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UNDERSTANDING kWh/kWp BY COMPARING MEASURED DATA WITH MODELLING PREDICTIONS AND PERFORMANCE CLAIMS

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ABSTRACT

The performances of PV arrays are usually compared by the kWh/kWp produced. Several recent independent studies in European climates [1][2][3][4] have found similar kWh/kWp (within experimental error ±5%) for different module technologies without a systematic bias in favour of any technology.

Sizing programs that estimate kWh/kWp values usually predict the IV curve of a PV module with a 1-diode model [5] to match the STC curve then correct for irradiance and temperature effects. They often predict higher kWh/kWp for thin film devices as their models give them better low light level performance than is measured.

Measured weather parameters such as tilted plane irradiance and detailed dc performance of several technologies at ISET has been compared and contrasted with predictions from three different sizing programs.

Many differences have been found between measured and modelled weather data, thermal coefficients and low light level dependency meaning kWh/kWp should not vary much between correctly declared PV technologies.

If kWh/kWp variations are small (i.e. <±5%) shown in Europe then other parameters have been suggested that can be used to differentiate PV technologies.

kWh/kWp PERFORMANCE CLAIMS

Some manufacturers claim "values of up to 30% higher kWh/kWp" for their products due to better performance under some or all of the following weather conditions :-

- low light levels
- high diffuse light fraction
- non optimal tilt (e.g. horizontal mounting)
- high temperatures
- bluer light (summer clear sky)
- thermal annealing (e.g. autumn will be better than spring)
- “foggy weather”

Often their published measurements appear to show better yields from their products than other competitors’ technologies that they have measured. However due to instabilities of Pmax (initial stabilisation, steady decline and changes due to thermal annealing and spectral mismatch) it is not known how their nominal STC values have been declared.

Previous publications [1][6][7] have shown that the yields of systems may vary by ±4-5% just due to uncertainties in reference module calibrations and the width of module bins (e.g. a 200W nominal module bin may contain modules from 200 to 210Wp).

If specific module technologies or manufacturers really did have large differences in energy yields then these results should be repeatable and measurable by all studies.

UNCERTAINTIES OF kWh/kWp STUDIES

Outdoor yield results are often given without quoting any inaccuracies or how any corrections are made for downtime, faulty or out of spec data or shading, Vmax mistracking etc.

If a module X is found to have a higher energy yield than a module Y then will these differences be applicable to just those two modules, all modules of those types, all modules made by the manufacturers or all modules of the technologies involved ?

Recent surveys have shown differences of kWh/kWp are less than the earliest measurements - it is probably due to better Rshunt performance which has raised low light level on c-Si and thin films, more accurate Pmax definitions and lower allowance for TF degradation.

Attempts to measure the real power in the field using translations for temperature and irradiance have limited accuracy (as proven by some round robin tests)- particularly for multi junction thin film devices with their thermal annealing, also for recent high power c-Si with their high capacitances.

Indoor measurements to show dependence of efficiency vs. light level etc are often incomplete as outdoors effects are correlated (for example as the light level rises the temperature will necessarily increase).

Tracking modules away from the sun to measure low light levels causes inaccuracies as these show higher angle of incidence reflectance effects at blue rich spectra that will never be achieved under these conditions.

kWh/kWp PREDICTIONS FROM MODELLING PROGRAMS

Sizing programs will usually perform the following steps to estimate kWh/kWp from a PV array

- Calculate stochastic tilted plane hourly irradiance series from monthly horizontal plane insolation.
- Estimate module temperature from NOCT value.
- Generate hourly dc Pmax as a function of Irradiance and temperature usually with a 1-diode model [5].
- Estimate other losses such as soiling, shading, and mismatch.
- Determine inverter efficiency, Vmax tracking and wiring losses.

- Results: sum over a year to get kWh/kWp.

The programs usually treat weather data as independent variables but all weather parameters are correlated [6]. Figure 1 illustrates module temperature vs. air mass for clear skies in Kassel. A correlation is seen from the slope of the trend line such that any attempt to extract a coefficient (for example of module temperature) will have a spectral dependence to be considered.

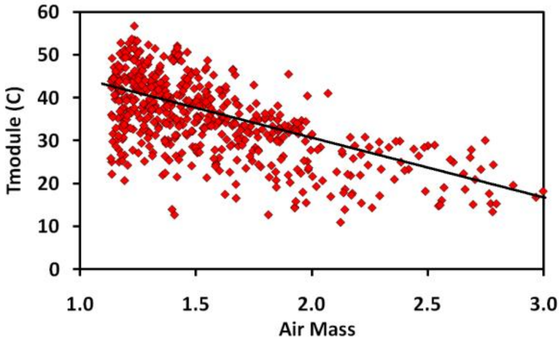


Figure 1: Plot of module temperature vs. air mass for clear sky conditions for a c-Si module in Kassel.

PLANE OF ARRAY INSOLATION vs. IRRADIANCE

It has been found previously [8] that averaging high frequency meteorological data to hourly will change the distribution of the irradiance vs. insolation curve as there will be variable weather hours (some partly sunny, other partly cloudy conditions) that will be averaged to be a "dull hour".

Figure 2 gives the percentage of insolation measured at each irradiance bin when measured at 15 second intervals in Kassel for 2003. When averaged to hourly values there is a steadily rising amount of irradiance to 900W/m² then a fast drop to zero at 1100W/m². Increasing the sampling frequency to every 10minutes, every 1 minute and finally every 15 seconds shows an increasing amount or insolation occurring at higher irradiances – up to 1350W/m² for brief periods for example when there might be direct sun in a white sky where the diffuse reflection was higher than expected.

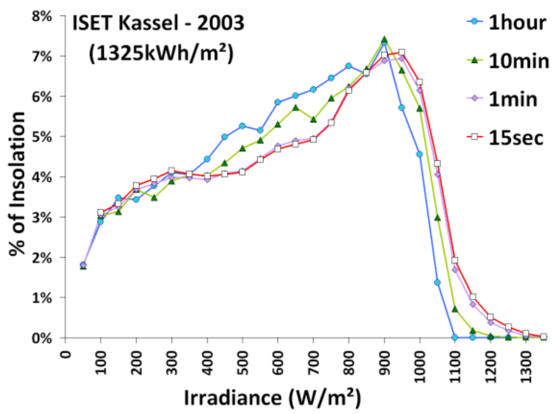


Figure 2. In plane insolation measured at 15second intervals at Kassel, Germany and averaged at different frequencies down to hourly.

Figure 3 gives the total insolation measured vs. irradiance (y-axis) and Tmodule bins (x-axis) for a c-Si with the weather data from figure 2.

The peak insolations occur around 900W/m² and Tmodule=45C.

Figure 4 shows the percentage change in insolation at each irradiance and module temperature bin when the 15 second data is averaged to hourly. The bins around 800W/m² irradiance and 40C Tmodule fall dramatically (by 10 to 50%) and the apparent irradiance bins on a line from 200W/m² @ 20C to 800W/m² @ 50C are increased.

This will affect energy yield predictions somewhat for modules that are modelled not to have a constant efficiency with irradiance and or temperature (whether or not this is true in reality).

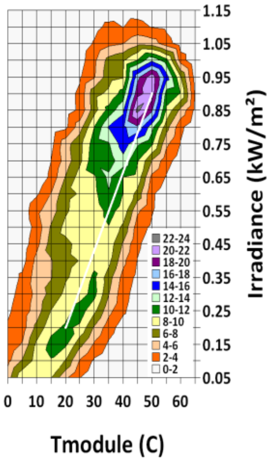


Figure 3. Distribution of plane of array insolation vs. module temperature and Irradiance measured every 15 seconds at ISET

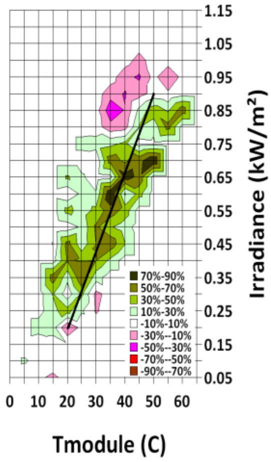


Figure 4. Change in insolation (% of kWh/m²/y) per Tmodule and irradiance bin from 15 sec to averaged 1 hour values.

MEASURED vs. MODELLED PV EFFICIENCY vs. LIGHT LEVEL

The measured performance of 7 PV modules was compared with the model in Sizing programs' databases as listed in Tables 1 and 2.

Table 1: PV module technologies tested

PV Modules	Technology (not in same order as module #)
c-Si #1, #2, #3	mc-Si, high performance and standard sc-Si
TF #4, #5, #6, #7	Thin Film (1J and 3J a-Si, CIS and CdTe)

Table 2: Sizing programs used

Sizing program	Comment
X	Commercial or freely available Sizing programs
Y	
Z	

Figure 5 illustrates the measured relative efficiency vs. irradiance and module temperature for a thin film module measured in Germany (top left) and that predicted for three different sizing programs X, Y and Z.

The measured module (top left) had degraded below its nameplate value. It would have experienced all of the weather parameters in Figure 5 correlated with the irradiance, for example the module temperature of 55C has a higher relative performance than other temperatures presumably because at high temperatures the solar height will be tend to be higher, the air mass lower and hence the spectrum bluer plus any thermal annealing will have come into effect.

The models used by the three sizing programs X, Y and Z are not only different from the measured data but different from each other. X has a falling efficiency with light level then a small peak, Y is flat and Z is rising all the way as the irradiance falls.

Figure 6 shows similar graphs for a mc-Si module and its nearest equivalent in the three Sizing programs' databases.

There is a little more similarity between the module and the models but programs X and Y have a worse low light response than expected.

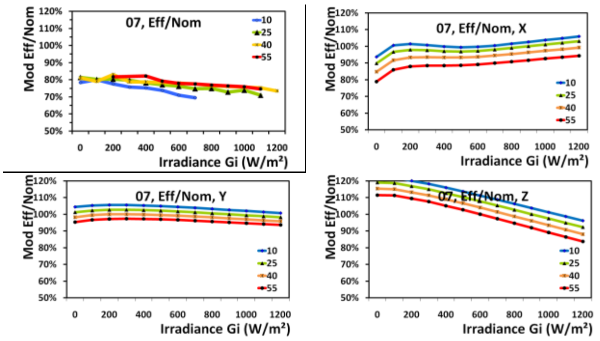


Figure 5. Thin Film module #7: Normalised efficiency vs. irradiance and average module temperature (10, 25, 40, 55 and 70C) Clockwise from top left: Measured, X, Z, Y.

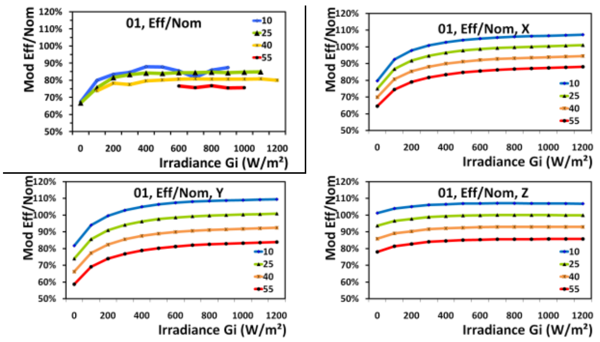


Figure 6. c-Si module #1: Normalised efficiency vs. irradiance and average module temperature (10, 25, 40, 55 and 70C) Clockwise from top l: Measured, X, Z, Y.

INCONSISTENCIES FOUND IN SOME OF THE MODELS

Modelling of the efficiency vs. irradiance and module temperature should agree with the measurement data on the manufacturers' spec sheets. The following four values are illustrated in figure 7.

(1) Pmax @ STC (1000 W/m², Tmodule=25C)
(2) Gamma (1/Pmax * dPmax/dT) @ 1000W/m²
(3) Eff @ NOCT (800W/m² and Tmodule ~47C)
(4) Efficiency reduction at low light levels: 200W/m² / 1000W/m² (EN50380)

Not all manufacturers are yet quoting values (3) and (4) (according to EN50380) but (1) and (2) are available.

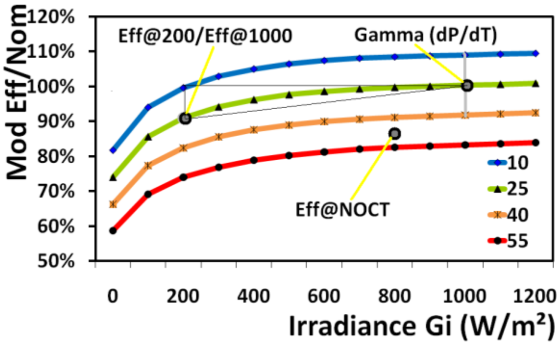


Figure 7: Checking a Sizing program's derived efficiency parameters with those on a manufacturer's spec sheets.

A random study of several different modules from their latest spec sheets and web data with the different programs gave varying values of the 3 values (2) to (4), almost all differing from the manufacturers' published data which will affect the predicted energy yield.

Table 3: Manufacturers data vs. modelled assumptions for some present PV modules

	TF (i)	TF (ii)	c-Si (iii)	c-Si (iv)
(2) Gamma (= 1/Pmax * dPmax/dT)				
(manuf)	**-.33%**	**-.21%**	**-.45%**	**-.34%**
(models)	-.25% -.27%	-.24% -.25%	-.43% -.58%	-.38% -.46%
(3) Eff@NOCT/ EffSTC				
(manuf)	**93.8%**	**96.3%**	**90.9%**	**91.7%**
(models)	91.1 95.4%	92.2% 95.8%	86.5% 90%	89.1% 90.8%
(4) Eff200/ EffSTC				
(manuf)	**102%**	**n/k**	**98.6%**	**n/k**
(models)	91.6% 102%	94.2% 100.8%		92.9% 82.6%

ESTIMATING THE EFFECT OF EFFICIENCY MODELLING ON kWh/kWp DATA

Sizing programs essentially calculate kWh/kWp by multiplying the hourly plane of array irradiance by the efficiency at the given weather conditions (irradiance and module temperature. This can be summed by multiplying the insolation * efficiency by module temperature and irradiance bin. Figure 8 plots surfaces of insolation and efficiency vs. Tmodule and irradiance, two values are marked for a cool low light and a warm high light condition to illustrate how these should be multiplied and summed together.

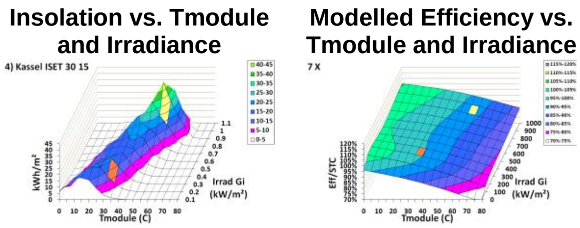


Figure 8: Illustration of kWh/kWp summing by multiplying insolation * predicted efficiency at each Tmodule and irradiance bin

kWh/kWp results are given in Figure 9 for sizing program X. Differences of up to 9% favouring the thin film module #7 over the c-Si module #1 for all three sites from the modelled data.

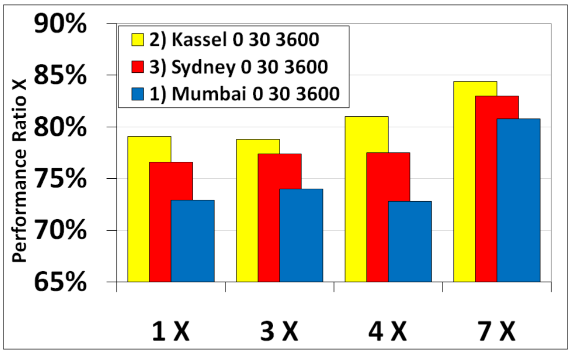


Figure 9: Predicted performance ratio check from sizing program X.

Predictions for kWh/kWp have been made with Met data from Kassel – both from an hourly generator and also from 15 second averaged to 5 minutes and 1 hour. The overall plane of array insolation for the hourly model was scaled to the same value as that from the measured data for a fair comparison. Figure 10 illustrates the data looking for changes for each model. All of them predict a slightly higher relative performance ratio (less than 1%) from the 15 second data than the hourly for both c-Si 1 and TF 6 but the hourly model data is predicted to give a 1% higher energy yield for all models + programs except for 6Z which is around 3% as its model gives a much higher efficiency at low light level than occurs.

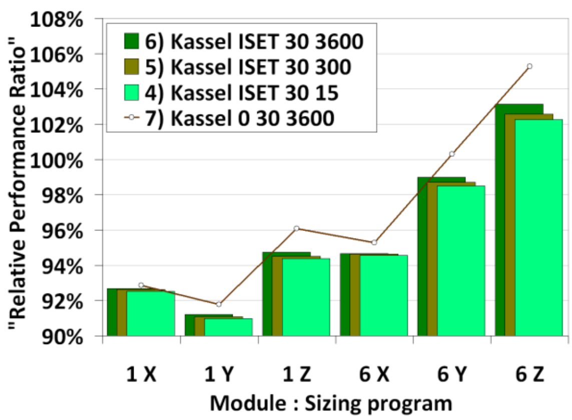
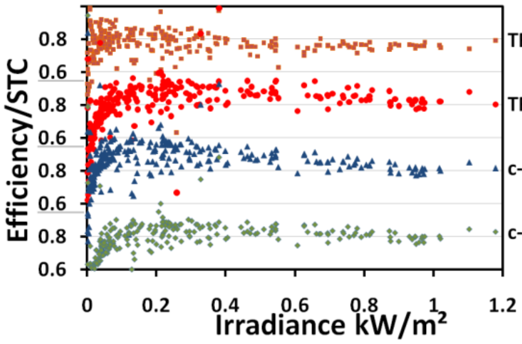


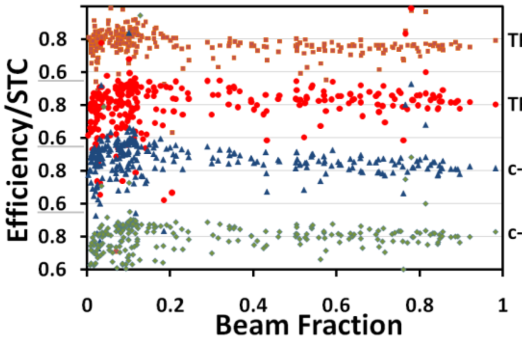
Figure 10 : Estimated relative performance ratio for a c-Si module #1 and a Thin Film module #6 calculated by modelling data from Sizing programs X, Y and Z for Kassel with measured and averaged to hourly (3600), 5 minute (300) and 15 second data vs. hourly modelling data

MEASURED EFFICIENCY vs. WEATHER PARAMETERS

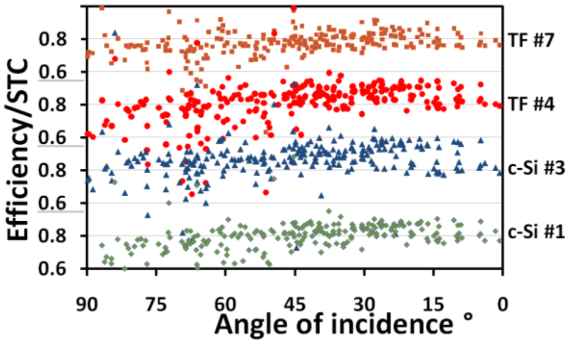
The relative efficiency vs. light level for various meteorological parameters was measured and plotted for four different module technologies – two c-Si and two thin films and is shown in figure 11 - each quarter section shows the relative performance from (60 to 100% of nominal) vs. Irradiance (top), Beam Fraction (centre) and Angle of incidence (bottom). In each case the lines are remarkably similar to one another, there are no steep rises nor falls under extreme weather conditions that differentiate any of the technologies from each other that could give rise to large differences in kWh/kWp (assuming the Pmax.actual/Pmax.nominal are similar).



(i) IRRADIANCE



(ii) BEAM FRACTION – Diffuse (left) to Direct (right)



(iii) ANGLE OF INCIDENCE – Normal incidence right

Figure 11 : Performance factor of four modules vs. Irradiance, Beam fraction and angle of incidence

WHICH OTHER PARAMETERS CAN DIFFERENTIATE TECHNOLOGIES ?

If kWh/kWp expected from correctly declared and stable (or nearly) technologies really are within measurement accuracies (±5%) then other parameters will need to be used to distinguish between different technologies.

Difficulties in the definitions of kWp will be experienced when comparing technologies that are not monofacial and planar – for example curved or bifacial devices or passive or active trackers will have a different apparent Wp from what a standard flash tester will measure.

Some other options to differentiate technologies are are listed below in table 4.

Table 3 : Other parameters that can differentiate pv technologies better than kWh/kWp

Technology	High Efficiency c-Si	Standard mc-Si	Thin Film a-Si, CIGS, CdTe	Organics/Plastic
kWh/kWp	Tests in Europe show often within ± 4-5% for correctly labelled, non degrading modules			n/k
W/m² @ STC	170-200	140-170	50-110	n/k
\$/Wp (will vary) Solar Buzz - Jan 2009 Photon - Apr 2009 [9]	4.00USD 3.05EUR	3.99USD 3.05EUR 3.17USD 2.40EUR	3.27USD 2.50EUR 2.64USD 2.00EUR	Should be very low
Lifetime to >80% Initial Power (see guarantee)	20-25y guarantee	20-25y guarantee	~20-25y guarantee	n/k
Flexible substrates – are they necessary ?	No	No	Some	Yes
Visual Appearance Aesthetics	~Squares (with bus bars except back contact) Multi crystalline may be more reflective Coloured back sheet or transparent glass		Monolithic with narrow parallel cuts	
Shade tolerance	May be worse as squarer cells		May be better with high aspect ratio cells if oriented with cells perpendicular to shading	
kg/Wp (no structure) (Framed) (Frameless) (Flexible)	(1 glass) 0.06-0.08	(1 glass) 0.07-0.09	(2 glass) 0.16-0.22 ~0.16 0.06	n/k
kg/m² (no structure) (Framed) (Frameless) (Flexible)	(1 glass) ~12	(1 glass) ~12	(2 glass) ~17 ~17 ~4	n/k
Temperature coefficient	~-0.35%/K	~-0.45%/K	~-0.25%/K	n/k
Large spectral difference with. Pyranometer ?	No	No	Yes, particularly multijunction	Yes
Seasonal/Thermal annealing ?	No	No	Yes	n/k
Restrictions in use ?			Some technologies may be banned in certain countries	
Ruggedness (ability to function after damage)	c-Si mostly laminated with glass and usually unable to function after breakage		TF on plastic or metal foils may function even after being damaged	
Energy Cost c/kWh	To be confirmed – depends on \$/Wp, Efficiency and longevity and Insolation			

CONCLUSIONS

- Weather data generators in sizing programs often predicts more insolation at low light levels than that which occurs
- Real kWh/kWp measurements are often similar at least in Europe (within experimental error ±5%) for different module technologies when correctly declared stable Pmax values are used.
- Studying the efficiency vs. irradiance, beam fraction, angle of incidence for thin films and crystalline indicate less variation between the technologies than is claimed
- Sizing program models for efficiency vs. irradiance and module temperature can be very different from measured data for c-Si and thin films, their kWh/kWp predictions depend critically on the curve shape
- Errors in the values of gamma (1/Pmax*dPmax/dT), Eff@NOCT and Eff@200/Eff@1000W/m² have been seen vs. manufacturers claims.
- No effects have been found which could give widely varying kWh/kWp values (i.e. ±30% claimed) between technologies as long as the correct Wp at STC is achieved.
- As kWh/kWp values do not differentiate various PV technologies at least in Europe then other

parameters have been suggested that can be used instead.

- Further checks should be taken in more extreme climates

ACKNOWLEDGEMENTS

Peter Funtan and ISET, Kassel for the dc measurements

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