COMPARING PV SIMULATION MODELS AND METHODS WITH OUTDOOR MEASUREMENTS

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ABSTRACT

- Several recent independent kWh/kWp studies have found similar energy yields (<±5%) for various c-Si and thin films without any consistent technology bias [1].
- A comparison of various modelling methods such as the matrix method, 1 or 2 diode models, SV method and empirical equations has been performed to see how they predict PV performance.
- The values of thermal and low light level coefficients used in some simulation models have been found to be different from what is measured to IEC standards [2], [3], [4].
- These discrepancies mean simulation programs often predict larger variations between technologies and usually favouring thin films [5].
- Suggestions are made as to the best way to predict and validate system performance.

INTRODUCTION

Due to many uncertainties simulation models may merely coincide with measurements without modelling correctly (e.g. predictions of kWh/kWp can have errors in two or more assumptions that cancel out).

There are many reasons an array could have poor performance such as shading, periods of downtime, incorrect rating or setup, faulty or mismatched balance of systems components. None of these system effects can be differentiated from poor module characteristics such as degradation or fall off at low light levels, high temperatures or diffuse light unless there is a much more detailed analysis of the performance.

Measured low light level responses are site specific (e.g. clear sunrises and cloudy days with the same tilted plane irradiance would be averaged together and the proportion of each will depend on the site). Also sites with high horizons to the east and west will mean much of the red component of high airmass will be lost.

Several models do not attempt to model some energy yield determining factors such as spectral response, thermal annealing and degradation.

Good fits to one module can be made with sufficient variables but this will not in general be able to be applied to similar modules or to measurements at other sites.

A SUMMARY OF SOME EARLIER STUDIES

Several much earlier 3rd party energy yield papers which did report large differences in kWh/kWp have been studied further to ascertain their reasons – below summarises findings from five of them.

a) A thin film module was found to have a 20% better battery charging current than two c-Si modules. A "higher current per watt" (= lower voltage) was obtained on a very hot day in June in California (when high module temperatures lowered the c-Si Vmax "knee" to below the battery charging voltage) so that the charging current fell rapidly. Battery charging systems will usually be dumping power when they are hot as the high irradiance means a battery is likely to be already fully charged as systems are sized to survive the worst insolation winter months- whereas kWh/kWp comparison measurements use maximum power point trackers so there is no limitation due to a fixed voltage and a lower loss in performance with temperature.

b) Better low power (i.e. at low light level) efficiency inverters were used for the thin films and worse low power/low light inverters used for c-Si for a kWh/kWp technology comparison in Europe.

c) Low light level efficiencies of different technologies were measured by tilting a 2D tracker away from the sun (when it was around 1100W/m² optimally tilted plane in northern Europe) – i.e. a very clear blue sky. This not be typical conditions for fixed tilt panels as 100W/m² would occur from either "a clear sunrise or sunset with reddish sky, high beam fraction and high incidence angles." or "dull overcast skies with low beam fraction and irrelevant incidence angles as it is dull" measurements. kWh/kWp values were then calculated from erroneous efficiency vs. irradiance curves and hourly predicted irradiances and temperatures ignoring any spectral or angle of incidence effects.

d) Lower kWh/kWp was found with c-Si modules with sub standard shunt resistances which caused a bad low light level response – shunt resistances have generally increased in more recent modules as both c-Si and thin film producers have improved their processing to lessen the effect of shunts, mismatched cells and non uniformities.

Earlier modules also had higher uncertainties in module calibration and a worse absolute and variability in degradation so that much of the variation in energy yield would have been due to these effects which have since improved.

THE STATUS OF ENERGY YIELD MODELLING

Many simulation models seem to be "validated" by comparisons of one module of each type at one given site which makes 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.

A series of algorithms is used to predict energy yield, the final accuracy of which depends on the uncertainties of all steps. An over prediction from one algorithm could be compensated by an under prediction from another but this is coincidence and not accurate modelling.

Many models use hourly weather data but it is seen [6] that this overestimates the fraction of irradiance at low light levels as illustrated in figure 1.

Generally a yearly plane of array insolation of ~1100kWh/m² or higher will experience steadily increasing insolation at light levels from 100 to 900W/m² as long as the measurement frequency is fast enough to measure the distribution correctly (around 1 minute or faster), lower frequencies such as hourly will tend to average dull and bright transient weather together which affects the predicted yield if the array efficiency is not constant with irradiance.

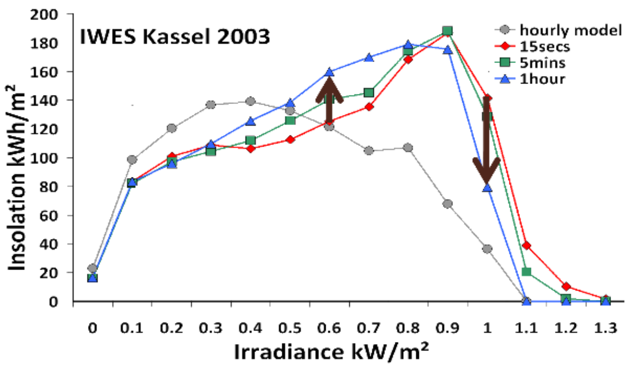

Figure 1 Averaging frequent (15secs) measurements of insolation vs. irradiance changes the apparent distribution by lowering the apparent proportion of energy generated at high light levels (5mins and 1hour traces) but none of them coincide with (hourly model line).

The ratio of Direct:Diffuse insolation is important in determining the tilted plane irradiance from horizontal plane measurements (tilting the module will in general collect more direct (tilted towards the sun) and less diffuse (sky behind the tilted module is not visible) radiation).

The module temperature (which affects the module performance) is estimated from NOCT, values of irradiance, wind speed and mounting methods (e.g. freely ventilated backs, roof tile etc.)

WEATHER PARAMETER CORRELATION

Weather parameters are correlated as shown in figures 2 and 3 which plot dc yield vs. seven weather measurements (clockwise from top : dc yield, irradiance, ambient and module temperatures, angle of incidence, air mass, season : winter=-1 to summer=+1 and beam fraction). These are arranged so that “good weather” as in the red lines in figure 2 are towards the outside [5]

Figure 2 shows that low irradiance (blue) tends to be associated (be predominantly on the inside of the graph) with low temperature, high angles of incidence and air mass, low season (i.e. nearer winter) and low beam fraction (i.e. mostly diffuse).

Figure 3 illustrates the act of taking only low irradiance data and separating between high and low clearness. High clearness (red) correlates with high angles of incidence and air mass, i.e. a clear sky early morning or late evening. The low clearness (blue) goes with low angles of incidence and air mass and low beam fraction, meaning cloudy skies up to a few hours either side of noon.

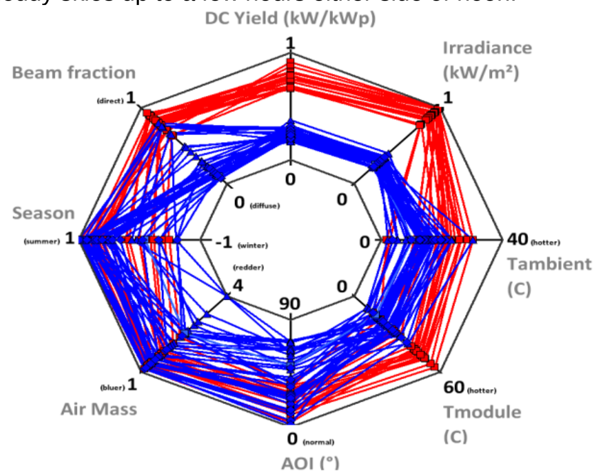

Figure 2 High (red) vs. low irradiance (blue) showing correlation between seven different weather parameters.

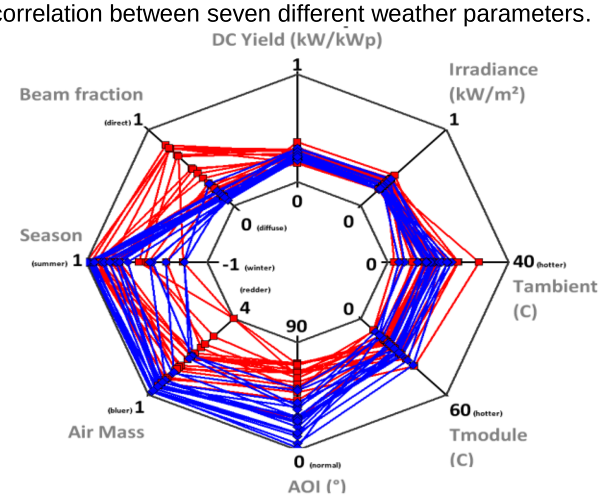

Figure 3 Low irradiance: comparing high clearness (red) with low clearness (blue).

Weather modelling doesn't usually consider these correlations so risks under or over counting of losses – for example a module with both a poor response at high air mass and high angle of incidence should suffer less loss overall as these two parameters often go together.

To be a good model we must be able to generalise to other modules at arbitrary sites.

Various modelling methods have been used and these will be compared and contrasted with real measurements.

SOME OF THE MODELLING METHODS STUDIED

a) Equivalent Circuit 1 or 2 diode IV model

An equivalent circuit as shown in figure 4 is either fitted to IV curves as in figure 5 made indoors or outdoors at different irradiances and temperatures, or the data used is to fit four "knowns" from an IV curve (on manufacturers spec sheets) which are (I,V) = (Isc,0); (Imp,Vmp); (0,Voc) and the fact that at the maximum power point gradient is known:

$$\frac{d(Imp*Vmp)}{dV} = 0; \text{therefore } \frac{dI}{dV} = -\frac{Imp}{Vmp} \quad \text{<1>}$$

A value for Rshunt must also be guessed as this will not be on the manufacturer's datasheet and will vary - some extra corrections may be made to make the Rshunt value depend on irradiance – this value does appear to change but differences are seen between measured and modelled predicted values.

Although often the manufacturer is guaranteeing minimum specs and this curve will not be the same for all of the modules.

The equations used from the 1 diode model [7] also make predictions for the thermal coefficients expected which are then sometimes used in the simulation programs even if these don't agree with measurements made by manufacturers according to IEC standards such as IEC 61215, IEC 61646 and EN 50380.

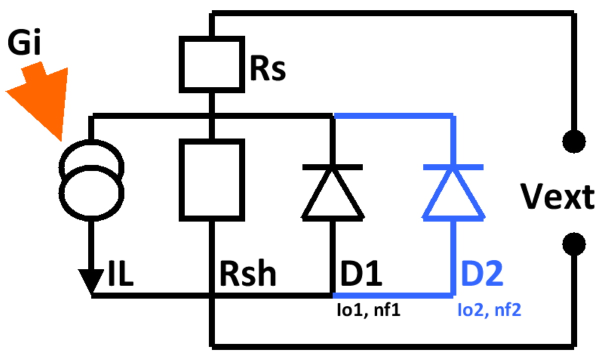

Figure 4 1 (or 2) diode equivalent circuit

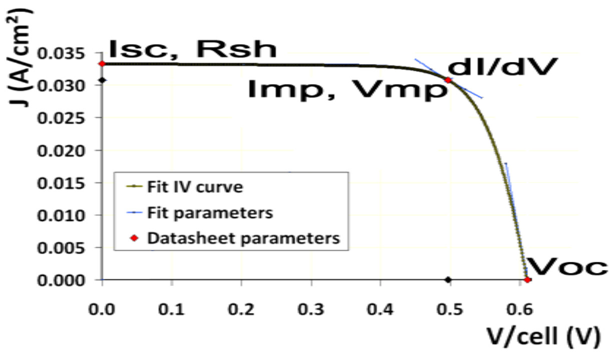

Figure 5 Modelled vs. IV curve vs. database points.

Difficulties are encountered trying to fit a 1-diode model to PV modules such as the best c-Si which have very good shunt resistances, often the simulator gets the closest fits with unphysical negative series resistances.

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

Spectral response and annealing are not usually taken into account.

b) Matrix method

The matrix method [8] shown in figure 6 models the PV efficiency as a smooth plot vs. irradiance and module temperature. It must also derive coefficients for angle of incidence losses and module temperature losses for indoor measurements.

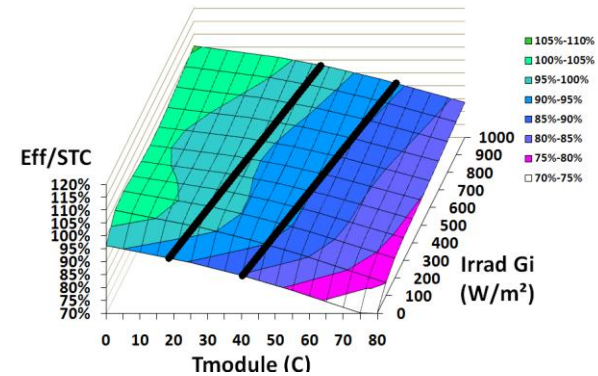

Figure 6 An example smooth plot of modelled PV efficiency vs. module temperature and irradiance – most insolation occurs between the black lines.

Smooth interpolations between measured data points are performed with empirical equations such as <2> and <3> [8].

$$Imp = \frac{Imp.stc*G}{1000}\left(1+\alpha\left(\frac{\Delta T*G}{1000}+Tamb-25\right)\right) \quad \text{<2>}$$

$$Vmp = Vmp.stc + C0\cdot\ln\left(\frac{G}{1000}\right) + C1\cdot\left(\ln\left(\frac{G}{1000}\right)\right)^2 + \beta\left(\frac{\Delta T*G}{1000}+Tamb-25\right) \quad \text{<3>}$$

The α and β coefficients are the physical Isc and Voc temperature coefficients respectively but C0 and C1 are non physical voltage related coefficients.

The matrix method assumes that the efficiency is a smooth function vs. irradiance and temperature, however measurements such as figure 7 illustrate that efficiency also depends on the beam fraction. Mostly direct radiation (high Beam Fraction = BF shown in orange) shows higher peak light levels than mostly diffuse (low BF in blue). At lower light levels the efficiency for low BF is quite variable and higher than high BF as the former will have variable spectra and in general be colder, whereas the latter will have a high angle of incidence and the spectrum will be redder.

Therefore the averaged measured low light level performance will depend on the different relative spectral and angular responses of the irradiance sensor and the module, averaging these high and low beam fraction measurements together as in the matrix method will be site specific as there will be a larger proportion of high beam fraction in better insolation sites and lower clear morning/evening contributions from high horizons in the east and west..

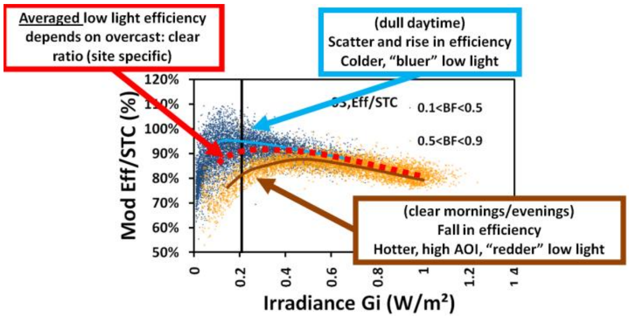

Figure 7 Measured/nominal efficiency vs. irradiance for a typical module in Germany

c) Non-normalised empirical with many coefficients

Some models use equations such as polynomial curve fits to generate their efficiency vs. the input parameters for example the Sandia model [9] <4a - 4d>

$$I_{sc} = I_{sco} \cdot f_1(AM_a) \cdot \{(E_b \cdot f_2(AOI) + f_d \cdot E_{diff}) / E_o\} \cdot \{1 + \alpha_{Isc} \cdot (T_c - T_o)\}$$

$$V_{oc} = V_{oco} + N_s \cdot \delta(T_c) \cdot \ln(E_e) + \beta_{Voc}(E_e) \cdot (T_c - T_o)$$

$$f_1(AM_a) = a_0 + a_1 \cdot AM_a + a_2 \cdot (AM_a)^2 + a_3 \cdot (AM_a)^3 + a_4 \cdot (AM_a)^4$$

$$f_2(AOI) = b_0 + b_1 \cdot AOI + b_2 \cdot (AOI)^2 + b_3 \cdot (AOI)^3 + b_4 \cdot (AOI)^4 + b_5 \cdot (AOI)^5$$

The more parameters used then the better the mathematical fit possible on any given data, however adding more fitting parameters makes them more unphysical (for example this has a term in Air Mass^4) and means that "good fits" to one module might not match modules from the same production run that differ slightly in performance. Also non physical components make it hard to distinguish what is a good measurement from a fit involving out of spec points.

d) Simpler, normalised empirical equations

Simper empirical equations can be used to validate the performance where irradiance is usually less that the STC standard of 1000W/m² and the module temperature mostly much greater than 25C. The empirical equation <5> modelled by PVUSA [10] (with dimensioned empirical coefficients labelled A to D) was normalised and extended to also predict module temperature and Vmp in equations <6-8> (their empirical coefficients are written in the form A_{XX} to E_{XX} where $_{XX}$ indicates the equation type).

$$P = G * (A + B * G + C * T_{MOD} + D * Ws) \quad <5>$$

$$T_{MOD} = C_{TM} * T_{AMB} + G * (A_{TM} + D_{TM} * WS) + E_{TM} \quad <6>$$

$$V_{MP}/V_{MP.STC} = A_{MP} * LOG_{10}(G) + B_{MP}/G + C_{MP} * T_{MOD} + D_{MP} * WS + E_{MP} \quad <7>$$

$$YA = P_{dc}/P_{dc.STC} = G * (A_{YA} + B_{YA} * G + C_{YA} * T_{MOD} + D_{YA} * WS) - E_{YA} \quad <8>$$

An example of modelled vs. measured values for (T=module temperature, V=Vmax/Vdc and P=Pmax/Pstc) is shown in figure 8

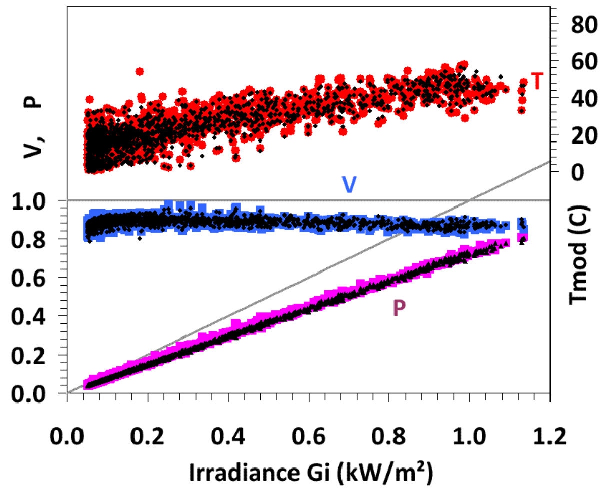

Figure 8 Fitting of simpler normalised empirical coefficients to measured data

Because the coefficients are normalised and correspond to real physical effects they can be associated thus:

A_{YA} = approximate mid light level performance factor
B_{YA} = I²R loss factor
C_{YA} = temperature derating (%/K)
D_{YA} = wind speed derating (%/ms^{-1})
E_{YA} = low light level efficiency drop

Similar comparisons with real effects of coefficients with the T_{MOD} and V_{MP} equations can be made.

Normalised values of coefficients (e.g. YA = Pmax.measured / Pmax.nominal) help enable the quality of the performance to be determined – checking V_{MP} and I_{MP} gives further information for example low V_{MP} but correct I_{MP} may be due to higher than expected temperatures, whereas variations in I_{MP} may be due to spectral effects, dirt or sensor calibrations.

These empirical equations can be used as a first guess to predict output data, and then used in field measurements to compare expected with actual data (for rebate if needed). They can validate instantaneous performance and also find problems such as shading and inverter tripping by modelling the maximum performance by month and hour.

PV EFFICIENCY vs. IRRADIANCE and TEMPERATURE

Simulation program databases store coefficients in models to enable them to generate Efficiency/STC vs. irradiance and module temperature curves as shown in Figure 9.

This shows the user how to calculate the LLEC and the Gamma factor for comparison with measured data.

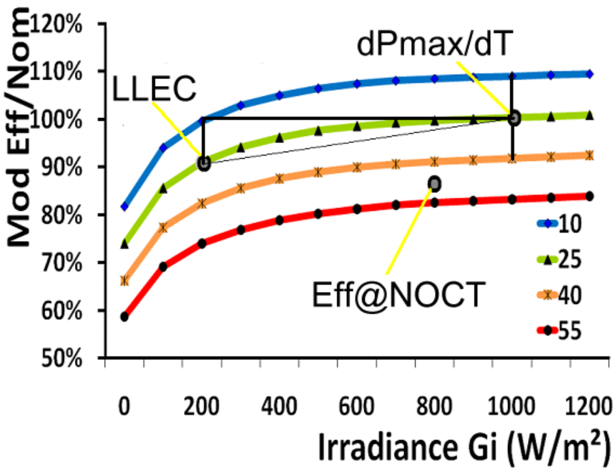

Figure 9 Example simulation program generated curves of relative efficiency vs. irradiance and module temperature.

Comparisons were made between measured and simulation program database values for LLEC and Gamma with 4 different commercially available simulation programs (W to Z) for 13 currently available PV modules of many different technologies

- H1-H3: High efficiency c-Si
- S1-S5: Standard efficiency c-Si
- T1-T4: Thin film
- O1: 'Other'

Figure 10 plots the measured and predicted LLECs which show very large disagreements such as –

	Measured	Modelled
All standard c-Si	~ -5%	-2% to -15%
Thin film #T2	+2%	-6% to +17%

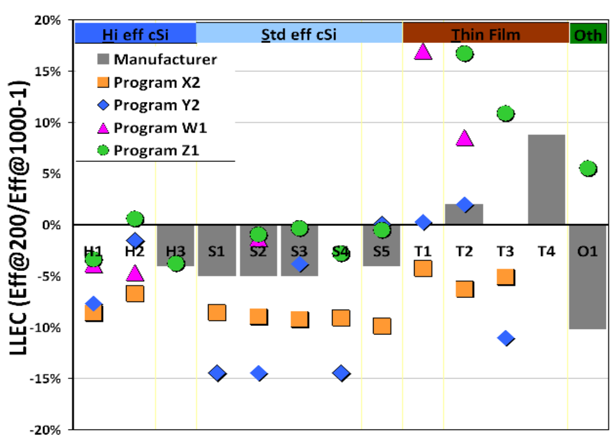

Figure 10 Modelled and measured LLEC low light efficiency change

Figure 11 gives the gamma factors which have slightly better agreement than LLEC but there are still large errors such as:

	Measured	Modelled
Standard c-Si #S2	-0.50%/K	-0.43 to -0.58%/K
Thin film #T3	-0.37%/K	-0.20 to -0.44%/K

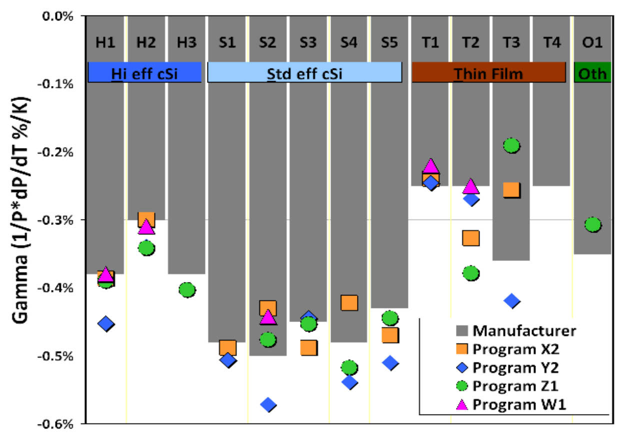

Figure 11 Modelled and measured Gamma Pmax Temperature coefficient

Manufacturers' data sheets were measured according to IEC 61215/61646 and EN 50380, but simulation programs often ignore these values !

These anomalies will cause large differences in modelled kWh/kWp (Over 8% error has been found with simulation programs using "incorrect Gamma and LLEC coefficients") [11]

PREDICTED BOS AND OTHER LOSS MODELLING

There are many different “other” losses (approximately 14) which affect kWh/kWp production. Estimations of yearly kWh/kWp need to predict these every measurement time.

Simple mathematical predictions of the easiest to understand losses like shading, I²R loss, temperature etc. are used but effects such as low light efficiency change LLEC, degradation and thermal annealing effects are usually not modelled.

Methods such as “SV”” or sophisticated verification seem to be useful in determining failure modes or degradation/underperformance of arrays even though not all stages are modelled properly as it tends to be able to identify “step” changes such as shading, downtime and thermal cut out well, also derived values of parameters such as wiring resistance can be spotted as out of the normal range.

Some of the many “loss” stages which cause kWh to be different from expected are listed below :

1. Pmax.initial/nominal - manufacturers' calibration and binning
2. Pmax.actual/initial - degradation and annealing.
3. Shading (far horizon, near object, row to row) - effect depends on stringing arrangement, cell aspect ratio, bypass diodes etc.
4. Snow (seasonal - shading when some snow cover after partial melting).
5. Dirt (daily increase until heavy rain or cleaning).
6. Spectral effects – sensor dependent (particularly for thin film and/or multijunction).
7. Angle of incidence/reflection losses sensor dependent.
8. Thermal losses (Tmodule usually >25C)
9. DC Wiring = I^2R losses/
10. MPP tracking errors (not finding Vmax).
11. Inverter efficiency; clipping/turn on/thermal cut-out
12. Transformer losses.
13. AC wiring = I^2R losses.
14. Downtime, either partial or total system loss.

These losses may vary with time in different ways and need to be modelled correctly

- Constant (e.g. Pmax. Initial/nominal).
- Vary continually (e.g. shading, angle of incidence, and module temperature).
- Vary seasonally (e.g. snow, dirt, thermal annealing).
- Vary monotonically (catastrophic degradation).

Some losses are indistinguishable from each other if they have the same dependence on inputs such as irradiance, e.g. dirt and module Pmax/nominal as both effects are proportional to irradiance.

Detailed measurements of date+time, irradiance, wind speed, Imax.dc, Vmax.dc, Pmax.ac Tambient and Tmodule each 5 minutes or so are the minimum that can be used to differentiate some of the losses.

One unknown (e.g. dirt) can be adjusted to make an exact fit of measured and predicted kWh/kWp

Two unknowns may compensate each other (e.g. Pmax too low with dirt factor too low)

~14 unknowns cannot be quantified with just one value of kWh/kWp !

CONCLUSIONS

- There is a smaller measured variability between kWh/kWp for different technologies than had been thought – mainly due to module improvements.
- Measured kWh/kWp is dominated by Pmax.actual/nominal
- Normalised empirical formulae are best at validating PV performance
- Simulation program predicted kWh/kWp are dominated by database values for "efficiency change at low light" and "Pmax vs. temperature"
- These errors vary by technology and simulation program – 8% errors have been seen.
- Uncertainties in kWh/kWp measurements and predictions are high, close values may just coincide rather than validate multiple unknowns in algorithms
- Many simulation program authors have been contacted , their databases have been changing to make LLEC and gamma factors more realistic.

DEFINITIONS

Low light efficiency change LLEC:

$$= \frac{\text{Efficiency@200W/m}^2}{\text{Efficiency@1000W/m}^2} - 1 \qquad \text{<9>}$$

Beam Fraction BF:

$$= \frac{\text{Beam}_{\text{Horiz.}}}{(\text{Beam}_{\text{Horiz.}} + \text{Diffuse}_{\text{Horiz}})} \qquad \text{<10>}$$

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