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THE PRESENT STATUS OF kWh/kWp MEASUREMENTS AND MODELLING

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ABSTRACT: Some PV module manufacturers have claimed up to an extra 30% kWh/kWp for their modules than their competitors but several recent independent tests e.g. [1][2][3] have found a much lower variability between technologies (mostly within ±4-5%) with measured values being dominated by Pmax.actual/Pmax.nominal[1][2]. These tests have not shown a systematic performance bias towards any manufacturer or technology.

Some commercial PV simulation programs have been found to predict >5% differences in energy yield between various technologies usually favouring thin films [4]. A study of five programs [4] found that whereas many use the same 1-diode equation [5] to fit IV curves from the manufacturers' datasheet values at STC, their modelled performance vs. irradiance and temperature varied between themselves and they did not always agree with the values on manufacturers' datasheets which are measured to standards such as IEC 61215, IEC 61646 and EN 50380[6][7][8]. Discrepancies have been found in their assumptions of Rshunt as a function of irradiance which is not on the manufacturers' datasheets and will vary for each module type.

To ensure the most accurate energy yield simulations possible these discrepancies need to be reduced. All intermediate measurement and calculation stages need to be compared and the uncertainties in calibrations and measurements better understood [9][10].
Keywords: Energy performance, Modelling, System performance, Energy rating

1 THE STATUS OF ENERGY YIELD MODELLING

Simulation models validated with just one module of each type at a given site make no allowance for the variability of module performance at STC or with variable weather conditions (for example the fraction of insolation at low light level, diffuse light fraction or spectral data at other locations).

Simulation programs use a series of algorithms to calculate an energy yield, the final accuracy of which depends on the uncertainties of all intermediate steps. An over prediction from one algorithm could be compensated by an under prediction from another but this would be coincidence and not accurate modelling.

Five commonly used commercial simulation programs have been studied (more will be investigated in future papers) as to the sensitivity of their energy yield predictions to different inputs such as low light efficiency change (LLEC) and Pmax temperature coefficient Gamma as defined in equations (1) and (2)

$$LLEC = \frac{Efficiency@200W/m^2}{Efficiency@1000W/m^2} - 1 \quad (1)$$

$$Gamma = \frac{1}{P_{MAX}} \times \frac{dP_{MAX}}{dT} \quad (2)$$

Many simulation programs perform curve fits using a 1-diode model [5 de Soto] (equation 3) as shown in figure 1 to four "known" conditions from the manufacturer's data sheet at STC conditions as listed in table I and illustrated in figure 2.

A fifth condition often used is Rsc = -1/(dI/dV@Isc) which is dominated by the intrinsic Rshunt but will vary for each module and is not in the manufacturers' datasheets. Some programs model the Rshunt as irradiance dependent which will be discussed later on.

$$I = IL - Io\left(e^{q(V+I.Rs)/nkT} - 1\right) - \frac{V+I.Rs}{Rsh} \quad (3)$$

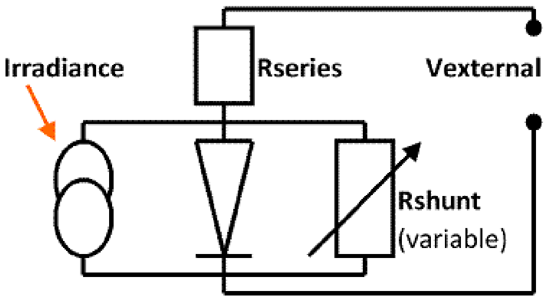

Figure 1: 1-diode model as used by simulation programs.

Table I: Four conditions to curve fit the 1-diode model; also the Rsc gradient.

Point	(V,I)	Comment
1) Isc	(0,Isc)	
2) Pmax	(Vmp,Imp)	
3) Pmax gradient		$\frac{dI}{dV}@V_{mp} = -\frac{Imp}{Vmp}$
4) Voc	(Voc,0)	
5) Rsc gradient		$\frac{dI}{dV}@I_{sc} = -\frac{1}{R_{sc}}$

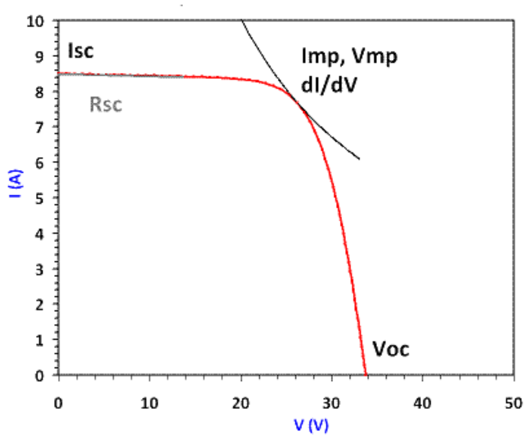

Figure 2: IV curve showing constraints and Rsc slope.

The 1-diode model [5] also contains equations for its proposed temperature dependence of ideality factor n and saturation current Io as given in equations (4),(5) and (6). These equations predict LLEC and gamma coefficients which do not always agree with measured values.

$$a = \frac{q}{nkT} \quad (4)$$

$$\frac{a}{a_{ref}} = \frac{T_c}{T_{c,ref}} \quad (5)$$

$$\frac{Io}{Io,ref} = \left[\frac{Tc}{Tc,ref}\right]^3 e^{\frac{\varepsilon N_s}{a_{ref}}}\left(1 - \frac{Tc,ref}{Tc}\right) \quad (6)$$

The 1-diode model also assumes that light current I_L is directly proportional to irradiance and that the intrinsic Rs and Rshunt are independent of temperature, time and irradiance (which will not be true of all module technologies).

Difficulties are encountered trying to fit a 1-diode model to PV modules with very high shunt resistances (such as the best c-Si); often the simulator gets the closest fits with unphysical negative shunt resistances.

As only one diode is used (rather than two that exist in other models and are nearer reality) unphysically large diode ideality factors are found approximately 1.3-1.5 for c-Si and nearer 1.8-2 per junction for thin film.

The spectral response and seasonal annealing are not usually taken into account in the 1-diode model – whereas both of these will affect measured energy yields.

2 MEASURED vs. MODELLED PARAMETERS FOR MANY PV TECHNOLOGIES

Thirteen commonly available PV modules from a wide range of suppliers and all common present production technologies shown in table II have had their manufacturers' datasheet values for LLEC and gamma checked with calculations from five simulation programs.

Table II: Module types and simulation programs

Colour	Module	PV technology type
	H1-H3	**H**igh efficiency c-Si
	S1-S5	**S**tandard efficiency c-Si
	T1-T4	**T**hin film
	O1-	'**O**ther'
Symbol	**Program**	**"Version since study started"**
	V	1 – new data planned
	W	1 – new version planned soon
	X	2 – regular updates
	Y	2 – regular updates
	Z	2 – regular updates

Figure 3 compares the measured Pmax temperature coefficient gamma with that in the five simulation programs. The five standard crystalline Silicon modules have declared values between -0.42% to -0.5%/K (the expected value is around -0.45%/K from the physical properties of c-Si) whereas the values in the simulation programs vary by up to -0.06% from measured.

In general program V2 is more optimistic than measured and Y2 is more pessimistic but there is still a wide spread in values. The assumptions for the high efficiency crystalline are usually worse than the manufacturers' declarations; the scatter on the thin film devices is much larger with no obvious trends.

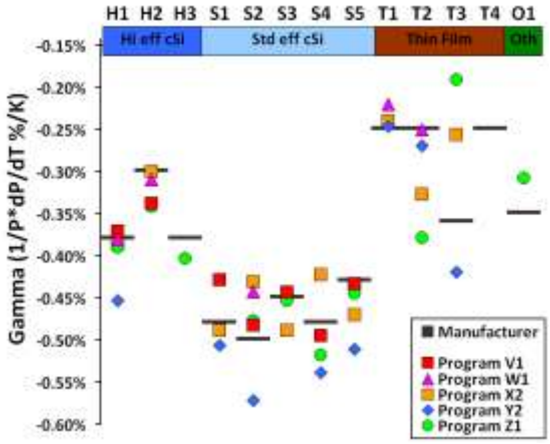

Figure 3: Manufacturers' datasheet values of Pmax temperature coefficient gamma vs. the values used by five different commercial PV simulation programs.

Figure 4 compares the low light efficiency change LLEC in a similar manner. Some of the manufacturers have chosen to publish a range of values (i.e. manufacturer H2 declares LLEC to be between -2.5% and -4.5% as the values will vary dependent on the shunt resistance and cell variability). The five standard crystalline Silicon modules have declared values spread around -5% whereas the values modelled in the simulation programs vary from around 0% to -30% (module S5 has the worst disagreement for c-Si between measured and modelled ranging from ~0% to -30%).

Because thin film devices have their efficiencies limited at high irradiances and currents due to their I^2R loss in the thin conducting oxide window layers their efficiencies can be a little higher at low light levels (+2 to +8% relative has been claimed) however the simulation programs model from -15% to +15%, the only obvious trends are that program X2 is quite consistent across the technologies, program V1 is pessimistic and both W1 and Z1 are very optimistic compared with real measured data.

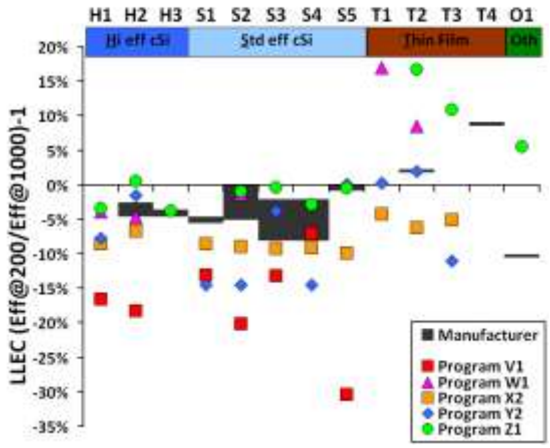

Figure 4: Manufacturers' datasheet values of LLEC vs. values used by five different commercial PV simulation programs.

The simulation programs' authors have been contacted regarding these errors and their module databases are being updated, the version number after the simulation program letter shows their update versions since this study started.

3 WHAT CAUSES THESE DISCREPANCIES ?

Because the manufacturers' datasheets don't give a value for Rsc the model must guess it. Rsc values are known to vary with irradiance (increasing as the irradiance falls) but there is no general consensus yet on how best to model this (and it may be technology and module dependent).

Some simulation programs assume the value is constant; others model it varying with a power dependency on irradiance. Exactly how fast the Rsc rises as light level falls will dominate the LLEC value.

The apparent measured Rsc has also been seen to vary depending on bias levels particularly for some thin film devices due to "voltage dependent collection". The depletion width of thin film devices is narrower under load voltage than nearer short circuit conditions. If the diffusion width is narrower than the active device thickness then under low bias conditions (=wide depletion region) the device can capture more electron-hole pairs, appearing as an increased current with voltage and appearing as a parasitic resistor in series with the real shunt resistance.

Cell mismatch (i.e. some cells having higher Isc than others will also "appear" as a shunt resistance i.e. a higher than expected –dI/dV at Isc. The apparent Rsc may appear as the combination of the three components in equation (X) – this is being studied further.

$$\frac{1}{R_{SC}} = \frac{1}{R_{SHUNT}} + \frac{1}{R_{BDC}} + \frac{1}{R_{MISMATCH}} \quad (x)$$

4 WHY RECENT kWh/kWp MEASUREMENTS MAY DIFFER FROM OLDER STUDIES

Recent improvements in efficiency of both thin film and crystalline devices have come from a wide variety of reasons including

- Better light capture from improved AR films, texturing, window materials and reflectors, spectral response.
- Improved material performance and uniformity.
- Better matching and rejection of underperforming strings.
- Lower I^2R loss from better tabbing and finger resistivities.
- better matching of multi junction devices
- Lower degradation etc.

Crystalline Silicon cell efficiency has improved from a standard 12% a few years ago to near 18% for "standard processing"; thin films have improved from around 5% to some being now over 10%.

It seems likely that the Pmax-Irradiance linearity of modules has improved as low light level performance has increased partly due to better control of Rsc; also the thin film devices no longer show a much higher efficiency at low light level as they once did when their high light level performance was limited by I^2R losses.

It can be interesting to plot the datasheet values of cells and modules from different Pmax bins to see what is causing the improvements. In general manufacturers may be continually improving their processes and the module power bands on offer will rise each year. As

$$Pmax = Vmpp \times Impp = Voc \times FF \times Isc \quad (X)$$

we can determine the proportion of the Pmax increase due to the constituents.

Figure 5 shows the improvement in Pmax from seven different thin film module bins over their lowest rated version –it shows a slightly higher Impp than Vmpp ratio; also the FF is dominant and the relative effects of Isc and Voc are small. This may be due to improvements in the device being due to lower Rs and a better junction.

(Also note now that the highest rated module is nearly 36% higher than the lowest – more than would be expected for a c-Si module which is a more mature technology).

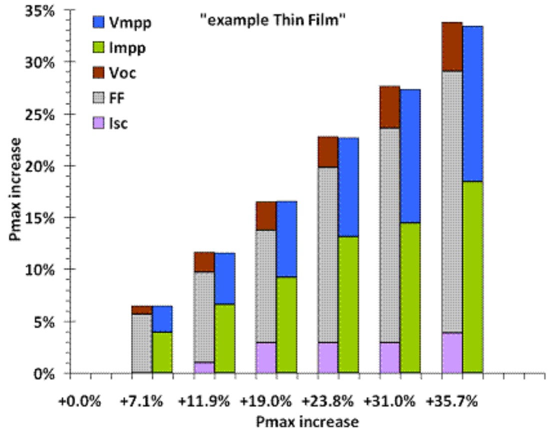

Figure 5: Contributions to increasing Pmax (x-axis) due to improvements in Vmpp+Impp or Voc+FF+Isc for a Thin Film from a Manufacturers' datasheet.

Figure 5 shows that at the absolute minimum there will be a finite range in the Isc, Voc values etc. from modules in a particular bin. Manufacturers don't typically make their variabilities known, but assuming the purchaser is buying a non top or bottom range module (i.e. there are bins above and below) then the absolute minimum variation will be the difference between bins. Assuming a thin film module with 6% difference between Pmax bins and where half of the improvement is due to Impp and the rest is Vmpp then there cannot be a variation of less than 3% in either across modules in the same bin (assuming a continuous distribution of measurements of Isc, Impp, Vmpp, Voc etc. from modules from the production lines).

The 1-diode model as it has been used is often based on just 1 module from a manufacturers' datasheet which may be just indicative of a production average or may be just a lower limit. It does not mean that every module will behave as fitted by the 1-diode model

5 kWh/kWp PREDICTION SENSITIVITY

When calculating kWh/kWp the simulation process will multiply the modelled efficiency as a function of irradiance and module temperature times the input insolation at the same irradiance and temperature [10].

$$\frac{kWh}{kWp} \propto \sum_{Gi,Tm} Eff(Gi,Tm) \times YR(Gi,Tm) \quad (x)$$

Figure 6 shows how a simulation program models the efficiency for a typical 220Wp c-Si module. Two important points that can be checked against the manufacturers' datasheet are the LLEC (relative drop in efficiency at 200W/m² vs. that at 1000W/m²) and the gamma factor (power derating vs. temperature) which can be calculated by dividing the rate of drop at 1000W/m² by the difference in module temperature in °C. This example shows it falling to an efficiency corresponding to 86% nominal at 200W/m² and the temperature drop at 1000W/m² is approximately 5%/10°C change = -0.5%/C.

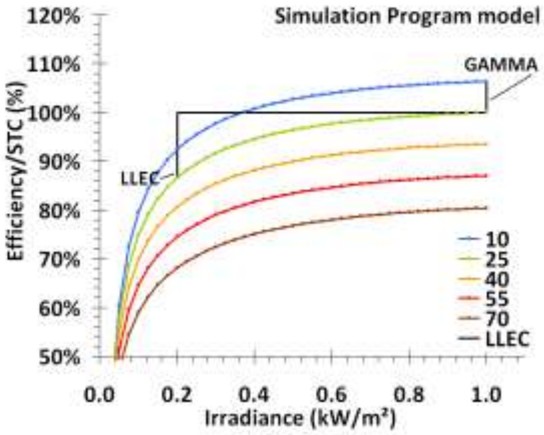

Figure 6: Efficiency/STC vs. irradiance and module temperature as modelled for a typical c-Si module.

The predicted values of efficiency at given light levels and two temperatures of 25C and 55C as from the five simulation programs for a given standard technology c-Si module S2 are given in figure 7 and are compared to the data from the manufacturer's datasheet. (Note that the ripples on simulation program W seem to be due to some rounding errors). All five of the 25C lines should start at the manufacturer's STC rated power of 100% at 1000W/m² (marked 25C). These lines should pass through the vertical line with three circles marking the mean and limits for the manufacturer's measured LLEC of 97±3% of efficiency. Programs W1 and Z2 shows almost no change in efficiency at lower light but the other programs drop far below the manufacturer's lowest measured spec of 94%.

The drop at 1000W/m² to the 55C lines should match the gamma value from the datasheet.

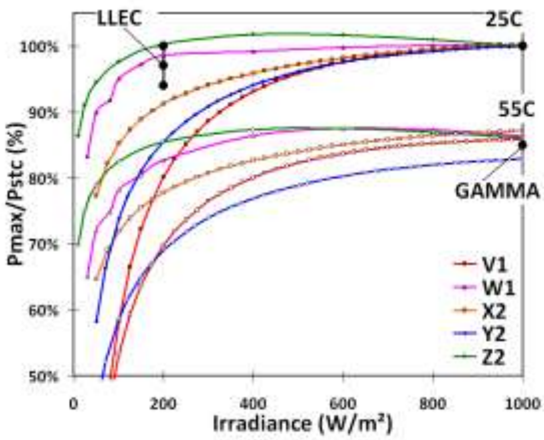

Figure 7: Comparing simulation program predicted efficiency vs. irradiance and module temperature for c-Si module S2 with the manufacturer's measurements.

Table 1 compares the manufacturer's guaranteed values with the values obtained from the simulation programs.

Table III: Comparison of manufacturers measured vs. simulation program modelled LLEC and Gamma factors

	LLEC %	Gamma %/K
Manufacturer	-0 to -6%	-0.50%
V1	-20%	-0.48%
W1	-1.4%	-0.45%
X2	-9%	-0.43%
Y2	-14%	-0.57%
Z2	+0.3%	-0.46%

To study the reasons for this further figure 8 shows the predicted IV curves from simulation programs V, X and Y for module S2 for irradiances from 200 to 1000W/m² and the value of Rsc against irradiance. (Note that one program predicted Rsc rising rapidly at low voltage, an estimate at Voc/5 was taken to contrast with other programs)

Program V has a low and constant Rsc which is why it has the worst LLEC value. Programs X, Y and Z model the Rsc as increasing at lower light levels. Program X has the "most optimistic" LLEC – this may be due to the fact that program Y's Voc falls faster at lower light levels. Program W could not be persuaded to output the data in the correct format.

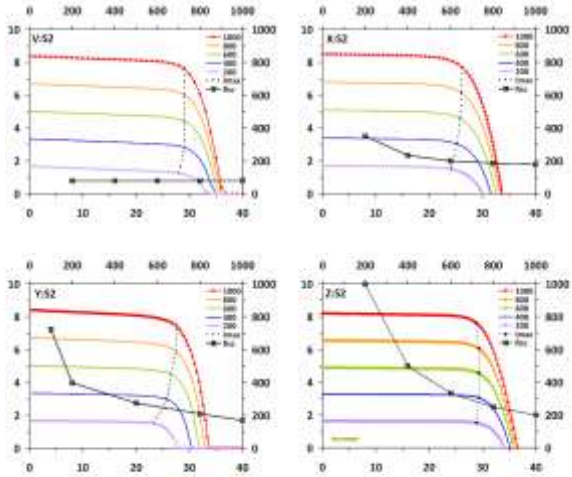

Figure 8: IV curves, Imax and Rsc vs. irradiance 200-1000W/m² for c-Si module S2. V (top left)
X (top right),Y (bottom left), Z(bottom right)
Axes - Left Current 0-10(A),Bottom Voltage 0-40 (V),Top Irradiance 0-1000 (W/m²), Right Rsc 0-1000(Ω)

6 PREDICTED kWh/kWp vs. LLEC AND GAMMA INACCURACIES AT DIFFERENT SITES

Figure 9 illustrates the distribution of hourly plane of array (tilted 30°) insolation in kWh/m²/y vs. module temperature C (x axis) and irradiance kW/m² (y axis) for four sites taken from a stochastic weather data generator for Helsinki (Finland), Munich (Germany), Valencia (Spain) and Albuquerque (New Mexico USA).

All four sites show a continuous band from cool/dull to hot/bright conditions. For Helsinki and Munich the distribution of kWh/m² is relatively constant along this band, for Valencia there is much more insolation at higher light levels but a relatively small temperature range over the year, at Albuquerque there is higher insolation at very high irradiance but a larger variation in temperature at a given irradiance over the year than the other sites.

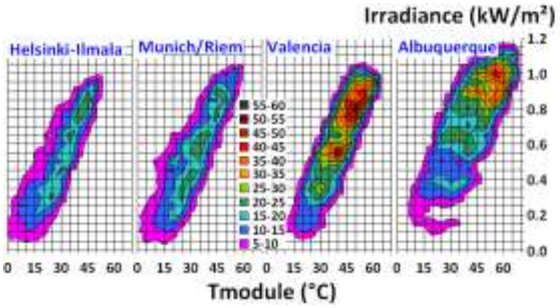

Figure 9: Predicted hourly distribution of insolation in kWh/m²/y vs. module temperature C (x axis) and irradiance kW/m² (y axis) for four sites.

One of the c-Si modules (S2) was then analysed to show the variation in predicted kWh/kWp over the year at the four sites by varying the LLEC from the correct value of 95% to cover values predicted in the simulation programs.

Figure 10 indicates as expected that errors in LLEC have a much bigger effect on lower insolation regions such as Helsinki than higher insolation like Albuquerque. An LLEC of 70% (as predicted by program V1 for module S5) would under predict the energy yield by over 13% for Helsinki to -5% for Albuquerque. The most optimistic LLEC of around 100% (as is claimed by manufacturer S5) would give an over prediction of only from 1% to 2% from Albuquerque to Helsinki.

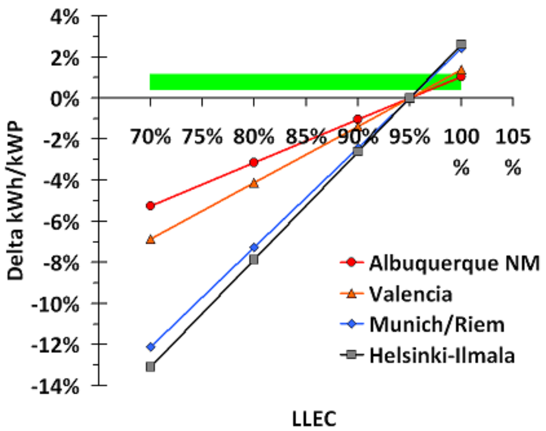

Figure 10: Change in kWh/kWp predicted for errors in LLEC for four different locations.

Figure 11 indicates as expected that errors in gamma have a much bigger effect on higher insolation regions such as Albuquerque than Helsinki. A gamma of -0.5% would under predict by less than 1% for all sites. The Gamma error is far less important than that for the LLEC as the magnitude of error is always lower and even for a discrepancy of 0.05% this only leads to a kWh/kWp change of around 1% for Albuquerque and less for the other sites.

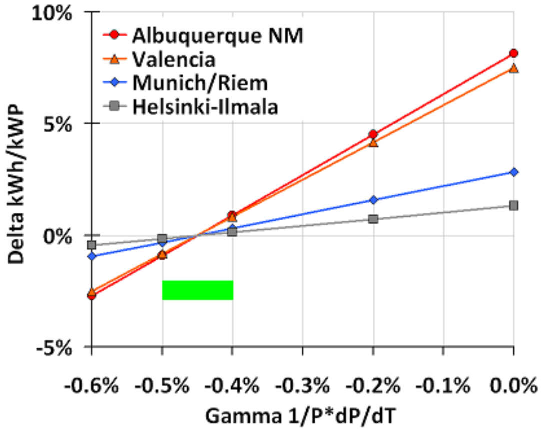

Figure 11: Change in kWh/kWp predicted for errors in gamma for four different locations.

7 MODELLING Rsc IRRADIANCE DEPENDENCE

As figure 8 showed some simulation programs model the Rsc as a variable with respect to irradiance but there is no general agreement on how best to model this yet. It is known that for most PV modules the Rsc rises as the irradiance falls but the equation is not known and might be technology dependent.

Measuring Rsc(G) internally means that the spectrum, temperature, angle of incidence, beam fraction are tightly controlled but if a filter is not a perfect fit to the desired irradiance then an interpolation is needed.

Measuring Rsc(G) externally means that as weather data values are correlated there may be more spread (e.g. low light levels can be due to clear sky morning/evening with high angle of incidence/redder light or cloudy noons with high diffuse content and bluer light filtered through clouds).

Rsc for crystalline modules in particular can be very high and scatter is sometimes a problem, for thin films it is often lower and a lower scatter on measurements.

Figure 12 shows the results of internal measurements by BP Solar who measured the IV curves of their modules on a flash tester and lowered the irradiance by using meshes and/or neutral density filters. It shows the limit points (Isc, Rsc, Pmax, dI/dV@Pmax and Voc) for a c-Si module filtered from 1000 to 120W/m². The dark points are measured; the white points indicate the tangential slopes to the dark points.

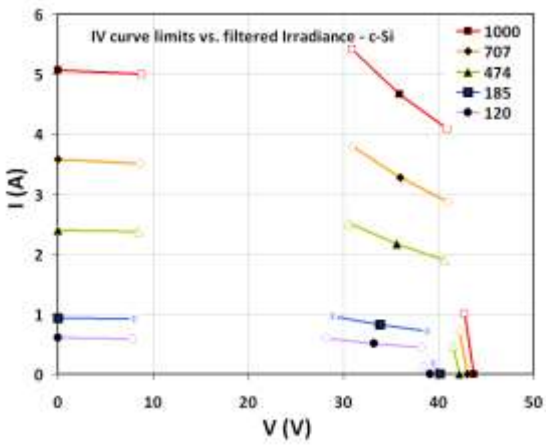

Figure 12: Limiting conditions for an IV curve on a BP Solar module from an internal flash tester vs. irradiance.

Figure 13 shows a power fit to Rsc/Rsc@1000W//m² for three modules of different types from BP Solar which are quite similar to each other. The Rsc@200W/m² looks to be 2.5-3 times that at 1000W/m².

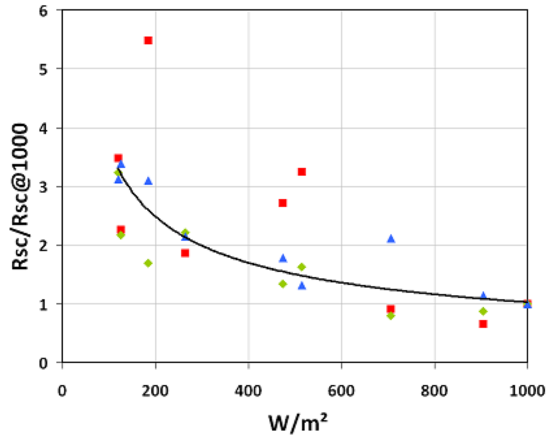

Figure 13: Power fit for Rsc/Rsc@1000 vs. irradiance for BP Solar c-Si modules from an internal flash tester

Figure 14 gives an example of Rsc (kΩ) vs. irradiance for an outdoor measured Oerlikon Solar thin film module at different light levels in Switzerland measured with an ISE reference cell. There is some scatter due to the difficulty of measuring high resistances (a spline fit is used to give the slope of the iv points near the Isc) in variable weather conditions (the irradiance, temperature, angle of incidence and spectrum all change continually) but a general power trend can be seen and the Rsc@200W/m² may be about 4-5 times that at 1000W/m².

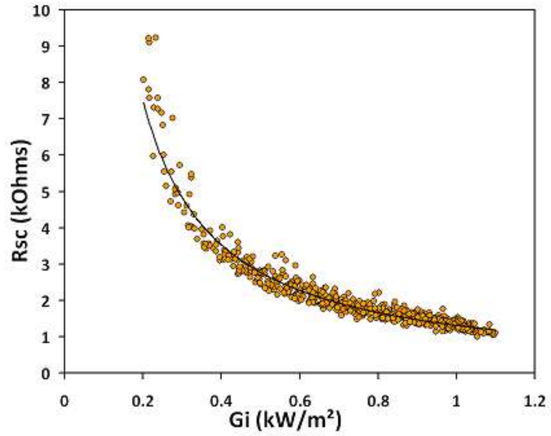

Figure 14: Rsc(kΩ) vs. irradiance for an outdoor measured Oerlikon Solar thin film module vs. irradiance.

Example graphs from two manufacturers show differences from how some simulation programs model Rsc with irradiance and further work is needed.

It is not yet known how the change in Rsc with light level varies between technologies, manufacturers, or if it is different between indoor and outdoor measurements.

8 CONCLUSIONS

Simulation programs still use different values for LLEC and Gamma than are listed in manufacturers' data sheets (as measured according to IEC 61215/61646 and EN 50380).

These anomalies can cause large differences in modelled kWh/kWp (over 14% error has been found with simulation programs using incorrect Gamma and LLEC coefficients[11]).

Rsc as a function of irradiance is the main cause in inaccurate kWh/kWp modelling and steps need to be taken to optimise, measure and model it correctly from manufacturers, standards committees and simulation program authors.

Note: The authors of these simulation programs have been contacted and being kept up to date with this work, their databases have been changing in recent versions to make LLEC and gamma factors more realistic.

9 ACKNOWLEDGEMENTS

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Daniel W. Cunningham and BP Solar for indoor data and figures 12 and 13.

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