IEC 60904-1

Edition 3.0 2020-09

INTERNATIONAL STANDARD

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colour inside

Photovoltaic devices –
Part 1: Measurement of photovoltaic current-voltage characteristics

Dispositifs photovoltaïques –
Partie 1: Mesurage des caractéristiques courant-tension des dispositifs photovoltaïques

IEC 60904-1:2020-09(en-fr)

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PHOTOVOLTAIC DEVICES –

Part 1: Measurement of photovoltaic current-voltage characteristics

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60904-1 has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

This third edition cancels and replaces the second edition published in 2006. This edition constitutes a technical revision.

The main changes with respect to the previous edition are as follows:

- Updated scope to include all conditions.
- Added terms and definitions.
- Reorganised document to avoid unnecessary duplication.
- Added data analysis clause.
- Added informative annexes (area measurement, PV devices with capacitance, dark *I-V* curves and effect of spatial non-uniformity of irradiance).

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

FDIS	Report on voting
82/1760/FDIS	82/1786/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 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 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

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

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PHOTOVOLTAIC DEVICES –

Part 1: Measurement of photovoltaic current-voltage characteristics

1 Scope

This part of IEC 60904 describes procedures for the measurement of current-voltage characteristics (I-V curves) of photovoltaic (PV) devices in natural or simulated sunlight. These procedures are applicable to a single PV solar cell, a sub-assembly of PV solar cells, or a PV module. They are applicable to single-junction mono-facial PV devices. For other device types, reference is made to the respective documents, in particular for multi-junction devices to IEC 60904-1-1 and for bifacial devices to IEC TS 60904-1-2. Additionally informative annexes are provided concerning area measurement of PV devices (Annex A), PV devices with capacitance (Annex B), measurement of dark current-voltage characteristics (dark I-V curves) (Annex C) and effects of spatial non-uniformity of irradiance (Annex D).

NOTE The methods provided in this document can also be used as guidance for taking I-V curves of PV arrays. For on-site measurement refer to IEC 61829.

This document is applicable to non-concentrating PV devices for use in terrestrial environments, with reference to (usually but not exclusively) the global reference spectral irradiance AM1.5 defined in IEC 60904-3. It may also be applicable to PV devices for use under concentrated irradiation if the application uses direct sunlight and reference is instead made to the direct reference spectral irradiance AM1.5d in IEC 60904-3.

The purposes of this document are to lay down basic requirements for the measurement of I-V curves of PV devices, to define procedures for different measuring techniques in use and to show practices for minimising measurement uncertainty. It is applicable to the measurement of I-V curves in general. I-V measurements can have various purposes, such as calibration (i.e. traceable measurement with stated uncertainty, usually performed at standard test conditions) of a PV device under test against a reference device, performance measurement under various conditions (e.g. for device temperature and irradiance) such as those required by IEC 60891 (for determination of temperature coefficients or internal series resistance), by IEC 61853-1 (power rating of PV devices) or by IEC 60904-10 (for determination of output's linear dependence and linearity with respect to a particular test parameter). I-V measurements are also important in industrial environments such as PV module production facilities, and for testing in the field. Further guidance on I-V measurements in production facilities is provided in IEC TR 60904-14.

The actual requirements (e.g. for the class of solar simulator) depend on the end-use. Other standards referring to IEC 60904-1 can stipulate specific requirements. Where those requirements are in conflict with this document, the specific requirements take precedence.

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 60891, *Photovoltaic devices – Procedures for temperature and irradiance corrections to measured I-V characteristics*

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

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

IEC 60904-4, *Photovoltaic devices – Part 4: Photovoltaic reference devices – Procedures for establishing calibration traceability*

IEC 60904-5, *Photovoltaic devices – Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method*

IEC 60904-7, *Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*

IEC 60904-9, *Photovoltaic devices – Part 9: Solar simulator performance requirements*

IEC 60904-10, *Photovoltaic devices – Part 10: Methods of linearity measurement*

IEC TR 60904-14, *Photovoltaic devices – Part 14: Guidelines for production line measurements of single-junction PV module maximum power output and reporting at standard test conditions*

IEC 61215 (all parts), *Terrestrial photovoltaic (PV) modules – Design qualification and type approval*

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

IEC 61853-1, *Photovoltaic (PV) module performance testing and energy rating – Part 1: Irradiance and temperature performance measurements and power rating*

IEC TR 63228, *Measurement protocols for photovoltaic devices based on organic, dye-sensitized or perovskite materials*

ISO 9060, *Solar energy – Specification and classification of instruments for measuring hemispherical solar and direct solar radiation*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

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

3.1
sweep rate
temporal rate of change of the voltage applied to the measured PV device

Note 1 to entry: The term ramp rate is also used interchangeably.

3.2
sweep direction
direction of change of applied voltage during I-V measurements; a positive sweep rate is referred to as forward or direct sweep (I_{sc} to V_{oc} direction), while a negative sweep rate is referred to as reverse or backward sweep (V_{oc} to I_{sc} direction)

3.3
time delay
time interval between the change of voltage applied to PV device and the measurement of PV device current

4 General requirements

4.1 General

For illustration purposes a schematic current-voltage characteristic (I-V curve) is shown in Figure 1 and the corresponding power-voltage characteristic (P-V curve) in Figure 2.

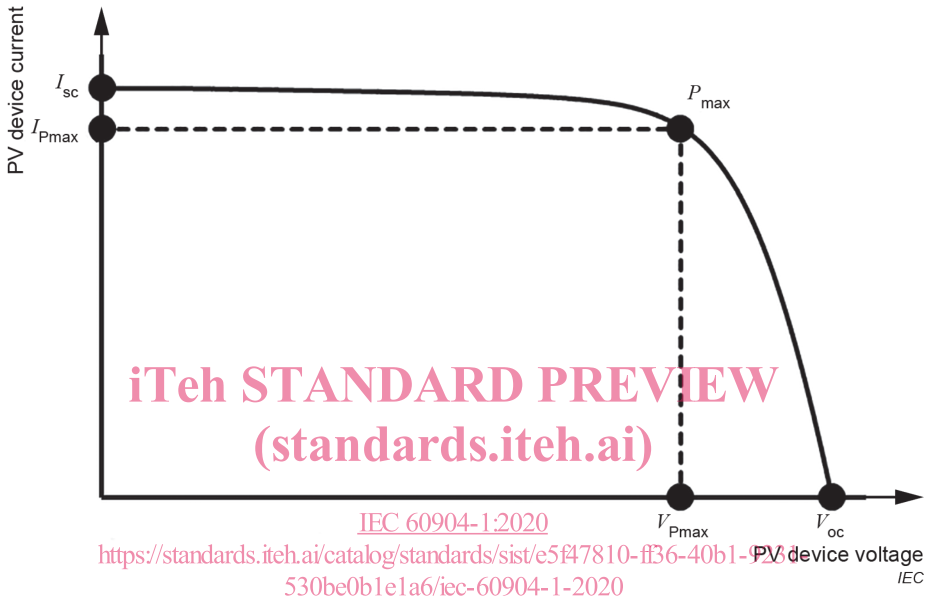

Figure 1 – Schematic current-voltage characteristic (I-V curve) depicting typical I-V curve parameters short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), maximum power (P_{max}), voltage at maximum power (V_{Pmax}) and current at maximum power (I_{Pmax})

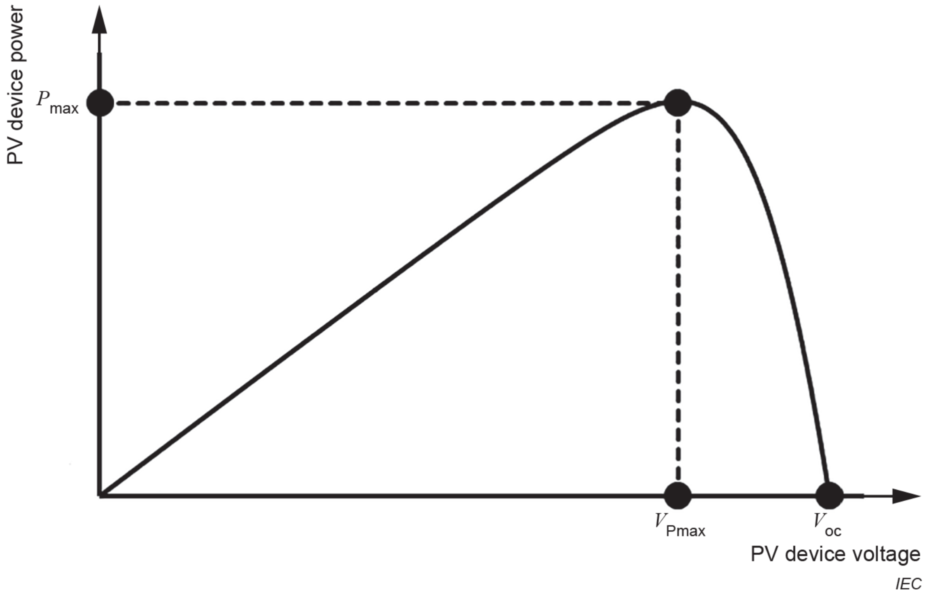

Figure 2 – Schematic power-voltage characteristic (P-V curve) depicting typical I-V curve parameters open-circuit voltage (V_{oc}), maximum power (P_{max}) and voltage at maximum power (V_{Pmax})

4.2 Measurements

a) When the measurements are intended to be reported at standard test conditions (see 4.5) the in-plane average irradiance during measurement shall be between 800 W·m^{-2} and 1 200 W·m^{-2} to minimise errors arising from large corrections.

b) Temperature sensors should be located so as to detect as closely as possible the temperature of the respective device cell junction. If a temperature gradient between the sensor and the cell junction is suspected, an appropriate contribution to the measurement uncertainty should be included. Consideration should also be given to any possible non-uniformity of temperature across either device, particularly for PV modules, where the temperature of individual cells can vary due to their electrical characteristics, particularly when the module is illuminated under short-circuit conditions. The Equivalent Cell Temperature (ECT) method specified in IEC 60904-5 can be useful in dealing with either a temperature gradient or temperature non-uniformity. The cooling effect from airflow (for example due to wind during outdoor measurement or due to air conditioning of the room for indoor measurements) on the temperature sensors should be considered in the uncertainty of the temperature measurement.

c) The active surface of the device under test shall be coplanar within ±2° with the active surface of the reference device.

d) Voltages and currents shall be measured using independent leads from the terminals of the device under test and keeping them as short as possible. If the device under test is a module, a subassembly or an encapsulated solar cell, the 4-wire connection should start at the terminals or connectors. If the device under test is a bare PV cell, the 4-wire connection should start at the cell bus bars. The connection method for bare cells (i.e. provided without connectors) should be carefully evaluated. Differences can occur if soldered tabs are used compared with non-soldered methods such as bars having contact springs or conductive plates having a large-area contact with the cell back contact. Non-soldered methods can result in higher fill factors than are observed in the module. The contacting method should be appropriate to the intended use of the cell or of the measurement. The contact method used (bare cells) or the contact point (modules) for 4-wire connection shall be stated in the report. For bare solar cells without busbars or cells with low surface conductivity such as multi-busbar cells, 4-wire connection should start at the contacting structure in order to avoid artificially increased fill factors in the measurement caused by voltage drop at the resistance between current and voltage probe on the cell. Possible deviations between the calibration of the measurement system (typically under static load conditions) and its use during I-V curve measurements (dynamic load conditions) shall be considered.

e) The I-V curve should be measured such that both the short-circuit current point and the open-circuit voltage point fall within the bounds of the data set, including after correction to the reporting conditions (Clause 8). For possible extrapolation to calculate these points from measured data, see Clause 8.

f) The I-V curve can also be measured without illumination (dark I-V) (see Annex C), but this is generally not required.

4.3 Stabilisation

Care shall be taken in measuring PV devices that are metastable. If it is possible to stabilise the device, stabilisation should be performed before any characterisation (I-V or spectral responsivity measurement). Any stabilisation procedure performed shall be reported together with the test results. The IEC 61215 series of standards provides guidance on technology-dependent appropriate stabilisation. In the case of a stabilisation procedure being applied, the device under test should be measured before and after the procedure. The change in I-V characteristic parameters should be evaluated and included in the report.

If it is not possible to stabilise the device, or stabilisation was not attempted, this shall be indicated in the measurement report.

4.4 Equivalence to steady-state performance

The I-V characteristic for the device under test shall be measured such that it reflects, as closely as possible, the performance of the device under steady-state conditions, i.e. where there is no influence due to drifts in irradiance or device temperature or the voltage sweep rate. Sweep rate effects occur when the voltage bias is stepped or swept too rapidly for the device response to equilibrate for each measurement of the current. This effect can be due to device capacitance, as is the case for some crystalline silicon PV devices, or it can be due to a more complex device response, as is frequently observed in some thin-film devices such as perovskite cells, see IEC TR 63228.

Errors due to PV device capacitance are related to the combination of the PV technology and I-V curve measurement parameters (sweep direction, time delay per measurement point, number of pulses (in multiple-pulse method) and rate of change of applied voltage, current or irradiance). The errors due to PV device capacitance are normally most pronounced for the maximum-power point and the open-circuit voltage of the I-V curve, whereas errors in short-circuit current due to capacitance are in general minimal. More guidance on ensuring that the measurement approximates steady-state conditions is provided in Annex B.

The contribution of transient effects to the overall measurement uncertainty shall be considered.

4.5 Reporting conditions

In general, test results are reported for various conditions. The three main parameters that shall be reported together with any test result are:

a) Total in-plane irradiance.

b) Spectral irradiance in the test plane (graph or table), if spectral mismatch corrections are required.

c) Cell junction temperature of the device under test.

The most common reporting conditions are the Standard Test Conditions (STC), which are 1 000 $W \cdot m^{-2}$ total in-plane irradiance with a spectral irradiance distribution as defined in IEC 60904-3 (global) and 25 °C cell junction temperature. However, sometimes the test result is desired at other conditions. For any test result the three main reporting parameters listed above shall be clearly indicated.

4.6 Translation from test conditions to reporting conditions

At times, the test conditions at which an I-V curve is measured are different from those at which the test results are reported. Therefore, an I-V curve translation from the test conditions to the reporting conditions can be required. This translation shall be made according to IEC 60891 (irradiance and temperature correction) in conjunction with IEC 60904-7 (correction for spectral mismatch) and IEC 60904-10 (correction for non-linearity). Module characteristic parameters (e.g. series resistance or temperature coefficients) can considerably affect the result if temperature and irradiance corrections are performed across wide ranges. Therefore, care shall be taken regarding the applicability of the I-V curve translation procedure according to IEC 60891 and the relevance of the module parameters used in the I-V curve translation procedure. Also, their contribution to uncertainty in the translated I-V curve shall be considered.

The contribution to measurement uncertainty due to the deviation of test conditions from reporting conditions shall be evaluated.

For an I-V curve measurement to be referred to the reporting spectral irradiance, two correction methods are available (IEC 60904-7):

a) If possible, adjust the total in-plane irradiance, e.g. by adjusting the solar simulator's intensity, so that the effective irradiance as determined according to IEC 60904-7 equals the reporting irradiance. Proceed to measure the I-V curve as per Clause 6 or Clause 7.

b) Otherwise, measure the I-V curve as per Clause 6 or Clause 7 using the given irradiance. Determine the effective irradiance at the reporting spectral irradiance using IEC 60904-7. Then translate the I-V curve to the reporting irradiance using IEC 60891 with the effective irradiance so determined.

If the reference device and the device under test are constructed using the same cell technology and encapsulation package (Clause 5 a)), the irradiance measured by the reference device and the effective irradiance max be assumed identical.

Method a) is preferred for simulated sunlight, as the actual measurement is performed at the correct short-circuit current or maximum power, thus minimising errors and uncertainties arising from translating the I-V curves. Method b) is usually chosen for measurements in natural sunlight, as the light's spectral content and total in-plane irradiance cannot be easily controlled.

5 Apparatus

The following equipment is required to measure I-V curves:

a) For measuring the irradiance: a PV reference device packaged and calibrated in conformance with IEC 60904-2 or in the case of natural sunlight alternatively a pyranometer in conformance with ISO 9060. The calibration of either device for measuring the irradiance shall be traceable according to IEC 60904-4. The output of the reference device shall be linear with respect to incident irradiance as defined in IEC 60904-10 over the irradiance range of interest. A spectral mismatch correction shall be performed in conformance with IEC 60904-7 and reported with the measurement results. Alternatively, the reference device shall be constructed using the same cell technology and encapsulation package as the device under test. This includes the glass (type, thickness, texturing, and spectral transmission), anti-reflective coatings, encapsulant, and backsheet (type, colour, and spectral back-reflection). The stability of the reference device shall be assessed before it is used for the measurements of the device under test.

b) For monitoring the temporal fluctuations of irradiance: An irradiance monitor that tracks the instantaneous irradiance during the acquisition of *I-V* curves. This irradiance monitor should have an output linear with respect to incident irradiance according to IEC 60904-10 in the range of irradiances over which the measurements are taken and a time response sufficiently fast to be able to reveal temporal fluctuations in the incident irradiance. The data recorded from the irradiance monitor shall be used to evaluate the stability criteria and to correct the temporal instability of the total in-plane irradiance for each data point of the *I-V* curve as well as to correct for variations in irradiance for the consecutive measurements in case strategy 7.1 b) is followed. The reference device may serve as such an irradiance monitor if it fulfils the above requirements and if it can be measured concurrently with the device under test (measurement strategy 7.1 a)).

c) For measuring the temperature of the reference device and of the device under test: temperature sensors and instrumentation with instrumental measurement uncertainty of 1 °C or less. Temperature measurement of the reference device is not required if it is a pyranometer.

d) For measuring voltages and currents: instrumentation with instrumental measurement uncertainty of 0,2 % or less of the open-circuit voltage and short-circuit current. The measurement ranges of the data acquisition should be carefully chosen.

e) For measurement in simulated sunlight: a solar simulator classified in accordance with IEC 60904-9, i.e. with Class CCC or better. The actual solar simulator requirements depend on the end-use. Other standards referring to IEC 60904-1 can require different classes. Therefore, the classes of the solar simulator to be used should reflect the requirements specific to the case. The designated test area shall be equal to or greater than the area that is spanned by the device under test (including its frame or package) and the irradiance monitor.

EXAMPLE 1 IEC 60891 requires a class BBB solar simulator for determination of temperature coefficients.

EXAMPLE 2 IEC 60904-2 requires a class AAA solar simulator for calibration of secondary reference devices against primary reference cell.

f) For measurement under natural sunlight: a two-axis solar tracking system to hold the device under test plus the reference device and capable of tracking the sun with a maximum deviation of ±5° (for PV calibration) or a fixed rack mounting (e.g. for energy rating and monitoring). The two-axis solar tracking system is required for PV calibration, but at choice of the user it may be used for other types of measurements, like for example the power rating of PV modules. In any case for the alignment between reference device and device under test refer to 4.2 c) .

g) For spectral mismatch corrections and effective irradiance calculation (if required): a spectroradiometer in accordance with the requirements in IEC 60904-9 capable of measuring the spectral irradiance of the natural or simulated sunlight in the range of the spectral responsivity of the device under test and the reference device. For simulated sunlight, care should be taken in the use of lamps with narrow intense peaks in their spectral irradiance, such as Xenon lamps or some LEDs, when testing PV cells with spectral responsivity showing a significant dependence on temperature. As the band gap changes due to temperature, the device responsivity can pass through various emission lines in the lamp spectral irradiance and give rise to large variations in spectral mismatch and shifts in performance.

EXAMPLE 3 Crystalline silicon is a well-known example of an indirect bandgap material that shows a spectral responsivity strongly dependent on temperature.

6 Measurements in natural sunlight

6.1 General

Measurements in natural sunlight shall be made only when global solar irradiance is stable within ±1 % during the measurement of a complete *I-V* curve.

Two types of measurements should be distinguished. Firstly, the measurement of the electrical performance of the device under test that is normally aimed at reporting at STC (conditions for typical PV calibration), but sometimes also at other relevant conditions (e.g. for power rating as described in IEC 61853-1). In this case, the device under test and the reference devices are mounted on a two-axis tracking system. Secondly, the measurement of electrical performance over time, normally aimed at energy rating and monitoring of devices under test. In this case, normally the device under test and the reference device(s) are mounted on a fixed rack (to simulate the conditions in a real-world PV system installation or to periodically measure installed PV modules). This document applies to both types of measurement and therefore, in the following, the respective list items of the test procedure have to be understood for either case, if not otherwise specified. In any case care shall be taken to avoid shadowing or reflected light from the surroundings (e.g. from windows or glossy metal parts) on both the reference device and the device under test.

6.2 Test procedure

The test procedure is as follows:

a) Mount the reference device as near as possible to the device under test. For PV calibration or power rating by use of solar tracker, both shall be normal to the direct solar beam within ±5°. For the alignment between reference device and device under test refer to 4.2 c). Connect to the necessary instrumentation.

b) If the device under test and reference device are equipped with temperature controllers, set them at the desired level. The temperature of the reference device should be brought and kept as close as possible to the temperature at which it was calibrated and the temperature of the device under test to the desired reporting temperature. If active temperature controllers are not available, the latter may be achieved by bringing the device under test to a point below the target temperature and letting it warm up naturally under the natural sunlight in combination with temporary shading. In general, there can be differences between average device temperature and average sensor temperature during warming up. Therefore, either correction or proper accounting for it in the uncertainty calculation shall be done.

c) Sweep through the I-V curve and take readings of the current and voltage of the device under test concurrently with recording the output of the reference device. The temperature of both devices shall also be recorded, but one measurement for each device during the acquisition of the I-V curve or immediately before or afterwards is sufficient. In general, the temperature should be measured as close to the V_{oc} condition as possible. In most cases the thermal inertia of the device under test and the reference device will limit the temperature rise during the first few seconds after removing the shade and their temperatures will remain reasonably uniform. However, the variation of temperatures for the device under test and the reference device during the I-V measurement with respect to the temperature measurement will contribute to measurement uncertainty and shall be evaluated.

d) Ensure that the irradiance as measured by the reference device remains constant within ±1 % during the recording period for each I-V curve. The latter can usually only be determined by using a PV device as irradiance monitor, as a pyranometer typically has a response time longer than the time required for measuring a complete I-V curve.

e) Measurement should be performed on a clear sunny day (no observable clouds around the sun, diffuse contents of solar irradiance not higher than 30 %). If a pyranometer or a PV reference device, that is not constructed using the same cell technology and encapsulation package as the device under test, is used as reference device, perform a simultaneous measurement of spectral irradiance using the spectroradiometer oriented consistently with the device under test (i.e. pointing to the sun for solar-tracking measurements and normal to the test plane for fixed-rack module mounting). Calculate the effective irradiance for the device under test under the reporting spectral irradiance (see IEC 60904-7).