ANALYSIS OF MEASURED kWh/kWp FROM GRID TIED SYSTEMS – MODELLING DIFFERENT TECHNOLOGIES WORLDWIDE WITH REAL DATA

Steve Ransome
BP Solar
12 Brooklands Close, Sunbury on Thames,
TW16 7DX, UK
Tel: +44 (0) 1932 765947 Fax: +44 (0) 1932 765293
Email: ransomsj@bp.com

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

ABSTRACT: Rapid growth in the use of Photovoltaic systems around the world makes it increasingly important to have a fast and accurate method of predicting and understanding energy production for yearly totals and during design, commissioning and fault finding stages. Previously this has been accomplished by measuring individual modules in the lab, creating a simple model for the balance of system and extrapolating the performance to predicted weather data. This procedure can be inaccurate as not all performance limiting effects (e.g. dirt, mismatch, stability) are modelled correctly if at all.

An empirical model has been developed where logged field data are analysed to characterise the performance of complete arrays. This model can then be folded into weather data from new sites to predict array performance under various weather conditions. The model has been extended to predict array temperature and voltage to allow those commissioning new systems to determine quickly whether their array is working correctly and to do on line fault analysis once the array is running. All performance effects are included. As data are gathered under real meteorological conditions the effects of low light level or high temperature performance, seasonal trends or degradation can be analysed. Some differences have been seen with respect to previously published data.

Keywords: Monitoring - 1: Performance - 2: Modelling – 3

1. INTRODUCTION

BP Solar is continually analysing performance data [1] from various PV technologies (single to triple junction a-Si, Screen print and LGBG (laser groove buried grid) Multi and Mono X-Si, CdTe etc.) from many different suppliers in a long term test program using measurement sites in Africa, Europe, Asia, Australia and the United States (Figure 1). Data come from a variety of sources including third parties either publishing their data on the Internet [2][3][4], sending data to BP Solar for analysis, or being commissioned by BP Solar to collect the data[5][6], as well as measurements from arrays at BP Solar sites. Only reliable, screened data were included in this work.

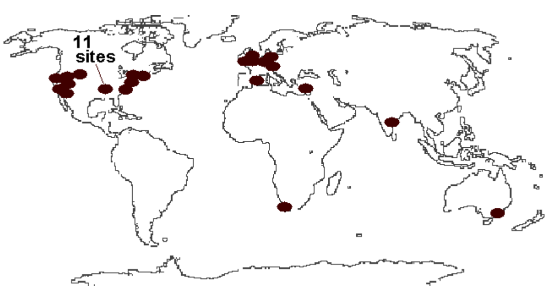

Figure 1: Locations of some of the 30+ PV sites studied

Data are gathered for either grid tied arrays (usually 1-100kWp) or individual modules with either Maximum Power Point Trackers (MPPTs) or swept IV curves to determine the energy output.

Raw data files are converted into a standard database format to make comparisons between sites easier. Parameters measured and used in the model are listed in Table I, those listed in brackets are not available from all sites.

Table I: Parameters measured at the different sites

	Parameter	Units
G_I	Average Plane of Array Irradiance	kW/m²
T_{AM}	Average $T_{AMBIENT}$	°C
P	Average P_{ARRAY} ac	W ac
WS	(Wind Speed)	ms^{-1}
V_A	(V_{ARRAY})	V
T_A	(T_{ARRAY})	°C
P_{DC}	(Average P_{ARRAY} dc)	W dc

The following definitions are used throughout this paper :

FINAL YIELD YF : Total AC Energy out / nominal DC STC Wp over the measurement period

$YF = E_{USE,PV} / P_0$ (units kWh/kWp or h ac)

PERFORMANCE RATIO PR : the ratio between actual performance and that expected from the nominal rating

$PR = YF / \int_{day} G_I \, dt / G_{STC}$ (dimensionless)

ARRAY YIELD YA : Total DC Energy out / nominal DC STC Wp over the measurement period

$YA = E_A / P_0$ (units kWh/kWp or h dc)

2. EMPIRICAL PERFORMANCE PREDICTION

An improved empirical model for Final Yield YF was previously published by the authors [1] as shown in equations <1> and <2>

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

<2> $YF_{ERR} = (YF_{MEASURED}^2-YF_{CALC}^2)^{0.5}$

SG_I = irradiance, T_{AM} = average ambient temperature, WS = average Windspeed, A..E are empirical parameters. The nomenclature has been changed since [1] to conform to standards)

Equation <1> can analyse measurements over different frequencies from instantaneous through hourly, daily or monthly sums and averages. A multivariate regression analysis optimises the five empirical parameters A-E to the module performance to minimise YF_{ERR} in equation <2>. Table II shows their typical values.

Table II : Explanation of the Empirical Parameters

	Meaning	Approximate value	Units
A	Overall system performance	0.75 ~ 0.85 (ac) 0.80 ~ 1.00 (dc)	
B	Non linear performance	~0	
C	Temperature derating	-0.1 ~ -0.5%	%/deg C
D	Wind speed derating	+1%	$\%/(ms^{-1})$
E	Constant loss	Depends on system	h/d

E makes the Final Yield vs. Insolation fit more linearly over all Insolations as it models inverter or line loss, turn ons or low light level loss due to shunting.

It has been found that on many systems the control of V_{ARRAY} is less than perfect so that the maximum P_{ARRAY} is not always achieved. Further models for T_{ARRAY} and V_{ARRAY} are therefore being developed. These may well differ depending on the module and BOS technology but equations <3> and <4> give reasonable fits for some technologies studied so far (cSi, mSi and aSi:aSi).

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

<4> $V_A = A''*LOG_{10}(\Sigma G_I) + C''*T_M + D''*WS +E''$

Figure 2 shows fits for Mono Si modules in Germany.

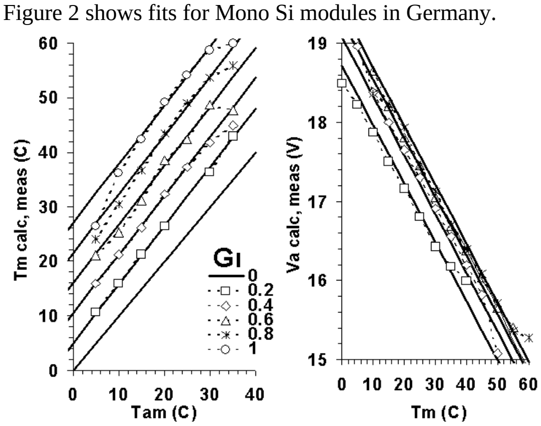

Figure 2 : Mono Si module. Array Temperature Calculated and measured (Left) Array Voltage Calculated and measured (Right) vs. Irradiance G_I (suns) in Germany.

3. EXAMPLE ARRAY LOGGING DATA

SEPA (formerly UPVG) has been monitoring one 3.25kWp sub array from a 26kWp BP Solar Millennia array at Montgomery College in Germantown, MD, USA [2]. The PV array was mounted on an old solar thermal structure (tilted at 55° to the south to maximise hot water production in the winter whereas a tilt of 35° would have been better for PV). The inverter is an Omnion 3.4 kilowatt series 2400. Figure 3 shows the daily PR of this array from May 1998 to Aug 2001. The PR varies around 80% (a good figure) on high insolation days and has been stable for three years, much better than most other thin film products. A sinusoid has been added to indicate how the PR on sunny days varies throughout the year. Note the peaks and troughs coincide with the high and low peaks of POA insolation in spring and autumn with a twice yearly frequency.

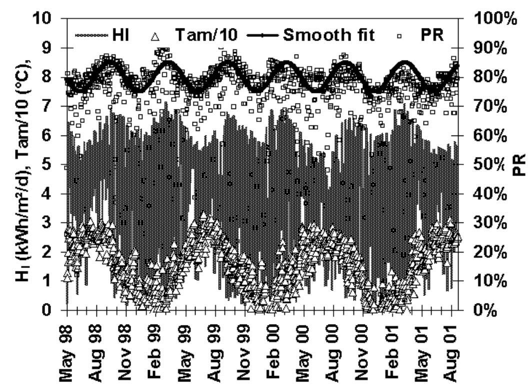

Figure 3 : Daily average PRac at MD, USA Millennia site 1998-2001.

Previously papers reporting sinusoidal variations throughout a year attributed them to seasonal thermal effects. [7] [8] The data from Montgomery college show that this explanation is likely to be incorrect (at least for the products measured in this study). For this system both POA insolation and PR have sinusoidal behaviour with a twice yearly frequency. The temperature however, has a sinusoidal behaviour with a one year period. Minima in array performance occur at the lowest temperature and at the highest temperature. Replotting the same data to show Final Yield (for each season Spring, Summer, Autumn and Winter) versus daily insolation (Figure 4) show that most of the variation in PR is due to the daily POA insolation and instantaneous temperature, not a seasonal effect of temperature.

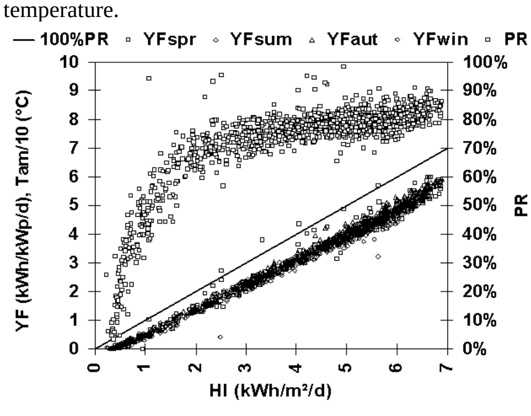

Figure 4 : Daily average PR, YF, T_{AM}/10 versus Insolation H_I , MD, USA Millennia site 1998-2001

The YF_{CALC} points have been fitted to the YF points without any seasonal dependence and have a much stronger variation with insolation than with Temperature.

(At this location there is a constant 45W loss in the electronics, meaning that the low light level performance appears worse than would be expected from a normal Millennia array.)

4. VMAX TRACKER ACCURACY

The system output depends not only on the performance of the PV at different irradiances and temperatures but also on the ability of the maximum power point tracker to find the optimum voltage. Figure 5 shows the fall in P that might be expected from mistracking V_{MAX}. It clearly shows the sensitivity rises with higher fill factor devices and also that the performance is more sensitive to over rather than under voltage.

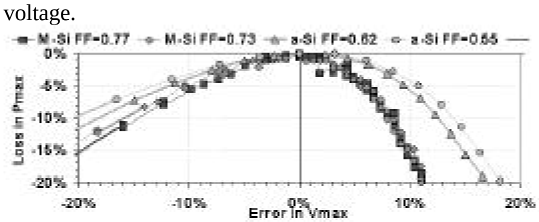

Figure 5 : Loss in P_{MAX} versus Error in Vmax for 4 different module types listed with their fill factors (calculated from IV data at STC).

Figure 6 shows how the distribution of the values of V_{ARRAY} occurred for a Mono X-Si module in Germany and also shows average PR in each temperature bin at 600±100W/m² irradiance for different Tambients. At 20C the maximum PR reached is 86% at 17.0V, but the mode V_{ARRAY} of 16.5V only realises a PR of 84%. Similar results are obtained from other temperatures, showing that the V_{ARRAY} is always low and thus lowering the overall PR.

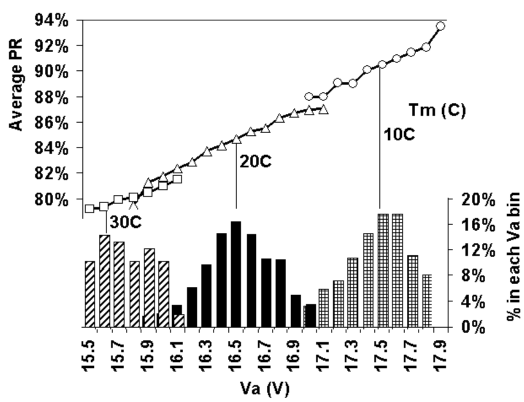

Figure 6: Average PR (left) and distribution in V_{ARRAY} values (right) versus V_{ARRAY} at different ambient temperatures for a mono X-Si Module in Germany at 600±100W/m² irradiation.

5. COMMISSIONING AND FAULT FINDING

The Empirical Sizing method is useful in commissioning and for fault finding. It enables the first hours/days of measurements to be validated (the fit parameters A..E found should be within design limits), then when the array is running any changes in the performance can be quickly seen.

For one of the Millennia sites in Tennessee [3] two faults (due to Inverter tripping) were found using the empirical method. The array had been characterized and the performance each day was studied to see deviations from predicted to actual. The array had been performing as expected (YF_{CALC} versus YF) until point A, recovered then went down again at point B (Figure 7).

Further analysis of the raw data (measured every 15 minutes) showed a large glitch in the data the afternoon of day A (Figure 7), the rest of the time the fit between measured and monitored was very good until B. It was found that one of the two inverters had to be reset (A) and had failed (B). Once fixed (C) the array behaved as normal again.

This method is very fast and has resulted in error conditions being spotted and reported quickly. Also when commissioning systems the traditional method has been to "correct" back to STC (with potential problems in temperature coefficients, linearity etc.) This model can find whether systems are working well at any temperature and irradiance.

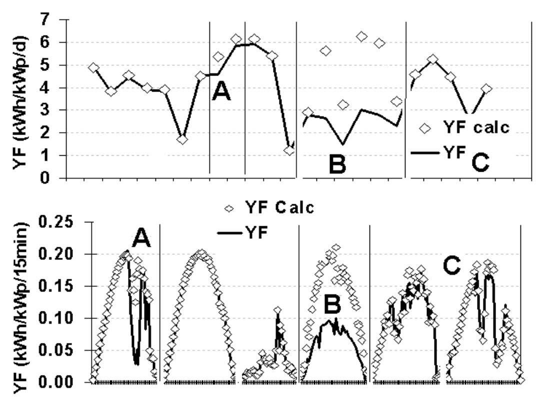

Figure 7 : YF_{CALC} versus measured showing faults at A and B, the problem was fixed at C daily (top) and every 15 minutes (bottom).

6. DEPENDENCE OF FINAL KWH/KWP ON LOW LIGHT LEVEL PERFORMANCE

Much is made of the relative merits of technologies at different light levels. But as long as the array is relatively unshaded and facing the equator at close to latitude tilt then the energy generated at lower light levels is not very significant.

Figure 8 (top) shows the relative amounts of radiation (kWh/m²) incident on the tilted plane in 100W/m² bin widths for measured sites in Germany, South Africa, Maryland, USA and Tennessee, USA. The sites receive only between four and ten % of the solar radiation at intensities below 100W/m², from nine to twenty % below 200W/m².

The radiation values were then folded into typical parameters for a-Si modules to see the proportion of the expected Energy performance (kWh) versus Irradiance (Figure 8 bottom).

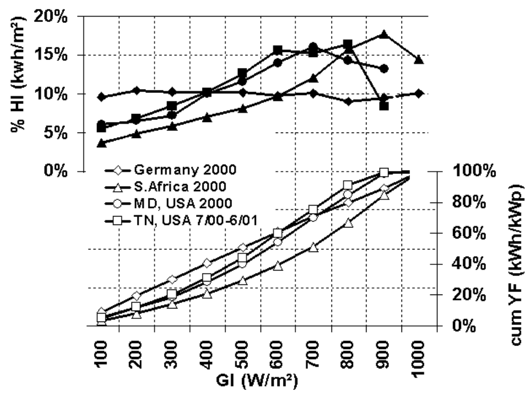

Figure 8 : Percentage of Insolation measured on a tilted plane (kWh/m²) (top) and Cumulative **%** of Energy out (kWh) (bottom) expected from an a-Si array at four sites per 100W/m² bin.

The worst weather site (Germany) only expects 20% of the kWh/kWp from below 200 W/m², the best site (South Africa) predicts around 8%. The conclusion is that well oriented, unshaded arrays still produce most of their energy at higher irradiances.

Because at higher irradiances the PV performance varies linearly with irradiance then the differences in performance between most array technologies will be small in terms of total kWh/kWp with respect to actual Pmax. These differences are less than 7%, which is the margin for error in most studies. Other studies also find differences usually of less than 7% for stable modules compared with actual Pmax [9][10][11][12].

Most differences have been due to poor Vmax tracking, the fact that unstable modules had not yet stabilised and were performing better than the name plate value or the manufacturer's name plate rating had been chosen to be below the actual Pmax.

Section 4 mentioned the inaccuracies in Vmax tracking. Note that this becomes more important at lower light levels as different shaped IV curves (i.e. with variable Rsh values) means that Vmax can vary from module to module at low light level. Also some trackers choose a fixed Voltage below a lower limit of say 200W/m² or have a fixed top or bottom Voltage range

7. kWh/kWp PREDICTIONS

Unlike internal measurements where Modules are characterised under conditions rarely achieved externally (e.g. 1000W/m², AM1.5 STC) the Empirical method fits real data and as every valid measurement is taken into consideration is statistically weighted to the most commonly occurring weather conditions.

An Empirical Sizing program (EMPSIZE) has been developed at BP Solar.

Figure 9 shows the steps followed to Calculate Empirical Parameters A..E and then to use these parameters to predict kWh/kWp performance at a new site.

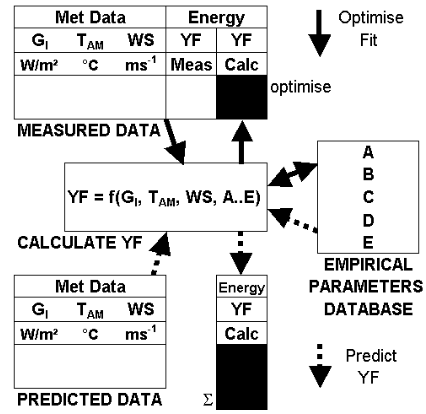

Figure 9 : Empirical Sizing flow diagram for EMPSIZE

Table III shows approximate values of some coefficients derived (values need to be calculated to the third significant figure but space does not allow here).

Table III : Approximate Daily Empirical values from different sites

Site	Techno'gy Arr/Mod		A	C %/C	D %/C	E h/d
TVA, USA	aSi:aSi	A	0.86	-0.3	+0.7	0.17
MCO, USA	aSi:aSi	A	0.84	0.0	+0.9	0.37
Kassel, D	LGBG	M	0.93	-0.5		-0.02
Kassel, D	mSi	M	0.94	-0.6		-0.02
Kassel, D	aSi	M	0.80	0.2		-0.06
RSA	LGBG	M	0.98	-0.4		0.06
RSA	mSi	M	1.00	-0.4		0.06
RSA	aSi	M	0.98	-0.3		0.05
RSA	aSi:aSi	M	1.00	-0.4		0.08

Key :
TVA is an average of eleven Tennessee Millennia sites [3]
MCO is the Maryland SEPA site [2]
Array/Module : **A**rray (ac) YF or **M**odule (dc) YA
(B is approximately 0 for these systems and is not shown)

Note that it is not just the PV technology that is being modelled, rather it includes the inverter efficiency (if present) and also depends on the way the V_{ARRAY} is being tracked. It is known that the MPPTs in Germany can respond to cool weather by increasing the V_{ARRAY} on a LGBG module to perhaps 18V, the MPPTs in South Africa (where the climate is hotter) presently never get above about 16.5V for a mono Si module. Therefore for identical technologies we would expect the parameters to be slightly different as they are calculating the effect of the differing V_{ARRAY}.

Table IV shows some calculations of kWh/kWp predicted at different sites from Northern and Southern Europe, the US and equatorial India from logged data at their original locations. Comparing the data below show a remarkable similarity between each of the modules of the different technologies. Note that these modules were all stabilised and showed a good agreement between actual Pmax and nameplate rating.

If the modules had not been stable and/or the actual ratings had not been close to the nameplate then this would not have been the case.

Table IV : Daily predicted kWh/kWp/y at new locations

Met Data from Meteonorm[13]	Mad rid	Washi ngton	Ham burg	Bang alore
Lat	40N	39N	53N	13N
Tilt	30S	30S	40S	10S
Horiz. kWh/m²	1663	1601	953	2006
Tilted kWh/m²	1907	1846	1098	2058
Tamb °C	13.9	12.3	8.8	23.8
USA, arrays (YF = kWh/kWp/y ac)				
MCO, MD aSi	1542	1488	838	1663
TVA, TN aSi	1558	1517	886	1619
Kassel, Germany, modules (YA = kWh/kWp/y dc)				
LGBG Si	1635	1600	966	1684
MSi	1642	1610	973	1673
aSi	1630	1566	935	1790
South Africa, modules (YA = kWh/kWp/y dc)				
LGBG Si	1746	1700	1011	1825
MSi	1746	1705	1016	1813
aSi	1742	1698	1009	1824
aSi:aSi	1755	1712	1017	1829

Differences can also be seen in the performance from the setups in Germany and South Africa. Whereas the German modules are tracked better (i.e. higher V_{ARRAY}) at cooler temperatures most of the energy production is done at higher irradiances. Comparing the A and E parameters from table III shows that South Africa has higher A (which dominates the high irradiance PR) but worse E (which determines the low light level performance). It is for this reason that the South African setup would give better field kWh/kWp production.

8. CONCLUSIONS

Empirical Methods have been used to compare and contrast many real arrays of various technologies being logged around the world. Most of the modules are one to three years old and represent a snapshot of some of the technologies on the market today.

- These methods are useful for fast predictions of expected kWh/kWp not only for yearly production but also for instantaneous performance during commissioning and fault finding.
- For unshaded arrays facing the equator at a reasonable tilt (close to latitude), kWh/kWp is dominated by performance at higher intensity irradiations. Technologies that claim "rising efficiency at low light levels" obviously lose out at higher intensities
- There seems to be little seasonal / memory effect, most thin film arrays studied so far depend almost exclusively on instantaneous irradiance, temperature and windspeed.
- Measurements from several BP Solar Millennia (a-Si:a-Si) arrays indicate good Performance Ratios and stable performance.
- Final Yield will depend on the reliability of the products and their stability.
- kWh/m² yield depends on module efficiency which is where high efficiency crystalline products do well.
- Similarity in kWh/kWp performance between different technologies indicates that true differences are small (less than 7%). Such small differences are currently not measurable with statistical significance , but future study will help discern any differences.

9. ACKNOWLEDGEMENTS

The authors would like to thank the following for their measurements and help : Chris Purcell (EDG, South Africa); Peter Funtan, Thomas Degner (ISET, Germany); Susan McKinney and Ed Stephens (Green Power/TVA, USA); SEPA

REFERENCES

[1] PREDICTING kWh/kWp PERFORMANCE FOR AMORPHOUS SILICON THIN FILM MODULES
S Ransome and J Wohlgemuth
28th IEEE PVSEC, Sept 2000, p. 1505

[2] SEPA (was UPVG)
http://www.solarelectricpower.org/pv/pv_performance_data.cfm

[3] Tennessee Valley Authority (TVA)
http://www.tva.gov/greenpowerswitch/solar.htm

[4] Sun Power Electric (SPE)
http://www.wattsonschools.com/spe.htm

[5] ISET, Kassel, Germany
http://www.iset.uni-kassel.de

[6] EDG, South Africa
http://www.edg.co.za

[7] "STABILIZATION AND PERFORMANCE CHARACTERISTICS OF COMMERCIAL AMORPHOUS SILICON PV MODULES"
D. King, J. Kratochvil and W. Boyson,
28th IEEE PVSEC, Sept 2000, p. 1446

[8] "BEHAVIOUR OF TRIPLE JUNCTION A-SI MODULES"
N. Cereghetti, D. Chianese, S. Rezzonico and G. Travaglini, TISO
16th European PVSEC, May, 2000, 2414

[9] MODELING ANNUAL ENERGY PRODUCTION FROM PHOTOVOLTAIC MODULES
D.L.King, Sandia
Quarterly Highlights of Sandia's Photovoltaics Program Dec 19 2000

[10] "MODULVERGLEICH" (MODULE COMPARISON)
Prof. Dr. Klaus Kaltenbach Dipl.-Ing. Eckhard Stuhr
University of Applied Sciences, Luebeck
http://solar.fh-luebeck.de/pv02.html

[11] 18 TYPES OF PV MODULES UNDER THE LENS
D. Chianese, N. Cereghetti, S. Rezzonico and G. Travaglini, TISO
16th European PVSEC, May, 2000, 2418

[12] http://solar.fh-luebeck.de/solardaten/pv-fue.html

[13] METEONORM Meteotest, Fabrikstr 14, CH-3012 Bern, Switzerland office@meteotest.ch