ASSESSMENT OF STC CONVERSION METHODS UNDER OUTDOOR TEST CONDITIONS

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ABSTRACT: In this paper we analyze the applicability of the IEC 60891 – Procedures for temperature and irradiance corrections to measured I–V characteristics – for translations to the Standard Test Condition (STC), in a broader range of irradiances than recommended in the norm. We focus on the 1st and 2nd procedures of the norm, as these were found more suitable for translations to STC for our measurements, than the 3rd method. For the evaluation we make use of an outdoor near-shore roof-site in The Hague (The Netherlands), with a comprehensive set of calibrated instruments, to measure in-plane spectral and broadband irradiance, as well as individual I–V curves for two different modules (c-Si and mc-Si). We use 3 criteria in order to further select the data: 1) linearity between the measured irradiance (G) and the short-circuit current (I_{SC}), 2) using correction parameters or not, and 3) self-referencing of the PV device. The criteria are used to define 4 case studies.

The results were similar for both modules and both, 1st and 2nd, conversion methods of the norm. The irradiance is not limiting the accuracy of the conversion if only highly correlated values for I_{SC} vs. G are used. Best results were found for correlations of 0.98 or better, yielding accuracies below 3% for both STC conversion methods. Translations with good accuracy were also found by self-referencing the PV devices. We conclude that by proper data selection, the irradiance range specified in the correction method of the norm can be extended.

1 INTRODUCTION

As the implementation of photovoltaic (PV) solar cells and modules for energy conversion progresses worldwide, so does the interest in performance evaluation of such devices and systems. Performance evaluation can be made by tracing the PV device I-V characteristic, from which key parameters, such as short-circuit current (I_{SC}), open-circuit voltage (V_{OC}) and maximum power output (P_{MAX}), are extracted. To compare and rate the PV devices, these key parameters are determined at so-called Standard Test Conditions (STC), i.e. 1000 W/m^2 of broadband irradiance with a spectral distribution according to the Air Mass (AM) 1.5 global spectrum and a device temperature of 25 °C [1,2].

Indoors, the STC can be met to some extent, with temperature control and solar simulators. However, outdoors the test conditions vary with the environmental conditions. As the performance, and thus the I-V characteristic, of a PV device is highly influenced by its temperature and the solar irradiance, the International Electrotechnical Commission (IEC) norm No. 60891 “Procedures for temperature and irradiance corrections to measured I-V characteristics” [3], provides three different methods to convert measured I-V curves into any temperature and irradiance condition.

These conversion methods all neglect the spectral irradiance distribution, while PV devices are spectrally selective devices. Outdoor spectral effects have been investigated for PV devices [4–9], showing a higher influence in a-Si and thin film based devices. Taking spectral effects into account may contribute to a more accurate conversion to STC, and using spectral indicators one can quantify in how far the spectra vary from the AM 1.5 distribution.

The aim of this research is to evaluate the IEC 60891 norm conversion methods to the particular case of the STC and to assess if they can be improved by taking spectral effects into account.

1.1 Translation methods

The IEC 60891 norm I-V curve translation procedures, contains three different translation methods.

The 1st procedure employs a translation that is mainly empirical, while the 2nd employs a semi-empirical one, based on the simplified 1-diode model that is commonly used to describe the operation of PV devices. Both procedures use two temperature coefficients, α and β (or α_{REL} and β_{REL} for the 2nd procedure), which, respectively, represent the variation of I_{SC} and V_{OC} with temperature. Additionally, these conversion methods require 2 to 3 correction parameters (R_S, κ and ɑ) that take into account changes in the shape of the I-V curve. In the 2nd procedure, particular care in the ‘knee’ part of the I–V curve is taken into consideration, which allows a better estimation of the maximum power point than with the 1st procedure.

The IEC 60891 Procedure 1 uses the following equations [3]:

$$I_2 = I_1 + I_{SC}.\left(\frac{G_2}{G_1} - 1\right) + \alpha.(T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_S.(I_2 - I_1) - \kappa.I_2.(T_2 - T_1) + \beta.(T_2 - T_1) \quad (2)$$

The IEC 60891 Procedure 2 uses the following equations [3]:

$$I_2 = I_1.(1 + \alpha_{rel}.(T_2 - T_1)).\frac{G_2}{G_1} \quad (3)$$

$$V_2 = V_1 + V_{OC1}.\left(\beta_{rel}.(T_2 - T_1) + a.\ln\left(\frac{G_2}{G_1}\right)\right) - R'_S.(I_2 - I_1) - \kappa'.I_2.(T_2 - T_1) \quad (4)$$

The thermal coefficients and the correction factors can be determined according to procedures as stated in the IEC 60891 norm. However they require a considerable set of measurements under specific conditions, within the range of interest. Also, the norm recommends applying the procedures only for irradiance levels that are within ±30 % of the irradiance level at which the coefficients are determined. Typical thermal coefficients are commonly given in a commercial module datasheet, as they differ with cell technology and manufacturer [10,11]. However, the correction factors are usually excluded and need to be determined experimentally. Furthermore, depending on the current and voltage range in which the I–V curves are traced, their translation from lower irradiance levels to higher ones may require extrapolations to determine the I_{SC} and V_{OC}.

The 3rd procedure uses a different approach. By combining two or more measured I–V characteristics at different temperature and/or irradiance conditions, the correction is made by interpolating to a different condition based on a constant, that depends on the conditions for which the I-V curves are traced, and the temperature and irradiance condition to which the translation is made. Unfortunately, only 0.6% of the considered measurements could be combined to irradiance and temperature coordinate points that allowed the interpolation to STC. Therefore, this method is not further analyzed in this paper.

Further discussion on the translation methods can be found in [12–16].

2 EXPERIMENTAL ASSEMBLY

For the evaluation we make use of an outdoor near-shore roof-site in The Hague (Netherlands), with a comprehensive set of calibrated radiation instruments and individual module I-V curve measurements. I-V curves of 2 different modules, one mc-Si and one c-Si are measured every 5 minutes (see Figure 1). Each module temperature is monitored with a thermocouple attached to the back of the module centered in the middle cell. The solar broadband irradiance is measured every second by means of one pyrheliometer (for the measurement of the direct solar component), and three pyranometers (for the measurement of the global horizontal, the diffuse, and the tilted solar irradiance). The spectral tilted solar irradiance is measured every five minutes with one grating spectroradiometer (EKO MS-700), measuring the global component between 350 nm and 1100 nm. Measurement uncertainties are listed in Table I. We also measure air temperature, air pressure, ambient humidity, and wind speed and direction at a height of 1.5 meters above the roof surface. All data, collected either through a data logger or read-out directly through serial data ports, are synchronically stored on a PC. With this system we started to measure in the beginning of March 2011.

Figure 1: Experimental assembly of EKO Instruments roof-site in Den Haag, Netherlands: PV modules, radiation sensors, and instruments cabinet

Table I: Uncertainties of the measured parameters relevant for the assessment

Device	Measured parameter	Measurement uncertainty
Secondary standard Pyranometer MS–802	Coplanar Broadband Irradiance	1.5% – 2% (depending on cosine response)
Spectroradiometer MS–700	Coplanar Spectral Irradiance	4% – 7% (depending on wavelength and cosine response)
Thermocouple type–T	Module Temperature	± 1 °C
I–V Curve tracer MP-160	Voltage	0.5%
	Current	0.5%

3 APPROACH

Determination of the required parameters for each translation method is performed with the measurements attained with the assembly, as described in the norm [3]. Also, for this assessment, we assume different reference STC P_{MAX} values for our modules, from the specified in the datasheet.

3.1 Assumption

To determine the reference P_{MAX} at STC for our analysis, we make use of the spectral measurements of a clear-sky day (Fig. 2). To minimize cosine errors [17,18], we consider values close to the solar noon within 995 to 1005 W/m^2 intensity, and identify the points for which the spectral distribution is closer to the AM 1.5 distribution by using the spectral indicator Average Photon Energy (APE) [4–6], which is a device independent spectral index. In the range in which we measure the spectral irradiance (350-1100 nm) APE equals 1.88 eV, but for the considered data points of this investigation the APE is lower (~1.86 eV), meaning that the AM1.5 spectral is slightly shifted more towards blue enriched energy than the considered points. After making temperature corrections with the 1st and 2nd procedure we translate those points to STC and, by giving the same weight to the 1st and 2nd procedure, we assume the average P_{MAX} of the translated curves as the reference STC value, P_{MAX_T}, which is barely within the 3 % tolerance from the datasheet value for both modules (Fig. 3).

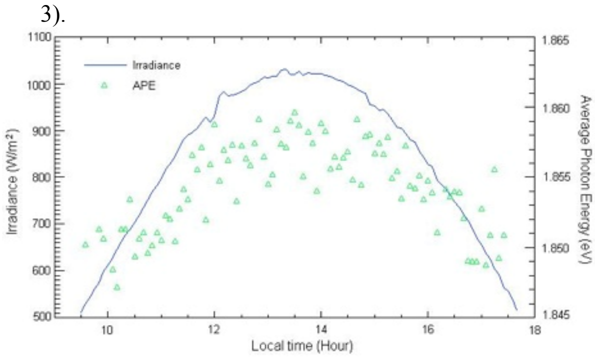


Figure 2: Irradiance and APE variation over time, for the considered clear sky day in April 2011.

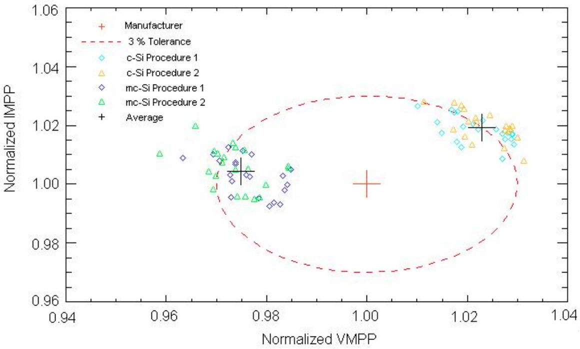


Figure 3: Scattering of the normalized maximum power points of the I-V curves translated to STC. The average corresponds to the considered P_{MAX_T} at STC for each module

3.2 Criteria

Using the determined reference P_{MAX_T} at STC we compare P_{MAX_T} with the resulting P_{MAX} of the I-V curves translated to STC, from measurements above 300 W/m^2, in the month of June 2011.

To better understand the methods sensitivity to the input data, we make I-V curve translations according to 3 criteria leading to 4 different case studies (summarized in Table II), reflecting linearity requirements as defined in IEC 60904-10 [19] and the inclusion of the correction parameters.

In the 1st case we select only the measurements within a maximum of 2% deviation from linearity of I_{SC} vs. G. In the 2nd case we consider the same data, within the 2% linearity and neglect the additional coefficients that more often than not are not given in a module datasheet and hence need to be determined manually. For the 3rd case, the data points measured outside this linearity are also used (see Fig. 4).

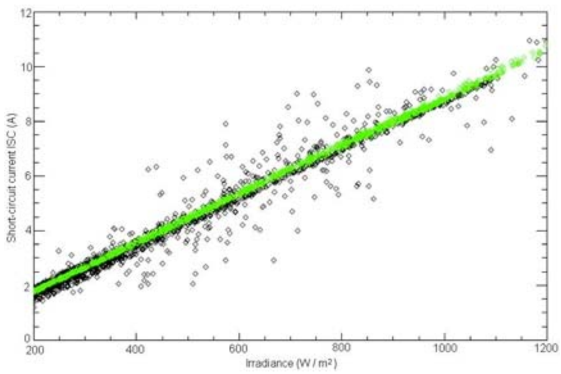


Figure 4: Example of a module's short-circuit current I_{SC} as function of the measured irradiance. In green the values within 2% linearity, representing 49.8% of the measurements considered.

In the 4th case we translate the curves, regardless of the linearity criteria, and self-reference the PV devices using the I_{SC} from the measured I–V characteristics and the I_{SC} at STC (determined with the approach stated in 3.1), i.e. we use I_{SC} as input variables instead of the irradiance G. This way we account for the spectral effects and reduce the effects of irradiance measurement uncertainties.

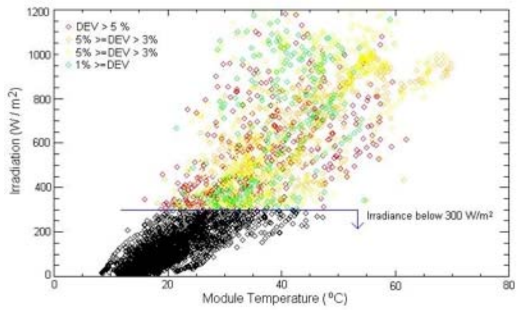
Table II: Criteria used for the selection of the data and the defined cases.

Criteria	I		II	III
Case	Values within 2% linearity from I_{SC} vs. G	Values outside 2% linearity from I_{SC} vs. G	Inclusion of the correction coefficients (R_S, k and α)	Self-reference of the PV device
1	✔	✗	✔	✗
2	✔	✗	✗	✗
3	✗	✔	✔	✗
4	✔	✔	✔	✔

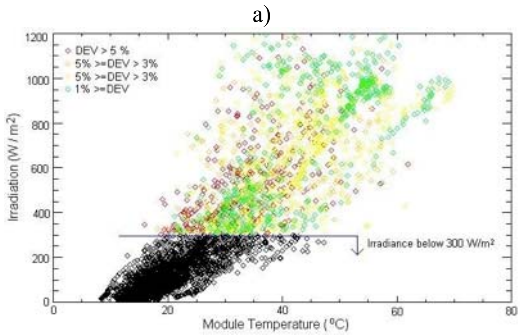
4 RESULTS

In Figure 5, the irradiance and module temperature condition of each measured I–V curve for the c-Si module investigated in the present study is represented. For both 1st and 2nd procedure, each I-V curve is translated to STC. The absolute deviation of the reference STC P_{MAX_T} from the P_{MAX} of the translated I-V curve is then represented with different marker colors. Similar results were found for the mc-Si module.

In Figure 6 we present the average deviation and the root mean square error (error bars) in percent for both 1st and 2nd translation procedures, as function of irradiance for each criterion.



a)



b)

Figure 5: Module temperature and irradiance for the outdoors measured I–V curves in the month of June 2011, for the c-Si module investigated in the present study. The colors represent the percentage deviation from P_{MAX_T} at STC, for the resulting translations with the 1st and 2nd procedures (a and b respectively), from green (best agreement) to red (worse agreement), black values are below 300W/m^2 which are not considered in the assessment.

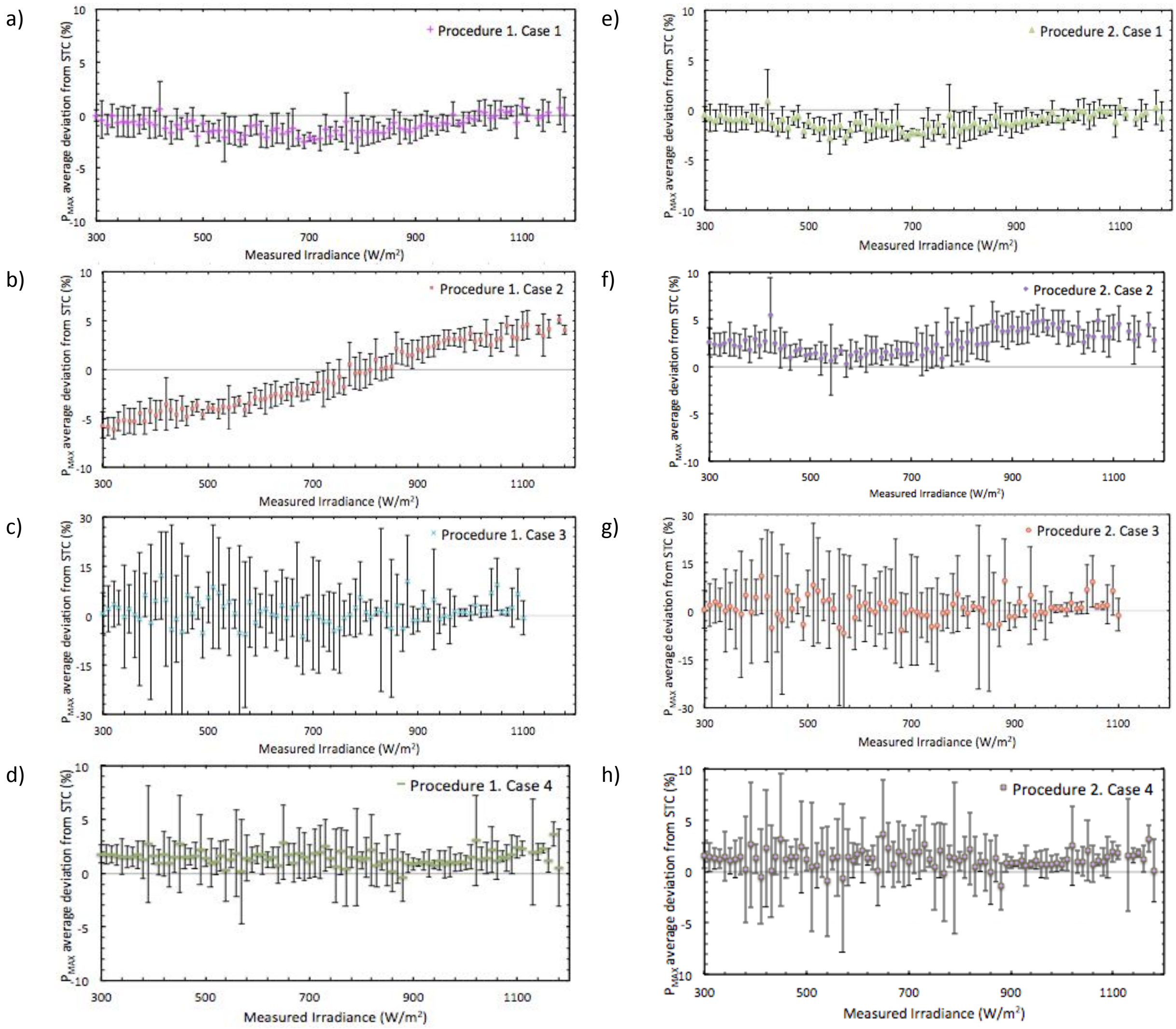


Figure 6: Statistical analysis of the STC translation as function of the irradiance from which the I-V curves are translated to STC: points represent the averages, error bars represent the standard deviations; a) 1st Procedure, Case 1: translations with measurements within 2% linearity, b) 1st Procedure, Case 2: translations neglecting the conversion parameters with measurements within 2% linearity, c) 1st Procedure, Case 3: translations with measurements outside 2% linearity, d) 1st Procedure, Case 4: translations by self-reference, e) 2nd Procedure, Case 1: translations with measurements within 2% linearity, f) 2nd Procedure, Case 2: translations neglecting the conversion parameters with measurements within linearity, g) 1st Procedure, Case 3: translations with measurements outside 2% linearity, h) 2nd Procedure, Case 4: translations by self-reference.

5 DISCUSSION

Best results are obtained for procedures 1 and 2 for the 1st case, where the deviation from linearity is less than 2% (Fig. 6a and 6e). It can be concluded that the 1st and 2nd procedures are more dependent on the linearity of the measured irradiance with the module I_{SC} than on the irradiance discrepancies between measured conditions and STC (Fig. 6a, 6c, 6e and 6g). This indicates that, if the data is carefully selected within the linearity, both procedures can be applied for a wide range of irradiances with a maximum deviation from STC lower than 3%. If the same linearity criterion is met and the correction parameters are neglected, the methods can be used but with less accuracy. Considering data outside this linearity the deviation in the resulting translations is high, with an average maximum deviation of over 10% (Fig. 6c and 6g). It can also be noted that the deviation is smaller if the difference between measured irradiance and STC is less than 100 W/m^2, showing that the ±30% margin indicated by the norm might be somehow optimistic in some cases.

Reduction of the measurement uncertainties and the spectral effects influence in the translations, can be obtained by self-referencing the devices as shown in Figures 6d and 6h.

Furthermore, regardless of the criteria, from Figure 5 it can be noted that the 2nd method produces more results with low deviations than the translations made with the 1st method.

A large number of outdoor measurements for different irradiance and temperature conditions are needed to determine the parameters in the 1st and 2nd procedures. This situation could be avoided by using the 3rd method, if measurement conditions close to STC were more commonly met. Note, that this may be the case for other times of the year, and/or other geographical locations. Nonetheless, once the parameters are determined, the 1st and 2nd procedure allow conversions to any temperature and irradiance condition with only one I-V measurement.

For the considered outdoor measurements, the 3rd procedure of the norm is found to be less suitable than procedures 1 and 2, for STC conversions: at least two I-V curves are required to make the interpolation, and not all I-V measurements meet the requirements to perform the conversion to STC with the 3rd method. However, extending the measurement campaign to a whole year would produce measurements in a larger set of conditions, which could make available a higher number of I-V curve combinations that allow conversions with the 3rd method to STC.

The reference STC values assumed for our assessment contain translation uncertainties. These uncertainties could be avoided by using STC values obtained from well-calibrated indoor test facilities. This would help to better understand the results of our assessment.

In this experiment, no direct correlation between the difference in the measured spectra and the error of the resulting translation was found, but it should be noted that the module technologies analyzed in this paper suffer more from temperature effects than from spectral effects [7]. Nevertheless, the spectral measurements allowed to identify the translations that were made with a spectral distribution close to the AM1.5 spectrum.

6 CONCLUSIONS

The STC translation according to IEC 60891 of I-V curve measurements under outdoor conditions for two modules (c-Si and mc-Si) was investigated.

Similar results were found for both modules and both conversion methods of the norm. The two methods showed a higher dependency on the correlation between short-circuit current and the measured irradiance, than on the irradiance difference in the translation.

Using highly correlated values of 0.98 and higher allowed translations with the 1st and 2nd procedures, to agree better than 3% with STC and for a wider irradiance range than the ±30% recommended value. If outside the linearity, the results are worse, with a shorter valid irradiance range than stated in the norm.

Self-referencing the PV device can be a good approach to minimize the measurement uncertainties and spectral effects influence in the translations, with a good accuracy.

The use of spectral measurements, allowed identifying the translations that were made with a spectral distribution closer to the AM1.5.

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