A REVIEW OF kWh/kW$_p$ MEASUREMENTS, ANALYSIS AND MODELLING

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ABSTRACT: kWh/kWp energy yield comparisons have been measured and modelled around the world for many years using individual modules or large arrays [1]-[7]. Most studies just publish one value of kWh energy yield over a year. Often tests disagree with each other as to which technology (e.g. c-Si or a Thin Film) or which manufacturer gives the highest yields. In their conclusions authors often attribute variations in yield to be technology related due to differences in intrinsic properties e.g. relative performance at low light levels, high angle of incidence, high diffuse fraction or high temperatures. However without analysing and reporting the raw data there is no way to determine which of several factors are the most critical to determine the final energy yield.

This paper analyses in detail a study performed by ISET on seven different technologies to determine how to tell which factors were the most important.

Keywords: Energy Performance, Modelling, System Performance.

1 INTRODUCTION

kWh/kWp figures are often considered important in the solar industry. Table 1 lists the interested parties and the effect of kWh/kWp for them.

Table 1: Relevance of kWh/kW$_P$ to parts of the solar industry.

Part of industry	kWh/kWp relevance
Manufacturers	Claim high performance from their products
Indoor testers	Try to measure parameters relevant to outdoor performance
Sizing programs	Claim accurate predictions
Customers	Expect high values
Financial	Demand guaranteed values over lifetime
3rd party outdoor comparisons	Get different rankings for each technology

However there will be inevitable differences between modules from the same production run as variability in for P_{MAX} and R_{SHUNT} cause variations in energy yield – the variability from nominally identical modules is rarely considered in kWh/kWp tests.

Many manufacturers grade modules into power bins of up to ±2.5% (e.g. 200-210W$_P$). The accuracy of calibration modules sent to test institutes is usually of the order ± 2% so a variability of around 4.5% can be expected from these two effects alone [4][5].

Thin film manufacturers have traditionally supplied modules with initial P_{MAX} higher than specified to cope with high expected initial degradation levels (up to 35% for some product types) so some may (at least initially) outperform crystalline silicon cells based on nominal or initial P_{MAX} [2].

Down time or measurement error can significantly influence kWh/kWp output (perhaps a thermocouple may not be working or an mpp tracker may not have found the optimum voltage). It is not often clear how studies have corrected for these errors (perhaps they have been interpolated, ignored or analysed by regression fit) and so any declaration of performance must acknowledge the uncertainty due to these corrections.

In studying raw data from other test sites many effects have been identified on one or more installations (and for which little or no attempt had been made to correct for them) which would invalidated their findings. These are listed in table 2:-

Table 2. Possible reasons found at other sites for wrong module performance.

Possible Reason	Comments	Origin of Fault
Overrated Pmax	Higher nameplate than measured Wp	Module manufacturer calibration
Degradation	Worsening performance with time	Module instability
Poor low light level performance	(could be due to Rshunt)	Module Technology or fault
Poor high Temperature performance	(c-Si is usually worse than Thin Film)	Module technology or mounting method (e.g. roof tiles)
Downtime	May vary between different channels	Measurement setup
Dry joints	May go open circuit under extreme conditions	Module or Measurement
Nearby shading (trees etc.)	May vary between channels	Measurement location
Inverter sizing	May saturate if poorly dimensioned	System design
Poor voltage tracking	Optimum string voltage may reach tracker end stops or tracker may not be working	Voltage tracker or system design
High horizon shading	Low performance early and late in the day	Location
Spikes in data	Large values can corrupt sums if not corrected for	Measurement, error, needs checking
Non coplanar	Performance will	Orientation of

array and sensor	appear to vary through the day.	sensor, must be close to array
Poor quality irradiance sensor	kWh/kWp values depend on accuracy and suitability of sensors	Sensor

For correct kWh/kWp comparison measurements the values of plane of array Irradiance, ambient and module temperature, M_{PP} voltage and current all need to be checked simultaneously that they are within sensible limits for all modules before the data can be included in the energy yield sum.

2 THIS STUDY

A thorough analysis was performed on data obtained from ISET, Kassel from their study of different module technologies in central Germany. Seven modules were measured for a year, all from different manufacturers. These are listed below in random order which is deliberately not the same as the graphs :-

Crystalline Si	**Mono** **Multi** **Ribbon**
Thin Film	**CdTe** **CIS** **Multi junction a-Si** **Single junction a-Si**

Figure 1 shows part of ISET's facilities. Modules were tilted at 32° south, loaded at V_{MPP} and averaged measurements taken every 10 minutes of T_{MODULE} (C), V_{MPP} (V), I_{MPP} (A) from which P_{MAX} was calculated

Figure 1: Test facilities at ISET, Kassel (courtesy ISET) http://www.iset.uni-kassel.de/abt/FB-A/Testfeld/Webcam.html

Meteorological data gathered included pyranometers for tilted global, horizontal diffuse and global irradiance (kW/m²); relative humidity (%), ambient pressure (P), precipitation (mm), wind speed (ms^{-1}) and ambient temperature (C).

Measuring modules then summing the energy output over a whole year and dividing by the module nameplate reading gives a value of kWh$_{DC}$/kWp.

Figure 2 shows the raw values achieved for the three c-Si modules (#1 to #3) in blue and the four thin film modules (#4 to #7) in red.

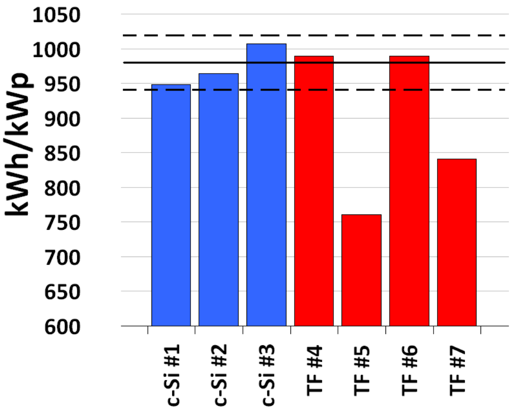

Figure 2: Raw data of measured kWh$_{DC}$/kWp for seven modules in Kassel, Germany measured for 1 year (not the same order as in the listing above).

The kWh$_{DC}$/kWp values for five of the modules (all the c-Si and TF modules #4 and #6) are within ± 4% of each other (horizontal lines) whereas the values for TF modules #5 and #7 are much lower. (The minimum variability of measurements will be ~±2% for the width of a module power band and ~±2% from the accuracy quoted by calibration laboratories [TISO])

Most reports seen so far show data in this format with little further analysis as to what causes the effects nor allowance for the ±4% uncertainty.

3 DEFINITIONS OF NORMALISED VALUES

For further analysis normalized values of parameters are used (where possible with the exception of temperature and wind) to compare the performance of modules of different technologies (defined in Table 3)

Table 3. Definitions and graph colours used of measured and normalized parameters.

Abbr.	Formula	Unit	Comment
G_I	$G_{I.MEAS}/G_{I.STC}$	kW/m^2	Normalised Tilted plane Irradiance
T_{AMB}	(air temperature)	C	Measured ambient Temperature
T	(back of module temperature)	C	Measured module Temperature
WS	(wind speed)	ms^{-1}	Measured wind speed
V	$V_{DM}= V_{DC} / V_{MAX.STC}$	Dimens-ionless	Normalised V_{MAX}
I	$I_{DN}= I_{DC} / I_{MAX.STC}/G_I$	Dimens-ionless	Normalised I_{MAX}
PF	$= V_{DM} * I_{DN} =EFF_{DC}/EFF._{STC}$	Dimens-ionless	Performance Factor
P	$= P_{DC} / P_{MAX.STC} = PF * GI$	Dimens-ionless	DC Power

4 PERFORMANCE FACTOR vs IRRADIANCE

(Figures 3-6 show approximately 10% of the 10 minute average measurements made over the year for clarity.)

Figure 3 compares the performance factor (PF=ηDC/ηSTC) of three modules #3, #5 and #7. Note that the c-Si module #3 has higher PF at all light levels than the poor Thin Film modules. Its value falls faster as the irradiance rises as the c–Si temperature coefficient is higher than those of a-Si. Note though how the PF of the TF#5 falls rapidly at low light level (below 0.4).

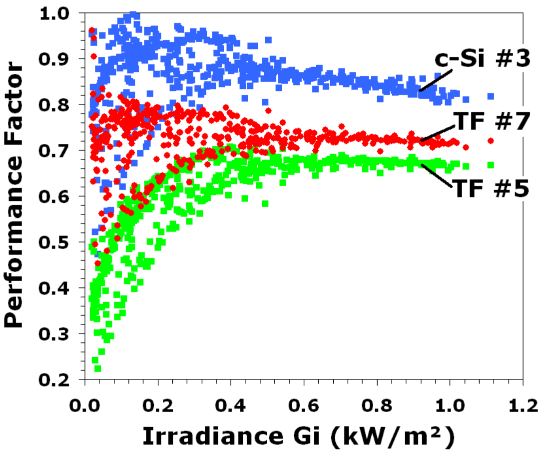

Figure 3: DC Performance factor vs. Irradiance for modules c-Si #3 and the poor TF modules #5 and #7.

To further analyse the performance of these three modules the values of V, I, P and T were plotted on three adjacent figures 4-6.

The usual shapes of these plots for modules performing well are described below

- **T** (red -right axis)– the average is around 15C at lowest light level and 45C at the highest values for Germany.
- **V** (blue). Usually the value will peak at around 0.95 and 0.4kW/m^2, falling fast at very low light levels and slowly at higher light levels (where the module temperature will be high).
- **I** (black) - will tend to be fairly flat at high irradiances. At lower values there may be two separate traces – one falling where there is a clear sky/high angle of incidence and one becoming increasingly variable at lowest light level – this indicates a mix of variable/diffuse irradiance/snow cover conditions.
- **P** (purple) illustrates the measured/nameplate power. For a perfect device with no thermal losses it should follow the grey straight line (with a gradient of 1:1). Usually modules will curve a little downwards at higher light/temperature due to thermal and I^2R losses. The slope at lower light levels indicates the apparent/nameplate power.

Figure 4 shows the c-Si module #3 which performs well (similarly to the other c-Si modules and TF #4 and #6). The I_{DN} current is around 0.95, the voltage peaks at ~0.95 and the power is close to the grey line at low light, deviating a little at higher light.

Module TF #5 in figure 5 has a very poor low light level voltage falling rapidly below 0.4kW/m². Also the high light current is lower at around 0.75, rising slowly below 0.2kW/m². Note the P line is much lower than for Figure 4.

Module TF #7 in figure 6 has lower values of current and voltage than the c-Si #3 although they do not vary as much with varying irradiance and temperature. Note the P line is much lower than for Figure 4

Voltage, Current, Power and Temperature of modules vs. Irradiance.

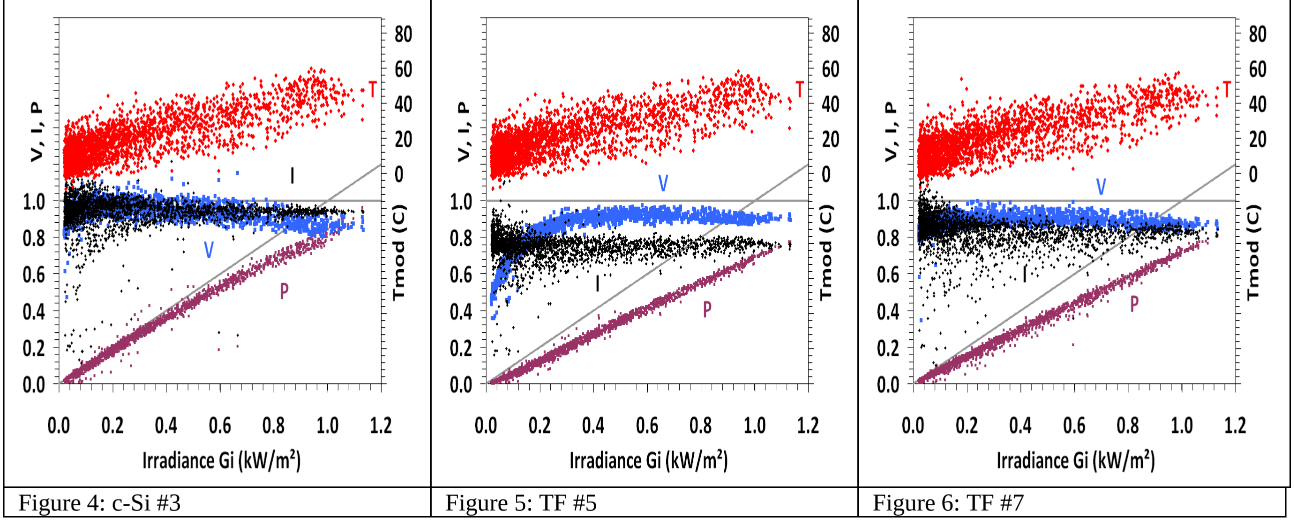

Figure 4: c-Si #3

Figure 5: TF #5

Figure 6: TF #7

5 EMPIRICAL MODELLING

Equations <1> to <3> can be used to help separate out the effects causing the variations between modules for the voltage, temperature and power.

Empirical coefficients A to E translate the performance values as they depend on Temperature, irradiance and Wind speed.

$$T_{MOD.CALC} = C_{TM}*T_{AMB} + Gi*(A_{TM} + D_{TM}*WS) + E_{TM} \qquad \text{<1>}$$

$$V_{DM.CALC}=A_{VDM}*LOG_{10}(Gi) + B_{VDM}/Gi + C_{VDM}*T + D_{VDM}*WS + E_{VDM} \qquad \text{<2>}$$

$$YA_{.CALC}=Gi*(A_{YA} + B_{YA}*Gi + C_{YA}*T + D_{YA}*WS) - E_{YA} \qquad \text{<3>}$$

RMS errors of <3C are usually found for the $T_{MOD.CALC}$; usually <2% for V_{DM} and ~1% for YA_{CALC}.

These coefficients are derived from a subset of the data and can then be used to determine the correct performance of the module, figures 7 and 8 compare the predicted vs. measured powers and voltages of module #3 and #5.

The good agreements show that the coefficients do accurately model the modules and that the poor performance of #5 is due to its low light level drop due to shunt resistance.

Predicted vs. measured powers and voltages

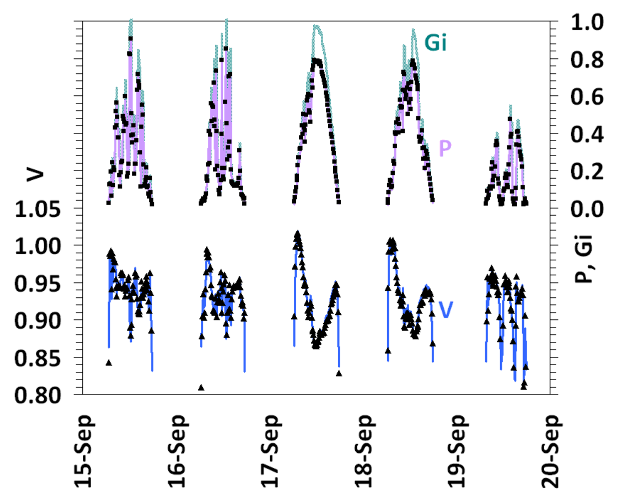

Figure 7: Empirically predicted vs. measured powers and voltages of module #3.

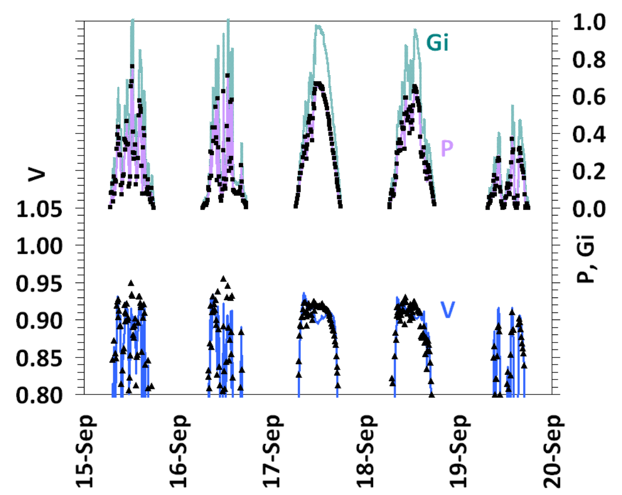

Figure 8: Empirically predicted vs. measured powers and voltages of module #5.

Table 4 Lists the values of the empirical coefficients for the three chosen modules #3, #5 and #7.

Table 4: Empirical coefficients

T_{MOD}	**A_{TM}**		**C_{TM}**	**D_{TM}**	**E_{TM}**	**RMS ERR_{TM}**
#3	28.4C		106%	-2.9	-0.9C	2.4C
#5	24.3C		109%	-1.6	-0.4C	2.9C
#7	25.1C		107%	-2.5	-0.5C	2.4C
VDM	**A_{VDM}**	**B_{VDM}**	**C_{VDM}**	**D_{VDM}**	**E_{VDM}**	**RMS ERR_{VDM}**
#3	-1.2%	-0.61%	-0.43%	-0.06%	107%	0.6%
#5	10.4%	-1.60%	-0.20%	-0.08%	103%	2.0%
#7	3.9%	-0.28%	-0.28%	-0.03%	99%	0.7%
YA	**A_{YA}**	**B_{YA}**	**C_{YA}**	**D_{YA}**	**E_{YA}**	**RMS ERR_{YA}**
#3	99.4%	-7.5%	-0.24%	0.4%	0.3%	1.2%
#5	71.2%	-4.6%	0.09%	0.0%	1.8%	1.2%
#7	69.1%	-7.2%	0.19%	0.8%	-0.4%	1.2%

Important points to note are :-

1) Temperatures are all well behaved

2) Value of B_{VDM} indicates shunt resistance/low light level fall in voltage in module #5

3) C_{VDM} is the beta voltage coefficient (distinguishing c-Si #3 from the TF modules)

$$\beta = 1/V_{MAX} * dV_{MAX}/dT_{MOD}$$

4) The most important parameter for overall performance due to efficiency vs. light level is A_{YA} and this is clearly superior for the module #3 over #5 and #7.

6 PERFORMANCE vs DIFFUSE FRACTION

Another effect often claimed but rarely measured or modelled correctly is the difference in performance vs. light level for “mostly beam” and “mostly diffuse” light. Figure 9 plots the performance factor vs. irradiance for mostly diffuse (left - light) and mostly beam (right - dark) radiation for modules #3 and #5. Whereas the PF of the c-Si module improves at lower light level (it has good diffuse light capture and the temperature is reducing) the performance of the poor module #5 falls rapidly as the light level falls.

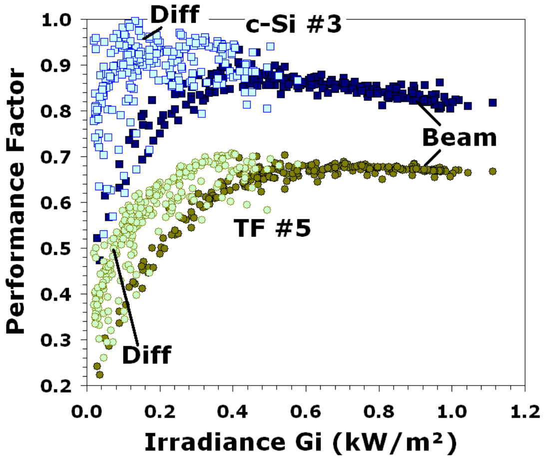

Figure 9: DC Performance factor vs. Irradiance for modules c-Si #3 and the poor TF module #5.

When studying the performance of modules vs. light level or diffuse:beam ratio it is important to know how much energy would be generated at each bin. For example most arrays spend half their time under star, moon and street lights but the efficiency under these extremely low irradiances does not affect the energy yield as by far the greatest insolation happens at higher irradiances.

Figure 10 gives the Insolation vs. Beam Fraction (green line) showing that although there is a local maximum near the diffuse end the majority of the insolation takes place at high direct radiation. The columns show the energy produced by the three modules, the drop in TF #5 is apparent under diffuse conditions.

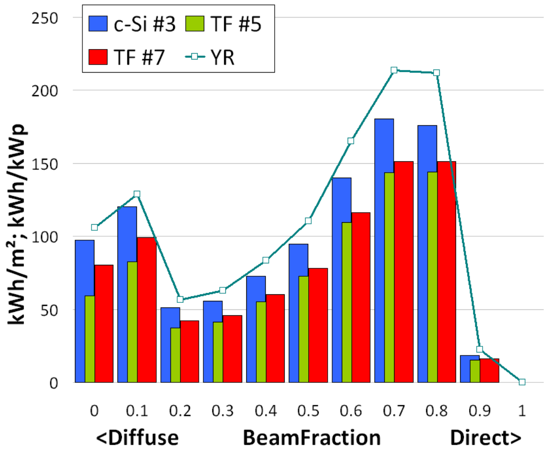

Figure 10: Insolation YR and DC Performance factor vs. Beam Fraction modules c-Si #3 and the poor TF modules #5 and #7.

In comparison figure 11 gives the Insolation vs. Irradiance (green line) showing that the majority of the insolation takes place at high irradiance. The columns again show the energy produced by the three modules, the drop in TF #5 is apparent under low light conditions

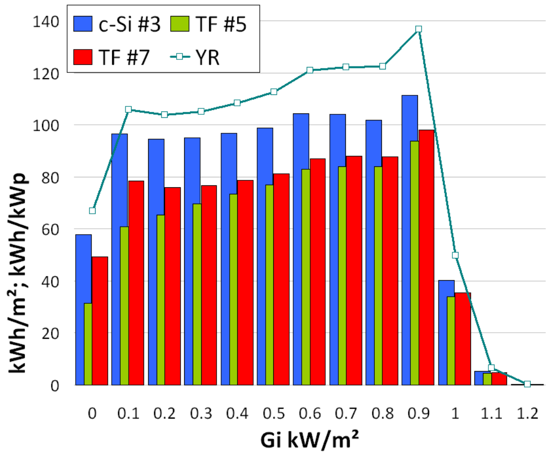

Figure 11: Insolation YR and DC Performance factor vs. Irradiance Gi for modules c-Si #3 and the poor TF modules #5 and #7.

10 CHECKING DOWNTIME AND DEGRADATION

Figure 12 illustrates how to check for downtime and or degradation for any or all of the modules. The graph shows an xy-plot giving the relative percentages of energy of each of the three modules #3, #5 and #7 vs. time. Table 5 explains how to read the graph.

Here we can see insignificant amounts of downtime (there are a few glitches in Feb and one in Nov where the a-Si #7 over performed – this could be snow on the other modules?), no apparent degradation during the test and only a small winter improvement of the fraction of energy from the c-Si, likely to be temperature (and perhaps a small amount of spectrum) dependent.

Table 5: How to understand figure 12 for checking downtime and degradation.

Electrical effect	**Appearance on Graph**
Degradation: of one or more modules :	The relative percentages of energy would change – for example rising Rseries would show at high Irradiance, falling Rshunt would worsen the low light performance.
Downtime: for all of the modules:	There would be periods of flat lines where no data was collected
Downtime: for some (not all channels)	These modules would not contribute and so the fraction of energy produced would jump for the remaining modules
Seasonal effects	There may be slight oscillations over the year as modules with different temperature, spectral or light level dependencies contribute changing amounts

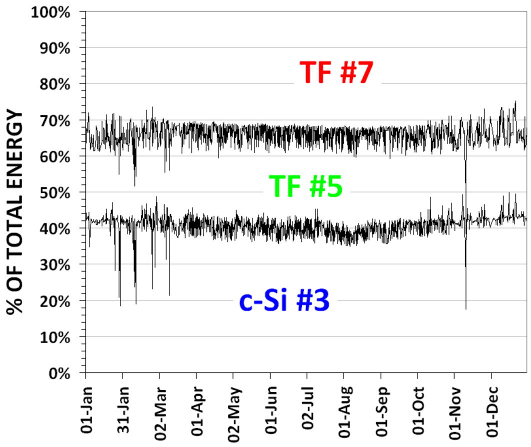

Figure 12: Percentage of total energy produced by three modules over time - checking for downtime and/or degradation.

7 CONCLUSIONS

- A study of yearly kWh/kWp values for seven different module technologies in Germany showed differences that could not have their causes identified from just the yearly sum alone.
- There was insignificant downtime or degradation during the tests.
- All three crystalline modules and two of the thin films modules gave kWh/kWp within ±4% of each other.
- All modules except one (#5) showed different power vs. irradiance curves for mostly diffuse or mostly direct radiation, at low light levels the direct fell due to angle of incidence and/or spectrum whereas the diffuse rose (presumably due to cooler temperatures and lower I^2R losses).
- Thin film module #5 gave poor kWh/kWp performance because of its low current and poor low light level voltage
- Thin Film module #7 gave poor kWh/kWp because of its low (but variable) current.
- Measuring just one module of each type does not show if poor performance is due to a lower than expected module or if degradation is due to just the one module or the technology in general.
- Little variability in energy yield was found in a German climate to be attributable to “low light level”, “high diffuse” or “high temperature” differences between c-Si and thin films.
- The other two thin film modules gave similar kWh/kWp values to the three crystalline although they were obviously lower efficiency.

8 ACKNOWLEDGEMENTS

Peter Funtan and ISET for the measurement data.

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