Modelling inaccuracies of PV energy yield simulations

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ABSTRACT

Commercially available sizing programs use many different algorithms and methodologies to attempt to predict the energy yield of PV systems (figure 1).

Weather data is often stored in a database of horizontal plane monthly averages and is usually calculated hourly in the plane of array POA (using Markov transition matrices).

PV modules under different weather conditions are simulated using various methods including data from manufacturers' spec sheets, 1 or 2 diode models from either internal or external measurements from test modules or performance matrices.

The performance of inverters is usually estimated from spec sheet data as efficiency vs P_{IN} (and perhaps V_{IN}) and some limits on maximum power point tracking.

Estimates for losses due to dirt, angle of incidence, wire resistance etc are taken from a combination of best guesses, local knowledge or simple algorithms.

The uncertainties of some of the inputs, unknown data and imperfect modelling algorithms compound at each calculation step and cause the performance predictions to become increasingly uncertain as the number of steps increases [1].

Sizing programs often predict answers close to what may is achieved, but is this really due to good modelling or is it coincidence due to inaccuracies?

In Milan 2007 [1] it was shown qualitatively how some of the modelling methods were inaccurate, for example suggesting more energy was produced at lower light levels than happened; also the models generally stored worse low light efficiency for c-Si in their databases than was realistic.

COMMON SIZING PROGRAM STEPS

Figure 1 illustrates some of the important stages usually modelled by sizing programs.

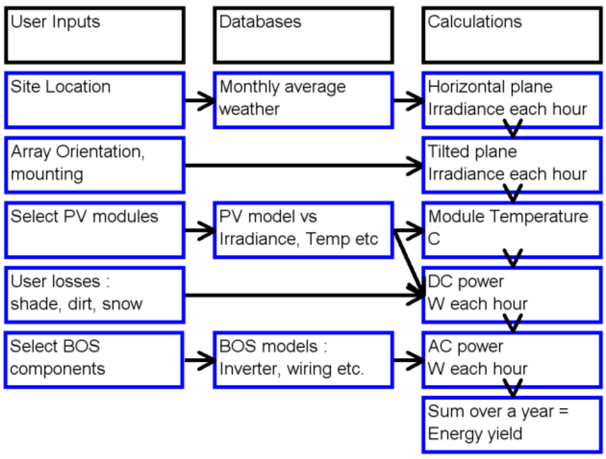

Figure 1: Simplified flow chart showing user input, database and calculation stages used by many sizing programs to predict energy yields.

Hourly weather predictions will usually overestimate the importance of low light level radiation as periods of erratic weather of bright and dull periods would be averaged together in hourly data [2]. During erratic weather the PV performance is dominated by the bright periods (where irradiance can be 20% or more above the value expected in clear skies due to extra reflections by bright clouds – called the "edge of cloud effect") whereas the PV temperature can be up to 10C lower than expected as the modules cool when under low irradiance in diffuse conditions.

VARIABILITIES IN MEASURED kWh/kWp

Performance Ratio PR (the achieved / lossless energy yield) is defined in equation (1).

$$PR = \frac{YF}{YR} = \frac{\text{AC Yield}}{\text{POA insolation}} = \frac{kWh/kWp}{kWh/m^2} \qquad (1)$$

As an example if the POA insolation YR was 1000kWh/m² and the final yield YF was 780kWh/kWp then PR = 780/1000 = 78%. (Note all other units for efficiency, area etc. cancel out as lower efficiency modules have larger areas to collect light for the same nominal maximum power). When quoting PR values it must be distinguished whether it is with respect to $kWp_{NOMINAL}$ or kWp_{ACTUAL} as this ratio depends on the manufacturer's calibration accuracy and also the variability of modules within a grading band. We can simply rearrange equation (1) and add a ratio for $kWp_{ACTUAL}/kWp_{NOMINAL}$ to calculate how $kWh/kWp_{NOMINAL}$ will depend on the variability of other parameters into equation (2).

$$\frac{kWh}{kWp_{NOMINAL}} = \underbrace{PR}_{(a)} * \underbrace{YR}_{(b)} * \underbrace{\frac{kWp_{ACTUAL}}{kWp_{NOMINAL}}}_{(c)} \qquad (2)$$

Table 1 lists some of the unknowns and variables affecting each value of PR, YR and $kWp_{ACTUAL}/kWp_{NOMINAL}$: -

Table 1: Some uncertainties affecting kWh/kWp.

Parameter	Unknown or variable	1) Diff sites	2) Diff sites corrected	3)Same site
(a) PR	Downtime, Vmax mistracking, Inverter loss, Low light perf ~ R_{SHUNT} variations, seasonal annealing	?	?	?
	Dirt	± 1%	0%	0%
(b) YR	Irradiance sensor calibration	± 2%	± 2%	0%
	Yearly insolation variability	± 4%	0%	0%
(c) $\frac{kWp_{ACTUAL}}{kWp_{NOMINAL}}$	Reference module calibration	± 2%	± 2%	± 2%
	Module bin width	± 2.5%	± 2.5%	± 2.5%
	Degradation	< -1%/y		0 to -1%/y

Column1 estimates some of the variations for arrays at different locations, column 2 is for corrected values at different sites and column 3 is for tests at the same location.

- There will be random variations due to downtime and V_{MAX} tracking, also there can be variabilities in the inverters. In general modules with higher R_{SHUNTS} will tend to perform better at low light levels than lower R_{SHUNT} devices, all four of these effects can only be estimated by considering each setup separately and have been ignored for this analysis (which would make uncertainties smaller than reality).
- Dirt factors in temperate regions (where there are randomly occurring rain showers) tend to have values of around 4% max, therefore a value of ±1% was estimated as the possible difference between sites or "same" meaning no variation between adjacent modules (although there could be small physical differences between plain, AR coated or stippled glass and plastic encapsulants, perhaps better rain cleaning with steeper tilts or whether the array was in towns or the countryside).
- The apparent YR (reference yield) will depend on irradiance sensor calibrations (pyranometers are often quoted to ±2% and reference cells are sometimes only given as ±5%) – pyranometers will tend to give different insolation readings from reference cells as their spectral response and angles of acceptance will tend to be different from that of the modules.
- The yearly variability in insolation in temperate climates has been found to be of the order of ±4%.
- Reference modules measured at calibration laboratories are often guaranteed within values around ±2%. Module manufacturers selling devices in the 200Wp range will often have a 10Wp tolerance meaning modules can vary ±2.5% and still be in the same nameplate bin (for example from 200 to 209.9Wp for -0% tolerance).
- Module stability values are routinely quoted as ">80% after 25years", meaning that a linear degradation of at worst -1%/year might be expected.

Gaussian uncertainties of different inputs combine together as

$$U^2 = u_1^2 + u_2^2 + \dots u_n^2 \quad (3)$$

For different sites in table 1

$$U1 = [(1\%)^2+(2\%)^2+(4\%)^2+(2\%)^2+(2.5\%)^2]^{0.5} \sim 6\% \quad (4)$$

Cleaning the arrays (dirt=0), correcting for yearly insolation and with a stable array

$$U2 = [(2\%)^2 + (2\%)^2 + (2.5\%)^2]^{0.5} \sim 4\% \quad (5)$$

For measurements at the same site

$$U3 = [(2\%)^2 + (2.5\%)^2 + (1\%)^2]^{0.5} \sim 3\% \quad (6)$$

Table 2 shows the range in PR expected from these uncertainties around a nominal PR of 75%. At best the uncertainties are 3% absolute (73-78%) indicating that measured and modelled PR will coincide rather than be calculated precisely.

Table 2. Range of uncertainties for PR

	1) Different sites	2) Different sites (corrected)	3) Same site
Uncertainty	6%	4%	3%
PR range	71-79%	72-79%	73-78%

ESTIMATING UNKNOWNS IN DC kWh/kWp vs IRRADIANCE ONLY

DC energy yield in programs can be estimated as the sum over all irradiances of the module efficiency * insolation (7).

$$kWh/kWp \;\alpha\; \Sigma_{Gi}(ModEff(Gi)*Insol(Gi)) \quad (7)$$

Figure 3 shows the measured and modelled (in a sizing program) module efficiency relative to STC vs irradiance for a mono Si module. It can clearly be seen that the modelled efficiency is worse than measured diverging rapidly below about 0.4kW/m².

Figure 4 plots the measured vs modelled (in a weather database) percentage of total tilted plane insolation vs irradiance in central Germany in 2004 measured at 10 minute intervals. The model can clearly be seen to be overestimating the lower light levels (<0.7kW/m²) while underestimating the higher.

Measured data was taken at 10 minute intervals – studies at this site [2] suggest an even bigger discrepancy with real data as measuring at more frequent intervals shows up even larger energies at high irradiance due to bright periods during erratic weather that get reduced when averaging to less frequent measurements.

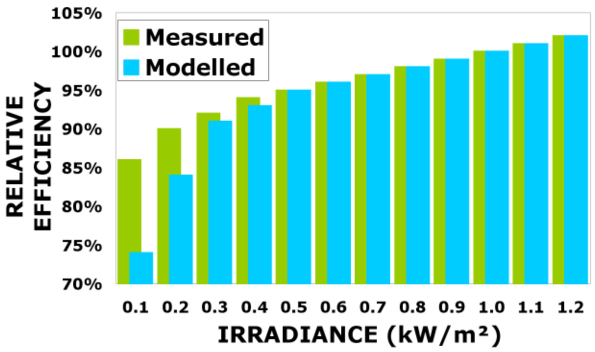

Figure 3. Measured vs a sizing program model for relative efficiency vs irradiance for mono Si module

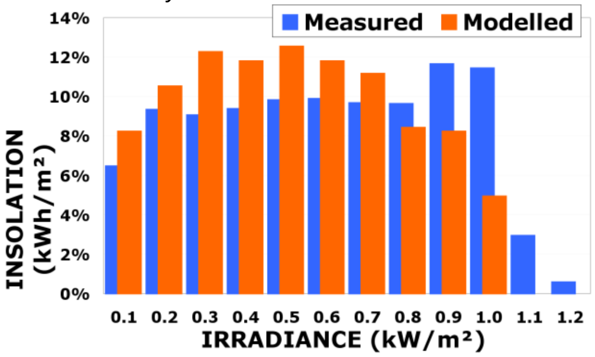

Figure 4: Measured (2004) vs a meteorological database modelled percentage tilted plane insolation vs irradiance in central Germany.

Table 3 shows the differences between calculated energy yields from equation (7) using measured and modelled values for efficiency and insolation vs irradiance as in figures 3 and 4 but correcting the total modelled insolation to be the same as that measured.

Table 3: Comparison of predicted energy yield using modelled and measured irradiance and efficiency.

	Modelled Efficiency	Measured Efficiency
Modelled Irradiance	97.0%	98.9%
Measured Irradiance	98.4%	100.0%

It can be seen that using either the model's worse module efficiency at low light or higher insolation at low light both result in an apparent fall of 1-2% kWh/kWp. If both inaccuracies were used then the calculation would underestimate by 3%.

EMPIRICAL CALCULATIONS TO VALIDATE PERFORMANCE

Outdoor performance can be modelled well by normalised empirical formulae in equations (8)-(10) [3].

The module is operated for a period of variable weather conditions, a fit is then performed between the data and that predicted by empirical formulae which calculate T_{MODULE}, V_{DM} and YA from inputs of $T_{AMBIENT}$, Irradiance and Windspeed. The values of the coefficients A..E show how well the module performs and if the fit is realistic.

$$T_{MOD}=C_{TMOD}*T_{AMB}+Gi*(A_{TMOD}+D_{TMOD}*WS)+E_{TMOD} \quad (8)$$

$$V_{DM}=A_{VDM}*LOG(Gi)+C_{VDM}*T_{MOD}+D_{VDM}*WS+E_{VDM} \quad (9)$$

$$YA=A_{YA}*(Gi+B_{YA}*Gi+C_{YA}*T_{MOD}+D_{YA}*WS)-E_{YA} \quad (10)$$

A typical fit for a mc-Si module is shown in figure 5. The coloured points show the T_{MODULE}, V_{DM} (=V/V_{STC}) and YA (=P/P_{STC}) vs irradiance, the black dots are their empirical fits.

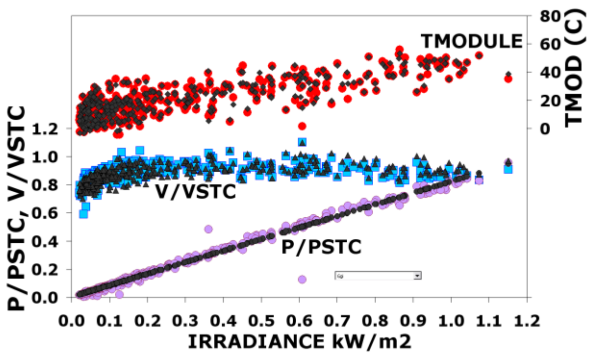

Figure 5: Empirical fits for temperature, voltage and dc yield for a mc-Si module at ISET

Once the coefficients have been determined for a few points they can be applied to subsequent data to determine whether or not the array is performing well. The fits are good when everything is working and means that complex equations do not need to be used to try to translate the performance back to STC. Figure 6 investigates 7 days in September at ISET, the only differences were on the 3rd day from the left when high erratic winds cooled the module more than expected. It is easy to enhance the empirical equations to take into account variable winds and the thermal lag in the module.

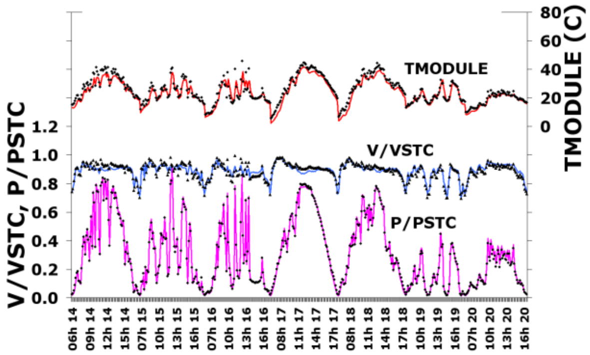

Figure 6: Measured and predicted T_{MODULE}, V_{DM} and YA for mc-Si module for 7 days in September 2004 at ISET.

MODELLING SOME OF THE UNCERTAINTIES

Module voltage depends on module temperature. Baumgartner et al [4] showed that the inverter efficiency depends not just on $P_{IN}/P_{NOMINAL}$ but also on V_{MPP}.

A modelling program has been written to investigate some of the uncertainties and modelling algorithms used in Sizing. Figure 7 shows the main design screen showing inputs and the monthly modelled outputs.

Figure 8 gives some of the input screen data for the PV and Inverter – various choices can be made for modelling for example PV efficiency with light level or the inverter efficiency vs input voltage.

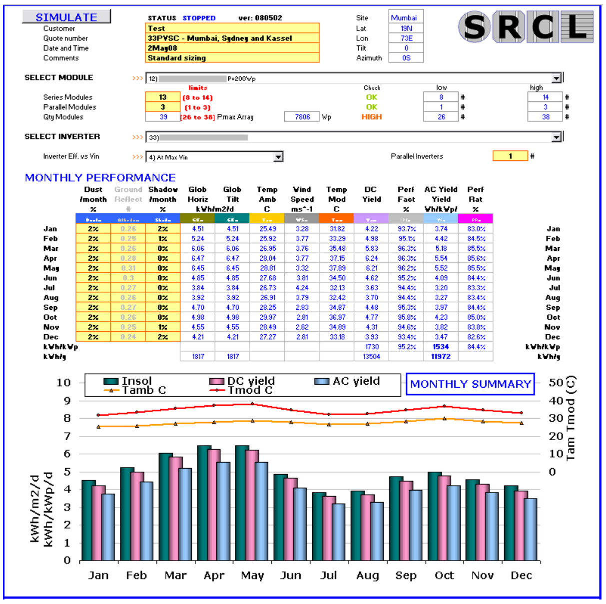

Figure 7: New sizing program to investigate inaccuracies and different modelling algorithms

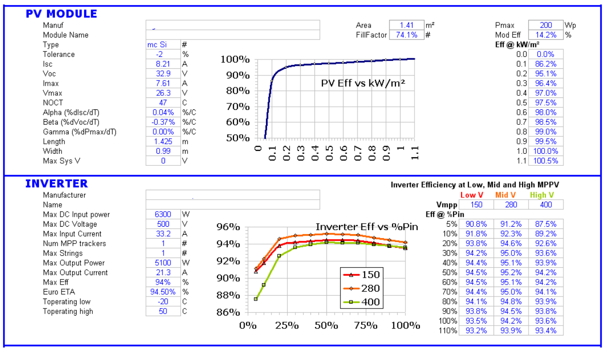

Figure 8: Input screens for PV and inverters.

Various changes were made to the modelling of the PV component and their effect on ac yield modelled at three sites – Mumbai India (1800kWh/m², $T_{AMB.AVG}$=28C), Sydney Australia (1800kWh/m², $T_{AMB.AVG}$=18C) and Kassel Germany (1100kWh/m², $T_{AMB.AVG}$=9C).

Figure 9 shows how the ac yield changes from nominal for the following changes(from top to bottom)

1) NOCT=20C (i.e. the module temperature does not rise above $T_{AMBIENT}$ as if it were connected to an infinite heat sink @ 20C)
2) The PV has a constant efficiency at all light levels (usually the PV efficiency falls a little at low light due to the logarithmic dependence of Voc in irradiance).
3) Poor R_{SHUNT}. An arbitrary poor shunt resistance was added to the module
4) NOCT=65C (i.e. the module temperature rises faster than usual perhaps due to no back ventilation as in roof tiles).

As can be see India and Australia are more susceptible due to the thermal changes 1) and 4) whereas Germany is more dependent on the low light efficiency changes from 2) and 3).

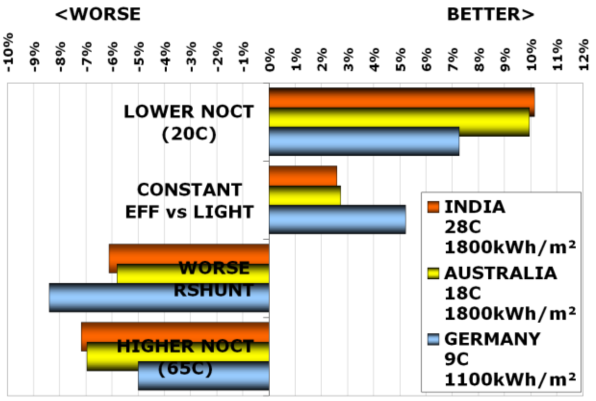

Figure9: Energy yield changes at three sites from light light and temperature effects

The effect of inverter efficiency vs V_{IN} was investigated in figure 10. Top row shows control (i.e. constant efficiency with V_{IN}) then subsequent rows show (respectively) modelling efficiency with variable V_{IN} then taking the efficiency as that at the V_{LOW}, V_{MID} and V_{HIGH} values of MPP. With this inverter at least there is little change between the average and low voltage efficiencies but at the highest voltages the efficiency for all sites falls around 3%. Note that normally highest irradiance happen with high ambient and module temperatures and therefore lowest V_{IN} at the inverter so V_{HIGH} is not experienced very often.

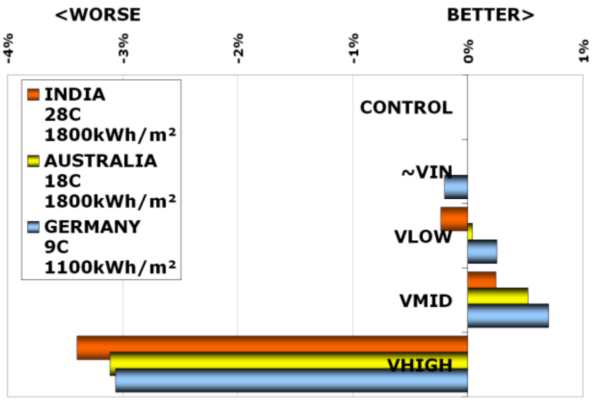

Figure 10: Energy yield changes at three sites from inverter efficiency modelling with input voltage,

This program will be developed further to provide a user friendly modelling program to study different algorithms and PV or inverterdependencies.

CONCLUSIONS

- Some DC and AC outdoor measurements can be very different from modelling algorithms
- Sizing programs are essential to design systems not to have avoidable losses
- kWh predictions can't be more precise than the input variable uncertainties
- Empirical equations can characterise performance and validate the correct operation of arrays.

- Errors in yield of several percent can be found from low light level and inverter voltage modelling

ACKNOWLEDGEMENTS

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