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ARE KWH/KWP VALUES REALLY THE BEST WAY TO DIFFERENTIATE BETWEEN PV TECHNOLOGIES ?

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ABSTRACT:

Various manufacturers have claimed much higher kWh/kWp energy yields (up to 30% better) for their products than those of their competitors or other technologies.

Some recent independent comparisons [1][2][3][4] have shown much more similar kWh/kWp (often within an experimental error of ±4-5%) for different module technologies when the correctly declared stabilised Pmax values are used without a systematic bias towards one manufacturer or technology.

A selection of parameters that differentiate PV technologies by more than ±4-5% have been listed and quantified.

Errors have been found in the kWh/kWp modelling of some sizing programs – their PV databases do not always match the manufacturers' measurements for thermal coefficients and low light efficiency changes LLEC (=Eff.@200 /Eff.@1000 W/m²-1) which are measured to international standards such as EN 50380[5] and EN 61215[6].

Keywords: Energy rating; Modelling; System performance

1 kWh/kWp PERFORMANCE MODELLING

For many years kWh/kWp values have been used to rate, compare and contrast PV technologies and systems. Modules are usually purchased in $/Wp whereas they produce kWh/year energy, so it would seem that the kWh/kWp value should help determine the financial value of an array.

Sophisticated modelling programs are used to predict system behaviour [7], these often follow the steps listed below and shown in Figure 1 :-

1) Use measured or generated (pseudo random) tilted plane weather distributions (irradiance, ambient temperature, wind speed).

2) Get modelled PV parameters from a database.

3) Model the PV module Pmax under these weather conditions.

4) Estimate "dc" losses (including dirt, mismatch, shading, angle of incidence, spectrum etc).

5) Estimate "ac" losses (including inverter efficiency, V_{MPP} tracking, clipping, wiring resistance etc).

6) Sum the PV power over time to calculate a final energy yield YF (kWh/kWp/year).

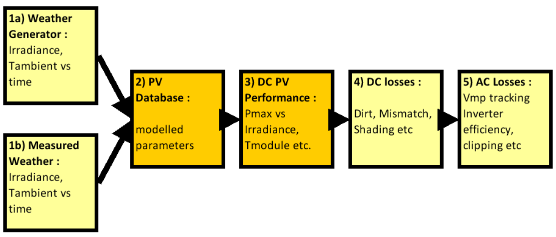

Figure 1: Simplified modelling PV performance

An array that performs optimally will have low losses at all stages including both the DC and AC loss stages (i.e. good component choices, little or no downtime, BoS components matched to the PV power etc). The accuracy of the entire system modelling will depend on each stage, particularly on the modelled vs. measured PV performance. If this is wrong then the whole system modelling cannot be correct. Some of the predictions used in commercially available models (for example the curves of insolation vs. irradiance and module efficiency vs. irradiance) have often been inaccurate[7][8], also the combination of uncertainties in PV nameplate declarations and BoS performance, irradiance sensor calibration and unknowns such as allowance for degradation, stabilisation, annealing, dirt, shading and mismatch mean that any "accurate" energy yields may just coincide rather than be predicted accurately [7][8].

2 kWh/kWp PERFORMANCE CLAIMS

Some manufacturers have claimed "high kWh/kWp" values for their products due to the "good performance" at low light levels, high module temperatures and/or mostly diffuse light conditions. Often their measurements appear to show better yields than other competitors' technologies (which sometimes behave worse than expected) that they have measured. The energy yields of systems may vary by ±4-5% 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) [4].

If specific module technologies or manufacturers really did have large benefits in energy yields then these results should be measureable and repeatable on all test sites.

3 A SUMMARY OF THE STATUS OF PRESENT kWh/kWp MEASUREMENTS

- Outdoor yield results are usually given without quoting inaccuracies or how any corrections are made for downtime, measurement errors, glitches or atypical weather conditions.
- If a module X is found to produce a higher kWh/kWp than module Y are these differences applicable to just those two modules, all modules of those types, all modules made by the manufacturers or all modules of the technologies involved ?
- Some of the earliest energy yield tests seemed to

imply that there could be differences of ±20% or more between technologies, however the results were very dependent on measurement errors, differences in balance of systems components, incorrect Pmax declaration (due to under/over optimistic ratings, reference calibration and degradation due to initial drops and allowances made for the module to maintain the end of lifetime power usually > 80% at 25 years) and modules with worse Rshunt than more recent devices. More recent surveys often show many kWh/kWp are within ±4-5% - 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 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 inaccurate as outdoors effects are correlated (for example as the light level rises the temperature will necessarily increase).
- Tracking modules away from the bright sun near noon to measure low light levels causes further inaccuracies as these show higher angle of incidence reflectance effects at blue spectra that will never be achieved at these angles of incidence.
- Rarely are outdoor graphs of efficiency vs. light level of competing technologies shown, some outdoor graphs show similar shapes [4][9].
- The choice of irradiance sensor will affect the measured performance of a PV module [9] as the sensitivity of the angle of incidence and spectrum may differ between sensor and module.

4 PERFORMANCE vs. LIGHT LEVEL

Plotting module efficiency vs. irradiance makes low light level performance look more important than it is. From indoor measurements (at constant temperature) the low light level efficiency will fall both due to the effect of Rshunt and the Vmax drop at low light. With outdoor modules the temperature will fall at lower light levels and tend to boost the relative efficiency. Figure 2 shows the outdoor measured Efficiency/Nominal vs. irradiance for a typical c-Si module (blue) and two thin film modules (green and red) for seven variable weather days in Germany. The data points make the modules look quite different to each other, in particular the c-Si module has a higher drop in efficiency with temperature and as this is real outdoor data it falls faster at high irradiance (and temperature) but rises faster at low irradiance (and temperature). The energy yield can be estimated by multiplying the shape of the "efficiency vs. irradiance" by the "insolation vs. energy" values which will usually have a higher distribution at high irradiance making the low light level points less important.

Figure 3 shows the same data as Figure 2 but replotted as dc Yield (i.e. W/Wp). Note now that the curves appear much closer together. They all fall away from the nominal line at high light level – the c-Si has dropped about 20% at 1 sun whereas the best thin film device has fallen about 15%. The c-Si is closer to the nominal line at lower light level and although there are more points (i.e. more time) spent at low light levels the energy yield is dominated by the higher powers resulting at high irradiance.

Figure 4 sums up the cumulative energy yield from the seven days (ranging from poor to good weather) and the cumulative kWh/kWp are very close together.

This proves that efficiency vs. light level plots (which may look quite different to each other) are closer together when plotted as energy vs. light level and have a smaller effect on energy yield than at first anticipated.

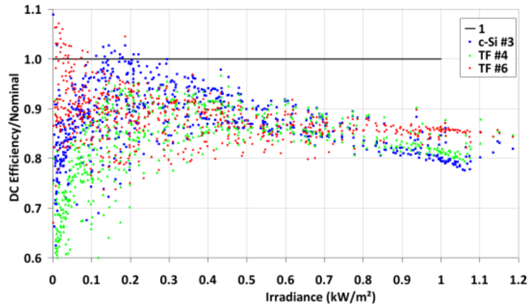

Figure 2: Measured efficiency/nominal vs. irradiance for 3 different module technologies in central Germany

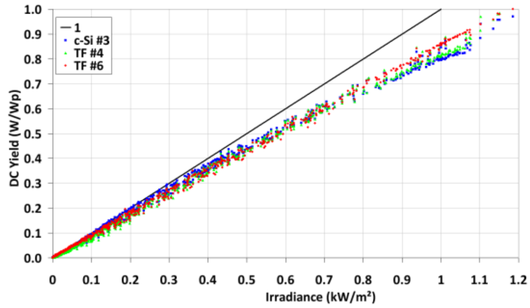

Figure 3: Measured DC yield vs. irradiance for 3 module technologies in central Germany (replotted from figure 2)

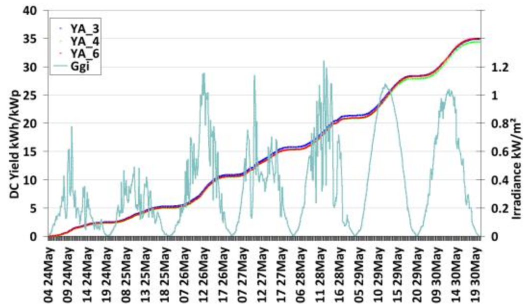

Figure 4: Measured cumulative DC yield Wh/Wp vs. time for 7 variable weather days in central Germany (replotted data as figures 2 and 3)

5 WHICH OTHER PARAMETERS CAN DIFFERENTIATE TECHNOLOGIES ?

If kWh/kWp expected from correctly declared and stable (or nearly) technologies are within measurement accuracies (±5%) then other parameters will need to be used to distinguish between different technologies. Some of these parameters are listed in Table I with estimates for available technologies – this cannot cover all manufacturers and technologies but should serve as a starting point in evaluating options.

Table I: A comparison of some parameters that can differentiate PV technologies more widely than kWh/kWp. These were obtained from examining some manufacturers' spec sheets but some devices may be outside these limits.

Technology → **Parameters**	**1) High Efficiency c-Si**	**2) Standard mc-Si**	**3) Thin Film a-Si, CIGS, CdTe, uc-Si etc**	**4) Organics/Plastic (not yet large scale)**
Energy Yield kWh/kWp/y	often within ± 4-5% for correctly labelled and performing, not shunted, non degrading modules			n/k
Wp/m²	~170-200	~140-170	~50-110	n/k expected <50
Cost $/Wp [10] **SolarBuzz Jan 2009** **SolarBuzz Aug 2009** **SolarBuzz Sep 2009**	 > $4 ? ~$3 ~$2.5	 $3.99 $2.48 $2.38	 $3.27 $1.76 $1.76	Ought to be very low
Lifetime >80% Pmax	20-25y guarantee proven in field		~20-25y guarantee	5-10y expected?
Transparent ?	Yes if cells spaced apart in glass-glass laminates		Possible	Possible
Flexible substrates ?	Not with present c-Si thicknesses >100um; will be possible with much thinner wafers		Some on steel or plastic foils	Yes
Visual appearance aesthetics (subjective)	~Square/rectangular cells, blue to black colours (usually bus bars), can have coloured back sheet		Monolithic with narrow parallel cuts Uniform colours magenta/green, dark red, etc.	
Shade tolerance	"worse" : limited by worst shadow on "square" cells, bypass diodes should help		"better" : limited by worst shadow on high aspect ratio (width/length) cells	
Wp/kg no structure **(Framed)** **(Frameless)** **(Flexible)**	(1 glass) 12-17 17-22 n/a	(1 glass) 11-14 13-17 n/a	(2 glass) 4-7 5-8 16	 n/k n/k n/k
m²/1000kg no structure **(Framed)** **(Frameless)** **(Flexible)**	 83 100 n/a	 83 100 n/a	 60 70 250	n/k
% Power vs. Temp. K	~-0.35%/K	~-0.45%/K	~-0.25 to -.40%/K	n/k
Spectral mismatch vs. pyranometer	Smaller		Larger, particularly multijunction	Yes
Seasonal annealing	No		Yes	n/k
Initial degradation	Small allowance for initial LID for some c-Si		Up to 30% initial,	n/k expected high
Steady degradation	steady <~0.5%/y ?		Some claims <1%/y?	n/k
Restrictions ?	No		Some ban on Toxics"?	
Pmax.stc tolerance %	Variable +3/-0% to +0/-10%, c-Si may have tighter specs			n/k
Certifications	CE/IEC/TUV/UL etc. Y/N?			
Max System Voltage	500-1000V			
Max Module Size m²	~2.5	~2.5	~5.7	
Imax A	Usually >5A		Usually lower than c-Si	
Vmax V	Approx 0.5V / series cell		Mostly higher than c-Si	
Energy c/kWh	To be confirmed /depends on $/Wp, Efficiency, longevity/degradation and Insolation assumptions			

6) EXPLANATION AND GRAPHICAL REPRESENTATION OF TECHNOLOGY DIFFERENTIATING PARAMETERS

The cost of solar modules has dropped considerably over the past thirty years but the Silicon shortage and then the global financial crisis of 2009 meant that the prices quoted on websites such as Solarbuzz were very variable over time. Figure 5 shows the cheapest prices for mono, multi and thin film reported by Solarbuzz[10] in Jan and Aug 09.

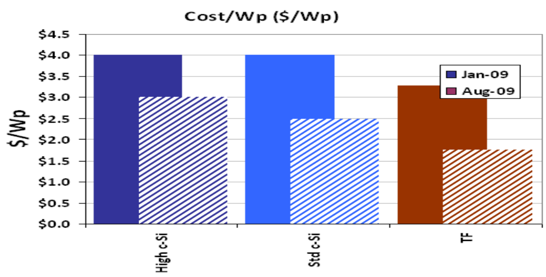

Figure 5: Solarbuzz minimum cost of PV modules

Figure 6 gives the stable module efficiencies used in this study, a variation of nearly 2:1 can be seen for the best c-Si vs. the best thin films. (Wp/m²@STC = module efficiency * 1000).

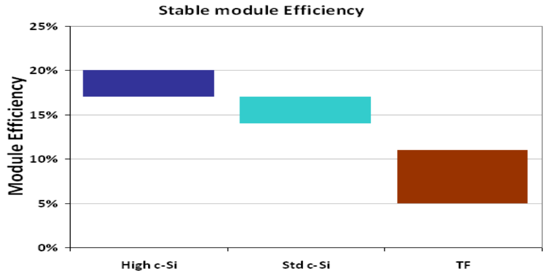

Figure 6: Stable efficiencies of PV technologies used in this study

The “power to mass” ratio may be an important factor for some roof mounted PV systems, this is illustrated in Figure 7 as Wp/kg for framed and unframed laminates with flexible substrates. The best results are nearly 22Wp/kg for the unframed high efficiency c-Si, about 50% higher than the flexible thin film as the higher efficiency outperforms the lower weight. (No account has been taken of mounting structure as there are many different options).

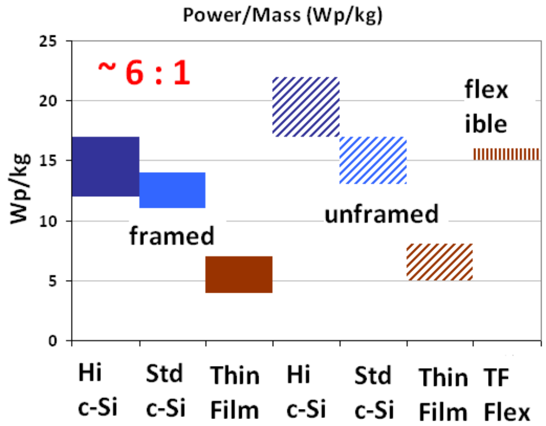

Figure 7: Power/mass of PV technologies (ignoring mounting structure) –higher is better.

The highest possible power output from any given technology on a flat roof is obtained by horizontally mounting modules with little to no gap between them. Tilting modules towards the equator (i.e. south in the northern hemisphere) will raise the amount of light impinging on each module (therefore raising the kWh/kWp/module), however to avoid shading the module rows must be spaced further apart thus reducing the number of modules on a roof.

Optimum tilting and spacing modules apart gives the best payback in terms of kWh/kWp (higher energy with fewer modules) but to maximize the kWh/roof then horizontal mounting with more modules (and therefore higher cost) is needed.

Figure 8 illustrates “mass per area”: the area of PV panel per 1000kg ignoring mounting. The high efficiency and standard c-Si are similar to each other for framed and a little better for unframed (the mass of a frame for a 220Wp Silicon module may be around 4kg) whereas the framed and unframed thin film are both worse because of the second layer of glass adding weight. The flexible laminate fares much better as it replaces both glass layers with flexible substrates and weatherproof encapsulants to cover more than twice the roof for the same mass, the lifetime of these modules becomes very important.

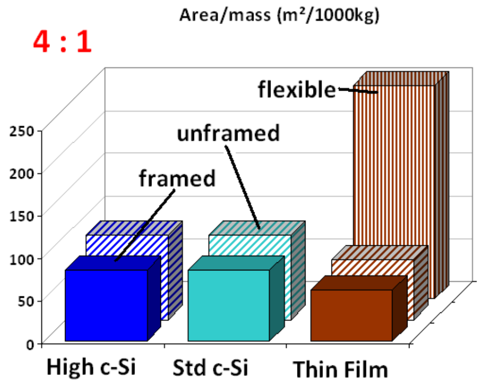

Figure 8: PV area for 1000kg mass for framed, unframed and flexible c-Si and thin films (higher is better).

7) CALCULATED ENERGY YIELDS vs. DATABASE VALUES FOR POWER TEMPERATURE COEFFICIENT AND LOW LIGHT LEVEL EFFICIENCY CHANGE

Two different sizing programs X and Y were used to calculate the energy yields of approx 100kWp PV array with 30° tilt and a ventilated back in Munich. The dc performance factor (PF = dc kWh/kWp / POA insolation kWh/m²) for all 10 module types given in Table II and both sizing programs was plotted against the gamma and LLEC “low light efficiency change” (measured as in EN 50380 3.3.3) factors from the databases, values obtained from program X are shown in Figures 9 and 10. (The values from program Y were similar).

LLEC “Low light efficiency change” =
(Efficiency@200W/m² / Efficiency@1000W/m²)-1

Table II. 10 present modules of different technologies used in this study

Module Numbers	Technology	Comments
1-2	“High Efficiency” c-Si	
3-7	“Standard” c-Si	#6 Not in Prog Y
8-10	Various thin film	

Apart from one or two outliers there is a clear trend for both the gamma and the LLEC, modules with the worst gamma and LLEC have a performance factor around 81%, those with the best are around 88%.

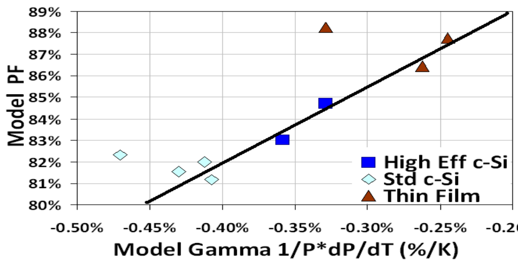

Figure 9: Predicted performance factor PF (dc kWh/kWp / POA insolation) for program X vs. its database Pmax temperature coefficient.

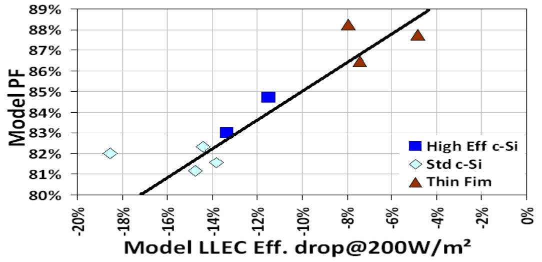

Figure 10: Predicted performance factor PF (dc kWh/kWp / POA insolation) for program X vs. its database low light efficiency change LLEC.

8) REAL OUTDOOR MEASUREMENTS OF DIFFERENT TECHNOLOGIES

Oerlikon Solar have been performing comparative testing of different PV technologies at two sites in Switzerland [9]. Figures 11 and 12 show the relative outdoor performances (not temperature corrected) against an unfiltered c-Si reference (outdoor temperature power coefficients depend on the irradiance sensor type [9]) cell divided by the indoor flash test measurement for Performance factor and normalised Fill Factor, Isc and Voc with definitions in equations <1> to <5>.

$P_{MAX.MEAS} = I_{SC.MEAS} * V_{OC.MEAS} * FF_{MEAS}$ <1>

Performance Factor $PF = I_{SN} * V_{OM} * FF_M$ <2>

Where normalised parameters are

$I_{SN} = I_{SC.MEAS}/I_{SC.NOM}/\text{Irradiance}$ <3>

$V_{OM} = V_{OC.MEAS}/V_{OC.NOM}$ <4>

$FF_M = FF_{MEAS}/FF_{NOM}$ <5>

ID	Technol	Gamma %/K	LLEC %	Comments
1065	mc-Si	~-0.5%	~+10%	FF: Higher fall off at high light
10xx	micromorph	~-0.25%	~+5%	

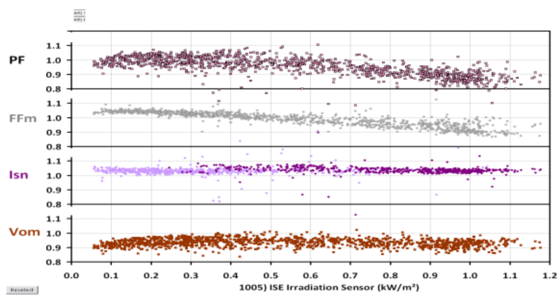

Figure 11: Measured performance factor and normalised fill factor, I_{SN} and V_{OM} (divided by their flash test measurements) vs. irradiance (c-Si sensor) of a multicrystalline Si module (1065) in Switzerland July-Aug 2009 (courtesy Oerlikon Solar).

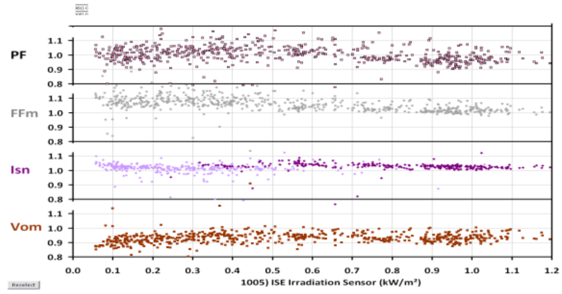

Figure 12: Measured performance factor and normalised fill factor, I_{SN} and V_{OM} (divided by their flash test measurements) vs. irradiance (c-Si sensor) of a micromorph module (1081) in Switzerland July-Aug 2009 (courtesy Oerlikon Solar).

The I_{SN} and V_{OM} seem similar, the main difference is the normalised fill factor FF_M of the mc-Si falls with rising irradiance. Note that as these are at real temperature conditions the LLEC is expected to be higher than at 25C.

9) SIZING PROGRAM PV DATABASE VALUES vs. REAL MEASUREMENTS

Figure 13 illustrates the difference in fraction of insolation per irradiance bin between a stochastic hourly plane of irradiance model and that measured at 1 min intervals in Switzerland by Oerlikon Solar. There is far more measured insolation at higher irradiances which confirms earlier measurements by BP Solar in Kassel and Sydney.

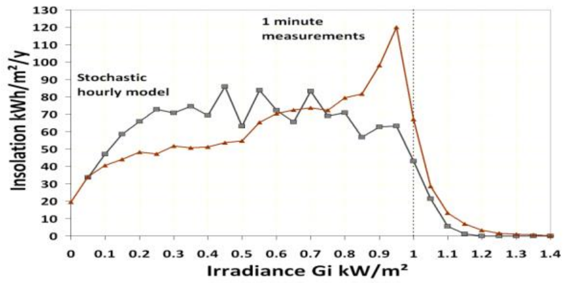

Figure 13: Comparing modelled vs. measured insolation against irradiance in Switzerland (courtesy Oerlikon Solar).

Figure 14 gives efficiency vs. irradiance and module temperature as predicted by a sizing program and shows how to extract its assumptions to check against manufacturers' spec sheets and real measurements [8].

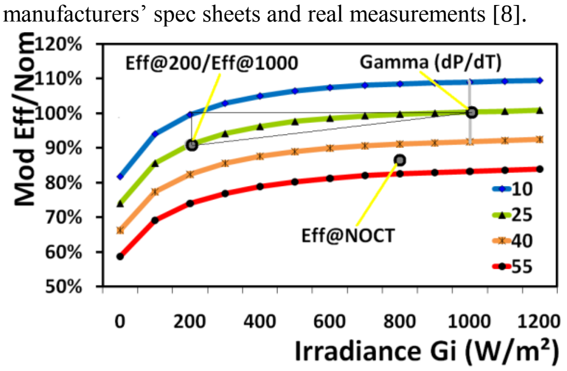

Figure 14: Checking a sizing program's derived efficiency parameters with those on a manufacturer's spec sheets.

The values of gamma and LLEC from the programs' databases were compared with the manufacturers' declared values. Note that not all manufacturers declare the LLEC (despite it being a requirement from EN 50380 3.3.3)[5]. Figure 15 shows disagreement between programs X, Y and manufacturer data – the worst agreement being Thin Film #10 where there is a range of -0.27%/K to -0.43%/K.

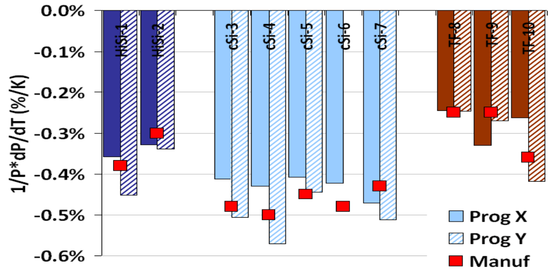

Figure 15: Database Pmax temperature coefficient (1/P*dP/dT) for Programs X and Y vs. Manufacturers' measured data.

Figure 16 shows even worse disagreement between programs X, Y and manufacturer data for the LLEC – there is some missing data but looking at the standard c-Si four manufacturers quote -4 to -5% change (one has missing data) but the programs show around 14% - meaning that the low light level response of c-Si modules is modelled to be much worse than manufacturers' data. There is insufficient data in both the high efficiency c-Si and the thin films to determine overall trends but manufacturer TF#9 quotes a +2% change and program X uses -8%.

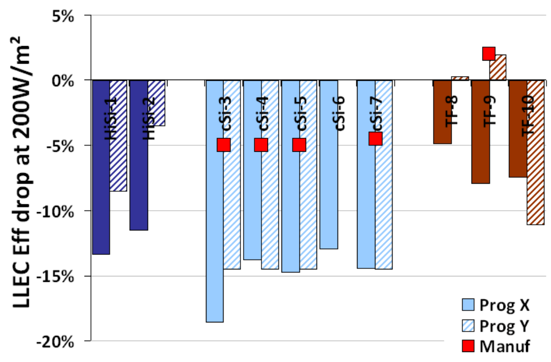

Figure 16: Database LLEC (Eff@200/Eff@1000 – 1) for Programs X and Y vs. Manufacturers' measured data (incomplete as not all manufacturers declare this).

It can be seen from Figures 11 and 12 that the two important parameters Gamma and LLEC are often very different in sizing program databases from manufacturers declared values.

Figures 9 and 10 show that performance factors can vary by around 9% absolute from the worst to the best values of gamma and LLEC in Sizing program databases.

Comparing the errors in modelled vs. measured LLEC (example -15% vs. -5%) for c-Si and the sensitivity in predicted kWh/kWp vs. LLEC (81% vs. 88.5%) shows almost a ± 5% relative error in kWh/kWp just from the error in LLEC.

10) CONCLUSIONS

- kWh/kWp measurements are often within experimental error ±4-5% for different technologies when correctly declared stable Pmax values are used.
- Low light level performance is not as important as had been generally thought.
- As kWh/kWp values do not differentiate some of the technologies then other parameters have been suggested that can be used instead.
- Sizing programs contain databases to calculate Pmax temperature coefficient (gamma) and low light level efficiency change (LLEC) however these values do not always agree with manufacturers supplied data.
- The energy yields calculated by these programs depend on the values used – in general these have been pessimistic with regards c-Si and maybe optimistic for thin films.
- A module manufacturer or technology with optimistic coefficients will have predicted energy yields higher than measured.
- Module manufacturers, sizing program authors and users should understand the modelling and calculations and the implications of these errors.

11) ACKNOWLEDGEMENTS

Peter Funtan and ISET, Kassel for the German dc measurements.

Juergen Sutterlueti and Oerlikon Solar for Swiss measurements and Figures 11-12.

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