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Temperature Coefficient Measurements of PV Modules and Uncertainty Analysis

B. Mihaylov*, M. Bliss, T.R. Betts, R. Gottschalg

Centre for Renewable Energy Systems Technology, School of Electronic, Electrical and Systems Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

*Tel.: +44 1509 635342, Email: B.V.Mihaylov@lboro.ac.uk

Abstract

Temperature coefficient (TC) measurements of PV devices are required for energy yield estimations. However, a large deviation in measurement results is still being reported. This paper outlines the measurement setup at CREST, the sources of uncertainty and their estimation and methods for propagating them to the final uncertainty of the TC. While for very small uncertainties Ordinary Least Squares (OLS) linear regression may be appropriate for realistic uncertainties a Weighted Total Least Squares (WTLS) is recommended.

1 Introduction

The TC for Isc (α), Voc (β) and Pmax (δ) of modules are essential for a number of analyses, comparisons between modules at different conditions and energy yield estimations. These are measured according to IEC standards 61215 [1] and 60891 [2]. The procedure involves measuring the performance parameters of the modules (typically full I-V curves) at different operating temperatures, fitting a straight line to each parameter from the measurement data via linear regression and using their slopes as the TC for the different parameters.

A recent inter-comparison between European laboratories of measurements of the TC of c-Si modules showed a deviation in the range of ±90% for α, ±10% for β and ±15% for δ with some laboratories significantly underestimating their uncertainties. The impact of this on power output at different temperatures or on energy yield for a site with a known meteorological data set can be estimated. For a typical c-Si module with δ = -0.4 %/°C, a 15% uncertainty corresponds to 0.06%/°C in Pmax. At an operating temperature of 55 degrees this corresponds to an error of 1.8% in Pmax. The impact of this would vary for different sites. For Penzance, UK for example, the difference in the predicted annual energy loss due to temperature with the smallest and the largest δ measurements is 0.2% for El Paso, Texas it is 2.15%.This translates into additional financial risk.

This paper outlines the TC measurement system at CREST. The uncertainty sources and their estimated contributions are described. Different methods for the regression and for propagating the uncertainties are compared and validated with a Monte Carlo simulation.

2 Setup description

TCs can be measured using indoor or outdoor methods, each setup having different advantages and disadvantages and different major sources of uncertainty. The TC measurement system at CREST is an indoor one. The measured module is mounted in an insulating case and heated to 75+°C via a contact heating mat. The temperature is monitored at three places at the back of the module and two places at the front (by integrated Pt100 sensors in the case door), whilst the case is closed. When the module temperature has stabilized (the difference between all sensors is within a particular tolerance e.g. 0.5°C), the case is opened and the module flashed while the I-V characteristics are taken. This process is repeated until the module has cooled to room temperature. The reference cell (RC) used for monitoring the irradiance is outside the case and remains at a steady temperature throughout. A thermal camera is used to check the temperature deviation across the front surface of the module. In Figure 1a) it can be seen that the junction box plays a role in the non-uniformity of the module temperature at higher temperatures, i.e. 70°C, because the amount of effective insulation at this point is limited. This effect is not as prominent at lower temperatures such as 35°C (see Figure 1b). However the effects of the module metal frame on the temperature non-uniformity due to its higher thermal conductivity and emissivity can still be observed.

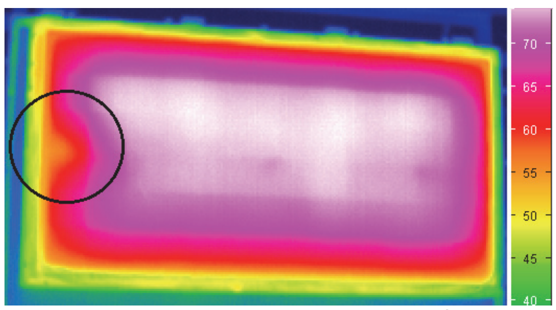

Figure 1a) Module temperature non-uniformity at 70°C. The circle highlights the junction box.

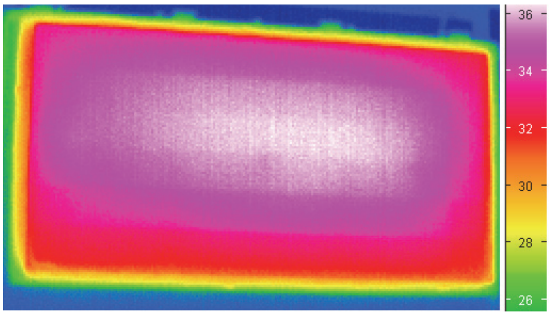

Figure 1b) Module temperature non-uniformity at 35°C. The junction box effect is no longer visible.

It should be noted that the front glass surface of the module can reflect other sources of heat and sometimes, where the setup allows, it is better to measure the uniformity at the back of the module.

Most indoor setups follow similar principles, but with varying cases and methods for temperature control. Most are temperature-controlled chambers with a glass window that could affect the measurements in a systematic way. This can be avoided by placing the RC behind the same glass but outside the temperature-controlled case.

3 Sources of uncertainty in TC measurements.

The sources of uncertainty in the Isc, Voc and Pmax measurements as well as those of temperature have to be considered first. Since only the slope of the straight-line fit is of interest, only relative measurements are important for both temperature (X axis) and current, voltage or power (Y axis) measurements. Therefore, the sources of uncertainty that cancel out can be neglected. An example of such a source is the calibration of the RC. Any error on its calibration value will remain constant during the measurement set. The same applies for the relative positioning and orientation of the reference cell and the device under test to each other. A list of all the sources is included in Table 1 with the non-relative contributors underlined and in italic.

Uncertainty sources in Temperature measurements	
	Deviation between sensors and junction
	Temperature difference across the module
	Calibration of temp sensor
Uncertainty sources in performance measurements.	
In Irradiance intensity	
	Reference cell calibration uncertainty
	Reference cell drift
	Biasing of the reference cell near I_{sc}
	Irradiance non-uniformity at the target
	Orientation of device-under-test and RC
	Position of device-under-test and RC
	Stability of source intensity
	Temperature of reference cell
In Irradiance spectrum	
	Mismatch factor (spectral response + irradiance spectral distribution)
	Filter deterioration and lamp aging
	Stability of source spectrum
Uncertainty sources in the data acquisition (DAQ)	
	DAQ offset and range
	Series resistance due to connectors and packaging
	Room temperature effect on the measuring equipment
	Shunt resistors calibration and temperature effect
	Parameter extraction uncertainty

Table 1 Sources of uncertainty in indoor TC measurements. Non-relative sources are underlined and in italic.

3.1 Estimating the uncertainty contribution

An estimate is made for each source of uncertainty and a probability density function assigned. These are propagated according to the GUM guide [3] into an overall uncertainty for performance measurements (e.g Pmax) and temperature measurements. The performance uncertainty is expressed in percentage terms. The temperature uncertainty is in absolute terms °C, but also varies with temperature. For the measurement system at CREST, the relative Pmax measurement uncertainty used for TC calculation is 0.5% (at k=1, assuming Gaussian distributions). The temperature measurement uncertainty is as shown in Table 2 below.

Temp	25.0	35.0	45.0	55.0	65.0	75.0
T dev across	0.5	1.5	2.5	3.5	4.5	5.5
Junction to Back	0.50	0.50	0.50	0.50	0.50	0.50
DAQ	0.05	0.07	0.09	0.11	0.13	0.15
Total (K=1)	0.409	0.914	1.473	2.042	2.615	3.190
T across effective	0.5	0.5	1.0	1.5	2.0	2.5
Total eff (K=1)	0.409	0.409	0.646	0.914	1.191	1.473

Table 2 Estimation of the temperature uncertainties. All estimates are in °C.

The difference in temperature uncertainty is due to the uniformity of the module and is based on thermal camera images (e.g. Figure 1) see second row of Table 2. This is a worst-case estimate and a very conservative one. The effective temperature of the module is approximately the average temperature of all the wafers in the module, which is closer to the temperature measured in the middle at the back than indicted by the full temperature deviation across the front surface of the module. The uncertainty in temperature can be minimised by correcting with the effective temperature of the module. The implementation of this is currently under development at CREST. Even though the correction is not currently implemented, its magnitude is known to be less than 2.5 °C at 75 °C. The effect of the temperature deviation across the module is then re-calculated and the total uncertainty used for the calculation of the TC measurement uncertainty is reported in the last row of Table 2.

3.2 *Additional uncertainty in the TC for energy yield*

It should be noted that the temperature dependence can be non-linear [4] and light source spectrum dependent, but it is often assumed that it is not. These assumptions can increase the uncertainty for some modules. A further consideration is that coefficients are often stated in %/°C, i.e. they are normalised by the measurement at 25°C, which has its own uncertainty. Finally King [5] differentiates between effective or apparent coefficients measured outdoors on the same mounting rack as they would be in practice and 'true' temperature coefficients measured indoors. This difference can introduce additional uncertainty in the energy yield estimates.

4 Uncertainty propagation.

In this section, different methods for calculating the temperature coefficients and their uncertainty are discussed alongside their limitations. A Monte Carlo approach is used to compare and validate the chosen methods.

4.1 *Ordinary least squares fit.*

Most tools used for linear fitting of data calculate the Ordinary Least Squares (OLS) regression that minimises the sum of squares of the differences between the predicted and measured values. The standard deviation of this type of regression is straightforward and can be analytically derived. Note that the 95% confidence interval has to be scaled using a student-t distribution and calculating the effective degrees of freedom based on the number of measurements. There are certain limitations to this approach, because it assumes that the uncertainty in the X axis is negligible, that the uncertainty in Y axis is constant and that the residuals are randomly spread.

4.2 *Total least squares fit*

Module temperature measurements have uncertainties that are not negligible. Using a total least squares fit minimises the orthogonal distance between the predicted value and the measurement point. Estimating the variance and standard deviation is no longer easily solved analytically but numerical methods or a Monte Carlo (MC) approach can be used. Alternatively an approximated analytical method can be used as in [6].

4.3 *Weighted total/ordinary least squares fit.*

Considering the residuals of a TC fit, it can be seen that they are not randomly scattered (see Figure 2). This is an indication that the uncertainties in X and Y are not constant as supported by our uncertainty analysis. In addition, the linear model used may not be appropriate for all modules as suggested in [4].

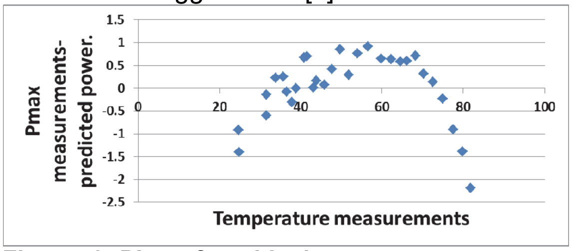

Figure 2 Plot of residuals versus temperature measurements.

A weighted least squares fit can account for varying uncertainties. The contribution of each point to the regression is weighted according to uncertainty of that point. Using this method will, for example, give a lower weight to the value measured at 75°C with high uncertainty. A stable algorithm that reduces the problem to a one dimensional minimisation is described in [7].The algorithm also calculates the variance and thus the uncertainty (standard deviation) of the fit.

In order to choose the appropriate method for calculating the temperature coefficients and their uncertainty for the system at CREST, 100000 simulated measurement data sets were created which follow the probability density functions assigned as part of the uncertainty assessment. Note that these are all randomly distributed. The temperature coefficients and their uncertainties were estimated using both an Ordinary Least Squares fit and Weighted Total Least Squares fit (WTLS).

A similar approach was taken for a hypothetical measurement system with lower uncertainties in both temperature measurements (X axis) and Pmax measurements (Y axis) and for one with lower uncertainty only in X axis. The uncertainties used for the simulation (Ux being the uncertainty in temperature measurements and Uy the uncertainty in Pmax measurements) are included in Table 3 below.

The results of the simulations are summarised in Tables 4-6. The first and third rows show the max, min, mean and standard deviation of all 100000 regression fits with the two methods. The standard deviation of all fits is the uncertainty of the parent population, i.e. the predicted uncertainty according to the MC method. The second and fourth rows show the statistical information for the uncertainties predicted by each method.

With low uncertainties in temperature measurements, both methods are appropriate and the mean uncertainty of all regressions, each corresponding to a set of measurements, agrees with the uncertainty predicted by the Monte Carlo method. However the OLS has a much larger spread in the uncertainties and can underestimate for certain measurement sets.

At higher uncertainties for temperature measurements the OLS method becomes less appropriate, the mean of the regression slopes moves away from the true value (-0.7458). Also the uncertainty estimate for some sample populations is significantly smaller than the standard deviation of the parent population. Swapping the dependent and independent variables used for the regression (not shown here) did not show any significant improvement for the OLS.

	Low Ux & Low Uy	Low Ux & Normal Uy	Normal Ux & Normal Uy
Upmax	0.30%	0.50%	0.50%
Utemp @:			
25°C-35°C	0.1°C	0.1°C	0.409°C
40°C-45°C	0.15°C	0.15°C	0.646°C
50°C-55°C	0.15°C	0.15°C	0.914°C
60°C	0.15°C	0.15°C	1.191°C
65°C	0.2°C	0.2°C	1.191°C
70°C-75°C	0.2°C	0.2°C	1.473°C

Table 3 Uncertainties of relative measurements of power and temperature used for the simulation.

Low Temp and Pmax uncertainty				
	Max	*Mean*	*Min*	*Std*
WTLS	-0.7086	-0.7458	-0.7837	0.0097
Unc WTLS	0.0098	0.0097	0.0096	3.3E-05
OLS	-0.7082	-0.7457	-0.7835	0.0097
Unc OLS	0.0166	0.0095	0.0021	0.0017

Table 4 Summary of regression slopes (TC of Pmax in W/°C) and their uncertainty at low Ux, Uy

Low Temp and normal Pmax uncertainty				
	Max	*Mean*	*Min*	*Std*
WTLS	-0.6874	-0.7458	-0.8067	0.0158
Unc WTLS	0.0160	0.0158	0.0156	5.1E-05
OLS	-0.6870	-0.7458	-0.8053	0.0159
Unc OLS	0.0259	0.0156	0.0039	0.0028

Table 5 Summary of regression slopes and their uncertainties at low Ux and normal Uy.

Normal Temp and Pmax uncertainty				
	Max	*Mean*	*Min*	*Std*
WTLS	-0.6615	-0.7460	-0.8321	0.0212
Unc WTLS	0.0237	0.0212	0.0191	5.6E-04
OLS	-0.6562	-0.7438	-0.8310	0.0216
Unc OLS	0.0404	0.0203	0.0035	0.0043

Table 6 Summary of regression slopes and their uncertainties at normal Ux and normal Uy.

5 Conclusions

Large deviations in the TC coefficients of modules are still being reported which can have a significant impact on energy yield predictions. Therefore any TC measurements have to be supported with a stated uncertainty. Producing an estimate involved identifying the sources of uncertainty and propagating them to estimate the total uncertainty in both Temperature and Pmax measurements. Two regression methods were compared. While the OLS method maybe appropriate for setups with extremely low uncertainties it can underestimate the uncertainty of the TC for other scenarios. The WTLS method always gave superior results. The uncertainty of the TC has to account for the normalisation to the STC measurements and their uncertainties. Finally for energy yield estimates the uncertainty of non-linearity and effective versus 'true' TC has to be considered.

Acknowledgements

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