A detailed comparison of measured outdoor performance vs. simulation program predictions for different PV technologies

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Abstract

Some manufacturers have claimed up to 30% higher energy yields than those of their competitors, but several recent independent kWh/kWp comparisons [1-6] have shown much more similar measured values (often within ±4-5%) for different module technologies - when the correctly declared stabilised Pmax values are used without a systematic bias towards one manufacturer or technology.

If certain module technologies or manufacturers really did have better energy yields then these results should be measureable and repeatable on all test sites.

Some simulation programs have been found to predict >5% differences in energy yield between various technologies, errors have been found in their modelling as their PV databases do not always match the manufacturers' measurements for thermal coefficients and low light efficiency changes which are measured to international standards such as EN 50380[7] and EN 61215[8].

kWh/kWp performance modelling

Sophisticated simulation programs are used to predict system behaviour [9], these often follow the steps illustrated in figure 1:-

1) Modelled or Measured Weather (Irradiance, Ambient Temperature vs. time)
2) Model PV performance vs. Irradiance, Temperature etc.
3) Estimate PV performance each time period
4) "DC" Loss (Dirt, mismatch, shading etc.)
5) "AC" Loss (Inverter efficiency, clipping etc.)

Figure 1: Simplified modelling steps

PV performance

An array that performs optimally will have low losses at all stages including both DC and AC losses (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.

Uncertainties in measurements for modelling

Table 1 lists some uncertainties in measurements that must be made to predict energy yields. The combination of uncertainties in PV nameplate declarations and BoS performance, irradiance sensor calibration and unknowns mean that any "accurate" energy yields may just coincide rather than be predicted accurately [9][10].

	Comment
Reference module Pmax	~±2.5% for c-Si, less accurate for thin films (from test labs calibration)
Flash tester	Repeatability error x%? Not a perfect AM1.5 spectrum.
Degrad-ation allowance	LID or outdoor degradation– 1-3% for B doped p type c-Si, greater for thin films (10-35%).
Pmax bin	~±2.5% e.g. 200<Pmax<-210W
Insolation	~±2-3% (pyranometer); ~±3-5%(reference cell);Satellite data, Tilted plane, site interpolation
Module Temp.	~3°C/sun ($T_{JUNCTION}$–T_{BACK}), important if corrected to STC
Weather variability	~±4%/year random variations, more effects such as el Niño etc.
Micro climate	Can't linearly interpolate near coasts, mountains etc.
Shading	Trees, buildings, self shading
Dirt	Site dependent daily increase, falls after clean or ~>5mm rain
Snow	Winter when low daily insolation
Mounting	Higher temperatures from close roof mounting, BIPV etc.

Table 1: Uncertainty of measurement values

Analysing weather data

Internal measurements to analyse the performance of PV modules usually treat the input parameters as varying independently, for example the test for low light level efficiency (3.3.3 EN 50380) varies the irradiance but keeps the module temperature, spectrum, angle of incidence and beam fraction constant.

Outdoors this does not happen, high irradiance measurements usually tend to occur with higher module temperatures, lower angle of incidence, bluer spectra, higher beam fraction, higher solar altitude and higher clearness. A new graphic has been developed shown in Figures 2 and 3 which allows the correlations between the six parameters listed in table 2 to be shown.

Parameter	“Poor”to “good”	Unit
GI=Plane of array Irradiance	0 to 1	kW/m²
TM=Module Temperature	0 to 60	C
AOI=Angle of Incidence	90 to 0	°
AM=Air Mass	4 to 1	#
SEA=Season winter to summer	-1 to +1	#
BF=Beam Fraction	0 to 1	#

Table 2: Correlated weather parameters and limits used in figures 2 and 3

The radial axes scale the individual measurements so that the values usually associated with low irradiance are in the middle, those with high are on the edge. Some parameters (e.g. AOI and AM) have values reversed as a high value of irradiance tends to occur with lower values of AOI and AM.

Figure 2 plots the parameters in table 2 showing 20 measurements with high irradiance (light red) vs. 20 measurements with low irradiance (dark blue). Most of the red lines are near the outer edge for AM, AOI and BF implying good correlation – there are a few on the inside for module temperature (perhaps on a cold day the sun suddenly comes out before the module warms up) and for season (there can be some high irradiance even in spring and autumn but this will depend on the module tilt and the solar altitude).

For low irradiances there tend to be two types of weather that can cause this, clear skies but early or late in the day or overcast conditions during the day. Figure 3 shows red lines for high angle of incidence and blue for low angle of incidence. We can see the correlation for red (high AOI, high AM and high BF) i.e. clear morning or afternoon whereas the blue is (low AOI, low AM and low BF) i.e. dull near midday.

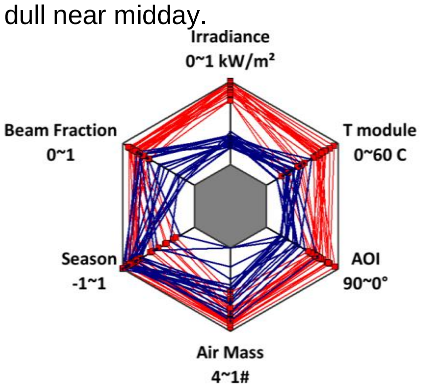

Figure 2:

Correlations in Germany for high(red) vs. low(blue) irradiance.

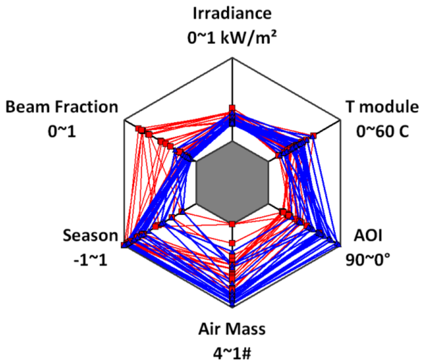

Figure 3:

Correlations in Germany for high(red) vs. low AOI

Simulation programs usually model the efficiency vs. light level regardless of the direct or diffuse component which will introduce errors into the simulations. Figure 4 gives efficiency vs. irradiance and module temperature as used by a simulation program and shows how to extract its assumptions to check against manufacturers’ spec sheets and real measurements [10].

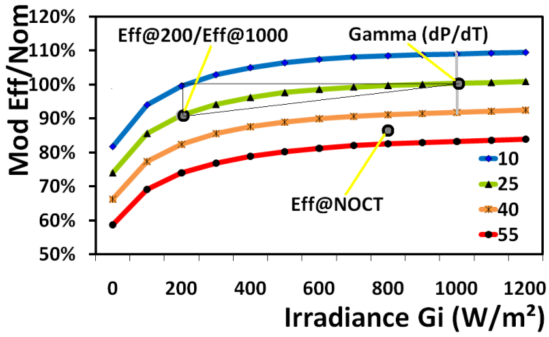

Figure 4: Checking a simulation program’s derived efficiency parameters with those on a manufacturer’s spec sheets.

Calculated yields vs. database values of gamma and LLEC

Two different simulation programs X (updated version X2) and Y were used to predict the energy yields of approx 100kWp PV array with 30° south tilt and a ventilated back in Munich. The dc performance factor PF (= dc kWh/kWp / POA insolation kWh/m²) for 10 module types (2-“high efficiency” c-Si, 5-standard mono and multi c-Si plus 3-Thin Film) was plotted against the gamma and “low light efficiency change” <1> factors from the databases as in EN 50380 3.3.3 and compared with the manufacturers’ declared values.

$$\text{LLEC} = \frac{\eta 200\text{W/m}^2 - \eta 1000\text{W/m}^2}{\eta 1000\text{W/m}^2} \qquad \text{<1>}$$

Note that not all manufacturers yet declare the LLEC. Figure 5 shows disagreement between programs X,X2,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 6 shows even worse disagreement between programs X,X2,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% LLEC and program X uses -8%.

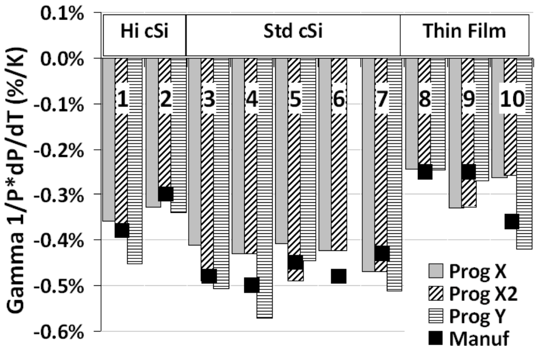

Figure 5: Gamma for Programs X, X2 and Y vs. Manufacturers' measured data.

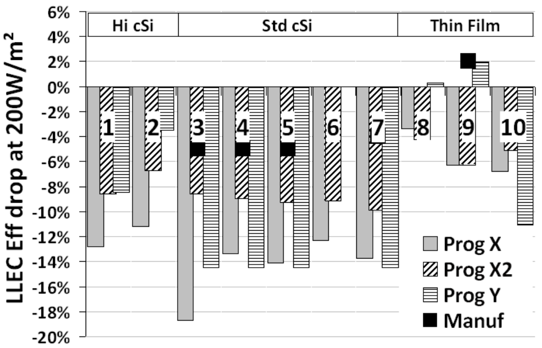

Figure 6: LLEC for Programs X, X2 and Y vs. Manufacturers' measured data.

Correcting efficiency curves

Figure 7 compares the simulated vs. manufacturer's efficiency vs. irradiance and temperature data for c-Si #3. The 25C curves were scaled linearly so that the 1000 and 200W/m² data matched, the temperature dependence was then scaled by "Gamma.manufacturer / "Gamma simulation". The manufacturer curves show much better low light level performance than the simulation program uses.

Thin film module #9 was also scaled to match the manufacturer's data but this was done using a different technique as for thin films there can be a slightly higher efficiency at low light levels due to them having higher series resistance than c-Si (due mainly to series resistance in the thin conducting oxide) giving an I^2R loss at higher light levels, restricting their STC efficiencies more than low light.

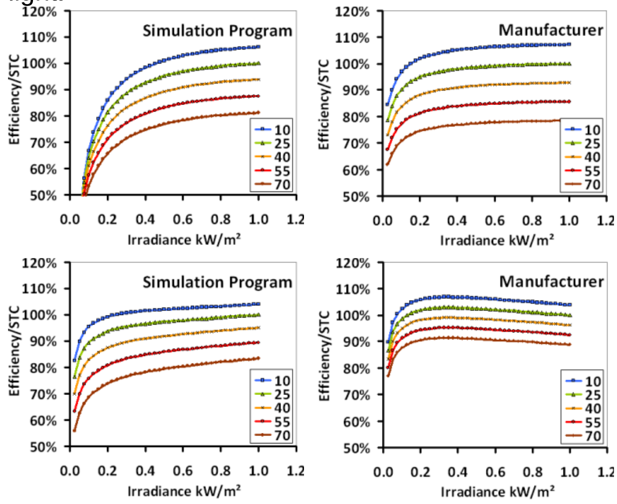

Figure 7-8: c-Si#3 (top) Thin Film#9 (bottom): Efficiency/STC nominal vs. irradiance and module temperatures from a simulation program's database (left) and corrected to the manufacturer's claimed values (right).

Simulations of energy yield using sites worldwide

The sensitivity of predicted energy yield from the inaccuracies in LLEC and gamma were modelled with weather data from five sites listed in table 4.

Site name, Country	Latitude°	Insol kWh/m²	Tmg °C
Munich, DE	48°N	1345 *	14.3 *
Albuquerque NM, US	35°N	2336 ***	18.7 **
Mumbai, IN	19°N	1988 **	30.3 ***
Seoul, KO	38°N	1299 *	15.4 *
Sydney, AU	34°S	1797 **	20.8 **

Table 4: Details of worldwide sites studies

Hourly weather data was generated by a commercial program for modules tilted at 30° towards the equator. Module temperature was estimated assuming a typical value for NOCT of 47C.

$$T_{MOD} = T_{AMB} + G_I/0.8*(NOCT - 20) \quad <2>$$

To compare the sites table 4 lists the sum of the plane of array irradiance (kWh/m²/y) and also the Tmodule weighted by irradiance (T_{MG}) where

$$T_{MG} = \Sigma(T_{MOD}*G_I)/\Sigma(G_I) \quad <3>$$

To understand how these two modules are predicted to perform against other sites the energy yield error was plotted by yearly insolation (Figure 9) and weighted module temperature (Figure 10) for both c-Si#3 (black) and TF#9 (grey).

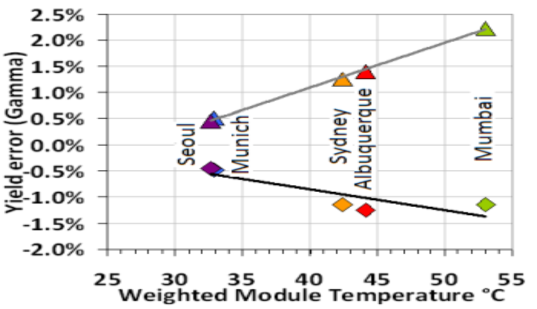

Figure 9: Energy yield error simulation program vs. weighted Tmodule T_{MG}

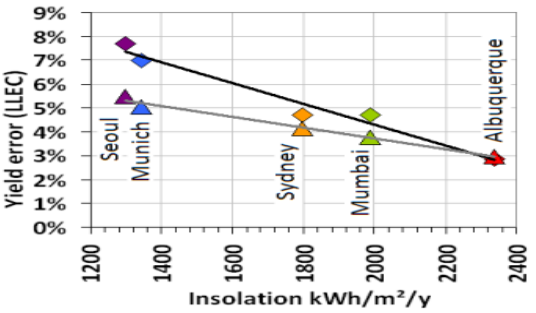

Figure 10: Energy yield error from simulation program vs. yearly insolation YR

The simulation program predicted yield errors vs. module temperature in Figure 9:

- #3 had a smaller gamma correction than #9 so had a lower error (~1 vs. 2 %/C)
- #9 rises with temperature as the manufacturer's measurements were better than simulation, whereas #3 was worse.
- The coolest sites (Seoul, Munich) have least difference (should be 0% at 25C site)

The simulation program predicted yield errors vs. yearly insolation in Figure 10:

- #3 had larger LLEC correction than #9 (13 vs. 8%) so a greater error (~8 vs. 5.5%)
- Both rise as light level falls (more time at low light) – higher change then Figure 9
- The sunniest site (Albuquerque) has little difference as low light is "unimportant".

Conclusions

- Several independent outdoor kWh/kWp measurements report < ~±5% variation, dominated by Wp.actual / Wp.nominal.
- Weather data is correlated so that efficiencies are not modelled properly
- Gamma and LLEC coefficients in simulation programs' databases do not agree with manufacturers' data and 8% energy yield error have been found.
- Calculated energy yields depend on the model values used – in general these have been pessimistic with regards c-Si and maybe optimistic for thin films.
- **Module manufacturers, simulation program authors and users should understand the modelling and calculations and the implications of these errors.**

Acknowledgements Peter Funtan,IWES

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Definitions

Parameter	Equation or comment	Unit or
GI Plane of array irradiance	Tilted Global	kWh /m²
BF Beam fraction	Beam/Global horizontal Irrad.	#
kT Clearness Index	Global/ Extraterrestrial horiz. irrad	#
I_{DN} Normalised I_{MAX} dc	$I_{MAX.MEAS}$ / $I_{MAX.STC}$ / G_I	#
V_{DM} Normalised V_{MAX} dc	$V_{MAX.MEAS}$ / $V_{MAX.STC}$	#
I_{SN} Normalised I_{SC} dc	$I_{SC.MEAS}$ / $I_{SC.STC}$ / G_I	#
V_{OM} Normalised V_{OC} dc	$V_{OC.MEAS}$ / $V_{OC.STC}$	#
FF_M Normalised Fill factor	FF_{MEAS} / FF_{STC}	#
PF Normalised dc Efficiency	$Eff_{MEAS}/Eff_{STC} = I_{DN}*V_{DM}$	#
LLEC Low light Efficiency change	$\frac{\eta_{200} - \eta_{1000}}{\eta_{1000}}$	#