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UNCERTAINTY OF FIELD I-V-CURVE MEASUREMENTS IN LARGE SCALE PV-SYSTEMS

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ABSTRACT: Field I-V curve measurements are an important means of quality assurance. They provide a possibility to verify the actual module power on a representative sample of modules in the field. The result is "worth money", so it is essential that the uncertainty is kept at a minimum. This requires good knowledge of PV measurement principles, even if measurement equipment is readily available. Operators have to be aware of the influence of environmental conditions during measurements on the result. We performed a detailed uncertainty analysis in order to improve our procedure and measurement equipment. With our procedure, which follows the principles of IEC 60904-1 and applies procedure 1 in IEC 60891, we achieve uncertainties between 2.2% and 5%. This requires traceable primary calibrated measurement equipment and a thorough determination of temperature coefficients and other needed parameters. The major contributions to the combined uncertainty of corrected power are discussed in this paper. As it is important that the performance of thin film technologies can be assessed, we included not only crystalline silicon technologies, but also CdTe and amorphous silicon technologies in our analysis.

Keywords: Field I-V curve measurements, Measurement uncertainty, Translation to STC, PV System

1 INTRODUCTION

Performing I-V curve measurements of PV arrays has always been a useful means of testing PV installations [1, 2]. Field I-V curve measurements allow testing a large sample of modules right where they are installed, and they reveal not only weak modules but also faulty connections, which differentiates them from laboratory measurements. Periodically performed field I-V curve measurements may also reveal degradation.

The situation has changed compared to 15 years ago, when field measurements were mainly performed by well-trained scientists. Today, as considerable sums are invested in large scale PV systems, performing field I-V curves is one of several common quality assurance measures. Their most important outcome is by far the verification of actual module power. The demand of investors for determination of actual power in the field is growing. In order to fulfill this demand, methods to measure field I-V curves have to be non-time-consuming, easy to perform and still give reliable results with small uncertainties. The market offers various kinds of field I-V curve measurement systems which promise to fulfill these requirements. However, reliable field I-V curve measurements require that the operator has good knowledge of the main influences on the measurements, and does not only rely on the I-V-curve tracer and the implemented correction procedure. It is important that the operator is aware of the specific uncertainties of his system and the correction procedure applied.

Is this paper, we review the most important points for performing field I-V curve measurements with the purpose of determining the actual module power. We discuss the sources of uncertainty when working according to IEC60891 [3] and present the results of our uncertainty analysis.

2 DETERMINATION OF ACTUAL MODULE POWER IN THE FIELD

As illustrated in Figure 1 the power determination consists of three steps: the measurement itself, the correction to STC, and the correction of external losses such as soiling, electrical losses or mismatch losses. Even if the latter is a crucial aspect – the assumptions about the external losses directly affect the decision, whether the modules meet label specifications or not – a detailed discussion is beyond the scope of this paper.

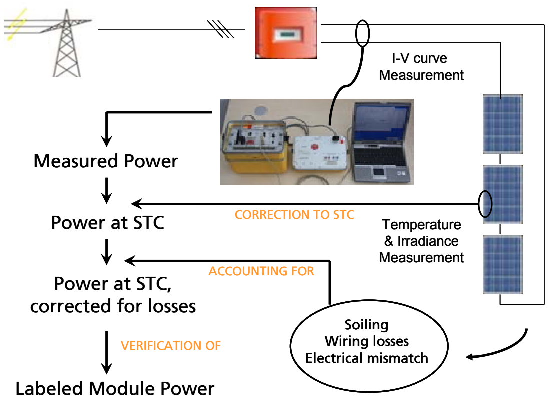

Figure 1: The three steps of verifying module power by performing field I-V curve measurements.

The process of determining the actual module power in a large scale PV system is usually as follows:

First of all, a representative sample with regard to installed module types, electrical configuration or time of installation has to be selected. We consider a sample of 10% to 30% of a system as large enough. The measurements are performed on PV arrays, i. e. system parts with a size of 5 kWp to 100 kWp. The size of the arrays depends on the range of the measurement system, the possibility to make the electrical connection and the size of the total system. Measuring small system parts gives a closer look at the modules, whereas measuring larger system parts allows a larger sample. For each array, the I-V curve is measured with a mobile I-V curve tracer. The conditions during measurement have to stable, i. e. clear blue skies and ideally no wind. Basic PV measurement principles as given in IEC60904-1 [4] have to be observed. Irradiance in the plane of the array and the array temperature have to be measured simultaneously with the I-V curve. This is necessary as module label values refer to Standard Testing Conditions (STC 1000 W/m², 25 °C, spectral distribution according to IEC60904-3 [5]). STC are almost never met in real operation which demands a correction from real to standard conditions. The correction can be performed directly after the measurement by the data acquisition unit in use, which is state of the art, or manually afterwards. The result of the correction is the actual array power, which might have to be corrected further for external losses before being fully comparable to label specifications.

To perform the correction from real operation conditions to STC, a model to describe the module behavior with different temperatures and irradiance levels is necessary. There are a large number of correction models available whose advantages and disadvantages have been discussed elsewhere [3, 6-9]. They can be divided into:

- analytical models like the two-diode model,
- interpolation procedures like the procedure 3 in IEC60891 which require several measurement at different conditions at each array to be tested, and
- algebraic methods like procedures 1 and 2 in IEC60891, which correct the measured I-V curve point by point and use parameters determined beforehand.

The latter are most common because they are easy to handle, whereas interpolation procedures are too time-consuming for field I-V curve measurements in large scale PV systems. Fraunhofer ISE uses procedure 1 in IEC60891. The correction equations are given in (1) and (2).

$$I_{STC} = I_m + (\frac{1000\ Wm^{-2}}{E_m} - 1)\ I_{SC,m} + \alpha\ (T - 25°C) \qquad (1)$$

$$U_{STC} = U_m - R_S(I_{STC} - I_m) - K\ I_{STC}(T - 25°C) + \beta\ (T - 25°C) \qquad (2)$$

where I is the current, V the voltage and E the irradiance. The index m stands for measured quantity, STC for the quantity corrected to STC. α is the temperature coefficient of short circuit current, β the temperature coefficient of open circuit voltage, Ⱪ the curve correction factor and R_S the series resistance.

The basic problem of algebraic procedures is the determination of model parameters that are technology or module-type-dependent – there is always a tradeoff between accuracy of the corrected result and complexity of parameter determination. It can be stated that correction procedures that promise to get along with only temperature coefficients for I_{SC} and V_{OC} will generally not reach the accuracy of procedures with more parameters. The challenge with more parameters is, that their determination requires measurements of temperature and irradiance dependency. This is easily possible for one or two modules under laboratory conditions, but only at high expenses for arrays. So an extrapolation from module to array has to be performed which can introduce additional uncertainty.

3 UNCERTAINTY CALCULATION

3.1 Approach

As explained above, the actual STC power is derived from measurement and correction. Hence, the uncertainty is composed of the actual measurement uncertainties introduced by the equipment and its traceability chain [10] and the uncertainties of the correction procedure [11]. The latter is basically composed of the ability of the model to describe the module behavior, the uncertainty of the model parameters in use and the environmental measurement conditions (see Figure 2). The closer the real conditions are to STC, the less uncertainty is introduced by the correction. It has to be kept in mind that each measurement has its own uncertainty, depending on measurement system and conditions. Indications that give general measurement uncertainties without referring to specific conditions are to be interpreted as a minimum value.

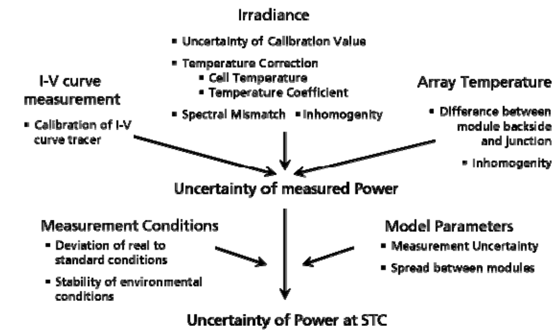

Figure 2: Major influences on the combined uncertainty of power at STC

Our uncertainty calculation includes first of all the results of a detailed analysis of the measurement chains for irradiance, temperature and I-V curve. Likewise, the uncertainties of necessary correction parameters for procedure 1 in IEC60891 (see equations (1) and (2)) are discussed. Since no statistically relevant number of measurements at one array is made, we refer only to measurement uncertainties type B according to GUM [12]. By applying the law of error propagation to the correction equations (1) and (2) according to GUM the combined uncertainty of the corrected power (P_{STC}) is calculated as given in (3) and (4).

$$U_{P_{STC}} = \sqrt{\sum_i^n u_{x_i}} \qquad (3)$$

With
$$u_{x_i} = (\frac{\partial P_{STC}(x_i,...,x_n)}{\partial x_i})^2 \Delta x_i^2 \qquad (4)$$

and $P_{STC} = U_{MPP,STC}\ I_{MPP,STC}$ according to (1) and (2). x_i are all measured quantities and parameters needed for the determination of P_{STC}.

We performed a sensitivity analysis by analyzing the relative contributions of the summands u_{xi} in (4) in order to find out, which parameters or measured quantities affect the combined uncertainty of P_{STC} most. The selected confidence interval is 95%, i. e. k=2.

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3.2 Measurement Uncertainties

3.2.1 Fraunhofer ISE measurement equipment

The field I-V curve measurement system is a PVCT-F1 (manufacturer h.a.l.m.) and the temperature sensor a common Pt100 sensor class A. The irradiance sensor is a Fraunhofer ISE crystalline silicon reference cell. Up to now, there was a secondary calibrated Fraunhofer ISE sensor with integrated shunt in use. As a consequence of the results presented in this paper, this will be changed into a primary calibrated Fraunhofer ISE sensor with an external shunt.

3.2.2 Standard uncertainty of measured irradiance

The irradiance has to be measured with a traceable calibrated reference device, preferably with a spectral response very similar to the modules of the array under test. The sensor has to be placed with the same inclination and orientation as the modules, preferably close to the array being measured. Measurements should only be taken at stable conditions.

It is important to consider the uncertainty introduced by the temperature correction of the irradiance signal. The closer the reference cell temperature is to 25 °C, the lower the uncertainty, as is shown in Figure 3. The contributions to the combined uncertainty of the measured irradiance are calculated according to the laws of error propagation (GUM, see also (3) and (4)) for the suggested temperature correction equation in IEC60891.

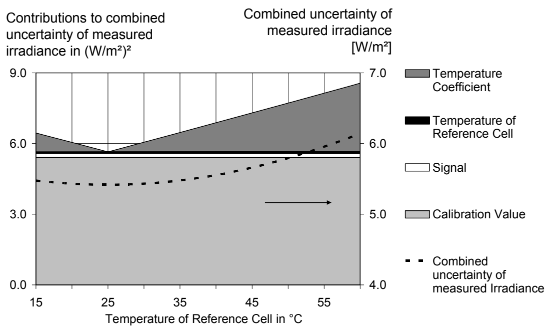

Figure 3: Combined uncertainty of measured irradiance versus reference cell temperature (dashed line). The contributions to the combined uncertainty u_{xi} are indicated as filled areas

The resulting combined uncertainty of the measured irradiance is listed in Table 1. Values refer to a primary calibrated sensor and a secondary calibrated ISE sensor with internal shunt. It is obvious that the uncertainty of the calibration values is noteworthy [10, 13, 14]. We estimate a maximum of 0.5% of spectral mismatch for crystalline silicon. For thin film technologies, the uncertainty introduced by spectral mismatch has to be estimated according to spectral response of module and reference cell and time and location of measurement (see [15-18]). Uncertainties due to inhomogeneity are estimated at 0.5%. If modules of an array are not equally orientated, this estimate might have to be enlarged. Angle of incidence (AOI) effects are neglected, as measurements are only to be carried out under stable conditions at high irradiances which are typically close to normal AOI. Under these conditions reference cell and modules are considered to have equal reflection behaviour.

Table 1: Combined uncertainty of measured irradiance for case A) secondary calibrated reference cell and case B) primary calibrated sensor with external shunt

Standard Uncertanties [%]	A	B
Calibration Value	2	0.6
Stability	2	1
Shunt	/	0.12
Temperature @ 40 °C	0.3	0.3
Temperature coefficient	25	25
Data aquisition	0.03	0.03
Spectral Mismatch	0.5	0.5
Inhomogenity	0.5	0.5
Resulting combined Uncertainty @ 40 °C	1.9	1.0

3.2.3 Standard uncertainty of array temperature

The temperature is measured with a Pt100 Sensor attached to the back side of the module. The sensor and the module have to be in thermal equilibrium before the measurement is started. As the back side temperature of the module isn't equal to the junction temperature, an uncertainty is introduced. Especially windy or unstable conditions increase this error, which has been discussed by Faiman et. al. [19].

The largest influence on the uncertainty of the array temperature is temperature inhomogeneity. It can only be measured at one point of the array although there is a considerable spread of temperature. We assume that the average temperature of the array represents the equivalent temperature of the array well enough, and estimate the uncertainty as the standard deviation of a rectangular distribution of the temperatures between minimal and maximal temperature. The calculation of the equivalent temperature according to IEC60904-5 [20] is not considered a better approach, because it requires additional unknown parameters.

For an array of 100 modules, a temperature inhomogeneity (TIH), which is referred to in the following as $(T_{MAX} - T_{MIN})/2$, of around 2 K to 3 K is typical. A TIH of less than 1 K can only be expected in absence of wind.

Table 2: Typical Standard Uncertainty of measured Temperature

	Absolute Uncertainty	Standard Uncertainty
Sensor		0.3%
Difference back/junction	0.5 K	0.7%
Temperature inhomogeneity	2 K	2.6%
Data aquisition		0.03%
Standard Uncertainty @ 45 °C		2.7%

3.2.4 Standard uncertainty of voltage and current measurement

The I-V curve of large arrays is measured with a capacitive load. Decisive for the uncertainty is the measurement instrument and its calibration. In addition to the measurement uncertainty of the instrument, the uncertainty in finding I_{SC}, V_{OC} and P_{MPP} has to be

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considered. As there is no active load available, I_{SC} and V_{OC} often have to be extrapolated.
Table 3 summarizes the estimated uncertainties.

Table 3: Measurement uncertainties of the I-V curve measurement

	Standard Uncertainty
current	0.03%
voltage	0.03%
I_{SC}	0.1%
V_{OC}	0.1%
P_{MPP}	1.2%

3.2.5 Summarized measurement uncertainties

Table 4 gives an example of the measurement uncertainties we achieve after optimizing our measurement equipment. The values refer to a typical PV array and typical measurement conditions (800 W/m², 45 °C).

Table 4: Standard Uncertainty of measured Temperature

	Measured Value	Standard Uncertainty
Irradiance	800 W/m²	1.0%
Temperature	45 °C	2.7%
Measured Power	2353.6 W	1.2%
Measured I_{SC}	6.731 A	0.1%
Measured V_{OC}	497.4 V	0.1%

3.3 Estimation of Parameter Uncertainties

3.3.1 Contributions to parameter uncertainty

With regard to the model parameters α, β, κ and R_S that are necessary for correction to STC according to IEC 60891, procedure 1, two cases can be distinguished: First and better case is that measured parameters are available from a module of the same type and power class. Second is that technology-averaged parameters are used. The contributions to uncertainty for both come from measurement uncertainties and the spread between modules of one type. For the second case, the spread between different module types of one technology must also be considered. In order to investigate the spread, we analyzed around 120 temperature coefficient measurements and around 80 measurements at different irradiance levels that were performed in Fraunhofer ISE CalLab PV Modules since 2009.

3.3.2 Parameter measurement uncertainties

α, β and κ are parameters that describe the behaviour of a module at different temperatures. K is in unit of Ohm/K and accounts for the fact that the temperature coefficients of I_{MPP} and V_{MPP} are different from the temperature coefficients of I_{SC} and V_{OC}. α, β and κ are determined from measurements at 1000 W/m² and temperatures between 35 °C and 65 °C. We estimate uncertainties of 25% (α), 10% (β) and 25 (κ) for all single junction technologies. This is a conservative estimate which will be investigated further, but corresponds to results of international round robin tests.

R_S is determined from measurements at 25 °C and irradiances between 1100 W/m² and 800 W/m² (depending on availability) with an estimated uncertainty of 5% for crystalline silicon and 10% for thin film technologies. As the measurements can be affected by a changing spectral mismatch with lower irradiance levels, the uncertainty for thin film modules is higher. This also will be investigated further.

It is important that κ and R_S are determined as indicated in IEC60891. R_S values derived from other sources, e. g. fitting a diode model, will cause incorrect results. Each model that describes module behaviour is only a more or less sophisticated approximation to the truth, switching models is not useful.

3.3.3 Parameter Spread and deviation from data sheet

Figure 4 shows the deviation of measured α and β from data sheet values. For crystalline and thin film technologies, considerable deviations of up to 20% were observed. It is obviously larger than the spread of parameters measured at different module types of the same technology (Figure 5), which is about 10%. All measured values are relative to the mean value of all measured polycrystalline modules. As a consequence, the usage of α and β data sheet values for the correction to STC is not recommendable.

The basic coherences for K and R_S are shown in Figure 6 and Figure 7. Again, all values are relative to the polycrystalline average. For better visibility, parameters for thin film modules are shown in a separate diagram. It is obvious that the values for thin film differ strongly from those for crystalline technologies. The very large spread of K and R_S for a-Si technologies is due to the small sample including not only single-junction amorphous silicon technologies, but also a-Si/a-Si and a-Si/μc-Si. Their parameters are given for reference, closer investigation is needed, especially concerning the determination of R_S.

Concerning crystalline technologies, the values for K and R_S turned out to be dependent on technology, cell size and number of cells. Grouping modules according to these characteristics reduces standard deviation of the mean value. Nevertheless is it not recommendable to transfer values from one module type to another, as the spread is considerable even for modules of the same cell number and size.

In order to derive an uncertainty for the use of technology-averaged values, the standard deviation from the technology mean was calculated for α, β, κ and R_S.

An estimate for the spread of modules was not easy to grasp, as most measurements of temperature or irradiance dependence are only carried out at one module. From the little sample of more than three modules of one type, we derived the standard deviation of each module type average as input for the parameter uncertainty. For crystalline silicon, roughly values of 6% (α), 2% (β), 6% (κ) and 5% (R_S) were observed.

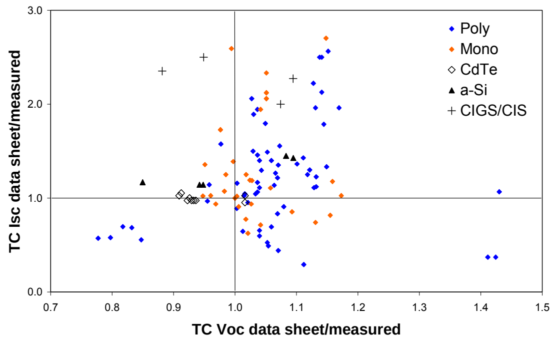

Figure 4: Deviation of relative measured temperature coefficients from data sheet values.

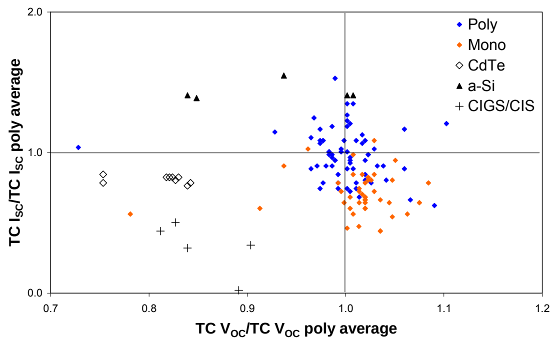

Figure 5: Measured temperature coefficients of I_{SC} and V_{OC} for modules of different technologies and type relative to the average of polycrystalline temperature coefficients.

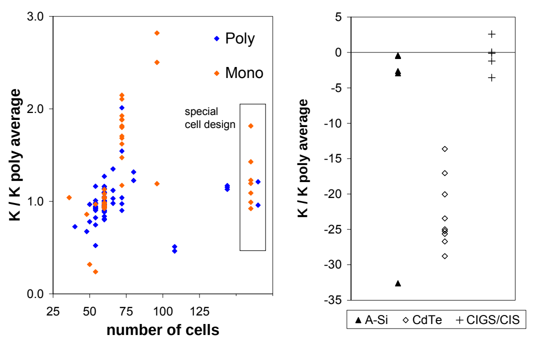

Figure 6: Curve correction factor K for modules of different technologies and to the average of polycrystalline K.

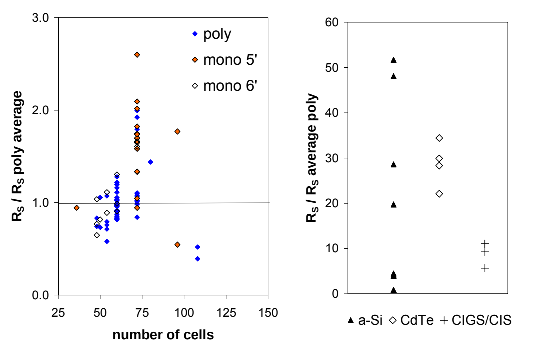

Figure 7: Series resistance R_S for modules of different technologies and type to the average of polycrystalline R_S.

3.3.4 Extrapolation from module to array

Applying equations 1 and 2 for an array instead of one module and considering the basic electrical laws for adding resistances (units for κ are Ohm/K) suggest the following extrapolation:

$$R_{S\_Array} = R_{S\_Module} \bullet N_{Series} / N_{Parallel} \quad (4)$$

$$\kappa_{Array} = \kappa_{Module} \bullet N_{Series} / N_{Parallel} \quad (5)$$

Additional uncertainties for the extrapolation are not taken into account, as they are assumed to be partly reflected in the considered spread of the parameters between several modules. Measurements at single modules and arrays have shown that this approach works correctly.

3.3.5 Summarized parameter uncertainties

Table 5 shows the results of our estimation of uncertainties of correction parameters. The standard uncertainties were calculated as root of square sums of the contributing uncertainties.

Note that only one type of CdTe modules was considered, which makes the uncertainties comparable to "measured c-Si" uncertainties. For amorphous silicon modules, the measurement sample was not large enough to derive values.

Table 5: Estimated Parameter Standard Uncertainties

	mono	poly	CdTe	measured (c-Si) for 1 module type
α	33%	35%	25%	26%
β	15%	11%	12%	10%
κ	47%	34%	39%	26%
R_S	35%	30%	26%	7%

3.4 Results of the sensitivity analysis

As expected, the results of the sensitivity analysis revealed that the measurement conditions are decisive for the combined uncertainty of P_{STC}: The more irradiance and temperature during measurement deviate from STC, the larger the uncertainty of P_{STC} will be. This effect is even stronger for high standard uncertainties of measured parameters. This stresses once again the advantage of using a primary calibrated reference cell. Concerning the sensitivity on model parameters, it turns out that the uncertainty of β affects the result the most. α, β and κ and R_S influence depends on the conditions – the more temperature deviation, the more influence from α, β and κ, and the more irradiance deviation, the more influence from R_S. High uncertainties of the parameters will above all increase uncertainties of measurements made at large deviations from STC.

Table 6 lists the contributions to the combined uncertainty of P_{STC} for two sets of typical measurement conditions and a best case and typical case scenario. The numbers are the absolute contribution to the uncertainty in W, i. e. the summands in equation 3. "Best case scenario" refers to a primary calibrated reference cell and parameters measured at a module of the same type, "typical case scenario" to a secondary calibrated reference cell and technology-averaged parameters. The relative combined uncertainties refer to the measured data as given in Table 4.

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Table 6: The contributions to the combined uncertainty of P_{STC} of all quantities for two different typical measurement conditions and a typical PV array

u_{xi} [W]	1000 W/m² 65 °C		800 W/m² 45 °C	
x_i	best case	typical case	best case	typical case
α	15	20	6	8
β	44	65	28	42
K	7	13	6	11
R_S	0	2	6	29
I_{MPP}	17	17	15	15
V_{MPP}	13	13	17	17
E	27	54	29	58
I_{SC}	0	0	1	1
t_{Array}	12	12	17	17
U_{PSTC} (k=1)	60	91	51	83
$U_{PSTC,relative}$ (k=2)	3.8%	5.7%	3.3%	5.2%

A further result is the possibility to estimate the uncertainty in dependence on the environmental conditions for a given set of parameter uncertainties and a given uncertainty of the calibration value. The environmental conditions are namely irradiance, temperature and temperature inhomogeneity. This is useful, because the measurement conditions are the only changing influence on the combined uncertainty of P_{STC}.

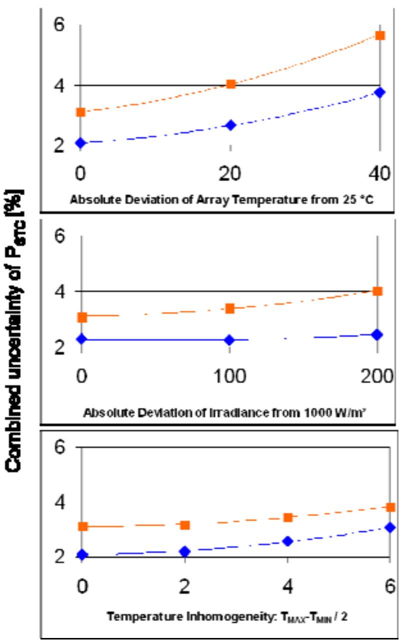

Figure 8: Influence of environmental measurement conditions on the uncertainty for the best case scenario (blue) and a typical scenario (orange).

Figure 8 shows the changes in the combined uncertainty of P_{STC} for each environmental factor. The other factors were kept at zero in each case. The combined uncertainty can be calculated as follows:

$$U_{P_{STC}} = U_0 + U_{\Delta E} + U_{\Delta T} + U_{TIH}$$

with
$$U_{\Delta E} = a_1 \Delta E^2 + a_2 \Delta E$$
$$U_{\Delta T} = b_1 \Delta T^2 + b_2 \Delta T$$
$$U_{TIH} = c_1 TIH^2 + c_2 TIH$$

U_0 is the pure measurement uncertainty for a measurement at STC and no temperature inhomogeneity, the uncertainty introduced by the deviation of irradiance from 1000 W/m² is $U_{\Delta E}$, the uncertainty introduced by the deviation of temperature from 25 °C is $U_{\Delta T}$ and the uncertainty introduced by temperature inhomogenity is U_{TIH}.
The coefficients a, b and c can be derived in dependence of the uncertainties of measurement equipment, especially the calibration value of the reference cell, a set of assumptions concerning spectral mismatch or inhomogeneity and the estimated set of parameter uncertainties.

3.5 Summarized results

The major contributions to the combined uncertainty of the power at STC determined by field I-V curve measurements were presented. Concerning the steps the operator can take to minimize the uncertainty, the following conclusions are drawn: The measurement uncertainty can be minimized by using primary calibrated equipment, especially a primary calibrated reference cell. Uncertainties introduced by the correction to STC can be minimized by using parameters that were measured at a module of the same type. The environmental conditions can hardly be influenced, but measurements at unstable conditions, with no clear blue skies and at irradiance much lower than 800 W/m² should not be performed. Those conditions are not covered by our uncertainty analysis.

All presented uncertainties refer to procedure 1 in IEC60891, but are qualitatively transferable to procedure 2 [11]. Table 7 summarizes the uncertainties Fraunhofer ISE achieves with a primary calibrated reference cell for measured and technology-averaged parameters.

Table 7: Fraunhofer ISE uncertainties for P_{STC} for case A) parameters determined at the same module type and case B) technology-averaged parameters

	1000 W/m²		800 W/m²	
	A	B	A	B
25 °C	2.2%	2.2%	2.6%	3.2%
45 °C	2.7%	3.2%	3.3%	4.2%
65 °C	3.8%	4.9%	4.6%	6.4%

4 MEASUREMENT RESULTS

4.1 Generator level

In order to find out whether the reproducibility of measurements under real conditions lies well within the calculated uncertainties, measurements were performed at different times in 2010. The three small test arrays (3xpoly, 4xCdTe, 3xa-Si) are part of installations on the roof of Fraunhofer ISE main building. For details concerning measurement equipment and setup see [21].

P_{STC} determined by outdoor measurements is compared to measurements in CalLab PV Modules. In case of the CdTe and a-Si test array, the array power was estimated from single measurements by adding the voltages for the lowest measured I_{MPP}.

Figure 9 shows the results of the measurements. The overall reproducibility of power measurement was within 2% for different conditions except for one a-Si measurement. The deviation from CalLab PV Modules measurement was within ± 3% for all technolgies, again except for one a-Si measurement. All deviations lied well within the uncertainties of CalLab PV Modules The uncertainties were estimated for this case at 3% for the polycrystalline array and 5% for CdTe and a-Si.

This shows that IEC60891 provides good results for thin film modules as well, and also shows that comparable and reproducible measurements of thin film arrays can be performed.

Details on uncertainty and measurement conditions of the field results are given in Table 8, Table 9 and Table 10. The given uncertainties refer to measurements with a secondary calibrated Fraunhofer ISE sensor (± 2%).

All measurements were conducted under clear blue skies. A-Si and CdTe measurements for June and July are mismatch corrected, for the earlier measurements no spectral irradiance was available. Nevertheless the missing mismatch correction is taken in account in the uncertainty calculation. With regard to a-Si annealing during the summer months, of course it may be discussed whether it makes sense to test the reproducibility of field I-V curve measurements by several measurements throughout the year. Nevertheless this is an important information for gaining experience for measurements in a-Si PV systems and defining the correct point of time for verifying labeled values. Definitely, more investigation has to be carried out concerning this issue.

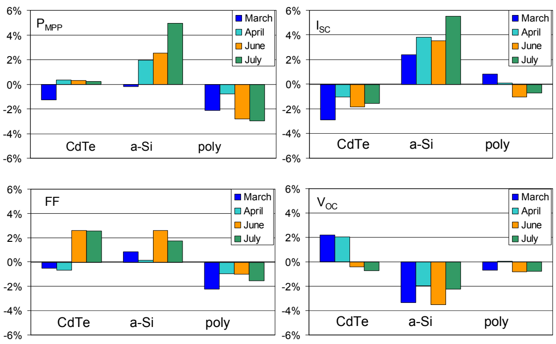

Figure 9: Deviation of field I-V curve measurements from CalLab PV Modules measurements

Table 8: Array of 3 serially connected poly modules

Measurement in	Mar	Apr	Jun	Jul
Irradiance [W/m²]	924	998	975	992
Temperature [°C]	53.5	50.3	62.9	64.5
P_{STC} [W]	351.6	355.9	348.7	348.1
I_{SC} [A]	7.67	7.62	7.53	7.56
V_{OC} [V]	64.9	65.3	64.8	64.8
Uncertainty of P_{STC} [%]	6.4	6.0	6.3	6.3
Deviation from CalLab PV Modules[%]	-2.1	-0.8	-2.8	-3.0

Table 9: Array of 4 serially connected CdTe modules

Measurement in	Mar	Apr	Jun	Jul
Irradiance [W/m²]	944	953	974	1007
Temperature [°C]	53.5	49.1	60.9	61.0
P_{STC} [W]	278.7	283.2	283.1	282.2
I_{SC} [A]	1.18	1.21	1.20	1.20
V_{OC} [V]	373.8	373.2	364.3	363.0
Uncertainty of P_{STC} [%]	5.8	5.9	5.5	5.4
Deviation from CalLab PV Modules[%]	-1.3	0.3	0.3	0.2

Table 10: Array of 3 serially connected a-Si modules

Measurement in	Mar	Apr	Jun	Jul
Irradiance [W/m²]	885	991	850	997
Temperature [°C]	50.9	45.6	55.4	61.8
P_{STC} [W]	255.8	261.3	262.7	269.0
Isc	1.47	1.49	1.49	1.52
V_{OC} [V]	270.6	274.5	271.1	273.6
Uncertainty of P_{STC} [%]	6.5	6.0	6.7	6.1
Deviation from CalLab PV Modules[%]	-0.2	1.9	2.5	5.0

4.2 Spread of real world results for different parameters

In order to investigate how large the influence of wrongly estimated correction parameters can be, four typical field I-V curves were manually corrected with varying sets of parameters. α, β, Ꝁ and R_S were separately set to extreme values by adding and subtracting the standard deviation as given in Table 5, column 1 and 3. Additionally, all parameter extremes that lead to overestimation and underestimation were accordingly combined. The results are given in Figure 10, they are relative to P_{STC} determined with measured parameters.

As expected, the spread in P_{STC} was larger for large deviations from STC (CdTe2, c-Si1). The comparison with a standard procedure with no Ꝁ and R_S and fully neglecting them in procedure 1 in IEC60891 showed different results for CdTe and c-Si, some of them beyond the uncertainty borders. This confirms that it is crucial to correctly determine the correction parameters.

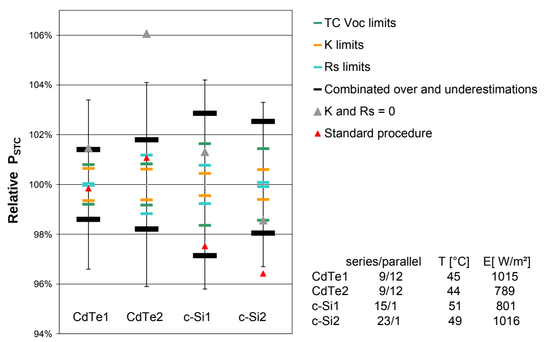

Figure 10: P_{STC} determined with varying correction parameters relative to P_{STC} determined with measured parameters.

5 SUMMARY AND OUTLOOK

Verification of actual module power by performing I-V curve measurements in the field is an important part of quality assurance. As module power is directly connected to investment sums, the measurement results have to be reliable and with low uncertainties.

In order to optimize our measurement equipment and procedure we performed a detailed uncertainty analysis. The correction procedure in use is IEC60891, procedure 1. As the power determination consists of two steps, the measurement and the correction to STC, the combined uncertainty of the determined power at STC (P_{STC}) is composed of contributions from both steps. Therefore using primary calibrated measurement equipment is recommendable. Especially the uncertainty of the calibration value of the irradiance sensor is determining for the combined uncertainty of P_{STC}. Just as dominant are the actual environmental conditions, i. e. deviations of irradiance and temperature from STC. I-V curve measurements should not be conducted at irradiances lower than 800 W/m² for that reason. The inhomogeneity of the array temperature is also an important factor. The uncertainty of correction parameters (temperature coefficients for short circuit current, open circuit voltage, curve correction factor and series resistance according to IEC60891) was estimated from 150 measurements of temperature dependence and 80 measurements of irradiance dependences performed in CalLab PV Modules since 2009. It is recommendable to always use parameters measured at a module of the same type as the array. If not properly determined, the correction parameters affect the result considerably – deviations of 1% to 2% from the correct result can easily occur. Especially the temperature coefficient of open circuit voltage has to be determined carefully. The parameter uncertainties affect the combined uncertainty of P_{STC} depending on environmental conditions.

As a consequence of the results of the uncertainty analysis, we changed our reference cell into a primary calibrated cell with an uncertainty of the calibration value of 0.6%. Fraunhofer ISE I-V curve measurements achieve uncertainties between 2.2% and 5% depending on environmental conditions. Measurements performed on test arrays of poly, CdTe and a-Si modules under real conditions at different points of time in 2010 showed a good reproducibility overall. They also agreed with laboratory measurements in CalLab PV Modules well within the CalLab PV modules uncertainty limits. This shows that IEC60891, procedure 1 provides good results for thin film modules as well, and also shows that comparable and reproducible measurements of thin film arrays can be performed.

In order to decrease the uncertainty further, the uncertainty of the correction parameters has to be reduced. First of all, it has to be worked on the reduction of measurement uncertainty of temperature and irradiance dependent measurements. Further, more experience about the spread of parameters within one module type has to be gained.

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