kWh/kWp DEPENDENCY ON PV TECHNOLOGY AND BALANCE OF SYSTEMS PERFORMANCE

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ABSTRACT

BP Solar is continually analysing performance data on various PV technologies in a long term test program using logging sites worldwide with data from third parties, test houses and in house measurements. kWh/kWp values are calculated to show the energy generated divided by the nameplate STC rating. This paper studies how only some of the differences found depend on the intrinsic properties of the PV module and how much depend on other factors like BOS performance (inverter, V_{MAX} tracking) and “rated versus actual” watts.

DATA COLLECTION

The data collection and analysis performed in this program were described in detail by the authors in two previous papers [1][2]. The data are all taken from grid tied arrays or modules with either Maximum Power Point Trackers (MPPTs) or swept IV curves to determine the energy output at the maximum power point. Data [3] are typically plotted as Final Yield Y_F and Performance Ratio PR to allow for comparison of arrays and modules of different sizes. Data from third parties have also been studied from joint collaborations, sample data and downloads from sites posting on the Internet.

COMPETITORS’ MODULES RANKING

Many teams running comparative tests between modules and arrays of different technologies are listed in Table 1

Single Modules dc	500Wp-1kWp arrays ac
Tiso[4]	pv compare[9]
Nist[5]	luebeck[10]
Iset/bp solar[6]	
Edg/bp solar[7]	
Bp solar Australia	
Nrel[8]	Nrel[8]

Table 1. Some of the sites logging data

These sites report kWh/kWp rankings in different orders, sometimes with thin film a-Si modules having higher kWh/kWp, but most of this can be explained by incorrect (and inconsistent?) Pmax definitions.

INTRINSIC MODULE PR PERFORMANCE

The only way to measure kWh/kWp due to the PV technology alone is to perform IV scans and derive the $V_{OPTIMUM}$ and hence the P_{MAX} (as MPPTs do not always find the optimum Voltage for maximum power). Figure 1 shows the average PR_{DC} versus Irradiance and T_{AM} for identical c-Si modules measured in South Africa (commercial tracker), Colorado USA[8] (IV sweep) and Germany (in house tracker). The German tracker follows the performance shape of the intrinsic module (with the optimum PR_{DC} at low light levels and temperatures) but with some loss, the commercial tracker has highest PR_{DC} at higher irradiances and low temperatures due to it not realizing the high V_{MAX} available at lower temperatures and irradiances.

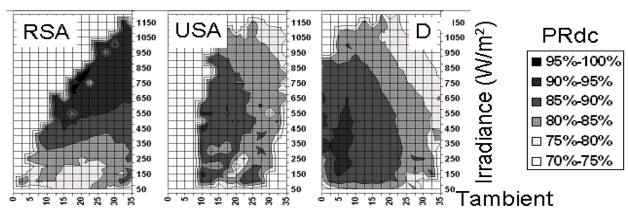

Fig 1. Average PR_{DC} versus T_{AM} and Irradiance for C-modules in South Africa (Left), Colorado USA (Centre) and Germany (Right)

Fig 2 shows how the dc yield (Y_A) and PR_{DC} from identical modules depend on the V_{ARRAY} tracking for sunny days in Australia (swept) and Germany (MPPT).

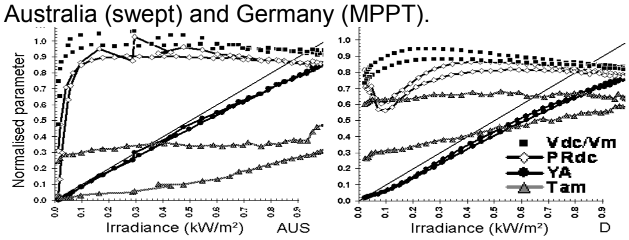

Fig 2.PR_{DC}, DC Yield Y_A, $V_{ARRAY}/V_{MAX.STC}$ and normalized T_{AM} (y axis) versus Irradiance (x axis, kWh/m²) for IV swept module (left) and MPPT tracker (right)

The MPPT shown here has too low a voltage at low light levels and too low a voltage at high light levels resulting in a lower than expected value of Y_A. (A linear device with no losses should have its Y_A trace coincident with the diagonal line, the MPPT is clearly lower at all light levels). As the PR and Y_A vs. Irradiance and T_{AM} depend on the BOS components used, reporting dc kWh/kWp does not just give the intrinsic performance of the module.

Most c-Si module production processes have historically been optimised for performance around STC (1000 W/m²) and to hold up their dc efficiency well at low light levels, usually not falling much until the irradiance falls below 100W/m² (unless a module is shunted). Thin film modules usually rely on a conducting oxide layer at around 10Ω/[], which reduces power due to I²R loss [11]. If this becomes significant due to poor design and/or high sheet resistivity then a Thin Film module can fall in efficiency at higher light levels which reduces its STC rating and appears to give higher dc performance values at lower light levels. (Similar Efficiency vs. Light Level performance for c-Si could be achieved by adding a series resistor to modules or reducing the number of grid lines or bus bars). However as there is a reasonable amount of energy at all irradiances from 100-1000W/m² even in climates like Northern Europe with reasonable tilts[2] highest kWh production comes from high efficiencies at all light levels. As Inverters become less efficient at lower powers from lower light levels ac kWh/kWp values will tend to be more similar to one another as any contributions to energy from low light levels are lessened.

THERMAL EFFECTS

The fall in P_{MAX} with Temperature ($\gamma=1/P_{MAX} * dP_{MAX}/dT$) is approximately –0.22%/deg C for a-Si and –0.45%/deg C for c-Si. Therefore it is beneficial to keep the modules cool by ventilating their backs whenever possible. When temperatures must be high (for example in some BIPV) then there will be a slight relative increase in the performance of a-Si over c-Si.

In the past some Thin Film manufacturers have claimed a rising Efficiency with temperature. Gottschalg et al [12] have shown that this has been due to the bluer spectra found at high irradiances and temperatures. Correcting for useful Spectrum values (i.e. how much of the Spectrum can be absorbed by narrow band technologies) means that Gamma values do turn out to be negative.

Some studies have been done to compare technologies at unnecessarily high Temperatures by mounting them close to the roof or thermally insulating the backs. However as they all reduce in performance at higher temperatures (albeit more rapidly with c-Si than thin films) it is in the interests of high kWh production to reduce temperatures where possible.

Recent studies [13] suggest that thermal annealing does not play a part in the performance of at least some a-Si arrays, most seasonal effects are due to instantaneous temperature, irradiance and spectral changes.

MEASUREMENT ACCURACY

The accuracy of some inverters in measuring Current, Voltage and Power can be poor. Sometimes the Energy reported (delta E in kWh) does not correspond to the sum of the Current x Voltage product over each time interval. Discrepancies have been seen between external measurements and the Inverter readings. In some cases the dc Voltage is measured and the Current estimated from a reference table of the Inverter's expected performance. Errors of 5% have been seen at high light levels and much higher at lower irradiances. In many cases raw data has to go through a recalibration and correction process, which could still allow large errors to remain or introduce further ones.

STABILISATION

The total yearly kWh performance depends on the degradation characteristics of the module. There is an initial drop with most a-Si and other thin films that tends to stabilize with time.

As manufacturers guarantee a minimum power at the end of life then for unstable modules the initial power supplied must be greater than the minimum by a predetermined amount often from 10 to 30%. Not all of the modules will degrade at the same rate (Fig 3) and therefore some unstable modules will behave in the field at a higher power than they are rated. For stable c-Si products the initial power may only be a few percent higher than the guaranteed P_{MIN} value. It is for this reason that sometimes thin film kWh/kWp values seem higher than for c-Si, it is predominantly due to the definition of P_{MAX}, not due to better performance at all light levels. If the modules were to be tested at STC then it is presumed that the thin film modules would show that they were incorrectly labelled with their P_{MAX} values.

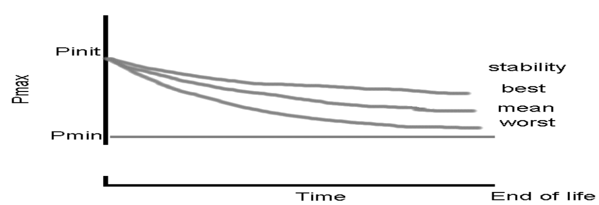

Fig 3 Stabilisation traces of Thin Film modules to their end of life.

MODULE P_{MAX} BINNING

Manufacturers usually measure their modules under pulsed simulators at STC conditions to grade them into P_{MAX} bins. For example a c-Si manufacturer might have bins of 100Wp ($90<P_{MAX}<=99.9$Wp) and 90Wp ($80<P_{MAX}<=89.9$Wp). With a-Si an allowance is usually made for degradation. Assuming a degradation factor of 20%, a simulator measurement of between 112 and 125Wp (far higher than for c-Si) would go into the 90-100Wp bin meaning some a-Si modules can occasionally appear to out perform other technologies, but this is just due to incorrect Pmax assumptions.

In Production Module Pmax distributions (Fig 4) the high P_{MAX} tail will normally be sharper than the low P_{MAX}. If the cut off region is near the mode (as can happen) if a customer buys several modules from the top band statistically the mean will be in the lower part of the band. If the modules bought are in the low band then statistically they will average high in the low band. Therefore the lower band modules will be closer to their defined P_{MAX} than the upper band

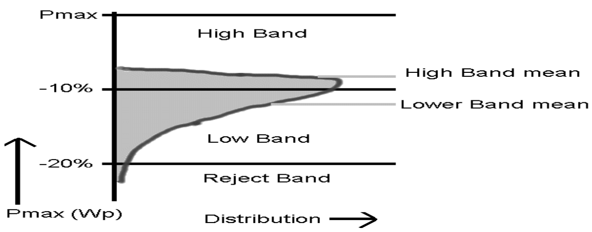

Fig 4 A hypothetical module distribution diagram between a higher band, a lower band and a reject band.

If a comparative test is made between two manufacturers with similar module distribution shapes and one is taken from the high band modules and the other from the lower then the average P_{MAX} will appear better from the lower band. This means that "2nd band products" will appear to have better kWh/kWp than "1st band".

PR SURFACES vs. TAMBIENT AND IRRADIANCE

Performance Ratio surface plots versus Irradiance and T_{AM} (as in fig 1) show whether a module is really performing better under certain weather conditions or if the shapes from the two modules are similar, then any difference in kWh/kWp is probably due to incorrect P_{MAX} rating or a different distribution in the bins.

SPECTRAL EFFECTS

c-Si should not suffer too large a spectral effect, but multi junctions should be worse at Air Masses different from AM1.5 as the different junctions are in series. If they are matched for AM1.5 they will not be matched for other spectra. King et al [14] found the relative response of triple junction a-Si falling linearly from 1.0 to 0.75 as the Air Mass increased from AM 1.5 to AM 5.0, whereas for five other technologies the response varied less than ± 5%.

Recently ECN [15] characterised the performance of modules at low light levels by tilting them away from a bright noon sun so that the spectrum would not change. However in real systems the light level is usually low because the solar angle and hence the air mass is high. Their measurement would have overestimated the low light level performance of multi junction devices, which are less efficient at high Air Mass.

MISMATCH

Several test houses measure performance on individual modules. Mismatch however should be taken into account on arrays as series strings are usually limited by their worst module. If one module is shunted but still has a good high light level performance then its low light level will be affected which will bring down the whole string. Some studies investigated clearly show sub standard performance (possibly by a poor module or BOS component) that may have given more meaningful comparisons between different arrays if the problems had been fixed.

BOS EFFECTS

The effects of V_{MAX} mistracking (both steady state and due to transients [16]) can seriously reduce measured kWh/kWp. Also when combining paralleled strings to the same MPPT then due to differences in string IVs and/or wiring losses not all of the strings may have the same $V_{OPTIMUM}$, meaning that they cannot all be matched simultaneously resulting in losses. This can be studied by looking at average V_{MAX} versus Insolation and T_{AM} to see if it is behaving as expected from Empirical simulations. For each value of Irradiance and T_{AM} there is an optimum value of V_{MODULE} to give a maximum performance ratio PR. If the MPPT finds a different V_{MODULE} then the PR and therefore the energy production will be lower than the optimum. The effective PR achieved is found by summing the fraction of each V_{MODULE} bin times the PR at each Voltage :

$$PR_{EFFECTIVE} = \Sigma_i(f(V_i) * PR(V_i)). \qquad (1)$$

This is then multiplied by the energy in each T_{AM} and Irradiance bin to give the Energy produced, then summed over each T_{AM} and Irradiance to give the total Energy out. Low light level performance of ac systems can be dominated by low Inverter Efficiency and also its inability to track V_{MAX} at Low light levels [17].

SUGGESTIONS

The use of kWh/kWp values (because consumers currently buy Wp and may be paid for kWh produced) encourages the manufacturers to maximize this figure. One way to do this is to reduce the rated efficiency only at higher light levels. This paper suggests that it is kWh/lifetime using given BOS components (at a specified location) of the product that is most important. To reach high values manufacturers need to

- increase the efficiencies at all light levels (not just low levels)
- reduce degradation with time
- reduce thermal losses (by reducing module temperature, open backs etc.)
- reduce mismatch (by better binning ?)
- improve BOS performance (V_{MAX} tracking, Inverter efficiency, uptime, wiring and connector losses etc.)
- optimize tilt and azimuth of arrays where possible

CONCLUSIONS

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.

Systems kWh/kWp is a complex subject. Table 2 shows some of the effects that need to be considered before publishing kWh/kWp figures.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Steven J. Ransome and John H. Wohlgemuth, "Predicting kWh/kWp Performance for Amorphous Silicon Thin Film Modules", 28th IEEE PVSC, Alaska 2000, p. 1505.

[2] Steven J. Ransome and John H. Wohlgemuth, "Analysis of Measured kWh/kWp from Grid Tied Systems– Modelling Different Technologies Worldwide with Real Data" 17th European PVSEC, Munich 2001, OA4-3

[3] IEC 61724

[4] http://leee.dct.supsi.ch/ LEEE-Tiso, Various

[5] Fanney, A. H. et al "Measured Performance of Building Integrated Photovoltaic Panels " http://fire.nist.gov/bfrlpubs/build01/PDF/b01040.pdf

[6] http://www.iset.uni-kassel.de/

[7] http://www.edg.co.za/

[8] NREL http://www.nrel.gov

[9] C. N. Jardine et al, "PV-Compare: Direct Comparison of Eleven PV Technologies at Two Locations in Northern and Southern Europe" 17th European PVSEC, Munich 2001, VD1-13

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

[11] Willing et al "Power optimisation for Large Area a-Si Solar Modules" 21st IEEE PVSC 1990 pp1432-1437

[12] Gottschalg et al "Experimental Investigation of Spectral Effects on Amorphous Silicon Solar Cells in Outdoor Operation" 29th IEEE PVSC New Orleans, 2002

[13] John H Wohlgemuth and Steven J Ransome "Performance of BP Solar Tandem Junction Amorphous Silicon Modules" 29th IEEE PVSC New Orleans, 2002

[14] David L. King et al, "Field Experience with a New Performance Characterization Procedure for Photovoltaic Arrays", 2nd World PVSEC, 1998, pp 1947-1952

[15] Jaap Eikelboom, ECN, Private Communication Nov 2001

[16] Hirotaka Koizumi et al "Dynamic Response of Maximum Power point tracking function for Irradiance and Temperature fluctuation in commercial PV Inverters" 17th European PVSEC, Munich. 2001, VD1-48

[17] Mariano Sidrach and Cardona Ortin "Influence of the inverter threshold losses in the grid connected photovoltaic systems efficiency" 17th European PVSEC, Munich 2001 VD2_26

Module power	Stringing	Met Data	System	V Tracker	Inverter	Measurements
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 2. Some of the factors affecting kWh/kWp measurements that are not just due to the module technology.