

TECHNICAL REPORT



Photovoltaic devices –

**Part 14: Guidelines for production line measurements of single-junction PV
module maximum power output and reporting at standard test conditions**

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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PHOTOVOLTAIC DEVICES –

**Part 14: Guidelines for production line measurements
of single-junction PV module maximum power output
and reporting at standard test conditions**

FOREWORD

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IEC TR 60904-14, which is a Technical Report, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
82/1748/DTR	82/1785A/RVDTR

Full information on the voting for the approval of this Technical Report 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

- reconfirmed,
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PHOTOVOLTAIC DEVICES –

Part 14: Guidelines for production line measurements of single-junction PV module maximum power output and reporting at standard test conditions

1 Scope

This document provides guidelines for measurements of the maximum power ($P_{\max}$) output of single-junction photovoltaic (PV) modules and for reporting at standard test conditions (STC) in industrial production line settings. Such measurements typically:

- Record current-voltage (I - V) data while illuminating the module with a solar simulator;
- Are performed on 100 % of manufactured modules, in order to determine whether they meet nameplate requirements for various bins spanning different power output levels.

This type of measurement is widespread and performed in high volume by PV module manufacturers worldwide. As it is desirable to have consistent measurement practices across the industry, this document describes the following features of such measurements:

- Essential elements, in order to provide common understanding;
- Common issues or complications;
- Sources of error and uncertainty, including recommendations to minimize them.

Understanding of $P_{\max}$ measurement uncertainties is expected to be useful in application of other IEC documents, such as IEC 61215-1 and IEC 62941, where $P_{\max}$ tolerances and uncertainties must be determined. Whenever possible, this document references specific IEC documents covering topics in more detail. Where no such documents exist, this document provides guidance and recommendations based on other publications relevant to the PV industry.

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 60512-2-1, *Connectors for electronic equipment – Tests and measurements – Part 2-1: Electrical continuity and contact resistance tests – Test 2a: Contact resistance – Millivolt level method*

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

IEC 60904-1:2020, *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics*

IEC 60904-2:2015, *Photovoltaic devices – Part 2: Requirements for photovoltaic reference devices*

IEC 60904-3:2019, *Photovoltaic devices – Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data*

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

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

IEC 60904-9:2020, *Photovoltaic devices – Part 9: Classification of solar simulator characteristics*

IEC 60904-10, *Photovoltaic devices – Part 10: Methods of linear dependence and linearity measurements*

IEC 61215-1, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval - Part 1: Test requirements*

IEC 61215-2:2016, *Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 2: Test procedures*

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

IEC 61853-2:2016, *Photovoltaic (PV) module performance testing and energy rating – Part 2: Spectral responsivity, incidence angle and module operating temperature measurements*

IEC 62941:2019, *Terrestrial photovoltaic (PV) modules – Quality system for PV module manufacturing*

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

JCGM 200, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836, IEC 60904-1, IEC 60904-9, ISO/IEC Guide 98-3, and JCGM 200 apply.

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

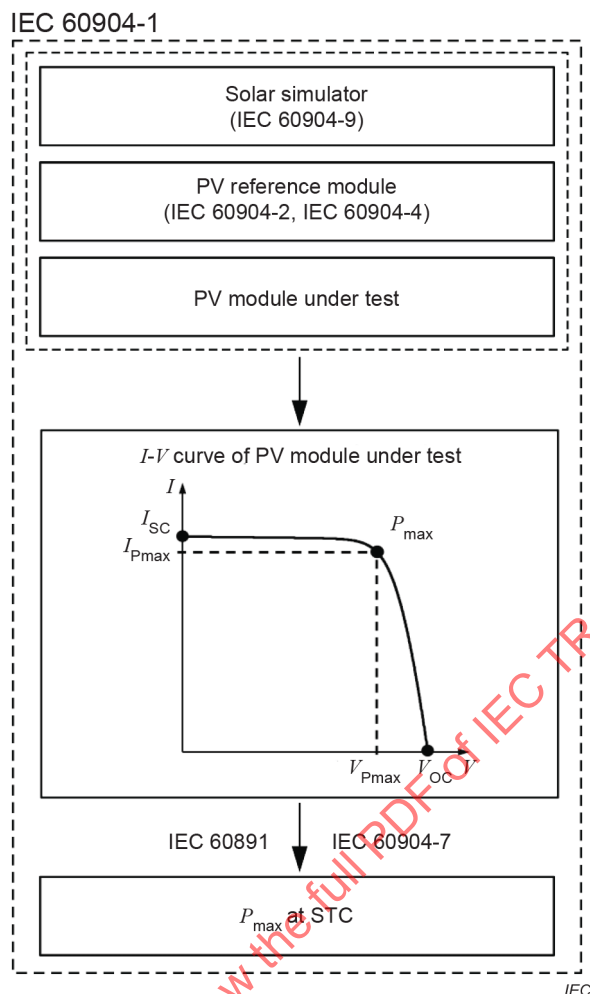
- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO online browsing platform: available at <http://www.iso.org/obp>

4 Measurement principles

4.1 Measurement of I - V curves

Figure 1 summarizes the application of IEC documents in order to measure PV module I - V curves and report STC $P_{\max}$ values in production line settings. The following symbols refer to common parameters measured directly from a module I - V curve:

- Short-circuit current and open-circuit voltage: I_{SC} and V_{OC} , respectively
- Current and voltage at the maximum power point: $I_{P_{\max}}$ and $V_{P_{\max}}$, respectively
- Maximum power: $P_{\max}$, which is equal to the product $I_{P_{\max}} \times V_{P_{\max}}$



Documents referenced by the correction procedures of IEC 60891 and IEC 60904-7 are omitted for simplicity.

Figure 1 – Application of IEC documents to report STC P_{max} values, adapted from published work [1]¹

4.2 Standard test conditions

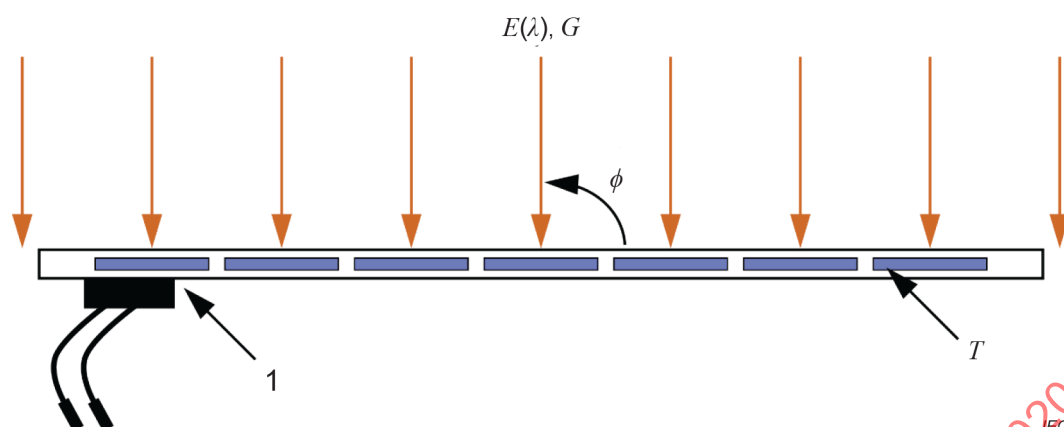
4.2.1 General

STC give the essential properties of the light to which the PV module is exposed and the thermal state at which the PV module is kept during measurement of its $I-V$ characteristic. STC are intended to give a common and standardized reference point for a practical assessment of PV module performance in both laboratory and industrial settings; they are not necessarily intended to describe all conditions under which a PV module operates when installed outdoors. STC are defined in IEC TS 61836 as follows:

- A spectral irradiance equal to the global spectral irradiance defined in IEC 60904-3 (essential light property);
- Total irradiance equal to $1\,000\text{ W m}^{-2}$ (essential light property);
- Cell junction temperature within the module equal to 25 °C (thermal state of the PV module).

IEC 60904-3:2019, Clause 5 further specifies that the angular distribution of irradiance is defined such that "the complete radiation hits the solar device perpendicularly under normal incidence." STC are summarized graphically in Figure 2.

¹ Numbers in square brackets refer to the Bibliography.

**Key**

- 1 PV module under test
- $E(\lambda)$ global spectral irradiance as defined in IEC 60904-3:2019
- G total irradiance equal to $1\,000\text{ W m}^{-2}$
- T cell junction temperature within the module equal to $25\text{ }^{\circ}\text{C}$
- ϕ normal (perpendicular) incidence angle of irradiance as defined in IEC 60904-3:2019

Figure 2 – Graphical summary of STC (cross-sectional view of module)

It is commonly understood that STC describe spatially uniform conditions across the module area, and temporally uniform conditions during measurement of the module I - V curve. For example:

- Spectral irradiance and total irradiance should be uniform across the module area, and for the duration required to measure the module I - V curve;
- Cell junction temperature should be uniform for all cells in the module, and for the duration required to measure the module I - V curve.

4.2.2 Additional practical considerations

The measured electrical characteristics of a PV module can vary depending on additional factors not included in STC, such as:

- The prior illumination history of the module (light soaking or metastability effects);
- The instantaneous rate of change of voltage or current versus time during measurement of the I - V curve (capacitive or hysteresis effects);
- The electrical connection to the module (contact resistance and cable resistance).

Stabilization techniques for metastabilities specific to different PV technologies are described in the IEC 61215 series (e.g. IEC 61215-2:2016, MQT 19). Methods for minimizing capacitive effects are described in IEC 60904-1:2020, Annex B. Effects of contact resistance and cable resistance are described in 4.5.4.3.

4.2.3 Deviations from STC, errors, and uncertainties

In practice, actual measurement conditions always deviate from STC. This can cause errors in measured I - V curve parameters relative to their STC values, as summarized in Table 2. Errors in various I - V curve parameters related to total irradiance and temperature can be corrected by the methods of IEC 60891 if they fall within the relevant ranges allowed by that standard. Errors in I_{SC} due to spectral irradiance can be corrected by the methods of IEC 60904-7.

Even after all significant errors have been identified and corrected for, reported I - V curve parameters, including $P_{\max}$, will still have some (non-zero) uncertainty. For guidance on evaluating and reporting all measurement aspects contributing to the overall uncertainty, refer to ISO/IEC Guide 98-3. If the uncertainty of a correction is comparable in magnitude to the error that it is intended to correct, such correction may be omitted, provided the error is still considered in the uncertainty evaluation. Unless otherwise specified, uncertainty values stated in this document are standard uncertainties (coverage factor $k = 1$), consistent with ISO/IEC Guide 98-3:2008, 6.1. In addition to the corrections described above, reduction of $P_{\max}$ uncertainty is generally accomplished by one or more of the following strategies:

- Minimizing deviations from STC as in 4.3;
- Setting solar simulator total irradiance using a reference module that is matched to the production module under test. “Matched” refers to similarity in spectral responsivity, as well as several other factors described in 4.4.4.

Often, several interacting factors contribute to $P_{\max}$ uncertainty, as described in the remainder of this subclause. In general, a single factor (for example, the solar simulator’s characteristics) cannot be used in isolation to reliably evaluate $P_{\max}$ uncertainties. However, these factors can still be grouped together for convenience:

- Characteristics of the irradiance produced by the solar simulator as described in 4.3;
- Dimensional, optical, and electrical characteristics of the reference device used to set irradiance described in 4.4, and in particular, the device’s matching (or lack of matching) to the production module under test as described in 4.4.4;
- Dimensional, optical, and electrical characteristics of the production module under test;
- Operation procedures of the solar simulator and other measurement equipment as described in 4.5.

Table 1 (adapted from a previous publication [1]) lists these factors approximately according to their expected contribution to $P_{\max}$ uncertainty reported from various publications [3][5][7][10], with largest uncertainty contributions listed first. Table 1 can be considered a checklist for PV module manufacturers to be used in developing a $P_{\max}$ uncertainty evaluation according to ISO/IEC Guide 98-3.

Not all factors in Table 1 will affect all PV module manufacturers equally; therefore, each PV manufacturer should implement a detailed evaluation of the elements that can contribute to the $P_{\max}$ uncertainty within their specific production processes and production lines. Factors having significant uncertainty contributions should be systematically monitored to keep $P_{\max}$ uncertainties within acceptable limits. The procedures described in Clause 0 can be used as a starting point for quantifying some uncertainty factors using gauge study methods.

Table 2 lists these factors according to their effect on the module I - V curve parameters. Each factor affects $P_{\max}$ indirectly, since $P_{\max} = I_{P\max} \times V_{P\max}$.

Table 1 – Factors contributing to $P_{\max}$ uncertainty

Source of uncertainty and reference to this document	Factors to be considered
Reference modules Subclause 4.4	Stated uncertainty of I_{SC} or $P_{\max}$ from calibration certificate Use of I_{SC} or $P_{\max}$ for setting solar simulator irradiance as in 4.5.4.1 Drift of I_{SC} or $P_{\max}$ since last calibration of reference module Matching of dimensional, optical, and electrical characteristics between reference module and production module under test as in 4.4.4 Drift of electrical connector resistance since last calibration
Optical Subclause 4.3	Spectral distribution of irradiance Spatial distribution of irradiance Angular distribution of irradiance Placement of modules in test plane, possibly including translational misalignments and/or rotational misalignments (x, y, z, and θ)
Electrical Subclause 4.5.4.3 Subclause 4.3.5	Four-terminal connection (Kelvin connection) to module Drift of electrical connector resistance of I-V measurement equipment Uncertainty of data acquisition channels (from manufacturer datasheets and calibration certificates), including possible drift of channel properties over time (e.g. gain and offset) Uncertainty of shunt resistor used for current measurement, including possible drift of its electrical resistance over time Capacitive (hysteresis) effects during I-V measurement
Thermal Subclause 4.5.4.2	Uncertainty of temperature sensor(s) Temperature non-uniformity across PV module Deviation of reference module temperature from its calibration temperature Deviation of production module under test from target temperature Deviation of cell junction temperature from measured module temperature Drift of module temperature during exposure to simulated sunlight
Measurement capability Clause 0	Measurement of reference modules under intermediate precision condition Measurement of production modules under intermediate precision condition
Measurement corrections	Corrections related to total irradiance and temperature (IEC 60891) Corrections related to spectral irradiance (IEC 60904-7) Uncertainty of correction factors

Table 2 – Summary of effects due to deviations from STC and factors of 4.2.2

Type of deviation and reference to this document	Primary effect	Secondary effect	Critical metrics
Spectral distribution of irradiance Subclause 4.3.3	Module current (I_{SC} , I_{Pmax})	None	Spectral irradiance of solar simulator Mismatch in spectral responsivity of reference module and production module under test Spectral mismatch correction factor as per IEC 60904-7 (if used)
Spatial non-uniformity of irradiance Subclause 4.3.4	Module current (I_{SC} , I_{Pmax})	Module voltage (V_{Pmax})	Spatial distribution of irradiance across module area Variation of cell electrical and optical characteristics within module Mismatch in module and cell dimension between reference module and production module under test Mismatch in cell electrical interconnection between reference module and production module under test
Module temperature Subclause 4.5.4.2	Module voltage (V_{OC} , V_{Pmax})	Module current (I_{SC} , I_{Pmax})	Deviation of cell junction temperature from measured module temperature Temperature non-uniformity across module Drift of module temperature during exposure to simulated sunlight Temperature correction factors as per IEC 60891 (if used)
Capacitive effects Subclause 4.3.5	Module current (I_{Pmax})	Module voltage (V_{Pmax} , V_{OC})	Rate of change of voltage, current, and irradiance during I - V measurement Mismatch in capacitance of reference module and production module under test
Electrical connection effects (contact resistance and cable resistance) Subclause 4.5.4.3	Module voltage (V_{Pmax})	None	Electrical resistance of reference module connectors Electrical resistance of I - V measurement equipment connectors
Angular distribution of irradiance Subclause 4.3.6	Module current (I_{SC} , I_{Pmax})	None	Angular distribution of solar simulator irradiance Mismatch in angle-of-incidence responsivity of reference module and production module under test

4.3 Solar simulators

4.3.1 General

IEC 60904-9 describes several solar simulator characteristics and provides a classification system based on those characteristics. By design, this classification is based solely on characteristics of the solar simulator itself, and excludes considerations of solar simulator end-use (e.g. PV module technology, installation environment, calibration and operation procedures, etc.). The classification system consists of three letters, with the first being related to the spectral distribution of irradiance, the second being related to the spatial non-uniformity of irradiance, and the third being related to the temporal instability of irradiance.

4.3.2 Solar simulator requirements in relevant IEC documents

For quality assurance in PV module manufacturing, IEC 62941:2019, 4.2.2 suggests the use of a solar simulator with minimum BBB classification, and requires I - V curve measurements to be performed according to a recognized standard such as IEC 60904-1. In turn, IEC 60904-1:2020, Clause 5 requires the use of a solar simulator with minimum CCC classification, which is therefore the minimum requirement for solar simulators used in production module $P_{\max}$ measurements. Subclauses 4.3.3 to 4.3.6 discuss individual recommendations specific to each solar simulator characteristic, based on available publications and proven experience.

4.3.3 Spectral distribution of irradiance

The IEC 60904-9 spectral match classification is not a direct measure for spectral mismatch errors [2][3][4]. Evaluation of spectral mismatch errors requires methods comparable to IEC 60904-7, which considers together the spectral irradiance of the solar simulator, the spectral responsivity of the reference device, and the spectral responsivity of the production module under test. IEC 60904-9:2020, Annex A describes such evaluation methods, and PV module manufacturers are encouraged to use them. However, the results of such evaluations are informative, and are not used in determining solar simulator classification.

Manufacturers should verify that the spectral distribution of irradiance extends across all wavelengths where the reference module and the production modules under test have significant spectral responsivity. The spectral distribution of irradiance should be reverified if the spectral responsivity of the production module design changes due to a modification of the bill of materials. This is crucial in particular when PV modules having direct-bandgap photoactive materials are illuminated by solar simulators having spectral irradiance characterized by steep and intense variations as a function of wavelength (e.g. emission lines from xenon arc lamps, or emission peaks from light emitting diodes). In such cases, relatively small changes in PV module spectral responsivity or solar simulator spectral irradiance can result in measurable changes of I_{SC} and $P_{\max}$.

EXAMPLE 1 A change from UV-blocking to UV-transmissive encapsulant is a modification of the bill of materials.

EXAMPLE 2 A change to the cell and/or module antireflective coatings is a modification of the bill of materials.

Manufacturers should be aware that certain PV cell and module materials (e.g. passivation layers and UV coatings) are only effective in certain wavelength regions for which presence of spectral irradiance should be verified. For all wavelength regions where a solar simulator's spectral irradiance is zero, $P_{\max}$ measurements performed using that solar simulator will be unable to detect production variations in module spectral responsivity. The IEC 60904-9 spectral coverage metric (SPC) can provide a useful starting point for such a verification. Manufacturers should verify that the wavelength ranges considered by the SPC metric are relevant to their module materials.

PV module manufacturers have discretion to use solar simulators of various spectral classifications as long as consideration is given to the factors discussed in this subclause. Use of matched reference modules as described in 4.4.4 is recommended to minimize spectral mismatch errors. Manufacturers should also consider stability of the reference modules' electrical and optical characteristics over time as in 4.4.4. In cases where matched reference modules cannot be stabilized within acceptable levels, it can be preferable to use non-matched reference modules that are more stable; spectral mismatch corrections as per IEC 60904-7 should be used in such a case. No additional recommendation is given regarding solar simulator spectral classification for PV module manufacturers, other than the minimum requirement noted in 4.3.2 (class C spectral match classification).

4.3.4 Spatial non-uniformity of irradiance

The influence of spatial non-uniformity of irradiance depends on solar simulator operation procedures, in particular on whether solar simulator irradiance is set using the reference module's I_{SC} or P_{max} , because generally I_{SC} is more affected than P_{max} by spatial non-uniformity of irradiance. IEC 60904-1:2020, Annex D provides some basic guidance on the influence of spatial non-uniformity of irradiance on measured I - V parameters of PV modules. No standard method exists for numerical correction of errors related to spatial non-uniformity of irradiance.

Discussion in the remainder of this subclause applies primarily to PV modules in which cells are electrically connected in series, as this represents the majority of PV modules on the market today. The user/reader of this document should consult the bibliographic references cited in this subclause for principles used to analyse PV modules in which cells are electrically connected in parallel or in series-parallel combination.

Numerical models [6] generally show the effects of spatial non-uniformity of irradiance and their associated P_{max} uncertainties easily exceed 1 % if spatial non-uniformity of irradiance is between 5 % and 10 % (class C as per IEC 60904-9). Therefore, use of solar simulators with class C spatial non-uniformity of irradiance is not recommended. Since most solar simulators can achieve spatial non-uniformity of irradiance less than 5 % (class B as per IEC 60904-9), and since this capability is consistent with the recommendation of IEC 62941:2019 noted in 4.3.2, further discussion is restricted to this range.

Generally, the P_{max} of a PV module will decrease monotonically, though not necessarily linearly, with increasing spatial non-uniformity of irradiance in a manner that correlates well to the standard deviation of irradiance in the test plane [4][8][9]. Errors due to spatial non-uniformity of irradiance on the module's P_{max} can therefore be similar for matched reference modules and production modules. This similarity provides a rationale for setting the solar simulator's irradiance using the P_{max} of a matched reference module in order to partially cancel such errors. In this case, experimental data [10] suggest that the P_{max} uncertainty contribution due to spatial non-uniformity of irradiance can be as low as 0,02 % for production modules, independent of the spatial non-uniformity of irradiance. Modelled data [7] that do not assume partial cancellation of such errors suggest the uncertainty contribution is between 0,4 % and 0,9 % for spatial non-uniformity of irradiance between 1 % and 5 %, respectively.

In contrast, I_{SC} of a PV module can vary non-monotonically with increasing spatial non-uniformity of irradiance in a manner that depends on I_{SC} tolerances of individual cells and their positioning within the module [6][7]. Therefore, errors due to spatial non-uniformity of irradiance on the module's I_{SC} are generally not similar for matched reference modules and production modules, and setting the solar simulator's irradiance using the I_{SC} of a matched reference module does not cancel P_{max} errors of the production module under test. In this case, modelled data [7] and experimental data [10] suggest the P_{max} uncertainty contribution due to spatial non-uniformity of irradiance for a production module is between 0,5 % and 2,8 % for values of spatial non-uniformity of irradiance between 1 % and 5 %, respectively.

The uncertainties stated in this subclause based on modelled data [7] are derived from Figure 7 of that publication, after accounting for the publication's stated coverage factor ($k = 2$) and the addition of uncertainties in quadrature. Quantitative guidance is not available for the case of severe mismatch between reference module and production module under test (e.g. modules of different sizes), but methods described by the cited publications [6][7] can provide a starting point for a case-by-case evaluation.

PV module manufacturers should use solar simulators with spatial non-uniformity of irradiance less than 5 % (class B as per IEC 60904-9), consistent with the recommendation of IEC 62941:2019 noted in 4.3.2. In this regime, the solar simulator's irradiance should be set using the reference module's $P_{\max}$ to best mitigate effects due to spatial non-uniformity of irradiance, consistent with the recommendations of other technical publications [6][7][10]. Alternatively, as described in 4.5.4.1, the solar simulator's irradiance can be set using the reference module's I_{SC} and requiring that the reference module's subsequently measured $P_{\max}$ is within acceptable control limits.

Additional considerations can apply for spatial non-uniformity of irradiance less than 1 % (class A+ as per IEC 60904-9), in which case $P_{\max}$ uncertainty contributions from temperature and contact resistance can exceed those from spatial non-uniformity of irradiance. In this regime, setting the solar simulator's irradiance using the reference module's I_{SC} can result in lower total uncertainties [7], depending on the uncertainty contributions from temperature and contact resistance described in 4.5.4.2 and 4.5.4.3, respectively. For additional information, refer to the cited publications and IEC 60904-1:2020, Annex D.

In all cases, spatial non-uniformity of irradiance effects should be included in the evaluation of $P_{\max}$ uncertainty.

4.3.5 Temporal instability of irradiance

Temporal instability of irradiance can relate to two types of errors:

- a) Errors that can be corrected for by the methods of IEC 60891, for example due to a change in irradiance from the solar simulator's target level set using a reference module. Such changes in irradiance can be related to the long term instability (LTI) of irradiance and short term instability (STI) of irradiance metrics described in IEC 60904-9. Measurement and calculation of such errors will depend on:
 - 1) Both systematic and random change in irradiance as detected by an irradiance monitoring device, as discussed in 4.4.2.
 - 2) The characteristics of the irradiance monitor device and PV module under test, namely, the linearity of their I_{SC} with respect to irradiance as described in IEC 60904-10.
- b) Errors related to capacitive effects in the module, for example due to a rapid change in the solar simulator's irradiance during $P_{\max}$ measurement. Such changes in irradiance are not necessarily captured by the STI metric. Calculation of such errors will depend on:
 - 1) The rate of change of excess charge carrier density (electrons and holes) versus time within the PV module during I - V curve measurement. This is related to more practically measurable quantities, including the simultaneous rates of change of irradiance, module current, and module voltage during I - V curve measurement [11]. These rates of change will depend on the measurement strategy (if any) employed to reduce capacitive effects; a list of such measurement strategies is given in IEC 60904-1:2020, Annex B.
 - 2) The applied correction factors, if any [12].

PV module manufacturers have discretion to use solar simulators of various temporal instability classifications as long as consideration is given to the factors discussed in this subclause. The use of an irradiance monitoring device as described in 4.4.2 is recommended in order to measure irradiance changes related to item a) and facilitate $P_{\max}$ corrections according to IEC 60891. Errors related to item b) will depend on the PV module capacitance and on the I - V curve measurement strategy. No additional recommendations are given to PV module manufacturers regarding solar simulator temporal instability classification, other than the minimum requirement noted in 4.3.2 (class C temporal instability of irradiance).

4.3.6 Angular distribution of irradiance

The reference angular distribution is defined in IEC 60904-3:2019, Clause 5 in such a way that the radiation for both direct and global spectral distribution hits the PV device perpendicular to its surface, i.e. at normal incidence. In other words, this means that the global reference beam is defined as a perfectly collimated beam and all its rays are perfectly parallel to each other and to the straight line that connects the light source and the test plane. A solar simulator metric relevant to angular distribution of irradiance is currently not included in the IEC 60904-9 classification system. Future IEC documents based on recent publications [13] are expected to address this point.

The angular distribution of irradiance as seen from the test plane generally can be influenced by the distance between the solar simulator's light source and the test plane, as well as by any elements of the solar simulator's installation environment that are optically relevant. The latter are critically important and sometimes underestimated. The same solar simulator can result in quite different irradiance distributions to the test plane when the surrounding environment changes in its optical characteristics (e.g. a room with or without baffles to prevent stray light from reaching the test plane).

EXAMPLE Optically relevant elements include any optics used to diverge, converge, or reflect light rays inside and/or outside the light source housing. Such elements also include coatings or other materials installed on walls, ceiling, and floor of the solar simulator's environment, as well as baffles and other elements that interfere with the beam rays' straight-line propagation along the optical path from the light source to the test plane.

Uncertainties related to angle-of-incidence effects depend on the optical materials and the front surface texturing employed in both the reference module and the module under test. A wide range of optical materials is used in industry, for example light trapping films, ribbons, or anti-reflection coatings applied on either solar cell or module laminate layers.

Published work [3], representing analysis of at least thirty silicon PV modules and four solar simulators having different angular distribution of irradiance, reports that:

- Uncertainties related to angle-of-incidence effects are generally less than 0,2 % when using a matched reference module with any of the investigated solar simulators;
- Uncertainties related to angle-of-incidence effects range from 0,2 % to 1,5 % when using a non-matched reference module, depending on the solar simulator's angular distribution of irradiance.

These uncertainties are derived from Figure 6 of the cited publication, after accounting for the publication's stated coverage factor ($k = 2$).

IEC 61853-2:2016, Clause 7 describes methods to characterize the angle-of-incidence responsivity of PV modules. These methods can be used to quantify the angle-of-incidence responsivity of reference modules and production modules, and assess the contribution of angle-of-incidence effects to $P_{\max}$ uncertainty.

PV module manufacturers have discretion to use solar simulators with various angular distribution of irradiance as long as consideration is given to the factors discussed in this subclause.

4.4 Reference modules

4.4.1 General

IEC 60904-2 describes reference devices, which are used to set solar simulator irradiance using the reference device I_{SC} or $P_{\max}$ value prior to I - V curve measurement of production modules. PV reference modules (rather than reference cells) are preferred for module production environments. The choice between using reference module I_{SC} or $P_{\max}$ is largely dictated by uncertainties due to spatial non-uniformity of irradiance (as described in 4.3.4 and IEC 60904-1:2020, Clause 7), temperature (as described in 4.5.4.2), and electrical resistance of the module connection (as described in 4.5.4.3).

4.4.2 Irradiance monitoring

IEC 60904-1:2020, Clause 5 requires the use of an irradiance monitor device for measuring I - V curves, and gives recommendations for the characteristics of such a device. An irradiance monitor device can be used as an integral part of solar simulator function and serve multiple purposes, such as:

- Providing real-time feedback to solar simulator equipment in order to maintain a target irradiance profile for the duration of the flash pulse;
- Measuring the total irradiance during I - V curve measurement in order to provide a basis for irradiance corrections according to IEC 60891, which may be applied to individual measured I - V points or to the entire I - V curve.

It should be emphasized that irradiance traceability for production module I - V curve measurements comes directly from the reference module used to set the solar simulator irradiance (Figure 3), with the irradiance monitor device acting as an intermediate step in the traceability chain. During the process of setting solar simulator irradiance, a numerical factor can be assigned to the irradiance monitor device in order to scale its output to units of irradiance, thus allowing measurement of deviations from the target irradiance in subsequent I - V curve measurements. Often the determination of the numerical scaling factor is an automatic process performed by the solar simulator equipment when irradiance is set using a reference module.

NOTE This process can also be viewed as transferring the reference module calibration to the irradiance monitor device, and subsequently from the irradiance monitor device to the module under test.

4.4.3 Reference device requirements in relevant IEC documents

For quality assurance in PV module manufacturing, IEC 62941:2019 requires I - V curve measurements to be performed to a recognized standard such as IEC 60904-1. In turn, IEC 60904-1:2020, Clause 5 requires the incident irradiance to be measured by a reference device that conforms to IEC 60904-2, having traceability that conforms to IEC 60904-4.

IEC 60904-1:2020, 4.2 requires that measurements intended to be reported at STC be taken with irradiance between 800 W m^{-2} and $1\,200 \text{ W m}^{-2}$. IEC 62941:2019, 6.1.2 requires the measurement conditions, such as total irradiance, to be chosen in order to minimize the need for corrections to STC. Verification of these requirements involves understanding of the traceability of the reference module(s) used to set solar simulator irradiance. An example traceability chain is shown in Figure 3. Working reference modules (sometimes called “silver” or “control” modules) are used for daily calibration checks of production line solar simulators. Secondary reference modules (sometimes called “golden” or “master” modules) are used to generate new working reference modules as needed, or to check for potential drift of working reference modules. The traceability for each PV module manufacturer can be more or less complex than the example shown in Figure 3, depending on the number of calibration transfers that separate the production module measurement from primary and secondary standards.

Generally, the generation of new working reference modules is performed in laboratories with stricter procedures than the production line. “Laboratories” can be third-party calibration facilities, or internal facilities operated by the PV module manufacturer. In any case, such laboratories should have appropriate equipment and competencies to apply the relevant procedures.

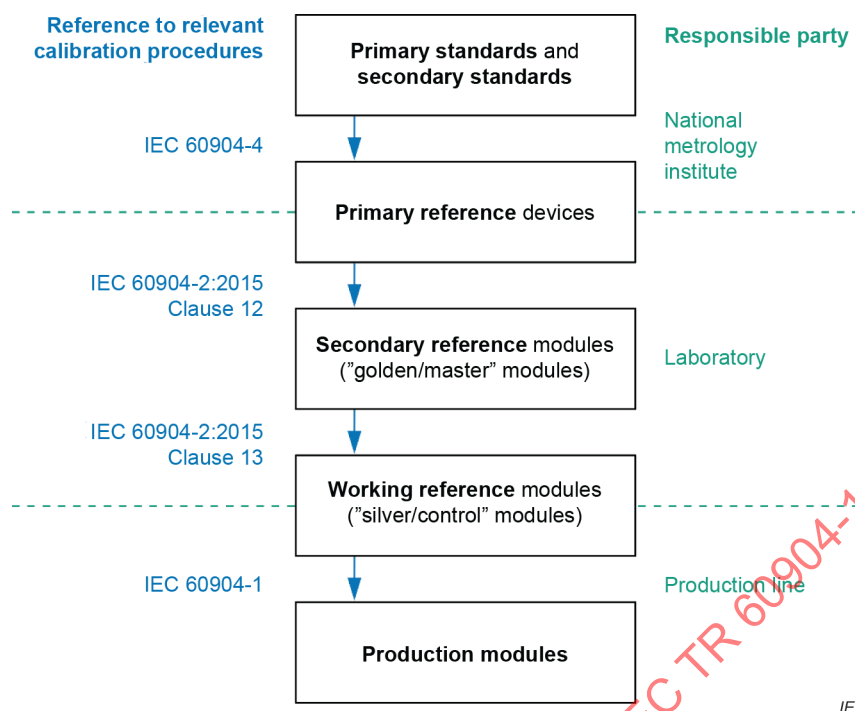


Figure 3 – Example traceability chain for production PV modules, adapted from published work [10]

4.4.4 Reference module characteristics

Reference module characteristics are often a significant contributor to $P_{\max}$ uncertainty [7][10] for the following reasons:

- Reference devices establish calibration of solar simulator irradiance through an unbroken traceability chain to international primary standards (Figure 3) accompanied by a calculation of measurement uncertainty.
- Uncertainties of the reference module's $I-V$ parameters directly propagate into the $P_{\max}$ uncertainty of the production module (Formulae (1) and (2) in 5.2). Possible drift of the reference module's $I-V$ parameters due to degradation or metastability will directly affect the production module's $P_{\max}$ uncertainty.
- Matching of dimensional, optical, and electrical characteristics between reference module(s) and production modules can minimize errors in $P_{\max}$ due to deviations from STC (Table 2), while lack of matching can exacerbate such errors if no appropriate corrections are put in place.

In general, reference modules should be constructed using the same bill of materials and manufacturing procedures as the production modules under test. Characteristics relevant to reference module matching should be monitored as part of the PV module manufacturer's control plans described in IEC 62941:2019, 5.5.4. Based on this information, PV module manufacturers should:

- a) Use reference modules having properties matched to the production module under test, which can include (but are not limited to):
 - 1) Dimensional properties
 - i) Module and cell size
 - ii) Number of cells
 - 2) Optical properties
 - i) Anti-reflective coatings

- ii) Glass type, thickness, texturing, and spectral transmission
- iii) Encapsulant type, thickness, and spectral transmission
- iv) Backsheet type, color, and spectral back-reflection
- v) Presence of double-glass module structure
- 3) Electrical properties
 - i) PV cell technology
 - ii) Electrical interconnection
 - Number of strings, and use of series strings versus parallel strings
 - Number of bypass diodes.
- b) Use separate matched reference modules for each product type identified by significantly different dimensional, optical and/or electrical properties.
- c) Monitor long-term electrical stability of reference modules and include drift of electrical parameters in the uncertainty evaluation for production module $P_{\max}$, including:
 - 1) Change of I_{SC} or $P_{\max}$ over time
 - 2) Change of electrical connector resistance over time
 - 3) Physical damage (e.g. cell cracking) due to mishandling
 - 4) Alteration of front surface (e.g. scratching, yellowing, or alteration of anti-reflective coating).
- d) Maintain reference modules in an environment that promotes long-term electrical, mechanical, and optical stability. In general, this means avoiding prolonged exposure to elevated temperatures and irradiance levels and unnecessary handling. If appropriate, stabilization procedures should be implemented to account for known light-induced degradation effects of specific PV technologies (e.g. IEC 61215-2:2016, MQT 19).
- e) Maintain and use multiple reference modules in a manner that allows for detection of damaged or degraded reference modules.

4.5 Calibration and operation procedures of measurement equipment

4.5.1 General

In order to perform reliable measurements, measurement equipment should be traceably calibrated to SI units; this includes equipment to measure voltage, current, temperature, total irradiance, and spectral irradiance. In particular, traceability of total irradiance is determined by the reference module used to set the solar simulator's irradiance. As such, each reference module should be considered as part of the manufacturer's measurement equipment and its I - V characteristics should be traceable to SI units by an uninterrupted traceability chain as in Figure 3.

4.5.2 Calibration and operation procedure requirements in relevant IEC documents

For quality assurance in PV module manufacturing, IEC 62941:2019 has several requirements related to calibration and operation procedures, including (but not limited to):

- Control of measurement conditions in order to minimize the need for corrections to STC (IEC 62941:2019, 6.1.2);
- Development of control plans for measurement procedures, including control of module temperature, module placement, electrical connections to the production module under test, and reference modules (IEC 62941:2019, 5.5.3);
- Characterization of measurement equipment using measurement systems analysis (IEC 62941:2019, 4.2.1).

Specifics are discussed in 4.5.4.

4.5.3 Calibration frequency

Generally, measurement equipment and reference modules should be calibrated at least once per year; further specifics are given in IEC 62941:2019. Traceable calibration of reference modules should be performed by accredited laboratories following accepted standards (e.g. IEC 60904-4) or recognized accredited methods, in order to ensure traceability to SI units. A traceable calibration should include a statement of uncertainty of the relevant measured I - V parameters, namely I_{SC} , V_{OC} , and P_{max} .

Setting of the solar simulator's total irradiance should be regularly performed using one or more working reference modules following the recommendations of the solar simulator manufacturer, together with the experience and documented procedures of the PV module manufacturer. The use of three or more reference modules is recommended, as it can allow detection of drift in the I - V parameters of one reference module outside its stated uncertainties. This is predicated on the assumption that it is less likely for similar drifts to occur in multiple reference modules simultaneously than it is for one reference module by itself to exhibit drift. An example procedure consists of using one reference module to adjust the total irradiance, with the adjustment then verified by measurement of subsequent reference modules, taking into account the respective uncertainties of all reference modules.

Typically, setting (or simply checking) the solar simulator irradiance is performed several times per day, for example, at the beginning of every working shift or when a change in production module type occurs. Such procedures can mitigate undesirable effects due to:

- Degradation of solar simulator irradiance due to lamp or equipment ageing;
- Degradation over time of electrical connection between production modules under test and the I - V measurement equipment as described in 4.5.4.3;
- Module temperature variation due to environmental factors in the production line as described in 4.5.4.2;
- Operator errors, faulty automation, or errors in equipment software settings.

Total irradiance, spectral irradiance, and spatial non-uniformity of irradiance on the test plane should be assessed after any changes are made to solar simulators. Such changes include replacing light sources (entirely or partially) and adjusting any optically relevant components, including those installed in the operation environment.

One possible implementation of a solar simulator control plan (according to IEC 62941:2019, 4.2) that is currently found in PV manufacturing environments is the frequent measurement of reference module P_{max} during each working shift, for example once every two hours. If the measured values of the reference module P_{max} exceed established control limits, an investigation is conducted to find and fix the root cause, and then corrective action is taken for all modules measured in the preceding two hours. In general, understanding of the tools and methodologies for statistical process control, such as control charts, is essential when setting action limits for any such control plan.

4.5.4 Factors affecting calibration of measurement equipment

4.5.4.1 Setting solar simulator irradiance

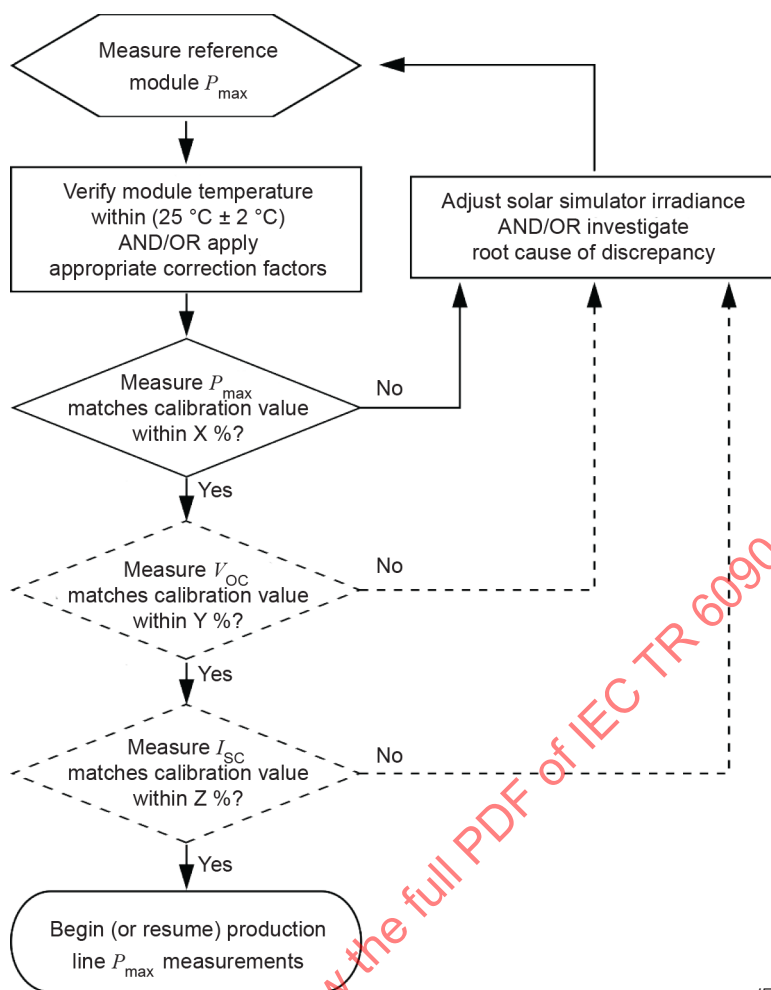
Solar simulator irradiance should be set using one or more reference modules matched to the production module under test as described in 4.4.4. Manufacturers have a choice to set the irradiance using either I_{SC} or P_{max} of the reference modules, and this choice is largely dictated by uncertainties due to spatial non-uniformity of irradiance (as described in 4.3.4 and IEC 60904-1:2020, Clause 7), temperature (as described in 4.5.4.2), and electrical resistance of the module connection (as described in 4.5.4.3). A general summary is given in Table 3.

Setting solar simulator irradiance using reference module $P_{\max}$ is recommended. Although this parameter is influenced by temperature and electrical resistance of the module connection, these parameters can be monitored by direct measurement as part of a control plan in order to quantify or limit their influence (see 4.5.4.2 and 4.5.4.3). On the other hand, the variation in reference module I_{SC} due to spatial non-uniformity of irradiance is generally unknown and difficult to quantify, due to its dependence on I_{SC} tolerances of individual cells and their positioning within the module.

Table 3 – Types of production module $P_{\max}$ errors that can be partially cancelled by setting solar simulator irradiance using a matched reference module

Source of error	Reference to this document	Reference module I - V parameter used to set irradiance	
		$P_{\max}$	I_{SC}
Spectral distribution of irradiance	4.3.3	Yes	Yes
Spatial non-uniformity of irradiance	4.3.4	Yes	—
Angular distribution of irradiance	4.3.6	Yes	Yes
Capacitive effects	4.3.5	Yes	—
Contact resistance of I - V test equipment	4.5.4.3	Yes	—
Contact resistance of reference module	4.5.4.3	—	Yes
NOTE Errors related to spectral distribution of irradiance can also be corrected using the methods of IEC 60904-7.			

Setting the solar simulator's irradiance with one reference module parameter (I_{SC} or $P_{\max}$) leaves the other floating, and in general it is not possible to perfectly match both parameters simultaneously [1]. However, manufacturer control plans can establish limits for both parameters, setting wider limits for the floating parameter on the basis of manufacturer experience and analysis of factors known to impact each parameter (Table 2). A check of a third parameter, namely V_{OC} , can also be included to monitor influences of temperature effects, as indicated in Figure 4.



IEC

Dashed lines represent optional validation checks.

Figure 4 – Flowchart describing solar simulator irradiance adjustment based on reference module P_{max} ; adapted from published work [7]

4.5.4.2 Module temperature

IEC 62941:2019, 5.5.3 requires module current and voltage measurements to be appropriately corrected for deviations of temperature and irradiance using methods of IEC 60891. To minimize such deviations and their corresponding corrections, IEC 62941:2019, 5.5.3 also recommends the temperature of the production module under test be controlled to $(25 \pm 2) ^\circ\text{C}$, with temperature sufficiently equilibrated such that the difference between the measured temperature and the cell junction temperature is less than $1 ^\circ\text{C}$.

Temperature sensors typically measure the temperature of the front or back of the module rather than the cell junction temperature; therefore, verification of the temperature equilibration requirement can be difficult. In general, however, manufacturers should ensure the modules under test have sufficient time to cool after manufacturing processes that are conducted at elevated temperatures (e.g. module lamination).

IEC 60904-1:2020, Clause 5 requires measurement of the temperature of both the reference module and module under test using instrumentation having an instrumental measurement uncertainty of $\pm 1 ^\circ\text{C}$ or less. IEC 60904-1:2020, 7.2 requires the temperature of the reference module to be as close as possible to the temperature at which it was calibrated. Some technical publications [1] recommend the use of multiple temperature sensors to detect temperature variations over the module area and provide a check in the case of a single sensor failure. If infrared temperature sensors (pyrometers) are used, they should be placed carefully such that

they detect primarily temperature variations of the module under test rather than temperature variations of the module surroundings.

When temperature corrections are applied, $P_{\max}$ uncertainties related to temperature will depend on which methods of IEC 60891 are employed, the magnitude of the temperature deviation from STC, and the uncertainty of relevant temperature coefficients determined according to IEC 60891. The relative temperature coefficient of $P_{\max}$ is typically between $-0,5 \text{ }^\circ\text{C}^{-1}$ and $-0,3 \text{ }^\circ\text{C}^{-1}$ [15]. Caution should be used if $P_{\max}$ measurements are made outside the recommended temperature range of $(25 \pm 2) \text{ }^\circ\text{C}$, as such temperatures can produce $P_{\max}$ uncertainties greater than 1 % when no corrections are applied. Even when corrections are applied, large temperature deviations ($\geq 10 \text{ }^\circ\text{C}$) can also produce $P_{\max}$ uncertainties greater than 1 % due to uncertainty of the temperature coefficients used for correction.

Temperature in the production line can fluctuate daily and seasonally. Daily temperature fluctuations can affect the temperature of the modules under test, as well as the temperature of reference modules at the time they are used to set solar simulator irradiance. Uncertainties related to reference module temperature fluctuations will depend on whether solar simulator irradiance is set using the reference module I_{SC} or $P_{\max}$, as I_{SC} is generally less sensitive to temperature than $P_{\max}$. The effects of such temperature variations on production module $P_{\max}$ measurement uncertainty can be quantified using gauge study methods described in 5.2.

4.5.4.3 Contact resistance and cable resistance

Since PV modules are generally two-terminal devices, making unambiguous four-terminal connection (Kelvin connection) to a PV module is difficult. At a given current and irradiance, the voltage and power measured from a module decrease as contact resistance and/or cable resistance increase. For a resistance R , the decrease in measured $P_{\max}$ is approximately equal to $(I_{P_{\max}})^2 \times R$.

Variation in electrical resistance can occur over time as PV electrical connectors degrade with use. This applies to any electrical connectors in the two-terminal region of the electrical connection path shown in Figure 5, including:

- Y-connectors or splitters that are used to transform between two-terminal and four-terminal connections. Such connectors can be internal or external to the I - V measurement equipment.
- Extension cables that are sometimes used when the module under test and I - V measurement equipment are separated by a significant distance. Such cables are not recommended because their resistances are often not well-controlled. If necessary, cable extensions should only be added in the four-terminal region of the electrical connection path.