MAX.STC}$
PR_{DC}	Performance Ratio DC	-	=YA/YR
PR_{AC}	Performance Ratio AC	-	=YA/YR
LC	Capture Loss DC	-	=YR –YA
LS	System Loss AC	-	=YA –YF

3. MET DATA

Met Data readings from sites around the world can be analysed for the availability of energy, plus persistence and variability (which are more important to Stand Alone systems).

Despite some claims in the literature it is not the number of hours at each light level that is important for Grid Connected Systems but the average energy at each hour. One hour at 1000W/m² contains ten times the incident energy as one hour at 100W/m².

Figure 2 shows the cumulative irradiant Energy available above a given Irradiance vs. that Irradiance for the six sites listed in Table II. Note that the worst sites (UK and Germany) have 25 to 30% of the energy below 300W/m², the others are from 13 to 19%. Note that the UK Site is calculated from a spectroradiometer which will give some erroneous high readings, data from a pyranometer at latitude tilt is being collected and will be added when available.

This resource is constantly being added to – if anyone wishes to contribute their kWh/m² vs Irradiance data please send it to the authors – it will be added and then the updated data will be sent back to all of the parties concerned. It is hoped in the future that kWh/m² versus Irradiance and Tambient matrices and hourly Markov Transition Matrices can also be added to this data.

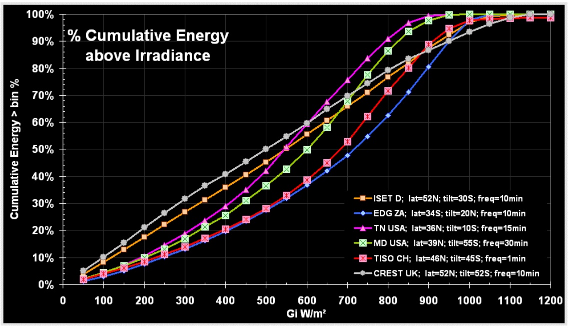

Fig 2. Percentage of incident energy above irradiances for well aligned sites in the UK (CREST), D=Germany (ISET), TN=Tennessee and MD=Maryland (SEPA), CH=Switzerland (TISO) and ZA=South Africa (EDG)

Table II. Metdata sites shown in Figure 2

Site	City	Country	kWh /m²	Lat °	Tilt °	Freq mins	Comments
EDG	Cape Town	ZA	1783	34S	20N	10	4 year ave
TISO		CH	1498	46N	45S	1	No data < 50W/m²
MD	German town	USA	1459	39N	55S	30	High Tilt
TN	Nash ville	USA	1284	36N	10S	15	Low Tilt
ISET	Kassel	D	1106	52N	30S	10	4 year ave
CREST	Lough borough	UK	808	52N	52S	10	Some high Spikes

4. kWh/kWp PREDICTIONS – MATRIX METHODS AND EMPIRICAL FORMULAE

Equation (1) is an empirical formula used to predict Yield as a function of Gi plane of array irradiance, T_{AM} ambient temperature and WS wind speed. A best fit to logged data is obtained by minimising rms errors (2) varying the parameters

- **A** (linear with irradiance, dominant total system performance figure)
- **B** (non linearity)
- **C** (Temperature derating)
- **D** (wind speed sensitivity)
- **E** (a BOS related constant loss figure).

Table III. Empirical formulae

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

$$Y_{ERR} = [\Sigma(Y_{MEASURED}-Y_{CALC})^2]^{0.5} \quad (2)$$

$$T_{MODULE} = C'*T_{AM} + \Sigma G_I*(A' + D'*WS) + E' \quad (3)$$

$$V_{ARRAY} = A''*LOG_{10}(\Sigma G_I) + C''*T_M + D''*WS + E'' \quad (4)$$

$$A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}* A_{STABIL'N}(exposure)*A_{SPECTRUM}(time\ of\ year) \quad (5)$$

Averages of the Yield ("|" axis) in kWh/kWp produced by a c-Si module in Germany at each irradiance ("/" axis) and $T_{AMBIENT}$ ("_" axis) in the method used at TISO [9] are shown in figure 3 (left)

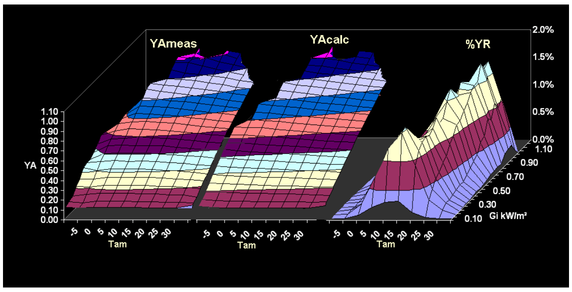

Fig 3. Measured (left) against Modelled (centre) dc Yield YA versus Ambient Temperature $T_{AMBIENT}$ and Irradiance G_I for c-Si in Germany. (Right) shows the percentage irradiance energy in each bin – there is a good fit between the modelled and measured data where most of the data occurs.

Other empirical equations for T_{MODULE} (3), V_{ARRAY} (4) and incorporating seasonal and stability effects into Yield (5) are shown in table III.

The value of kWh/kW$_P$ from different climates can be estimated by multiplying the expected array energy at each Irradiance and $T_{AMBIENT}$ 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/kW$_P$ depend on W_P tolerance, measurement errors and BOS losses. See also [10] for more details.

5. MODULE EFFICIENCY OR kWh/m²

Module Efficiency with respect to area (W/m²) can vary between the highest (c-Si) and lowest (usually a-Si) modules by a factor of almost 3 to 1.

Figure 4 shows how the daily average dc efficiency of four types of module technology varied during IV swept tests in Australia in 2003. Note that the triple junction amorphous fell during this test from 8% to 6% (-25%) in under two months when all the other modules (which had been under test since Nov 2002) were stable.

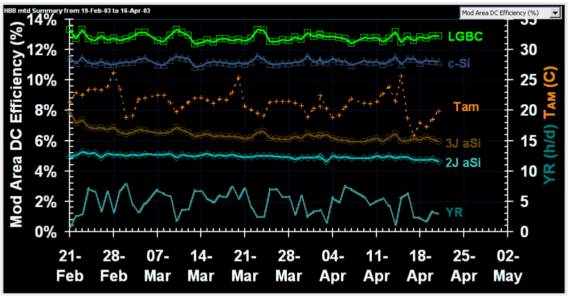

Fig 4. Average dc module area efficiency under operating conditions of 4 Module types versus Time. (Triple Junction a-Si was stabilising during this test.)

Figure 5 plots Daily Averages of dc Yield (YA), PR_{DC}, I_{DN} and V_{DM} versus Insolation for the LGBC module from Figure 4. It shows good performance at low insolations and only dips slightly at higher values as the ambient temperature rises. The normalised current I_{DN} is about 105% of its STC value (as the $T_{AMBIENT}$ rises the V_{MAX} will fall and the normalised current can rise), the V_{DM} is around 90%, and the PR_{DC} rises from 95% at high insolations to nearly 100% at low insolations showing good low light level performance. Note that this is true data with regards to the module technology as it comes from swept IV, so there are no errors due to V_{MAX} tracking or parasitic losses from Inverters to be attributed.

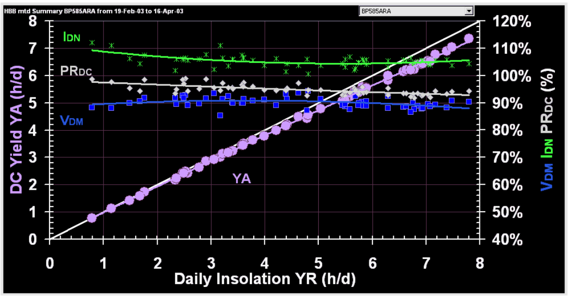

Fig 5. Performance of a LGBC c-Si module vs Insolation h/d measured by IV sweeping in Australia.

Instantaneous (rather than averaged) measurements can also be compared and Figure 6 shows the module efficiencies from the four modules on a day of intermittent sunshine. Here the LGBC module[1] averaged 13% under operating conditions, the screen print c-Si 11%, the triple junction amorphous was just over 6% and the double junction was around 5%.

[1] This technology has now been superseded by higher performance products.

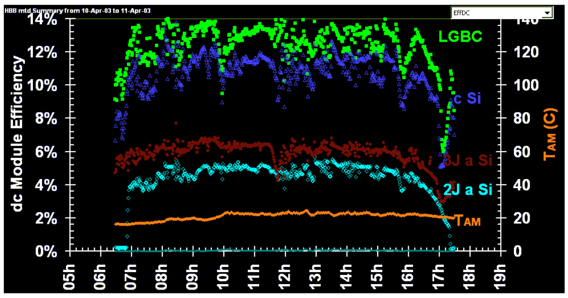

Fig 6. dc module area efficiency under operating conditions of four module types versus time during a day in Australia with intermittent sunshine.

Figure 7 shows how the instantaneous data from figure 6 varies as the light level. Note there is quite a lot of scatter due to transients in the insolation, but the difference in efficiencies at all light levels can clearly be seen.

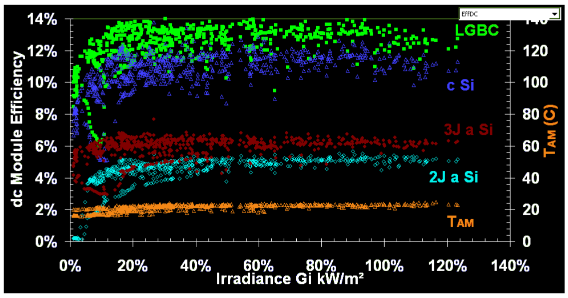

Fig 7. dc module area efficiency of four Module types versus irradiance during a day in Australia with intermittent sunshine.

Measuring IV traces of modules rather than the current and voltage at a MMPT's choice of voltage or the inferred dc values guessed by an inverter from a lookup table enables the modules to be characterised very well. Figure 8 shows the current ("|" axis) versus voltage ("\" axis) against time ("/") axis for a c-Si module on a Sunny day in Australia. The IV trace at bottom left is at 07:00 and shows a low current, high V_{OC} and high R_S (hence a lower than normal Fill factor). The trace at noon (where the Irradiance and the Ambient are high) shows a much higher current, lower V_{OC} and R_S plus a higher Fill factor.

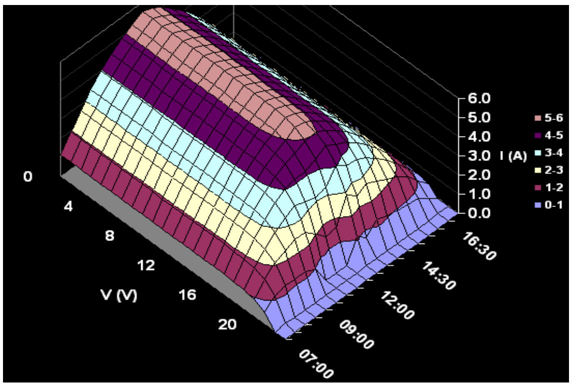

Fig 8. IV traces every 30 minutes from a c-Si module in Australia

6. FACTORS AFFECTING kWH/kWp VALUES NOT DUE TO THE MODULE TECHNOLOGY

In the analysis of these sites [6][7] a large number of factors were found that affected the kWh/kWp. Lists of some of these factors are given below, showing what are considered to be the "**Most important"** and "*Next most important"* factors.

6.1 Module factors

Actual vs Nameplate Pmax.
Variability in power drops due to stabilisation.
Pmax and Rsh variation within bands.

6.2 String factors

Module Mismatch / sorting.
Connections/ wiring losses.
Worst module in a string limits performance.
Have modules with similar shadowing/temperature profiles been strung in series (best) or parallel (worst) ?

6.3 Bos factors

Downtime
Fixing/Changing modules during test
Localised or overall dirt.
Free back / insulated mounting

6.4 Voltage tracking/inverter factors

V tracking accuracy (Turn on / staying at a constant value, not tracking.)
Inaccurate Inverter Power measurements.
Parasitic losses.
Inverter Efficiency vs. Light level.
Choice of particular BOS performance may match some technologies better than others.
BOS component variability.

6.5 Measurement factors

Inaccuracies/ drifts.
Instantaneous vs. Averaged values
Avg(P) <> Avg(I)*Avg(V) sampling
Irradiance meter spectral sensitivity
Irradiance meter drift with time.

7. CONCLUSIONS

- A 4 year study of different technologies world wide shows that kWh/kWp differences between PV Systems depend strongly on module power tolerance, BOS losses and downtime.
- kWh/m² or Module efficiency can vary by a factor up to 3 to 1 between the highest (c-Si) and lowest (a-Si) technologies.
- Empirical formulae have been used to predict array performance, identify faults and check for satisfactory installation.

ACKNOWLEDGEMENTS

The authors would like to thank C.Purcell (EDG); P.Funtan, T.Degner and M.Ries (ISET); R.Gottschalg and T. Betts (CREST); J.Hatmaker (Green Power / TVA); Prof Kaltenbach (Lübeck); SEPA, J Petersen (Oberlin) and G Friesen and D Chianese (TISO) for their discussions, logging and met data and help.

REFERENCES

[1] S. Ransome and J. Wohlgemuth "Analysis of measured kWh/kWp from grid tied systems – modelling different technologies worldwide with real data", *17th PVSEC Munich 2001,* OA4-3.
[2] **http://solar.fh-luebeck.de/solardaten/pv-fue.html**
[3] D.King et al "Analysis of factors influencing the annual energy production of photovoltaic systems", *29th PVSC New Orleans 2002* p1539.
[4] J Del Cueto "Comparison of energy production and performance from flat-plate photovoltaic modules technologies deployed at fixed tilt", *29th PVSC New Orleans 2002* p1523.
[5] Chianese et al "Power and Energy production of PV Modules (Cycle 8)", *PV in Europe Rome Oct 2002,* p575
[6] S. Ransome and J. Wohlgemuth "kWh/kWp Dependency on PV technology and balance of systems performance", *29th PVSC, New Orleans, 2002,* p1420.
[7] S. Ransome and J. Wohlgemuth "Understanding and correcting kWh/kW$_P$ measurements", *PV in Europe Rome 2002,* p699
[8] IEC 61724 **http://www.iec.ch/**
[9] Friesen et al "Matrix method for energy rating calculations of PV modules", *PV in Europe Rome 2002,* p639**.**
[10] S Ransome, J Wohlgemuth and Rhys Morgan "OPTIMISING PV ARRAY PERFORMANCE USING REAL TIME MEASUREMENTS", *WCPEC-3 Osaka, Japan 2003* 7P-B3-69.

Please note : BP Solar's technical publications are available at
http://www.bpsolar.com/ContentPage.cfm?page=154