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Edition 1.0 2009-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Photovoltaic devices – Part 4: Reference solar devices – Procedures for establishing calibration traceability

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

IEC 60904-4:2009

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FOREWORD

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

The text of this standard is based on the following documents:

CDV	Report on voting
82/533/CDV	82/561/RVC

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

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

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

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

PHOTOVOLTAIC DEVICES –

Part 4: Reference solar devices – Procedures for establishing calibration traceability

1 Scope and object

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

This standard applies to photovoltaic (PV) reference solar 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 solar device is required in the application of IEC 60904-1 and IEC 60904-3.

This standard has been written with single junction PV reference solar devices in mind, in particular crystalline Silicon. However, the main part of the standard is sufficiently general to include other technologies. The methods described in Annex A, however, are limited to single junction technologies.

2 Normative references

The following referenced documents are indispensable for the application 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 60904-2, *Photovoltaic devices – Part 2: Requirements for reference solar devices*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

ISO 9059, *Solar energy – Calibration of field pyrheliometers by comparison to a reference pyrheliometer*

ISO 9846, *Solar energy – Calibration of a pyranometer using a pyrheliometer*

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 following terms and definitions apply.

NOTE The different reference instruments for the traceability chain of solar irradiance are defined in this Clause. Table 1 lists and compares them with those in use for time. Figure 1 shows schematically the most common traceability chains, based on the methods described in Annex A.

3.1
primary standard
a device, which implements physically one of the SI units or directly related quantities. They are usually maintained by national metrology institutes (NMIs) or similar organisations 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, precision

and repeatability of measurement of the quantity it represents are guaranteed to the maximum extent possible by current technology.

NOTE 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
a 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. It does not necessarily use the same technical principles as the primary standard, but strives to achieve similar long-term stability, precision and repeatability.

NOTE 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.

3.3
primary reference
the reference instrument which a laboratory uses to calibrate secondary references. It is compared at periodic intervals to a secondary standard. Often primary references can be realised at much lower costs than secondary standards.

NOTE Typically a solar cell is used as a reference solar device for the measurement of natural or simulated solar irradiance.

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

NOTE The most common secondary references for the measurement of natural or simulated solar irradiance are solar cells and solar modules.

3.5
traceability
the requirement for any PV reference solar device, to tie its calibration value to SI units in an unbroken and documented chain of calibration transfers including stated uncertainties.

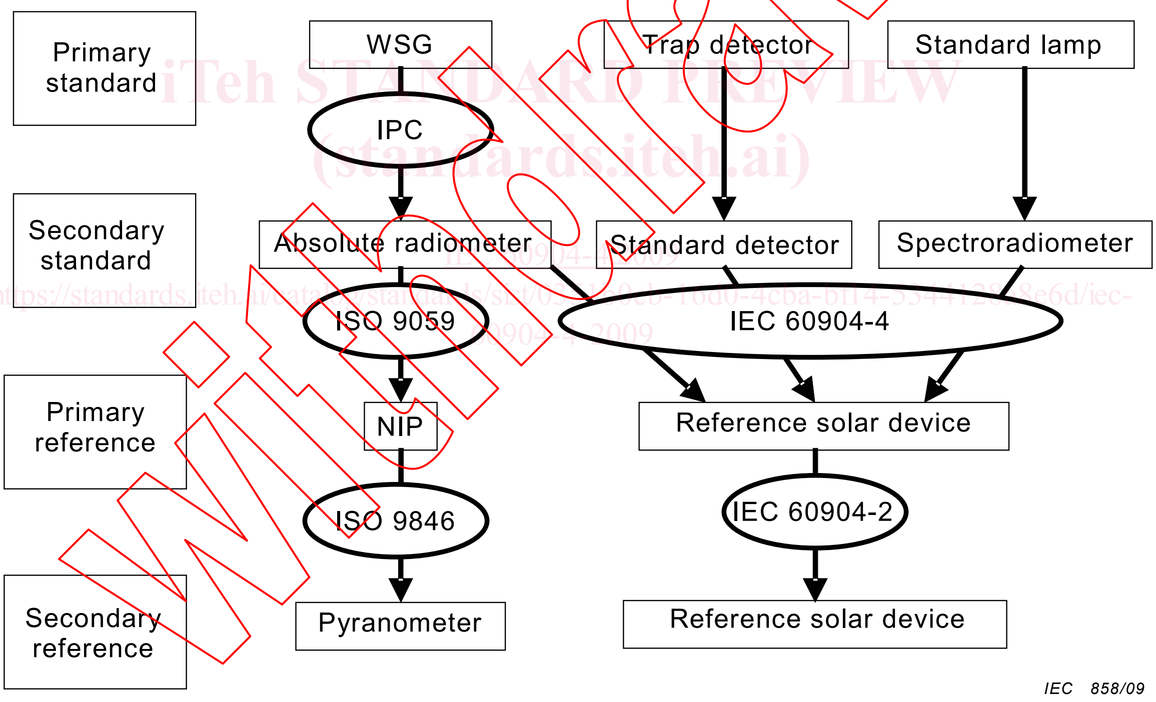
NOTE The WRR has been compared twice to the SI radiometric scale and shown to be within their mutual uncertainty levels. Therefore traceability to WRR automatically provides traceability to SI units. However, the uncertainty of the ratio WRR/SI units needs to be taken into account. The World Radiation Center (WRC) recommends a rectangular uncertainty distribution with 0,3 % half-width. A third comparison is currently underway and should be published in the future.

J. Romero, N.P. Fox, C. Fröhlich *metrologia* **28** (1991) 125-8

J. Romero, N.P. Fox, C. Fröhlich *metrologia* **32** (1995/1996) 523-4

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

Reference instrument	Time	Solar irradiance
Primary standard	Cesium atomic clock at National Metrology Institute (NMI)	Group of cavity radiometers constituting the World Standard Group (WSG) of the World Radiometric Reference (WRR) Cryogenic trap detector Standard lamp
Secondary standard	Cesium atomic clock on GPS (Global Positioning System) satellites	Commercially available cavity radiometers compared every 5 years at the International Pyrheliometer Comparison (IPC) Standard detector calibrated against a trap detector Spectroradiometer calibrated against a standard lamp
Primary reference	GPS receiver, set to show time	Normal incidence pyrheliometer (NIP) (ISO 9059) Reference solar device (IEC 60904-2 and IEC 60904-4)
Secondary reference	Quartz watch	Pyranometer (ISO 9846) Reference solar device (IEC 60904-2)



NOTE Direct traceability of absolute radiometers to SI radiometric scale may also be available.

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 solar devices

A traceable calibration procedure is necessary to transfer calibration from a standard or reference measuring solar irradiance (such as cavity radiometer, pyrheliometer and pyranometer) to a PV reference solar 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 precision, given by a limited number of intermediate transfers.

NOTE 1 Normally the transfer would be from a secondary standard to a PV reference solar cell constituting a primary reference.

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

5 Uncertainty analysis

An uncertainty estimate according to MISC UNCERT – ED. 1.0 (1995-01) 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).

Nevertheless a full uncertainty analysis has to be performed for the implementation of the calibration method by a particular laboratory.

6 Calibration report

The calibration report shall conform to the requirements of ISO/IEC 17025 and shall normally include at least the following information:

a) title (e.g. "Calibration Certificate");

b) name and address of laboratory, and location where the tests and/or 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) tested or calibrated;

f) date of receipt of calibration item(s) and date(s) of performance of test or calibration, as appropriate;

g) calibration results 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) authorising the report;

j) where relevant, a statement to the effect that the results relate only to the items tested or calibrated.

7 Marking

The calibrated reference solar 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 temperature coefficient (if applicable).

Annex A
(informative)

Examples of validated calibration procedures

A.1 General

This annex describes examples of calibration procedures for PV reference solar cells as primary reference devices, together with their stated uncertainties. These procedures serve to establish the traceability of reference solar 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 solar 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 should 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 standard is more generalised. 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 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 have to be based on an explicit analysis and cannot be taken by reference to the uncertainty estimates in this standard.

A.1.1 Examples of validated methods

A.2 Global sunlight method
A.3 Differential spectral responsivity calibration
A.4 Solar simulator method
A.5 Direct sunlight method

A.1.2 List of common symbols

I_{SC}	short circuit current of reference cell
T_j	temperature of reference cell
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/ °C
MMF	mismatch factor (see below)
λ	wavelength
$S(\lambda)$	spectral response of reference cell
$s(\lambda)$	differential spectral responsivity of reference cell
$E_m(\lambda)$	spectral irradiance distribution of natural or simulated sunlight
$E_s(\lambda)$	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

E_{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 W/m^2, 25 °C and $E_s(\lambda)$)
P	local air pressure
P_0	101 300 Pa
θ	solar elevation angle

A.1.3 Common equations

The methods described in Clauses A.2, A.4 and A.5 have some common calculations, which are detailed in this subclause. 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 reference cell varies linearly with irradiance, the following correction is made:

$$I_{SC}(1000\ \mathrm{Wm}^{-2}) = I_{SC} M_G = I_{SC} \frac{1000 \frac{\mathrm{W}}{\mathrm{m}^2}}{G_T} \tag{A.1}$$

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

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

The correction for the difference in spectral sensitivity of the reference cell to be calibrated and the device used to measure the irradiance can be described as a MMF

$$MMF = \frac{\int_{300\ \mathrm{nm}}^{4000\ \mathrm{nm}} S(\lambda)\cdot E_s(\lambda)\cdot d\lambda}{\int_{300\ \mathrm{nm}}^{4000\ \mathrm{nm}} S(\lambda)\cdot E_m(\lambda)\cdot d\lambda} \cdot \frac{\int_{300\ \mathrm{nm}}^{4000\ \mathrm{nm}} E_m(\lambda)\cdot d\lambda}{\int_{300\ \mathrm{nm}}^{4000\ \mathrm{nm}} E_s(\lambda)\cdot d\lambda} \tag{A.3}$$

NOTE The integration range is taken based on the definition of $E_s(\lambda)$. If the measurement range, in particular that of $E_m(\lambda)$, does not cover this entire range, suitable approximation, extrapolation or modelling can be used, but needs to be accounted for in the uncertainty calculation.

The calibration value CV of the reference cell is then calculated as

$$CV = I_{SC} M_G M_T MMF \tag{A.4}$$

A.1.4 References documents

– 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

The establishment of traceability is based on the calibration using the Continuous Sun-and-Shade Method as described in ISO 9846. The reference solar cell 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 shade device under normal incidence conditions. The total solar irradiance is determined by the sum of direct irradiance and diffuse in-plane irradiance. As a pyrheliometer, a secondary standard is used in the form of an absolute cavity radiometer compared at 5-year intervals with the World Standard Group (WSG) establishing the World Radiometric Reference (WRR). The calibration factor for the photovoltaic reference cell is determined from the measured short circuit current, scaled to 1 000 W/m^2 and corrected for spectral mismatch (IEC 60904-7) based on the measured spectral irradiance of the global sunlight and the relative spectral response of the reference solar cell to be calibrated.

Under certain conditions the simplified global sunlight method is applicable. The short-circuit current of the reference cell is scaled to 1 000 W/m^2 and then plotted versus pressure corrected geometric air mass. The calibration value is determined from a linear least square fit at air mass 1,5. A spectral mismatch correction is not required and hence the measurements of the spectral irradiance of the sunlight and the spectral response are not necessary. In the simplified version of the global sunlight method no explicit spectral mismatch correction is performed and it is replaced by conditions which should ensure that the spectral irradiance of the natural sunlight is sufficiently close to the defined standard spectral irradiance (IEC 60904-3) that the uncertainty component is smaller than quoted in Table A.1. Although this should be ensured by the conditions listed in the description of the method below, it should be explicitly verified (preferentially by using the global sunlight method). After this validation the simplified version can be applied as long as the boundary conditions are the same as during the validation.

NOTE 1 The verification and validation will produce numerical values for both methods. If the agreement between these numerical values is within the uncertainty budget of the methods, the simplified method shall be deemed validated.

NOTE 2 The simplified procedure gives accurate results for devices with a spectral response over a broad range of the solar spectrum e.g. crystalline silicon devices. Significant errors may be introduced for narrow spectral response devices.

A.2.1 Equipment

a) A mounting platform, which can be oriented normal to the sun within an accuracy of ±0,5° throughout the calibration run.

b) A cavity radiometer, traceable to WRR.

c) A pyranometer, traceable to WRR.

d) A shading device to provide shade to item c). The field angle, viewing angle and aperture angle provided by the shade shall compensate the respective descriptive angles of the cavity radiometer of item b).

e) A temperature controlled mounting block for the reference device under test capable of maintaining the cell temperature at (25 ± 2)°C throughout all calibration runs.

f) Traceable means to measure the short circuit current of the solar cell to an accuracy of ±0,1 % or better.

g) Traceable means to measure the signal of the pyranometer to an accuracy of ±0,5 % or better.

h) A spectroradiometer capable of measuring the spectral irradiance of the total in-plane natural sunlight in the wavelength range of 350 – 2 500 nm (or larger).

NOTE 1 Not required in simplified version.

i) Apparatus to determine the relative spectral response of the reference solar cell.

NOTE 2 Not required in simplified version.

j) Means to measure the sun's elevation to a precision of ±2°. Alternatively, the elevation of the sun during the data sampling can be taken from almanacs or computed, as long as the precision requirement is met for the instant of data sampling. The latter normally requires traceable means to measure time for the computation of air mass.

NOTE 3 Only required in simplified version.

k) A manometer to measure the local air pressure P to an accuracy of ±250 Pa or better.

NOTE 4 Only required in simplified version.

A.2.2 Measurements

A calibration according to this standard shall be performed only on clear, sunny days with no visible cloud cover within 30 degrees of the sun.

a) Determine the relative spectral response of the reference cell to be calibrated.

NOTE 1 Not required in simplified version.

b) Select the site and/or the season of the year to ensure that the sun's elevation reaches an angle during the course of the day which corresponds to AM 1,5 (41,8 degrees at P_0).

c) Mount the cavity radiometer on the sun-pointing device (item A.2.1.a). Available radiometers have their own electronic unit which shall be connected to the instrument following the manufacturer's recommendations. Allow sufficient time to stabilise the electronic unit.

d) Mount the reference solar cell to be calibrated coplanar on the mounting platform, attaching it to the mounting block and maintain the cell temperature at (25 ± 2) °C.

e) Mount the pyranometer intended to measure diffuse solar irradiance coplanar on the mounting platform. Ensure that within the field of view of the pyranometer no reflective surfaces may influence the measurement result. Mount the shading device and ensure that the sensitive area of the pyranometer is pointed to the centre of the shade.

f) Mount the spectroradiometer coplanar on the mounting platform.

NOTE 2 Not required in simplified version.

g) Take simultaneous readings according to the following steps:

   1) Ensure the alignment of all instruments with respect to the sun and the proper alignment of the shading device.

   2) Ensure that the temperature of the reference solar cell is within the limits given in d).

   3) Record G_{dir}, the direct normal irradiance as indicated by the cavity radiometer.

   4) Record G_{dif}, the diffuse in-plane irradiance as indicated by the pyranometer

   5) Record I_{SC}, the short circuit current of the reference solar cell to be calibrated

   6) Record $E(\lambda)$, the spectral irradiance of the global natural sunlight.

NOTE 3 Not required in simplified version.

   7) Measure θ, the solar elevation angle, or alternatively, record the hour, minute and second of the data sampling and calculate the sun's elevation.

NOTE 4 Only required in simplified version.

   8) Record P, the local air pressure.

NOTE 5 Only required in simplified version.

   9) Repeat Steps 1 to 6 several times.

NOTE 6 Not required in simplified version.