WHY HOURLY AVERAGED MEASUREMENT DATA IS INSUFFICIENT TO MODEL PV SYSTEM PERFORMANCE ACCURATELY

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ABSTRACT: Many commercially available PV Sizing and modelling programs use a simple dc performance model of a PV module multiplied by hourly weather data plus a simple model of "balance of systems" (BOS) losses to estimate the yearly ac energy output.

Studies of the meteorological data, dc module and ac inverter performance every 15 seconds in ISET, Germany show that hourly averaging of weather data overemphasises the importance of low light levels in yearly energy generation. Transient weather conditions show more inverter clipping than would be expected from hourly weather averages.

Higher maximum irradiances coincident with lower than hourly predicted module temperatures are also found, which mean higher module and inverter currents and powers need to be considered in component sizing.

Keywords: Monitoring, Modelling, Energy Rating.

1 INTRODUCTION

ISET[1] have been measuring outdoor data for BP Solar on various BP Solar and competitors' modules of different technologies in Kassel, Germany in a long term study since 1998 [2].

Frequent system measurements (<60 second intervals) in Germany, Australia[2] and also 3rd party studies[3] show that hourly averaging of the irradiance and temperatures underestimates the contribution from high irradiance conditions in energy generation

When averaging data each hour, short periods of high irradiance are combined with dull periods. However, as the power output of modules reacts quickly to changes of irradiance while temperature changes are slow (due to their relatively high thermal mass under variable irradiance conditions) modules will often give higher power than expected at lower module temperatures than calculated from hourly averages.

This study was undertaken to measure the fluctuations in weather conditions, dc and ac system performance and how these can affect component design limits and the energy yield.

2 SIMPLE kWh/kWp MODELLING

Table I defines some of the parameters used in this work (See also IEC 61724)

Symbol	Name, Equation	Units
G_I	Irradiance	kW/m^2
T_M	Module temperature	C
T_{AM}	Ambient temperature	C
WS	Windspeed	m/s
YR	Insolation = $\Sigma_t G_I$	kWh/m^2
V_{DM}	$V_{DC}/V_{MAX.STC}$	dimensionless
I_{DN}	$I_{DC}/I_{MAX.STC}/G_I$	dimensionless
YA	dc Yield	kWh/kWp
PF	dc Performance factor YA/YR	dimensionless
YF	ac Yield	kWh/kWp
IE	Inverter efficiency YF/YA	dimensionless
PR	ac Performance ratio YF/YR	dimensionless
Alpha	$1/I_{SC} * dI_{SC}/dT_{MODULE}$	% / deg C
Beta	$1/V_{OC} * dV_{OC}/dT_{MODULE}$	% / deg C
Gamma	$1/P_{MAX} * dP_{MAX}/dT_{MODULE}$	% / deg C
NOCT	Tmodule @ 800W/m^2, T_{AM}=20C, WS=1m/s	

Table I : Definitions of some meteorological and electrical parameters.

Many commercially available sizing programs for estimating kWh/kWp from PV systems follow the steps detailed below.

PV module database

Usually a simple dc model developed from indoor measurements and manufacturer's specification data (to estimate power vs irradiance and temperature).

Meteorological database

Input site latitude, longitude, array tilt and azimuth
Use TMY (Typical Meteorological Year) or a stochastic model to determine hourly values of

- Solar position, AOI (Angle Of Incidence) (calculated)
- POA (Plane of Array) irradiance, T_{AM}, WS (synthesized)

Site Data

- Simple estimate of shading
- Module temperature (depends on mounting method)

Simple BOS (balance of systems) model

- Inverter voltage limits for modules in a string
- Inverter efficiency vs P_{INPUT} and T_{AM}
- Likely $V_{TRACKING}$ errors.
- Estimate mismatch, wiring losses etc.

Each hour

- Use the POA Irradiance, T_{AM}, AOI etc.
- estimate T_M and PV Pmax.
- derate for dc losses, inverter efficiency, ac losses
- sum over the year to estimate kWh

Note that programs do <u>not</u> always take into account the following, which often dominate real kWh/kWp performance

- Actual/nominal Pmax ratio

- Allowances for degradation (particularly thin films)
- Spectral effects for multijunction devices
- Thermal annealing (for thin films)
- Dirt, snow etc.

3 WEATHER DATA ANALYSIS

ISET measure the following data every 15 seconds :

- Irradiance : 32° tilt, horizontal global and diffuse (using pyranometers and reference cells)
- Temperature : ambient and module temperature
- dc performance: (MPP) voltage and current
- ac performance : (Inverter) ac voltage and current

For this joint work the entire year 2003 was analysed at 15sec intervals. Figure 1 shows how the measured incident radiation (32° tilt) at each irradiance bin differed from that predicted by a stochastic model in a commercially available "Global Meteorological Database", where these are shown as 15 second measurements, 5 minute and hourly averages.

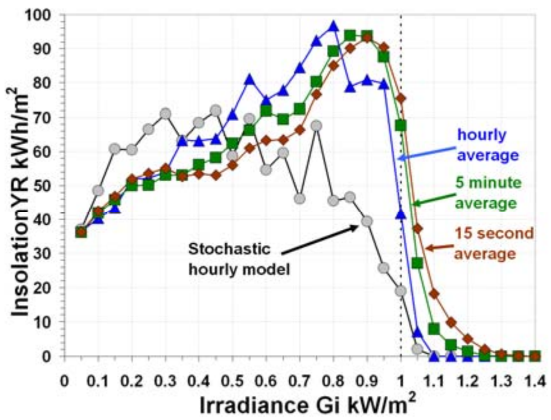

Figure 1: Plane of array insolation vs irradiance at ISET, 2003 comparing a stochastic hourly model to measured data and averages.

The stochastic model (based on [5]) suggests most of the incident radiation occurs below 0.6 kW/m², whereas the real measurements show that there is a steadily increasing amount of energy with rising irradiance from 0.1 to 0.8 kW/m^2. As the data is analysed at more frequent intervals it can be seen that an even larger proportion of energy occurs at higher light levels. On variable irradiance days (for example with bright scattered clouds) there are periods within the same hour of both cloudy and bright conditions. These would be averaged to a "dull" hourly irradiance value but over more frequent measurements the module would generate more energy at the high irradiance conditions and less at the darker times. Reference [4] shows how the irradiance distribution varied from 6 years of 10-minute data at the same site compared to hourly averages.

Figure 2 shows how the hourly stochastic model and hourly average of measured irradiance data suggest that there is less than 1% of energy available above 1 kW/m^2 however the 15 second averages for 2003 experienced more than 5% above this level. (Other sites in Germany have also found 5-7% of energy is generated at irradiances > 1kW/m^2)

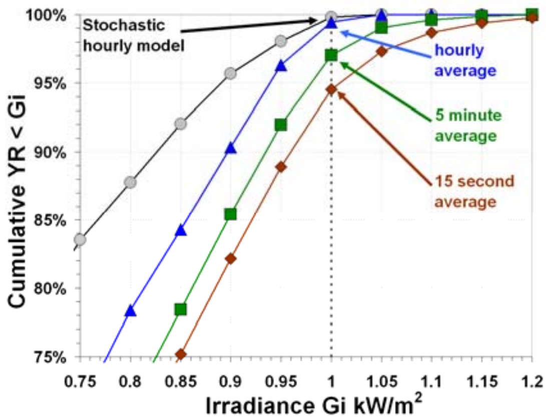

Figure 2: Cumulative percentage of yearly POA insolation below irradiance at ISET 2003.

It is common practice to install around 1.1 kWp STC of PV system per 1 kWp inverter. The assumption is that the PV system rarely produces the STC rating (as when the irradiance is high the module temperature will usually also be high and thermal effects will bring the modules to lower than their STC rating). A lower inverter power means that at low light levels the inverter is running at a higher Pin/Pnominal ratio and hence a higher efficiency, also a smaller inverter is cheaper than a larger one.

It can be expected that the greater "clipping" loss from a system from measuring at frequent intervals (compared with that expected from just hourly averaging) depends very much on the site and system parameters

- Weather : it will be worse for sites with a great deal of variable weather
- System size : it will be worse for systems with relatively low $P_{INVERTER}/P_{PV.STC}$ as the inverter saturation will be reached at a lower irradiance limit.
- Module technology : Hourly data will tend to over predict the performance of PV with falling efficiency as the light level rises, as it over predicts the insolation at low light levels.

A system designed with an inverter cut off when the Pin exceeded the Pinverter.nominal would give a 5% reduction in kWh/kWp as the energy above this value would be lost.

Figure 3 shows the amount of POA incident radiation at each module temperature bin.

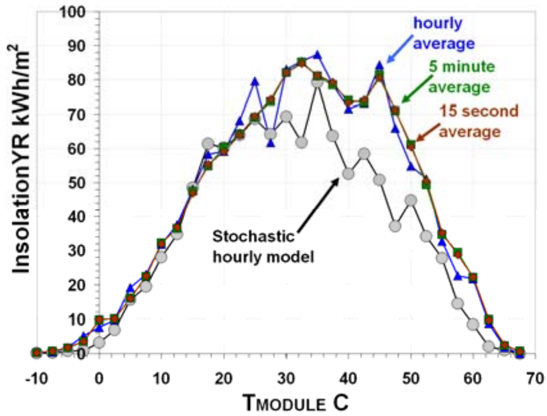

Figure 3: POA insolation vs module temperature in

ISET, 2003 showing a stochastic model vs measured data.

The stochastic model suggests a slightly lower module temperature than measured. Averaging the data from 15 secs to hourly has little effect on the distribution implying that the modules do not change temperature very quickly with varying irradiance due to their relatively high thermal mass.

From the entire year three different days of data "Clear", "Variable" and "Cloudy" were chosen to highlight the effect on performance. The days selected were close together to minimise any differences due to other effects like Tambient, AOI, day length etc. Table II summarises the days chosen.

Date Jun 2003	Weather Type	Insolation YR kWh/m^2	Max Gi noon kW/m^2	Max Tamb C	Max Tmod C
15th	**Clear**	8.07	1.05	28	55
20th	**Variable**	6.64	1.26	23	45
28th	**Cloudy**	2.28	0.1	24	34

Table II: Three different weather days studied

Figure 4 gives the POA irradiance vs time for the 3 days. The clear day only had a few dips below the expected bell shape irradiance curve. The variable day's irradiance varied from 0.2 (sun hidden by cloud) to 1.2 kW/m^2 (sun surrounded by bright cloud enhancing irradiance due to reflections). The cloudy day was below 0.1 kW/m^2 for most of the middle of the day.

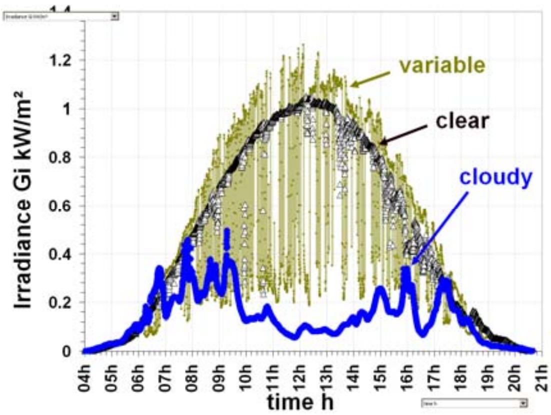

Figure 4: Irradiance measured every 15 second vs Time for three days at ISET, Kassel.

Figure 5 shows the corresponding module temperatures for the same days. Note how the module temperatures are around 10 °C lower for the variable cloud day than the clear day even from 11-13:00 when the irradiance was higher in Fig 4 (the module's temperature will change only slowly because of a high thermal mass after a step change in irradiance taking around 15 minutes to equilibrate) therefore the module temperature depends on the ambient plus a rise due to an average irradiance from the previous 15 minutes or so.

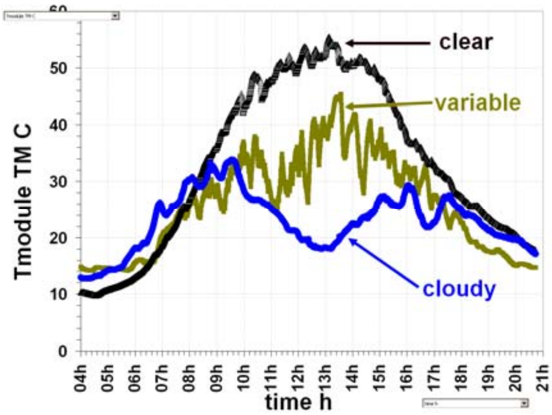

Figure 5: Module temperature measured every 15 seconds vs time for three days at ISET, Kassel.

5. AC PERFORMANCE vs IRRADIANCE INCLUDING SATURATION DUE TO INVERTER UNDERSIZE

Table III shows some of the technologies studied. Two ac crystalline modules were compared with one dc crystalline Si module in this test.

Abbreviation	Pmax Wp Module	Pmax W Inverter	Pmod/ Pinv
ac c-Si #1	130	150	0.87
ac c-Si #2	130	150	0.87
dc c-Si	85	N/A	∞

Table III: Module Technologies studied.

Figure 6 shows the ac yield YF kW/kWp vs irradiance for the variable day with respect to the clear and cloudy day. Apart from the scatter, for any irradiance > 0.6kW/m² the ac yield for the variable day is ~5% higher than for the cloudy day, at about 1.1 kW/m² it looks like the ac module inverter is saturating at around 0.9. Were it not for this then the power would probably rise even further – well above the clear day performance.

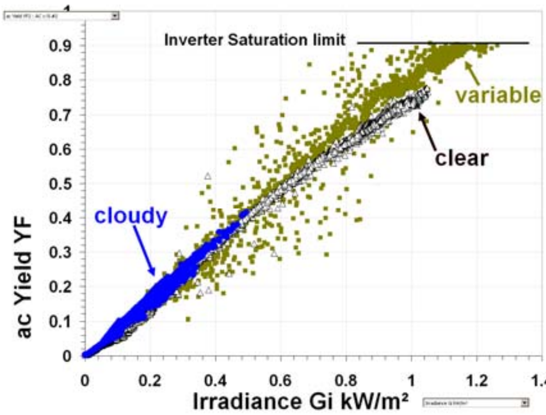

Figure 6 : ac yield vs irradiance for ac Si#2.

Figure 7 shows the dc data for a c-Si module showing there is no saturation at the higher light levels as there is no inverter present but the variable day still has ~5% better performance for a given irradiance than the clear day.

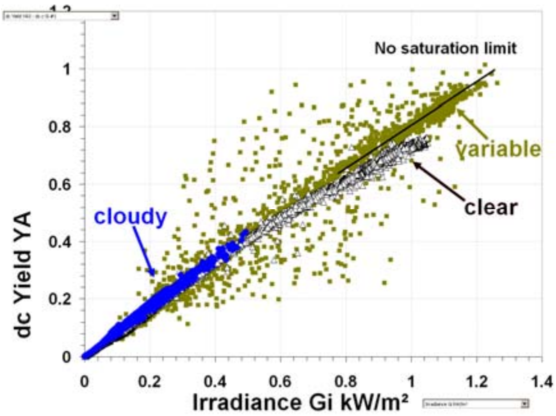

Figure 7 : dc yield vs irradiance for dc c-Si#1.

Figure 8 shows the Vdc/Vmax vs Irradiance for the ac c-Si#2. At higher irradiances (>0.2 kW/m²) we expect the Vdm value to fall with yield because the temperature of the module rises. This is true for the cloudy and clear days, this also happens on the variable day up to about 1.05kW/m². At higher irradiance the Vdm suddenly rises in an attempt to protect the inverter from too high an input power.

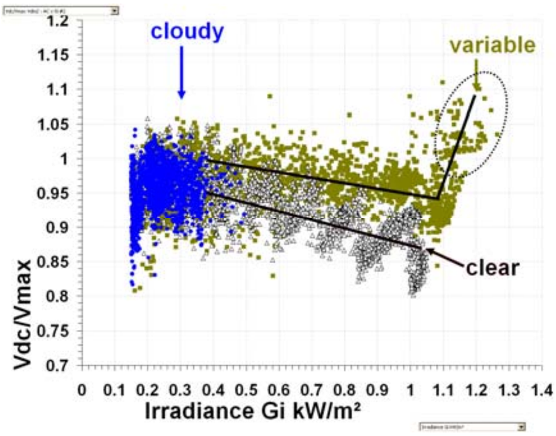

Figure 8: Vdc/Vmax vs Irradiance for the ac c-Si #2 system showing a rising voltage on the highest irradiances in an attempt to protect the inverter.

Figure 9 shows the irradiance, temperatures and Voltages with time for the ac c-Si#2 and dc c-Si modules. Note the Vdm of the dc module is only around 0.9 to 0.92 and varies slowly with module temperature. The Vdm of the ac system is much higher and varies quickly with the Irradiance. When the Gi is > 1.0 kW/m^2 the voltage rises in an attempt to stop the inverter overloading.

Note how irradiance is seen to change from 0.2 to 1.2 kW/m² in less than 15 seconds at 11:47.

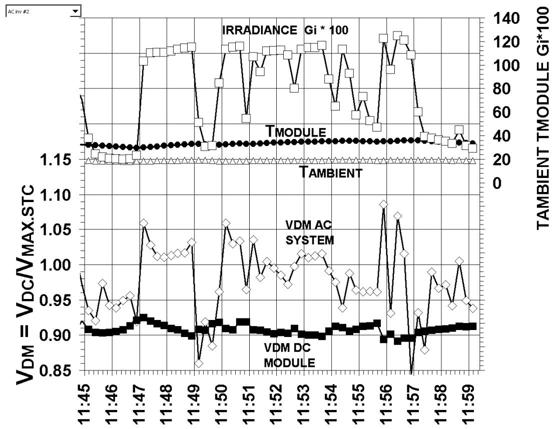

Figure 9 : ac Si#2 vs Time (variable day) showing dc Voltage Vdm very high (>>0.95) as the irradiance rises to lower the input power and protect the inverter. This is not the case with the dc module.

7 CONCLUSIONS

- Real, very frequent measurements show higher energy at higher irradiance than hourly models predict.
- Inverter Power rating needs to consider the amount of energy at high irradiances (which may only be seen with frequent measurements) and also the maximum irradiance expected.
- Very rapid changes of irradiance have been seen in Germany, 200 to 1200W/m² in less than 15 seconds.
- Measurement frequencies of better than every 5 minutes are required to model modules which have a good > 1 kW/m^2 performance and distinguish those with falling efficiency at high light levels.

8 REFERENCES

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9 ACKNOWLEDGEMENTS

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