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A SUMMARY OF 6 YEARS PERFORMANCE MODELLING FROM 100+ SITES WORLDWIDE

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ABSTRACT

Since 1998 BP Solar has been involved in long term studies [1] on IV swept, maximum power point tracked or grid connected modules and arrays at more than 100 sites worldwide (predominantly in the USA, Europe, Australia and Asia).

Both BP Solar and competitors' products are being tested. Technologies studied include Laser Grooved Buried Contact "LGBC" (Saturn); screen printed mono and multicrystalline Silicon; HIT; single, double and triple junction amorphous Si and CdTe.

Different types of monitoring sites include independent test houses, third-party collaborations, BP Solar factories, downloads from the internet and petrol station roofs.

This paper describes the main findings from these tests.

IMPORTANT PARAMETER DEFINITIONS

Some of the important parameters measured and calculated to compare different modules and arrays are given below in Table I. (See also IEC 61724 [2]).

Suffixes are used to denote the measurement frequency summarised e.g. "h" hourly and "d" daily, "g" denotes average weighted by irradiance G_I.

Many of the measurements are normalised, for example normalised dc Voltage V_{DM} = "V_{DC} / $V_{MAX.STC}$". e.g. if a module with a nominal $V_{MAX.STC}$ of 20V is loaded at 18V then V_{DM} = 18/20 = 0.9. In an array with a string of 10 series modules under similar conditions the dc Voltage would be expected to be 10 * 20 * 0.9 = 180V. (Usually V_{DM} for maximum power will be in the region 0.85 to 0.95, slightly depending on module temperature).

When evaluating parameters such as kWh/kWp it is important to define which value is used for kWp – the nominal P_{MAX} at STC, the flash test P_{MAX} at STC or the derived PTC rating – so they should be referred to in the format $kWh/kWp._{NOM}$, $kWh/kWp._{STC}$, $kWh/kWp._{FLASH}$ etc

Table I : Some important normalised parameters, their ranges and definitions used in this study.

Name		Microsoft Colour number	Long Parameter Name	Unit	Usual Range	Definition	Daily Weighting Σ_t=sum(time)
G_I	□	14 Teal	Plane of array irradiance	kW/m²	0~1.4		
T_{AM}	Δ	44 Gold	Ambient temperature	C	-40~100		$\Sigma_t(T_{AM}*G_I)/\Sigma_t(G_I)$
T_M	o	46 Orange	Module temperature	C	-40~100		$\Sigma_t(T_M*G_I)/\Sigma_t(G_I)$
WS	o	16 Grey –50%	Wind speed	ms^{-1}	0~20?		
YR	□	14 Teal	Insolation or Ref yield	kWh/m²	0~1.4/h	$=\Sigma_t(G_I)$	
V_{DM}	□	41 Light Blue	Normalised DC voltage	-	0~1.4	$=V_{DC}/V_{MAX}$	$\Sigma_t(V_{DM}*G_I)/\Sigma_t(G_I)$
I_{DM}	□	04 Green	Normalised DC current	-	0~1.4/h	$=I_{DC}/I_{MAX}$	
I_{DN}	*	01 Black	Norm. DC current / G_I	-	0~1.4	$=I_{DC}/I_{MAX}/G_I$	
YA	□	39 Lavender	DC yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{DC})/P_{MAX}$	
YF	◊	37 Pale Blue	AC yield	Wh/Wp	0~1.4/h	$=\Sigma_t(P_{AC})/P_{MAX}$	
ΔT	◊	03 Red	$T_{MODULE}-T_{STC}$	Deg C	-40~100	$=T_M - 25$	
PF	◊	15 Grey –25%	Performance Factor(DC)	-	0~1.4	=YA/YR	
PF_T	Δ	53 Brown	Temp. corrected PF	-	0~1.4	$=PF*(1-\gamma)*\Delta T$	$(\gamma = dP_{MAX}/dT_M)$
PR	□	07 Pink	Performance Ratio (AC)	-	0~1.4	=YF/YR	
kTh	x	01 Black	Instantaneous Clearness Index	-	0.2~0.8	= Global horizontal / Extraterrestrial horizontal irradiance = G0/X0	
Gd/G0	+	56 Grey –80%	Diffuse fraction	-	0.2~1	= Diffuse horizontal / Global horizontal irradiance = Gd/G0	

MODULES GENERATE MORE kWh AT HIGHER IRRADIANCE AND LOWER TEMPERATURES THAN HOURLY MODELS SUGGEST

Many sizing programs create hourly stochastic series of weather data in an attempt to model changeable sunny and cloudy periods. They then use a model of the PV under different irradiances and temperatures to try to calculate kWh/kWp over a year by summing up the expected energy at each hour interval.

Studies of weather data at measurement intervals more frequent than hourly in both Sydney (measured every minute 2002-2004) and ISET Kassel[3] (taken every 15 seconds 2003) show that averaging data to hourly values distorts the actual energy versus irradiance curve to overestimate the low light level and underestimate the effect of high light levels.

The insolation per irradiance bin versus irradiance is shown in Fig 1 for an hourly stochastic model and for measured Irradiance averages every hour, 10 minutes and every 15 seconds for the year 2003 in Kassel. It shows a different shape that also depends on the averaging frequency, in reality more energy occurs at higher light levels than the hourly model suggests, meaning that hourly simulation programs based on this data will underestimate kWh/kWp performance at higher light levels.

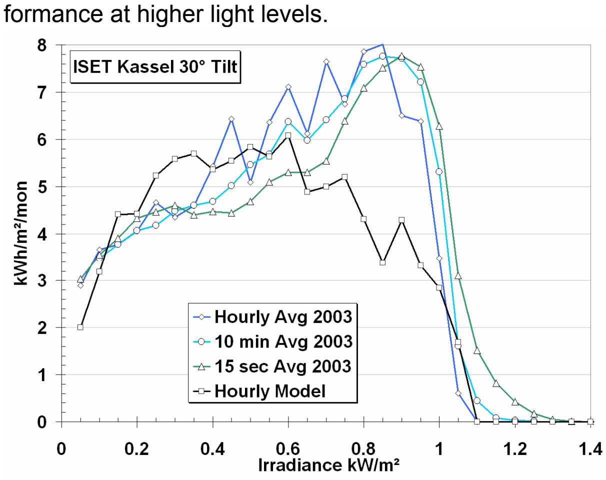

Figure 1 : Hourly stochastic and measured insolation vs irradiance at ISET, Germany.

On days with intermittent clouds, periods were found where, when the sun was obscured by clouds, the irradiance was 0.4 kW/m², when the sun was direct but surrounded by bright cloud the extra reflections gave an irradiance of up to 1.2 kW/m² and the irradiance oscillated between these values every few minutes. (An hourly average of these irradiances was around 0.8 kW/m²).

As the modules have a relatively large thermal mass their temperatures depend on the average irradiance for the previous 15 minutes or so, when they were at 1.2 kW/m² (with measured currents 20% above nominal STC) their temperatures were 7C lower than expected from an average irradiance of only 0.8 kW/m².

The instantaneous measurements showed that during intermittent clouds the modules operated simultaneously at both higher irradiances and lower temperatures than hourly averaged measurements or models would have predicted. (A joint paper with ISET has been submitted to Barcelona 2005 on this work [4]).

USEFUL EMPIRICAL FORMULAE

Table II shows some empirical formulae for yield (1) and (2), module temperature (3) and optimum dc array voltage (4) vs coefficients for irradiance A, irradiance² B, Tambient C, wind speed D and a constant E that can be used to model the system's performance and determine when the system is working well i.e. the voltage is near optimum and the yield is as high as expected.

Once empirical coefficients have been found to make a good fit to equation (1) the PTC power (PTC = 1kW/m²; $T_{AMBIENT}$ = 25C; WS = 1 ms^{-1}) can be interpolated and the ratio $P_{PTC.MEASURED}/P_{STC.NOMINAL}$ calculated to show how well the module performs with respect to its declared rating.

Table II. Useful empirical formulae

$Y_{CALC}= \Sigma G_I*(A+B*\Sigma G_I+C*T_{AM}+D*WS)-E$	(1)
$A = A_{SYSTEM}*A_{INVEFF}*A_{P.ACTUAL/P.NOMINAL}*A_{STABIL'N}(exposure)*A_{SPECTRUM}(time\ of\ year)$	(2)
$T_M = C'*T_{AM} + \Sigma G_I*(A' + D'*WS) + E'$	(3)
$V_{DM} = A''*LOG_{10}(\Sigma G_I) + C''*T_M + D''*WS + E''$	(4)

DAILY PERFORMANCE DATA SUMMARIES

The performance of arrays can be reported as daily insolations (YRd kWh/m²/d), dc and/or ac yield (YAd, YFd kWh/kWp/d) plus performance factor and/or ratio (PFd, PRd). It can also be useful to compare daily averages of module and array parameters such as T_{MODULE} , V_{DM} etc. These daily temperatures and voltages need to be weighted by the irradiance G_I (5) to (7) as the daytime operation does not depend on the night time temperatures and is affected mostly by the performance at highest irradiances.

$$T_{AMGd} = \Sigma_t(T_{AM}*G_I) / \Sigma_t(G_I) \quad (5)$$
$$T_{MGd} = \Sigma_t(T_M*G_I) / \Sigma_t(G_I) \quad (6)$$
$$V_{DMGd} = \Sigma_t(V_{DM}*G_I) / \Sigma_t(G_I) \quad (7)$$

It should be noted that any angle of incidence effects are reduced if the data is summed over the day and any spectral effects for thin films show as an annual variation of the daily data. Figure 2 shows the averaged daily data for one particular c-Si module in Australia. The dc yield YAd shows a good linear performance over an insolation range of 1 to 8 kWh/m²/d. The normalised dc voltage V_{DMGd} is flat at approximately 0.9, the normalised dc current I_{DNd} is approximately 1.0 rising slightly on lower insolation days. The irradiance-weighted ambient temperature T_{AMGd} is 15-20C and the weighted module temperature T_{MGd} is seen to rise from 20 to near 50C on the highest insolation days (7kWh/m²/d). Note the good low light level response of this module as PF_d is still above 0.9 even on days with insolations < 1 kWh/m^2/d

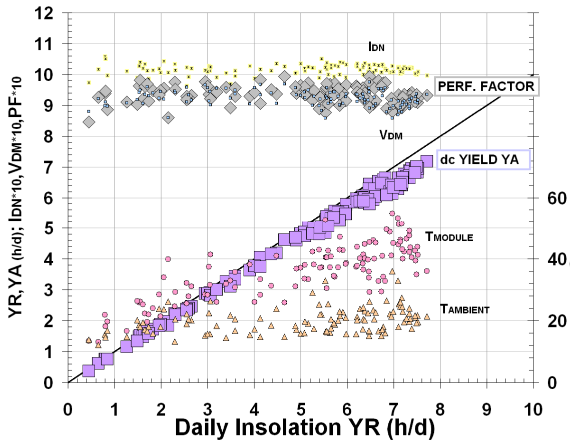

Figure 2 : Daily averaged parameter values versus Insolation for a c-Si module in Australia.

The stability of a module can be studied using the temperature corrected dc performance factor PF_{Td}, the weighted dc Voltage V_{DMGd} and module temperature T_{MGd}. Figure 3 shows stable performance (flat PF_T) from a c-Si module in the Australian spring (Jul to Nov). Although V_{DMGd} fell as the temperature rose, I_{DNd} is flat as expected.

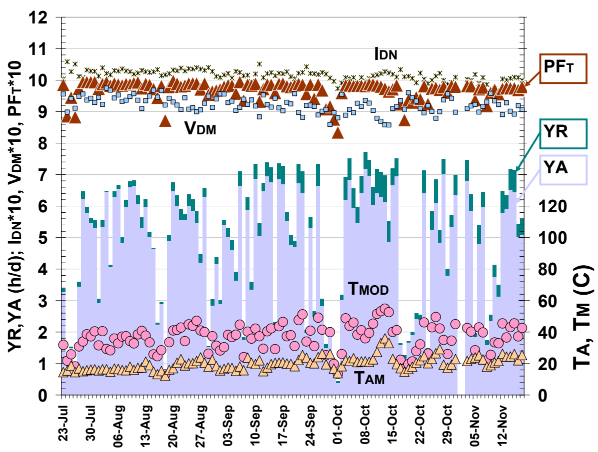

Figure 3 : Daily averaged parameters vs time showing flat PF_{Td} with time indicating stable performance.

DC TO AC - LOSSES AT EACH STAGE

Meteorological or site losses like snow, dirt and shading plus Balance Of Systems (BOS) limitations such as inverter inefficiency, voltage mistracking and wiring resistance mean that 15-20% of the possible energy out is lost to these effects, most performance ratios of well behaved, correctly declared $P_{MAX.NOMINAL}$ arrays are between 75 and 80%.

Figure 4 shows a study of 15 energy limiting "effects" where the loss at each stage was estimated with a model. The spread of expected parameters from different systems is shown by the height of the bar, while the black line shows the calculated value for a particular site in New York. The product of all of these losses implies an expected performance ratio for this system of 76% which was approximately what was measured.

Higher PRs can be obtained by minimising losses at each stage where possible. This site had fairly high losses due to snow and dirt but benefited from the cool climate.

One parameter that has a direct effect on the Performance ratio is the $P_{MAX.ACTUAL}$ / $P_{MAX.NOMINAL}$. Recently BP Solar have changed to "Real Power" when rating the BP 7 series, meaning that the P_{MAX} on the production line is no less than the nominal P_{MAX} rating.

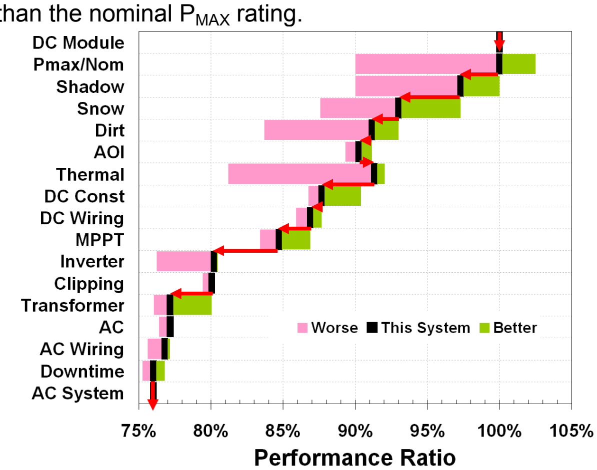

Figure 4 : Losses at each stage for a system in New York showing an expected performance ratio of 76% for this site.

SHOULD PERFORMANCE BE OPTIMISED FOR A GIVEN LIGHT LEVEL ?

Studies of the energy at each Irradiance level (as in Figure 1) for sites around the world show that for plane of array insolations of more than about 1000 kWh/m²/year there is more energy at higher irradiances than low[5]. But wherever the site, as long as the orientation is good and the shading low, there is some energy at a wide range of light levels from 50 to around 950 or more W/m².

Mostly the V_{DC} of a module will depend on the module temperature and will fall by around -0.22 to -0.45% (depending on technology) for every degree C the module is above 25C. The behaviour of the normalised current I_{DN} will then dominate the performance factor; Figure 5 shows how the I_{DN} of a Saturn 585 module varied at ISET for the whole of 2002. 18000 measurements were made that year (every 10 minutes) and the graphs show the I_{DN} vs irradiance, T_{MOD}, wind speed, diffuse fraction Gd/G0, clearness index kTh and angle of incidence.

All six of the graphs show very flat current collection meaning that the module's performance is optimised under all irradiance conditions. If a module were to be optimised for one irradiancecondition then it would be less than optimum at all other irradiances. The highest energy (kWh) out for a module is where the efficiency under all conditions is as high as possible.

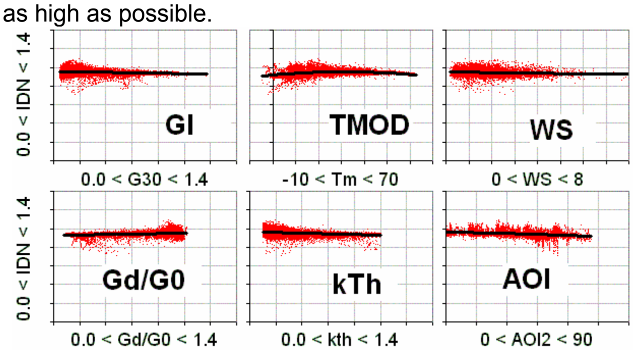

Figure 5 : BP585 I_{DN} versus GI, T_{MODULE}, Wind speed, diffuse fraction, clearness index and Angle of Incidence showing flat, optimised performance

OUTDOOR MODULE EFFICIENCY vs LIGHT LEVEL

All of the previous graphs have shown normalised performance (e.g. $P_{MAX.MEASURED}$ / $P_{MAX.NOMINAL}$) which make modules of different technologies look more similar than they really are. Figure 6 shows how measured absolute module efficiencies in Sydney under real conditions for four different modules (BP 7180 and competitors' mc-Si, double and triple Junction a-Si) varied from 4.5% (2J a-Si) to 13.5% (BP 7180) where module temperatures are up to 50C, irradiances up to approximately 1kW/m² and with real spectra, angles of incidence, dirt and direct/diffuse fractions).

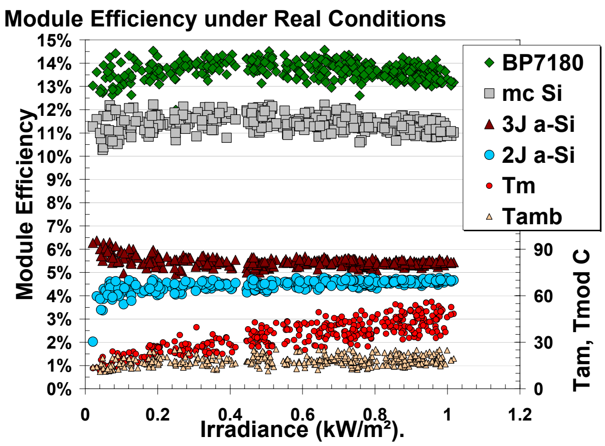

Figure 6 : Module efficiency vs Irradiance under real conditions (T_{MODULE} 20-50C) in Sydney for a BP 7180 versus mc-Si, 2J a-Si and 3J a-Si from competitors.

The modules had their IV scans performed every 30 minutes; the V_{MAX} and I_{MAX} were derived so that the efficiency could be found without there being any V_{MAX} tracking errors. The efficiency of the BP 7180 module is over 13% from 0.05 to 1kW/m² irradiance under real conditions (i.e. high module temperature) and is largely independent of irradiance.

SUMMARY

- Frequent measurements show modules generate more energy at simultaneously higher irradiances and lower temperatures than hourly averages of measured weather data or stochastic modelling predicts.
- Empirical equations have been found useful in determining the optimum performance of arrays.
- Weighting voltages and temperatures by the measured irradiance has proven useful in analysing daily outputs of arrays.
- All ac systems studied have shown kWh/kWp limiting effects (downtime, voltage mistracking, shading, inverter inefficiencies etc) that are not due to the modules.
- A model has been developed to predict losses due to 15 different effects like snow, shading, inverter loss and wiring loss.
- High values of kWh/kWp come from real power (i.e. Pactual>Pnominal)
- BP Saturn modules have been shown to have good, efficiency largely independent of light level, clearness, diffuse fraction etc.
- For highest kWh generation maximize module efficiency for the range of irradiances expected under normal outdoor operation.

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