IEC 60904-4

Edition 2.0 2019-11

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Photovoltaic devices –
Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

Dispositifs photovoltaïques –
Partie 4: Dispositifs photovoltaïques de référence – Procédures pour établir la traçabilité de l'étalonnage

IEC 60904-4:2019-11(en-fr)

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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ICS 27.160 ISBN 978-2-8322-7531-3

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CONTENTS

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PHOTOVOLTAIC DEVICES –

Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

FOREWORD

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International Standard IEC 60904-4 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This second edition cancels and replaces the first edition published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) modification of standard title;

b) inclusion of working reference in traceability chain;

c) update of WRR with respect to SI;

d) revision of all methods and their uncertainties in Annex A;

e) harmonization of symbols and formulae with other IEC standards.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
82/1618/FDIS	82/1638/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60904 series, published under the general title *Photovoltaic devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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PHOTOVOLTAIC DEVICES –

Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability

1 Scope

This part of IEC 60904 sets the requirements for calibration procedures intended to establish the traceability of photovoltaic (PV) reference devices to SI units as required by IEC 60904-2.

This document applies to PV reference devices that are used to measure the irradiance of natural or simulated sunlight for the purpose of quantifying the performance of PV devices. The use of a PV reference device is required in many standards concerning PV (e.g. IEC 60904-1 and IEC 60904-3).

This document has been written with single-junction PV reference devices in mind, in particular crystalline silicon, but it is sufficiently general to include other single-junction technologies.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60904-1, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2, *Photovoltaic devices – Part 2: Requirements for photovoltaic reference devices*

IEC 60904-3, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

IEC TS 61836, *Solar photovoltaic energy systems – Terms, definitions and symbols*

ISO/IEC Guide 98-3: 2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM: 1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836 and the following apply.

NOTE The different reference instruments for the traceability chain of solar irradiance are defined in this clause. Typical examples for each category are listed in Table 1, which also refers to relevant standards (where available). Figure 1 then shows schematically the most common traceability chains linking these instruments and the relevant standards (where available). Methods for the implementation of this document are described in Annex A.

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- IEC Electropedia: available at http://www.electropedia.org/

- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
primary standard
standard that is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity

Note 1 to entry: The concept of a primary standard is equally valid for base quantities and derived quantities.

Note 2 to entry: A primary standard is never used directly for measurement other than for comparison with other primary standards or secondary standards.

Note 3 to entry: Primary standards are usually maintained by national metrology institutes (NMIs) or similar organizations entrusted with maintenance of standards for physical quantities. Often referred to also just as the «primary», the physical implementation is selected such that long-term stability, accuracy and repeatability of measurement of the quantity it represents are guaranteed to the maximum extent possible by current technology.

Note 4 to entry: The World Radiometric Reference (WRR) as realized by the World Standard Group (WSG) of cavity radiometers is the accepted primary standard for the measurement of solar irradiance.

3.2
secondary standard
device which, by periodical comparison with a primary standard, serves to maintain conformity to SI units at other places than that of the primary standard

Note 1 to entry: A secondary standard does not necessarily use the same technical principles as the primary standard, but strives to achieve similar long-term stability, accuracy and repeatability.

Note 2 to entry: Typical secondary standards for solar irradiance are cavity radiometers which participate periodically (normally every 5 years) in the International Pyrheliometer Comparison (IPC) with the WSG, thereby giving traceability to WRR. Direct traceability to SI radiometric scale can also be available for these instruments.

3.3
primary reference
instrument which a laboratory uses to calibrate secondary references, compared at periodic intervals to a secondary standard

Note 1 to entry: Often primary references can be realized at much lower costs than secondary standards.

Note 2 to entry: Typically, a PV cell is used as a reference device for the measurement of natural or simulated solar irradiance. Primary references are normally used by calibration and testing laboratories.

3.4
secondary reference
measurement device in use for daily routine measurements or to calibrate working references, calibrated at periodic intervals against a primary reference

Note 1 to entry: The most common secondary references for the measurement of natural or simulated solar irradiance are PV cells and PV modules. Secondary references are normally used by calibration and testing laboratories, but sometimes also in industrial production.

3.5
working reference
measurement device in use for daily routine measurements, calibrated at periodic intervals against a secondary reference

Note 1 to entry: The most common working references for the measurement of natural or simulated solar irradiance are PV cells and PV modules.

Note 2 to entry: Working references are normally used in industrial production.

3.6
traceability
<of a PV reference device> requirement for any PV reference device, to tie its calibration value to SI units in an unbroken and documented chain of calibration transfers including stated uncertainties

Note 1 to entry: The WRR has been compared several times to the SI radiometric scale. While in previous comparisons the two scales were found to be indistinguishable within the uncertainty of the comparison, the latest comparison of scales established that there is a systematic shift between the scales, with WRR reading 0,34 % higher irradiance than the SI scale. The uncertainty of this shift was given as 0,18 % (k = 2). Therefore, traceability to WRR automatically provides traceability to SI units. However, the shift between the scales may be corrected for those measurements traceable to the WRR. The uncertainty of the scale comparison shall be included into the uncertainty budget. Essentially there are two possibilities for those measurements traceable to SI units via the WRR. Firstly, no correction is applied for the scale difference and a larger uncertainty of 0,3 % (rectangular distribution) shall be used. Secondly an explicit correction of the scale difference amounting to 0,34 %. In this case the uncertainty contribution is 0,18 % (k = 2). The value of 0,34 % for the scale difference is the latest available at time of publication of this document. The scientific literature should be checked for possible updates of this difference and its uncertainty. In particular, it is possible that in the future the WRR is adapted to take account of this difference and bring it into line with SI units. In this case no further correction shall be applied.

[SOURCE: A Fehlmann, G Kopp, W Schmutz, R Winkler, W Finsterle, N Fox, *metrologia* **49** (2012) S34]

Table 1 – Examples of reference instruments used in a traceability chain of solar irradiance

Reference instrument	Solar irradiance
Primary standard	Group of cavity radiometers constituting the World Standard Group (WSG) of the World Radiometric Reference (WRR) Cryogenic trap detector Standard lamp
Secondary standard	Commercially available cavity radiometers compared regularly (normally every 5 years) at the International Pyrheliometer Comparison (IPC) Standard detector calibrated against a trap detector Spectroradiometer calibrated against a standard lamp
Primary reference	Normal incidence pyrheliometer (NIP) (ISO 9059) PV reference device (IEC 60904-2 and IEC 60904-4)
Secondary reference	Pyranometer (ISO 9846) PV reference device (IEC 60904-2)
Working reference	Pyranometer (ISO 9847) PV reference device (IEC 60904-2)

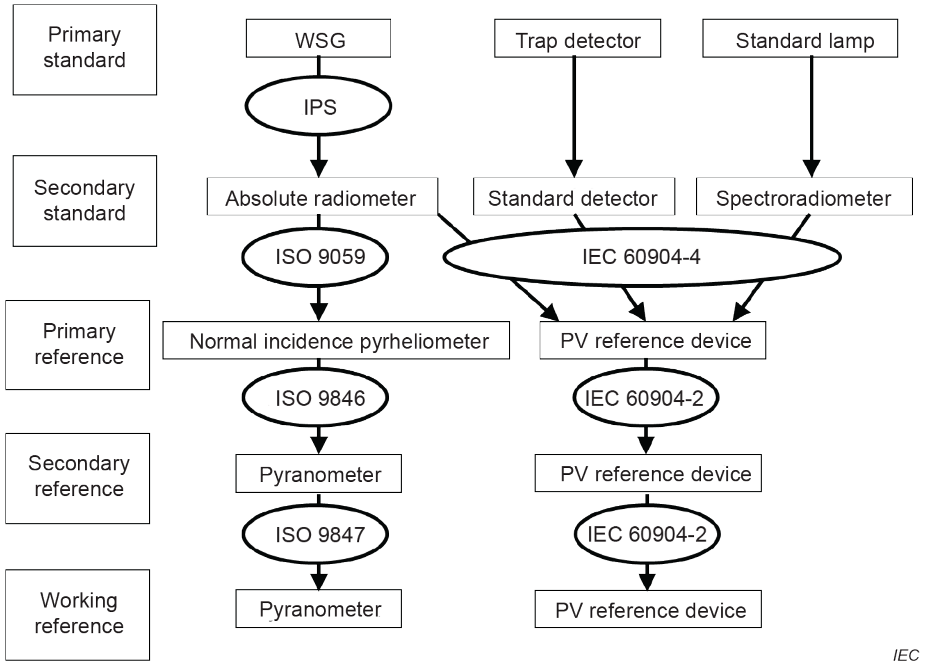

Figure 1 – Schematic of most common reference instruments and transfer methods used in the traceability chains for solar irradiance detectors

4 Requirements for traceable calibration procedures of PV reference devices

A traceable calibration procedure is necessary to transfer calibration from a standard or reference measuring solar irradiance and based on a physical principle other than PV effect (such as cavity radiometer, pyrheliometer and pyranometer) to a PV reference device. The requirements for such procedures are as follows:

a) Any measurement instrument required and used in the transfer procedure shall be an instrument with an unbroken traceability chain.
b) A documented uncertainty analysis.
c) Documented repeatability, such as measurement results of laboratory intercomparison, or documents of laboratory quality control.
d) Inherent absolute accuracy, given by a limited number of intermediate transfers.

Normally the transfer would be from a secondary standard to a PV reference device constituting a primary reference.

The transfer from one PV reference device to another is covered by IEC 60904-2.

5 Uncertainty analysis

An uncertainty estimate according to ISO/IEC Guide 98-3: 2008 shall be provided for each traceable calibration procedure. This estimate shall provide information on the uncertainty of the calibration procedure and quantitative data on the following uncertainty factors for each instrument used in performing the calibration procedure. In particular:

a) Component of uncertainty arising from random effects (Type A).
b) Component of uncertainty arising from systematic effects (Type B).

A full uncertainty analysis has to be performed for the implementation of the calibration method by a particular laboratory. Annex A provides examples of the main uncertainty components in some particular implementations. Due to the variety of methods available, it is impossible to give a detailed guidance on how a particular uncertainty analysis should be made. However, the following components shall be considered:

– uncertainty of all measurement instruments involved;
– offset and drift of all measurement instruments;
– uncertainty of all references used;
– uncertainty of measured device temperature;
– uncertainty introduced of deviations between actual and nominal device temperature;
– uncertainty of irradiance measurement (total and spectral irradiance);
– uncertainty introduced by deviations between actual and reference spectral irradiance;
– contributions due to repeatability and reproducibility;
– uncertainty due to instability of conditions and instruments.

6 Calibration report

The calibration report shall include at least the following information:

a) title (e.g. "Calibration Certificate");
b) name and address of laboratory, and location where the calibrations were carried out, if different from the address of the laboratory;
c) unique identification of the report (such as serial number) and of each page, the total number of pages and the date of issue;
d) name and address of the client placing the order;
e) description and unambiguous identification of the item(s) calibrated;
f) date of receipt of calibration item(s) and date(s) of performance of calibration, as appropriate;
g) calibration results and their uncertainties, including the temperature of the device at which the calibration was performed;
h) reference to sampling procedures used by the laboratory where these are relevant to the validity or application of the results;
i) the name(s), title(s) and signature(s) or equivalent identification of person(s) authorizing the report;
j) where relevant, a statement to the effect that the results relate only to the items calibrated;
k) where relevant the spectral responsivity of the PV reference device;
l) where relevant the temperature coefficient of the PV reference device.

7 Marking

The calibrated PV reference device shall be marked with a serial number or reference number and the following information attached or provided on an accompanying certificate:

a) date of (actual or present) calibration;
b) calibration value and its uncertainty;
c) identification of laboratory having performed the calibration.

Annex A
(informative)

Examples of validated calibration procedures

A.1 General

A.1.1 Overview

Annex A describes examples of calibration procedures for PV reference devices as primary reference devices, together with their stated uncertainties. These procedures serve to establish the traceability of PV reference devices to SI units as required by IEC 60904-2. Primary reference devices calibrated in accordance with these procedures serve to establish the traceability of further PV reference devices, which then constitute secondary reference devices.

As already mentioned in Clause 1, the methods in this annex are limited to PV single junction technology. Moreover, they have currently only been validated for crystalline silicon technology, although they could be applicable to other technologies.

The methods have been implemented in various laboratories around the world and validated in international intercomparisons, most notably the World Photovoltaic Scale (WPVS). However, the description in this document is more generalized. For details of the various implementations, the references in peer-reviewed publications are given at the end of each procedure.

The uncertainty estimates are based on U_{95} (coverage factor k = 2) for all single components. The combined expanded uncertainty is calculated as the square root of the sum of squares of all components. The uncertainties provided are simplified versions (restricted to the main components) as provided by the laboratories having implemented the procedure. These uncertainty calculations only serve as guidelines and will have to be adapted to the particular implementation of each procedure in a given laboratory. The uncertainties achieved by any implementation of these methods might be considerably different. Uncertainties quoted by a given laboratory have to be based on an explicit specific analysis and cannot be taken by reference to the uncertainty estimates in this document.

A.1.2 Examples of validated methods

A.2 Global sunlight method (GSM)

A.3 Differential spectral responsivity calibration (DSR)

A.4 Solar simulator method (SSM)

A.5 Direct sunlight method (DSM)

A.1.3 List of common symbols

I_{SC}	short-circuit current of PV reference device
T_j	temperature of PV reference device
M_G	irradiance correction factor (see below)
M_T	temperature correction factor (see below)
T_{coef}	temperature coefficient α of the short-circuit current (IEC 60891) normalized to the short-circuit current at 25 °C and expressed in 1/ K
SMM	spectral mismatch factor (IEC 60904-7)
λ	wavelength
$s(\lambda)$	spectral responsivity of PV reference device as a function of wavelength λ

$s(\lambda, T_j)$	spectral responsivity of PV reference device as a function of wavelength λ and temperature T_j
$\frac{\partial s(\lambda, T_j)}{\partial T}$	partial derivative of spectral responsivity with respect to temperature as a function of wavelength λ
$\tilde{s}(\lambda)$	differential spectral responsivity of PV reference device
$E_{meas}(\lambda)$	spectral irradiance distribution of natural or simulated sunlight
$E_{ref}(\lambda)$	standard or reference spectral irradiance distribution according to IEC 60904-3
G_{dir}	direct irradiance
G_{dif}	diffuse in-plane irradiance
G_T	total in-plane irradiance
G_{STC}	irradiance at STC (= 1 000 Wm–2)
CV	calibration value, i.e. I_{SC} at STC
AM	air mass
STC	standard test conditions (1 000 Wm^{-2}, 25 °C and $E_{ref}(\lambda)$)
P	local air pressure
P_0	101 300 Pa
θ	solar elevation angle

A.1.4 Common formulae

The methods described in Clauses A.2, A.4 and A.5 have some common calculations, which are detailed in A.1.4. Details of the various implementations are then described in each subclause.

The I_{SC} is normally not measured at exactly 1 000 Wm^{-2}, but at an irradiance level close to it. Under the assumption that the I_{SC} of the PV reference device varies linearly with irradiance according to IEC 60904-10, the following correction is made:

$$I_{SC}\left(G_{STC}\right) = I_{SC} M_G = I_{SC} \frac{G_{STC}}{G_T} \tag{A.1}$$

If the irradiance measurement is traceable to the WRR, then the irradiance reading may be corrected for the scale difference to SI units.

STC mandate a device temperature of 25 °C, but measurements will not always be taken at this temperature. The deviations in temperature should be accounted for in the uncertainty budget. It is also possible to correct I_{SC} from the measurement temperature T_j to 25 °C by multiplying with the temperature correction factor M_T defined by:

$$I_{SC}\left(25\ ^\circ\mathrm{C}\right) = I_{SC}\left(T_j\right) M_T = \frac{I_{SC}\left(T_j\right)}{1 - T_{coef}\left(25\ ^\circ\mathrm{C} - T_j\right)} \tag{A.2}$$

The correction for the difference in spectral responsivity of the PV reference device to be calibrated and the device used to measure the irradiance can be calculated as a spectral mismatch *SMM:*

$$SMM = \frac{\int_0^\infty E_{\text{ref}}(\lambda)d\lambda}{\int_0^\infty E_{\text{meas}}(\lambda)d\lambda} \frac{\int_0^\infty E_{\text{meas}}(\lambda)s(\lambda)d\lambda}{\int_0^\infty E_{\text{ref}}(\lambda)s(\lambda)d\lambda} \quad \text{(A.3)}$$

NOTE Formula A.3 is the same formula as in IEC 60904-7 for the case of a thermopile detector where the spectral responsivity of the device under test is now the spectral responsivity of the PV reference device to be calibrated.

The integration range is over all wavelengths. For $E_{\text{ref}}(\lambda)$ the irradiance is zero below 280 nm. This also holds normally for $E_{\text{meas}}(\lambda)$ in particular under natural sunlight. For practical reasons the explicit integral cannot be calculated above 4 000 nm, as $E_{\text{ref}}(\lambda)$ is not defined explicitly but only the integral irradiance between 4 000 nm and infinity. $E_{\text{meas}}(\lambda)$ is typically only measured for an even smaller wavelength range, for example up to 2 500 nm. In order to calculate the integrals, suitable approximation (truncation of the integrals) or extension of measured spectral irradiance data by extrapolation or modelling can be used, but has to be accounted for in the uncertainty calculation. For example, the truncation of the integrals at 4 000 nm for the DSM will lead to an error of 0,025 %, whereas truncation at 2 500 nm to an error of 0,116 %. These values have been determined from the direct and global spectral irradiance as defined in IEC 60904-3.

Cavity radiometers used for irradiance measurement are assumed to detect irradiance at all wavelengths perfectly. Possible deviations from such a perfect characteristic should be corrected or accounted for in the measurement uncertainty.

The calibration value (CV) of the PV reference device is then calculated as:

$$CV = I_{\text{SC}} \frac{M_{\text{G}} M_{\text{T}}}{SMM} \quad \text{(A.4)}$$

A.1.5 Reference documents

– IEC 60891: *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*
– IEC 60904-7: *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*
– IEC 60904-10: *Photovoltaic devices – Part 10: Methods of linearity measurements*
– C. R. Osterwald et al., “The results of the PEP'93 intercomparison of reference cell calibrations and newer technology performance measurements: Final Report”, *NREL/TP-520-23477,* 1998, 209 pages
– C. R. Osterwald et al., “The world photovoltaic scale: an international reference cell calibration program”, *Progress in Photovoltaics,* **7,** 1999, 287-297
– K. Emery, “The results of the First World Photovoltaic Scale Recalibration”, *NREL/TP-520-27942,* 2000, 14 pages
– Winter el al., “The results of the Second World Photovoltaic Scale Recalibration”, *Proc. of the 31st IEEE PVSC* , 3-7 January 2005, Orlando, Florida, USA, pp. 1011-1014

A.2 Global sunlight method (GSM)

A.2.1 General

The establishment of traceability is based on the calibration using the continuous sun-and-shade method as described in ISO 9846. The PV reference device to be calibrated is compared under natural sunlight with two reference radiometers, namely a pyrheliometer measuring direct solar irradiance and a pyranometer measuring diffuse solar irradiance by application of a continuous shading device under normal incidence conditions. The total solar irradiance is determined by the sum of direct irradiance and diffuse in-plane irradiance. As a