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Review of Uncertainty Sources in Indoor PV Calibration of c-Si and Thin Film Single-Junction and Multi-Junction Cells and Modules

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Abstract

The calibration of PV devices requires an uncertainty analysis. However, the benefits of such analysis are not limited to calibration procedures. It can be useful for all PV device measurements since it increases the validity of the results. The sources of uncertainty in indoor PV device calibration are outlined. The uncertainties are discussed for different measurement setups and technologies. Indoor secondary calibration uncertainty in P_{\max} can range from less than 1.5% for c-Si cells to more than 10% for large TF modules. The paper highlights the importance of understanding the uncertainty sources and conducting specific uncertainty calculations for a given measurement setup. The implications for research laboratories are that excessively large uncertainty in measurements can make comparison between results misleading and the conclusions questionable.

1 Introduction

Every measurement is an estimation of the true value of the measurand. The uncertainty associated with measurements is an indication of the quality of a test method and its results. It is fundamentally important to researchers and their publications and it is essential to laboratories and their stakeholders. Other indicators such as repeatability and reproducibility give confidence in the results, but do not necessarily imply accuracy due to possible systematic effects. This is applicable to all PV devices' performance indicators such as I_{sc} , P_{\max} , efficiency and Fill Factor. A comparison between laboratories or even different sets of measurements is only meaningful when accompanied with a robust uncertainty analysis.

The key difference between calibration and measurement is the accompanying traceability to SI units with the associated uncertainty. Even though uncertainty analysis is not a requirement for most measurements, it can improve the test method and the validity of the results. Based on calibration laboratories' uncertainty analysis the general sources of uncertainty are outlined. These are the same for all solar simulator I-V measurements, but the relative contribution of each is setup specific. Con-

sideration of these factors can help minimise both the random and systematic errors and thus improve routine I-V measurements in research laboratories.

In this paper a general overview of the uncertainty sources in indoor I-V measurements is presented as well as detailed examples that can affect the measurement results and lead to wrong conclusions.

2 Estimation and calculation of measurement uncertainty

The ISO 'Guide to the expression of uncertainty in measurement' [1] prescribes a framework for estimating uncertainty and a method for combining the contributions into an overall uncertainty. In summary, it involves assigning different probability density functions and range of values to all the contributing influences and approximating them to equivalent Gaussian distributions. Based on a Taylor approximation of the model equations these are combined into a single output Gaussian distribution as shown in Figure 1 below. The standard deviation of that distribution is the uncertainty of the measurement. For more complicated, non-linear and correlated contributors a Monte Carlo method can be used [2].

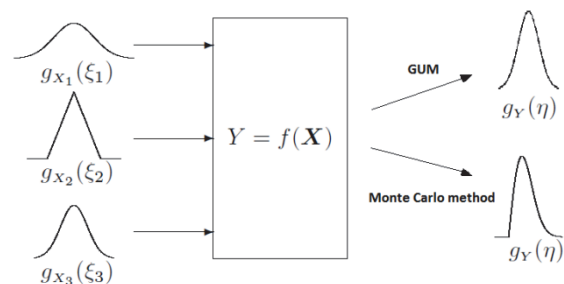


Figure 1 Propagation of distributions of input qualities based on [2].

3 Sources of uncertainty in I-V measurements and calibration

The procedure for I-V measurements under simulated sunlight is detailed in IEC 60904-1[3]. Secondary reference cells are mostly calibrated against primary reference cells using the same method but with more stringent requirements in order to minimise uncertainty. The method uses a solar simulator as the light source and a Ref-

erence Cell (RC) to adjust the irradiance level by matching the measured I_{sc} with the calibrated value. Relative spectral response measurements of the RC and Device-under-test (DUT) are required for the mismatch factor correction. A range of solar simulators and data acquisition systems are used in different laboratories. Usually continuous solar simulators are used for cells and mini-modules and large area flash solar simulators are used for large modules.

The Differential Spectral Responsivity [4] calibration method involves measuring the relative spectral response of the DUT for the whole wavelength range and the absolute spectral response for specific wavelengths. The result is then scaled and integrated and the I_{sc} calculated for a reference spectrum. This method has similar uncertainty sources to External Quantum Efficiency (EQE) measurement systems and is not in the scope of this paper.

A generalised list of uncertainty sources for the solar simulator method is outlined in Table 1. A detailed description of these sources along with the uncertainty calculations can be found in [5] and [6]. The uncertainty values cannot be read across since they are setup specific.

Uncertainty sources in the Standard Test Conditions (STC)	
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
in Irradiance spectrum	
	Mismatch factor (spectral response + irradiance spectral distribution)
	Filter deterioration and lamp aging
in Junction temperature	
	Sensor calibration uncertainty
	Measurement resolution
	Distance between the sensor and junction
	Temperature non-uniformity
	Temperature drift during measurement
Uncertainty sources in the Data acquisition (DAQ)	
	DMM/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
Uncertainty sources in measuring the Area	

	Area definition
	Light piping/Total Internal Reflection
	Measurement resolution
	Edge interpretation

Table 1 Source of uncertainty in indoor solar simulator calibration.

The relative contribution of each of these depends on the specific setup and DUT. For example, the irradiance distribution of a continuous simulator is easier to determine with lower uncertainty than that of a pulsed simulator and thus the mismatch factor uncertainty is lower. Furthermore, large area simulators have the reference cell next to the test sample. Continuous simulators have mostly the reference in place of the test sample (irradiance monitor is used during the changeover between the RC and DUT). As a result contributions due to the relative position and orientation in combination with the higher inhomogeneity increase the measurement uncertainty when large area simulators are used. This is one of the reasons why module measurements generally have a larger associated uncertainty than cells. The second is that calculating the mismatch factor for modules is more difficult since most laboratories are not capable of measuring the spectral response of specific modules under test with low uncertainty.

The overall uncertainty for *indoor* secondary calibration, i.e. using a primary reference cell as the working standard, varies between 1.5% in P_{max} for cells and 4% for large modules for c-Si and other stable technologies [5,6]. The overall uncertainty is higher for thin film, dye-sensitized and organic technologies. The reasons for the higher uncertainties are mainly due to the non-uniformity of the device during manufacturing and due to some of the challenges in characterising these devices [7-9]. These include: sweep effects with pulsed simulators, metastability of the devices, preconditioning effects, current limiting with multi-junction devices, etc. The measurement artefacts may vary, but the most significant change in the uncertainty for all is due to the mismatch factor correction. This is because reference cells with a matching spectral response are not available due to stability issues, thus filtered c-Si cells are used instead. In the regions where there is no overlap between the response of the device-under-test and the filtered reference cell the mismatch factor uncertainty is excessively high [10].

With multi-junction devices the difference between the AM1.5G [11] and the irradiance spectral distribution forces one of the junctions to be current limiting. A more involved procedure using a multi-source solar simulator is required as

well as a well-matched reference cell for each junction [12].

Figure 2 below shows the relative contribution of the sources of uncertainty in c-Si devices. The major sources are the Mismatch factor, the non-uniformity and the uncertainty of the calibration of the primary reference cell. However this is only the case if all other source are minimised due to a careful design of the measuring setup.

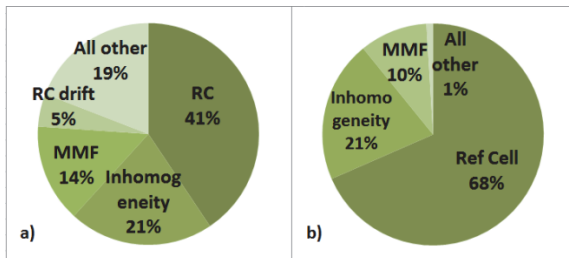


Figure 2 Relative contribution of the uncertainty sources to the overall uncertainty in I_{sc} of c-Si cells a) at ESTI [5]; b) at NREL [6].

4 Uncertainty sources implications in routine Solar Simulator measurements.

4.1 Temperature control

I-V measurements are particularly sensitive to the change in junction temperature. Not all laboratories have custom designed measurement chucks for temperature measurement and control (Figure 3). Thin film devices with contacts at the back, e.g. CdTe cells, are particularly difficult to measure while the temperature of the junction is controlled. **Measuring the temperature at the back of the photovoltaic devices is essential to validate the test results.** This can be done with a PT100 during a quick I-V measurement indicating if the results should be rejected. A good thermal contact between the sensor and the test device is essential. The device should be stabilised at 25° C prior to and during any measurements.

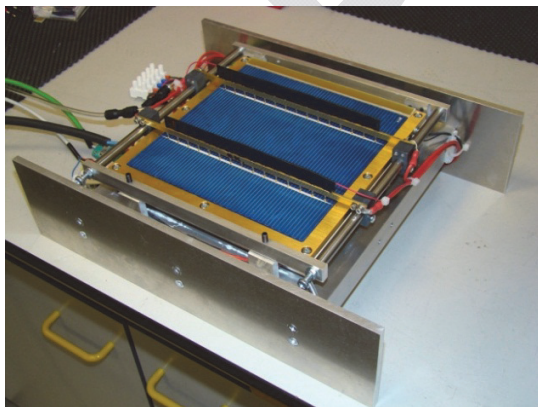


Figure 3 Temperature controlled, vacuum chuck for c-Si solar cells.

4.2 Irradiance inhomogeneity, relative position and orientation of the DUT and RC.

Low-cost solar simulators have poor light intensity homogeneity at the target plane and often the non-uniformity is not measured. It is falsely assumed that this is equal to the classification of the simulator. Typically lamps are not properly adjusted after installation introducing significant systematic effects into the measurements. The significance and the effect of this depend on the size of the sample and the relative position and orientation of the test device and the working reference cell or calibrated photodiode. Irradiance inhomogeneity is one of the dominant uncertainty sources and since the current is proportional to the irradiance level, a 5% inhomogeneity can introduce an excessively large systematic error. Measuring the inhomogeneity or at least comparing the I_{sc} of a reference cell or calibrated diode at different positions can help estimate the systematic error due to the inhomogeneity.

4.3 Irradiance spectral distribution and spectral response of the DUT and RC

Some laboratories cannot perform mismatch factor correction due to the difficulty of measuring the EQE of the device and the irradiance distribution of the light source. This is particularly difficult for large devices and pulsed solar simulators. The uncertainty sources of measuring the irradiance spectrum and lamp aging effects are discussed in [13]. Even though the irradiance spectral distribution is not known, reference cells are still used for setting up the irradiance level of the simulator. It is important to consider that a significant systematic error is possible due to the poor match of low-cost simulators to AM1.5G and between the spectral response of the device and the RC. For example, a CdTe device with a higher spectral response at the peaks of unfiltered Xenon source will seem more efficient during measurements but can be less efficient under AM1.5G.

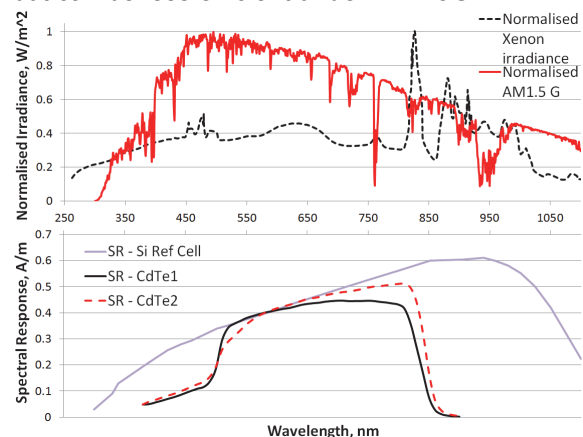


Figure 4 Xenon irradiance distribution and SR of Si reference cell and CdTe devices.

As seen in Figure 4 under AM1.5G there is a dip at around 825nm instead of a peak as under Xenon illumination. This coincides with the relatively large difference in spectral response of the two CdTe devices. Considerations for organic cells are described in [9].

4.4 Series resistance

The series resistance introduced when connecting the test sample can greatly affect the Fill Factor results and it should be done with a 4-wire Kelvin connection. A number of measurements should be made reconnecting the same sample to estimate the random error. If the standard deviation of the results is high a better connection scheme is required.

4.5 Data acquisition system range

Low irradiance level measurements can be misleading on one hand due to the non-linearity of the device and on the other due to using the same shunt resistor for measuring the short circuit current. This will change the voltage measuring range of the data acquisition system introducing high uncertainty due to the resolution and offset of the measuring equipment. This can be avoided by selecting an appropriate shunt resistor or selecting a lower measurement range.

4.6 Area calculation

The definition of the area can vary at different institutions for different technologies. Therefore it should be explicitly stated how the area was measured. The uncertainty in the area calculation is subjected to the resolution of the equipment used and the edge interpretation by the operator. For small samples this can have an excessively large effect on the efficiency calculation. Depending on the device, total internal reflection within the encapsulation can increase the effective device area due to increased light collection. The effect can be minimised or even eliminated by using a fixed aperture mask with bevelled edges.

5 Conclusions

There are numerous sources of uncertainty in secondary reference cell calibration. The careful consideration of these sources in any solar simulator measurement setup can minimise both random and systematic errors and increase the validity of the results. The paper summarises the general sources of uncertainty and details the implications of these on solar simulator measurements in research laboratories. The key sources to consider are the light inhomogeneity at the target plane and the relative position of the device-under-test and reference cell, the mismatch factor and temperature

monitoring and control during the measurement. Finally care should be taken to minimise the series resistance of the connection and to calculate and report the area correctly.

Acknowledgements

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