

TECHNICAL SPECIFICATION



**Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance –
Part 3: Photovoltaic modules and plants – Outdoor infrared thermography**

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

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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**Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance –
Part 3: Photovoltaic modules and plants – Outdoor infrared thermography**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

**PHOTOVOLTAIC (PV) SYSTEMS –
REQUIREMENTS FOR TESTING,
DOCUMENTATION AND MAINTENANCE –****Part 3: Photovoltaic modules and plants –
Outdoor infrared thermography**

FOREWORD

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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 62446-3, which is a technical specification, has been prepared by IEC technical committee 82: Solar photovoltaic energy systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
82/1188/DTS	82/1242A/RVDTS

Full information on the voting for the approval of this technical specification 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 62446 series, published under the general title *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance*, can be found on the IEC website.

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

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- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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PHOTOVOLTAIC (PV) SYSTEMS – REQUIREMENTS FOR TESTING, DOCUMENTATION AND MAINTENANCE –

Part 3: Photovoltaic modules and plants – Outdoor infrared thermography

1 Scope

This part of IEC 62446 defines outdoor thermographic (infrared) inspection of PV modules and plants in operation. The inspection can include cables, contacts, fuses, switches, inverters, and batteries. This inspection supports the preventive maintenance for fire protection, the availability of the system for power production, and the inspection of the quality of the PV modules. Included in this document are the requirements for the measurement equipment, ambient conditions, inspection procedure, inspection report, personnel qualification and a matrix for thermal abnormalities as a guideline for the inspection.

This document defines outdoor thermography on photovoltaic (PV) modules and Balance-of-system (BOS) components of PV power plants in operation, using passive techniques (standard system operating conditions under natural sunlight, without any external power or irradiation sources). IEC 60904-12-1 covers general methods for laboratory or production-line PV module thermographic imaging but not the specific details that are most relevant to outdoor imaging of operational power plants including BOS components.

Two different levels of inspections are currently used:

- a) A simplified thermographic inspection. This is a limited inspection to verify that the PV modules and BOS components are functioning, with reduced requirements for the qualification of personnel. For example, during a basic commissioning of a PV plant. Authoritative conclusions regarding module quality are not possible with this inspection, and examples of abnormalities are provided to aid the inspector.
- b) A detailed thermographic inspection and analysis. This may include thermal signatures which differ from the examples provided, and therefore requires a deeper understanding of the thermal abnormalities. For example, it may be used for periodic inspections according to the IEC 62446 series and for trouble-shooting the cause of underperforming systems. Absolute temperature measurements may be made. An authorized expert in PV plants, together with thermography experts can perform the inspection.

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 60050-131, *International Electrotechnical Vocabulary – Part 131: Circuit theory*

IEC 60216-2, *Electrical insulating materials – Thermal endurance properties – Part 2: Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria*

IEC 60216-5, *Electrical insulating materials – Thermal endurance properties – Part 5: Determination of relative thermal endurance index (RTE) of an insulating material*

IEC 60269-1, *Low-voltage fuses – Part 1: General requirements*

IEC 61095, *Electromechanical contactors for household and similar purposes*

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

IEC 61439-1, *Low-voltage switchgear and controlgear assemblies – Part 1: General rules*

IEC 61724-1, *Photovoltaic system performance – Part 1: Monitoring*

IEC 61730-1, *Photovoltaic (PV) module safety qualification –Part 1: Requirements for construction*

IEC 61730-2, *Photovoltaic (PV) module safety qualification –Part 1: Requirements for testing*

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

IEC 62109-1, *Safety of power converters for use in photovoltaic power systems – Part 1: General requirements*

IEC 62446-1, *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection*

IEC 62446-2:–, *Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 2: Grid connected photovoltaic (PV) systems – Maintenance of PV systems¹*

IEC 62930:–, *Electric cables for photovoltaic systems with a voltage rating of 1,5 kV d.c.¹*

ISO 9488, *Solar energy – Vocabulary*

ISO 9712, *Non-destructive testing — Qualification and certification of NDT Personnel*

VATH- Directive, *Electrical Infrared Inspections – Low Voltage. Planning, execution and documentation of infrared surveys on electrical systems and components ≤1kV* (http://www.vath.de/docs/richtlinien/VATH-Richtlinie_Elektro_NS+PV_engl_web.pdf)

EN 16714-3, *Non-destructive testing – Thermographic testing of electric installations*

EN 50110-1, *Operation of electrical installations – Part 1: General requirements*

DGUV BGV/GUV-V A3 E, *Accident prevention regulations, Electrical installations and equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TS 61836, ISO 9488, IEC 60050-131 and the following apply.

¹ To be published.

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

abnormal thermal behavior

thermal signature of an element that cannot be explained by its operating condition or its technical design, e.g. position of load resistors

[SOURCE:IEC 60050-903:2013, Amendment 1:2014, 903-01-22; modified: adapted to thermal behavior]

3.2

reflected temperature

T_{refl}

mean apparent temperature of the ambient that is reflected by the object towards the IR-camera

Note 1 to entry: Measured in Celsius (°C).

Note 2 to entry: Some manufactures of IR cameras use the term: ambient temperature.

3.3

atmospheric air temperature

defined in Celsius (°C) for the geographic installation location as measured and documented by meteorological services for this geographic location

3.4

Beaufort (scale)

Bft

quantifies wind speed by phenomenological criteria, e.g. movement of branches and trees

SEE: Annex E.

3.5

cloud coverage

for the inspection two types of clouds are to differ: Cumulus and Cirrus. The cloud coverage should be given in okta (part of eight of cloud coverage)

SEE: ISO 15469:2004[18]².

3.6

emissivity of the object

ε

ratio of the thermal radiation that is emitted by the surface of an object compared to a black body radiator both at the same temperature

3.7

Instantaneous Field of View

IFOV

field of view of one pixel of an IR-camera-lens combination

Note 1 to entry: Measured in milliradian (mrad).

² Numbers in square brackets refer to the Bibliography.

3.8**Noise Equivalent Temperature Difference****NETD**

smallest temperature difference detectable by an IR-camera

Note 1 to entry: Measured in millikelvin (mK).

3.9**thermal steady state conditions**

usable measurement conditions, which show stable temperatures and temperature differences

4 Requirements of inspection equipment**4.1 General**

This clause states the minimum requirements for equipment used for thermographic (infrared) inspection within the scope of this document. It includes requirements for the infrared (IR) camera, the photo camera and equipment to record ambient conditions.

All equipment shall be date and time synchronized prior to use, to easily match images to system conditions, for example the in plane irradiation, and DC-load of the plant.

4.2 Minimum requirements for IR-cameras used for inspecting PV plants

The specifications of the infrared camera shall fulfil the minimum requirements according to Table 1.

Table 1 – Minimum requirements for IR-cameras

	Features	Minimum requirements
a	Spectral response	2 μm to 5 μm (mid wavelength) or 8 μm to 14 μm (long wavelength) ¹
b	Temperature-sensitivity and calibration range (object temperature range)	-20 °C to +120 °C
c	Operating ambient air temperature range	-10 °C to +40 °C
d	Thermal sensitivity	NETD \leq 0,1 K at 30 °C
e	Geometric resolution	1) PV module: max. 3 cm of the module edge per pixel ² 2) Electrical connections: The geometrical resolution (Real measurement spot ³) has to match the smallest object area to be verified. Futher details can be found in Clauses A.1 and A.2.
f	Absolute error of measurement	< \pm 2 K
g	Adjustable parameters	Emissivity (ϵ), reflected temperature (T_{refl})
h	Adjustable functions	Focus, temperature level and span
i	Measurement functions	Measuring spot, measuring area with average and maximum temperature

	Features	Minimum requirements
j	Calibration	The measuring system (camera, lens, aperture and filter): The thermographic camera shall be traceably calibrated at least every two years. The calibration has to be documented. If the camera is not compliant (absolute temperature and/or temperature differences), it may be readjusted by the manufacturer.
k	Documentation	Storing of the infrared picture with all radiometric information to be able to determine absolute temperatures. Non-radiometric pictures can only provide pattern and eventually temperature differences.
<p>1 Cameras operating in wavelength range of 2 μm to 5 μm shall only be used for thermography of electrical BOS components, e.g. fuses. Due to the transparency of glass in the range of 3 μm the use of that range on PV modules can lead to measurement errors.</p> <p>2 3 cm length of edge per pixel equals 5 x 5 pixel on a 6" PV cell.</p> <p>3 The real measuring spot mostly is defined as 3 x 3 pixel, for high-quality optics.</p>		

Use of an IR camera with resolution ≥ 320 x 240 pixels and a separate photo camera are recommended, with monitor and remote control or a swivelling display.

4.3 Requirements for photo cameras for documentation of the findings

Visual photos documenting the state of the module/plant are recommended, however visual photos of any thermal abnormality are required. One photo of every safety relevant abnormality (see Table 4) shall be taken.

The resolution of the visual photo shall be significantly higher than the IR image and shall have a similar field of view to sufficiently capture all details of the object (e.g., busbars, ribbons of a solar cell, broken front glass, fuse and fuse holder). It shall be ensured that IR and visual photo capture the same area of interest while fulfilling the resolution requirement. A separate photo camera and IR camera are recommended, in order to ensure sufficient resolution of visual photo (typically at least 30 times higher).

NOTE In many cases, the basic photo camera which is integrated into the infrared camera is not able to provide the requested resolution. For an IR camera of 640 x 480 pixel a separate photo camera with at least 9 Mpix is suitable.

4.4 Requirements for equipment to record the ambient conditions

To detect thermographic abnormalities correctly, certain ambient conditions have to be met. Equipment to measure these conditions should be compliant to the minimum requirements in Table 2.

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Table 2 – Requirements for equipment to record the ambient conditions

	Parameter	Equipment	Accuracy
a	Irradiance	Irradiance sensor (crystalline silicon cell or pyranometer)	Calibration: $\pm 5\%$
b	Ambient (air) temperature	Temperature sensor (shielded from direct light and wind)	Calibration: $\pm 2\text{ K}$
c	Wind speed	Bft scale (visual) or anemometer	Estimation
d	Cloud coverage	Photo camera	Estimation
e	Degree of soiling	Photo camera	Estimation Estimation can be done using procedure according to IEC 61724-1
f	Module or string current	DC (clamp) ampere meter (or inverter reading) ¹	Calibration: $\pm 2\%$
¹ Note that the inverter reading may not give accurate results or be calibrated. Though it may be useful for some BOS components, it may also not have resolution for PV string-level current measurement.			

5 Inspection procedure

5.1 General

An inspection of the PV plant should be done during the commissioning and operation of the power plant, in accordance with applicable health and safety regulations. The recommended interval for periodic thermography inspections is four years but the applied intervals for a specific installation shall be agreed upon with the owner / operator, or they might be defined by national electric codes and safety regulations for electrical installations.

The owner, operator or an authorized person shall give the inspector(s) an introduction into the safety specific regulations of the PV plant to be inspected, including details of the plant and electrical layout. A second person should be present during inspection, and may be required by local safety regulations. At least one of the persons performing the inspection shall have technical knowledge of the specific system, and of PV plants in general. Inspections shall be done following applicable safety regulations, for example in accordance to EN 50110-1 or DGUV BGV/GUV-V A3 E.

The detailed inspection scope shall be defined prior to the inspection and agreed in writing between the involved parties.

The plant shall be under operating conditions. The part of the system under evaluation shall be in thermal steady state condition and free of partial shading (if possible). Soiling should be low (less than 10 % operating current I_{mpp} loss) and homogeneous, without causing partial shading (e.g., by bird droppings, leaves, vegetation) to avoid thermal effects. If strong soiling or partial shading due to, for example bird droppings, is observed on the PV modules, it is recommended to clean the entire system prior to inspection. Note that the performance of the system may change as a result of the cleaning. Ensure modules are at thermal steady state after cleaning prior to performing infrared imaging inspection.

For quantification of soiling, it is recommended to conduct measurements according to IEC 61724-1. This might be helpful to compare measurements from periodic inspections.

Collecting IR images can be done in different ways, e.g., using tripods, by hand or drones. Care shall be taken that the method selected still meets the resolution requirements, and to ensure understanding of the method used (e.g., reflections). Any known deviations or limitations shall be noted in the inspection report.

National regulations and laws may apply to using IR cameras and other equipment like drones.

The inspection results verify the status at the time of inspection. Issues of intermittent or changing nature may or may not be captured at the time of inspection.

5.2 Visual inspection

Prior to the thermographic inspection of the PV plant, it is recommend to do a visual inspection to determine whether the requirements of 5.1 are met. Observations such as bird droppings, strong soiling, burn spots on modules or other Balance of System (BOS) components shall be documented by photos and location prior to the thermographic inspection. If possible, those findings should be resolved (e.g. by cleaning) prior to the thermographic inspection especially during comissioning. Photos post-cleaning (pre-imaging) should be documented. However, it may be desiriable to conduct the thermography inspection without cleaning, e.g. for a root-cause analysis for a poor performing PV power plant.

Upon observation of thermal anomalies, it is desiriable to visually inspect the component and visually observe any abnormal conditions in the area. The PV module visual inspection procedures in IEC 61215-1 and IEC 61730-2 may be useful references. A visual photo shall be captured for every thermal abnormality type.

5.3 Environmental conditions

The inspection should be performed under the conditions specified in Table 3.

Table 3 – Required inspection conditions

	Parameter	Limits
a	Irradiance	<ul style="list-style-type: none"> Minimum 600 W/m² in the plane of the PV module for PV module inspection Measured operating current shall be a minimum of 30 % of rated system current within the inspected current path (typically > 30 % of PV module name plate I_{sc} at STC (equals typically > 300W/m² in the plane of the PV modules) for inspection of other electrical components (e.g. cables, connectors, connections). Recommended for inspection are > 600 W/m². <p>NOTE Example for single string with no parallel connection: 30 % of STC I_{sc} current. I_{sc} to be taken from PV module name plate and not to be measured on PV plants.</p>
b	Wind speed	Maximum 4 Bft or 28 km/h (see Annex E)
c	Cloud coverage	Maximum 2 okta of sky covered by cumulus clouds
d	Soiling	No or low. Cleaning recommend, e.g. if bird droppings exist.

NOTE For cloud coverage, find further information in ISO 15469:2004.

After change in operating conditions, for example load or irradiance (due to e.g. cirrus clouds) of >10 % per minute, a waiting time of 15 min is recommended to regain the steady state measurement conditions.

The cloud coverage should not consist of more than 2 okta of cumulus clouds, because of misleading reflections on the modules.

5.4 Imaging procedure

5.4.1 General

The distance between the inspected object and the IR-camera shall fulfil the geometrical resolution, specified in 4.2, while required safety distances according to safety regulations are met. (See Clauses A.1 and A.2)

The IR-camera image shall be taken as perpendicular to the PV module surface as possible. At the same time, self-reflection of measuring personnel and IR-camera apparatus, and reflection of heated objects like sun, near-by buildings and trees shall be avoided. In cases where the image cannot be taken perpendicular to the PV module surface, e.g. a small installation with limited ability to raise the camera, the angle between the camera and the PV module plane should still be greater than 30° (see Clause A.2).

Adjust the camera emissivity based on surface conditions of the object under investigation (e.g. soiling of module front glass or dust on shiny parts of e.g. fuse holders).

The DC-load of the plant shall be monitored and recorded to avoid measurements under undefined load conditions due to grid events (e.g. strings are open circuit or short circuit).

Together with the thermographic image, a photo of the same area shall be taken for each type of thermal finding. The exact position of all the findings in the inspected system shall be documented, as well as the operating conditions including local DC load and environmental conditions.

Two different levels of quality of examinations are currently used:

a) Simplified inspection:

The simplified thermographic inspection with reduced requirements for the qualification of personnel (see Annex B). This is for a limited inspection to test the basic functioning of the PV modules. For example, during the commissioning of systems. Authoritative conclusions regarding module quality are not possible. No absolute temperatures are determined, therefore thermal patterns are used to evaluate the abnormalities. Refer to the examples in Annex C.

b) Detailed inspection:

The detailed thermographic inspection and analysis, which may include thermal patterns which differ from the examples in the Annexes. This may be useful for trouble-shooting and for periodic inspections according to IEC 62446-1 and future IEC 62446-2. Absolute temperature measurements are determined during this detailed inspection. An authorized expert for PV plants, together with thermographic experts, shall have advanced qualifications as per Annex B.

5.4.2 Using fast carriers for IR-camera, e.g. aerial drones

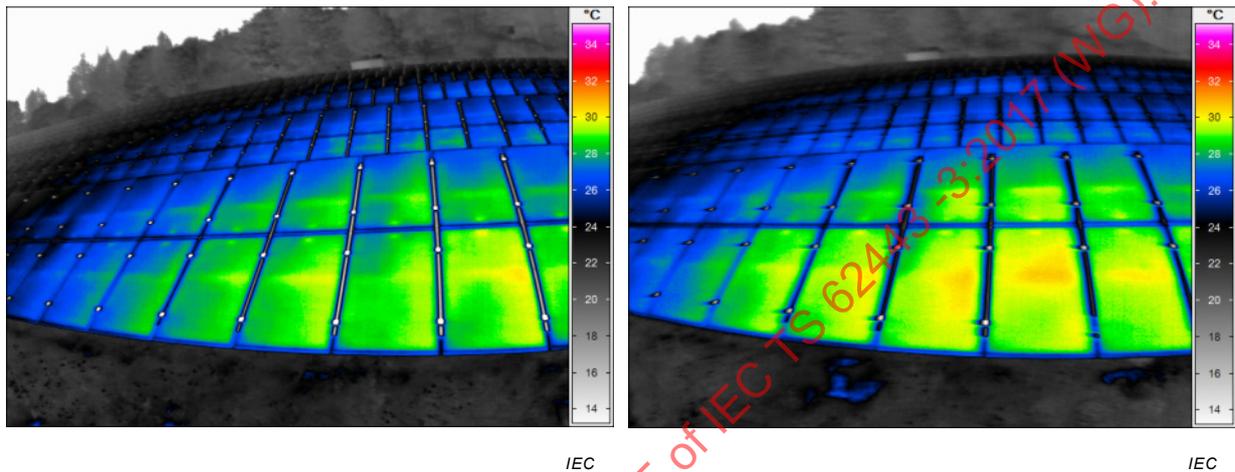
Aerial drones are increasingly being used as part of the tool kit for fault detection and localization in PV plants. It should be noted that while drones help scale, automate and accelerate detection of faulty areas within a large power plant, such techniques can lack the resolution to detect fine component artifacts or identify specific failure modes. Such an inspection by drones is classified as simplified inspection procedure of the whole PV array in order to find PV sub arrays/strings/modules with obvious noticeable problems.

In the case where imaging is performed using a fast carrier, the moving speed of the camera should always be chosen with respect to the time constant of the camera's IR-detector to avoid smearing effects (compare the following pictures in Figure 1). Smearing influences visual pattern and absolute and relative temperatures. Relevant smearing effects on common IR camera bolometer detectors, when used for PV-modules and systems, may already appear at a moving speed of 3 m/s.

For large-area imaging such as through use of drones, consider irradiance and system stability, especially if images will be stitched together and not individually mapped to system performance (instantaneous DC string current).

Ensure the geometric resolution requirements are met, especially if the distance between the IR camera and PV module is large. If the requirements are not met, it is a deviation to the procedure.

NOTE A typical approach is to do this simplified inspection at the whole PV array to find PV modules or strings with noticeable problems. Afterwards a detailed inspection is done at these PV modules. This partial or detailed inspection can be agreed in a contract, along with the thresholds for deciding what sort of issue in the simplified procedure would warrant the detailed approach described in this document.



a) Picture captured with slow camera moving speed without noticeable smearing b) Picture captured at high camera moving speed with unacceptable smearing

Figure 1 – Impact of camera moving speed

5.4.3 Emissivity

Estimating the emissivity of the examined surface is the responsibility of the qualified thermographer, particularly in the case of detailed inspection. The emissivity of a surface depends on many factors. Many of them are less relevant for the given task (such as the exact spectral range of the (LW)-IR-camera, surface and ambient temperature, surface geometry, etc.).

For the simplified inspection, the most important dependencies and some common values are given for common surface and ambient temperatures, surfaces without holes and (LW)-IR-cameras (note that less common MW-IR-cameras differ significantly):

For the practice of thermography on PV modules and BOS components, it is important to understand the following three dependencies: first material, second surface (includes soiling) and third angle of view. Dependencies and values are given by examples.

- a) Materials such as unoxidised metal (parts made out of stainless steel), polished aluminium parts and some BOS components have very low emissivities around $\epsilon = 0,1$ to $\epsilon = 0,3$, therefore an accurate temperature determination is not possible.
- b) Most insulation synthetics and ceramics have emissivity around $\epsilon = 0,9$.
- c) Rough oxidated aluminium of module frames and mounting clamps and some BOS components typically show values above unoxidised metal, but below glass, typically about $\epsilon = 0,4$ to $\epsilon = 0,7$.
- d) Materials like glass have higher emissivities around $\epsilon = 0,85$. Glass with a rough surface, such as textured glass or glass with high degree of soiling may have an emissivity up to $\epsilon = 0,9$.

- e) On non-ferrous glass the emissivity decreases with the angle of view, so at around 45° the emissivity will be around $\varepsilon = 0,8$ and at 30° it can be around $\varepsilon = 0,75$ or lower. (See Figure 2 and also Clause A.2.)

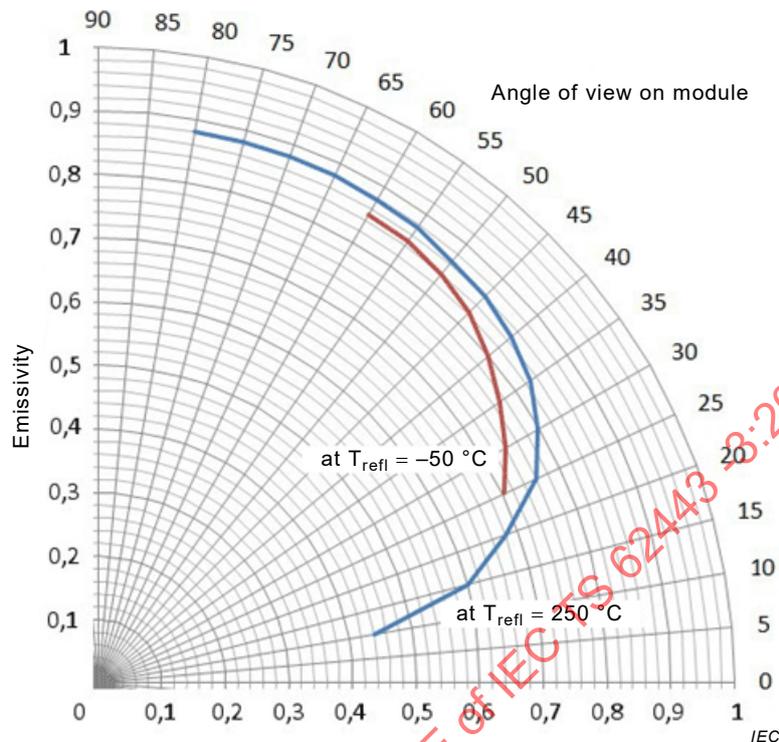


Figure 2 – Dependence of the emissivity of glass on the angle of view [10]

6 Software for evaluation

Using software, it is possible to transfer the radiation density values measured by the IR-camera into absolute temperature values. The calculations may be done directly using the IR-camera software, which updates the temperature labels on the display screen and in the saved file. Care shall be taken when interpreting any temperature values, as they may not be absolute temperatures if the correct parameters were not set. To obtain temperature values, it is necessary to set specific parameters, in particular:

- emissivity, ε ,
- reflected temperature, T_{refl} ,
- temperature level and span,
- different measuring tools (e.g. spot measurement, polygons) under specification of minimum, maximum and arithmetic mean value for the temperature data.

7 Evaluation

7.1 General

The following measurements and observations are important for evaluation or validation:

- maximum temperatures,
- temperature differences,
- temperature profiles,
- cloud, cloud movement, cloudiness (see example in Figure 3 right),

- e) wind speed and direction (see example in Figure 3 left),
- f) previous mechanical stress from installation history logfile,
- g) soiling,
- h) visual inspection,
- i) irradiance and/or DC load of system.

Results and recommendations of previous inspections should also be taken into consideration.

During a simplified thermographic inspection of a PV plant no exact temperatures are determined. Here the main focus is only on evaluating certain thermographic patterns as shown in Annex C. To evaluate absolute temperature and temperature differences, a detailed inspection shall be done with appropriate qualified personel (see Annex B). General guidance can be found in EN 16714-3 and VATH-Directive.

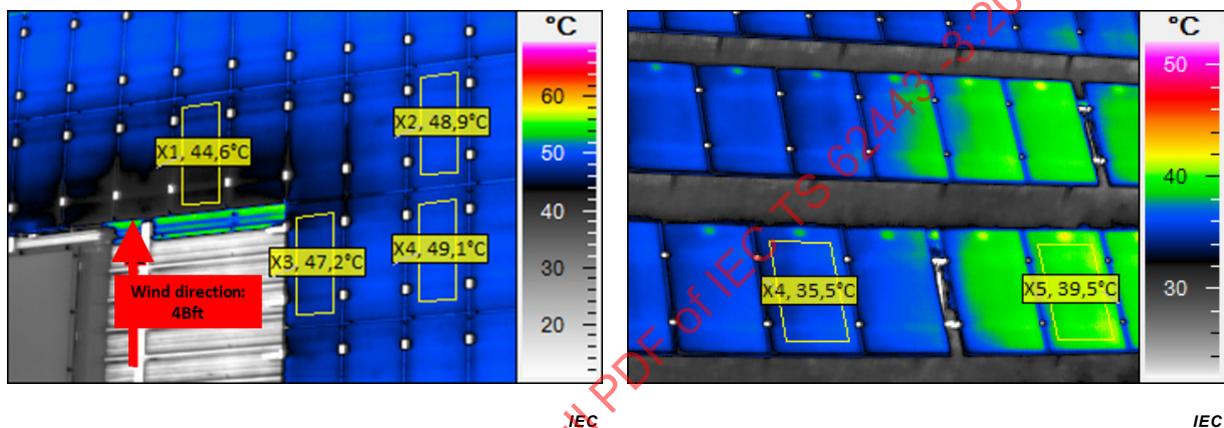


Figure 3 – Examples of influence of wind (left) and cloud movement (right) on observed temperature pattern

7.2 Evaluation of IR images

This subclause introduces several techniques to evaluate IR images. Other procedures exist and can be applied also.

- a) Patterns (Simplified inspection, see Annex C)

The abnormality is classified and evaluated by a known thermal pattern. Measurement of absolute and relative temperature values are not necessary but can supplement thermal patterns as plausibility check.

- b) Temperatures of point abnormalities (Detailed inspection, see Annex D)

Use an algorithm to determine highest temperature in the image. This can be done using different types of tools such as “freehand spot” or “maximum spot within an area” in the camera and image processing software.

- c) Extended areas (Detailed inspection, see Annex D)

Use different types of tools such as “rectangle”, “circle” or “polygon areas” to calculate the mean temperatures of the areas, using the camera and image processing software.

- d) Relative temperatures (Detailed inspection, see Annex D)

Can be calculated between point abnormalities and/or the mean values of extended areas, with consideration of the uncertainty of measurement.

- e) Absolute temperatures (Detailed inspection, see Annex D)

Can be measured at point abnormalities and the mean values of extended areas, with consideration of the uncertainty of measurement.

Attention: Absolute temperatures on PV generators vary due to wind and convection differences with time and position in the PV array and plant.

7.3 Thermal abnormalities

7.3.1 General

This subclause applies in particular for detailed inspection.

7.3.2 Classes of abnormalities (CoA)

For the allocation into classes of abnormalities (CoA), the specific patterns and measured temperatures have to be compared with the examples of thermographic images and differences in temperature shown in Annex C. Table 4 introduces three classes of abnormalities and their follow up action. This is important since there might be imminent danger (electric shock or fire) to personal and property.

Table 4 – Allocation in classes of abnormalities

Class of Abnormality (CoA)	1 (no abnormalities – OK)	2 (thermal abnormality – tA)	3 (safety relevant thermal abnormality – dtA)
Recommendation for actions	No imminent action	Checking the cause and, if necessary, rectification in a reasonable period.	Prompt interruption of operation, checking the cause and rectification in a reasonable period.

It is not always possible to classify thermal abnormalities without any doubt using thermography inspection alone. In this case additional appropriate inspections shall be applied.

7.3.3 Abnormalities of PV modules

Thermal images and resulting temperature differences shall always be evaluated in the context of the ambient conditions, type of mounting, and module assembly (glass-glass module, glass-foil module, integrated polymers, etc.).

If a doubtless classification from the front side of a PV module is not possible, a back side view (optical and thermographic) or further measurement techniques shall be utilized or a more qualified personnel (thermograph of level 2 or equivalent) shall become involved. Suggested actions for further measurements and rectification are described in Annex C.

7.3.4 Abnormalities of other BOS components

The BOS component inspection includes, but is not limited to, cables, contacts, fuses, switches, inverters and batteries. An example is given for a faulty (abnormal) contact.

Classification of abnormalities will depend on the BOS component. No specific PV requirements are developed, yet. For the time being, refer to the applicable product standards and general electro thermography techniques for electrical components and their defined requirements. See Figure 4.

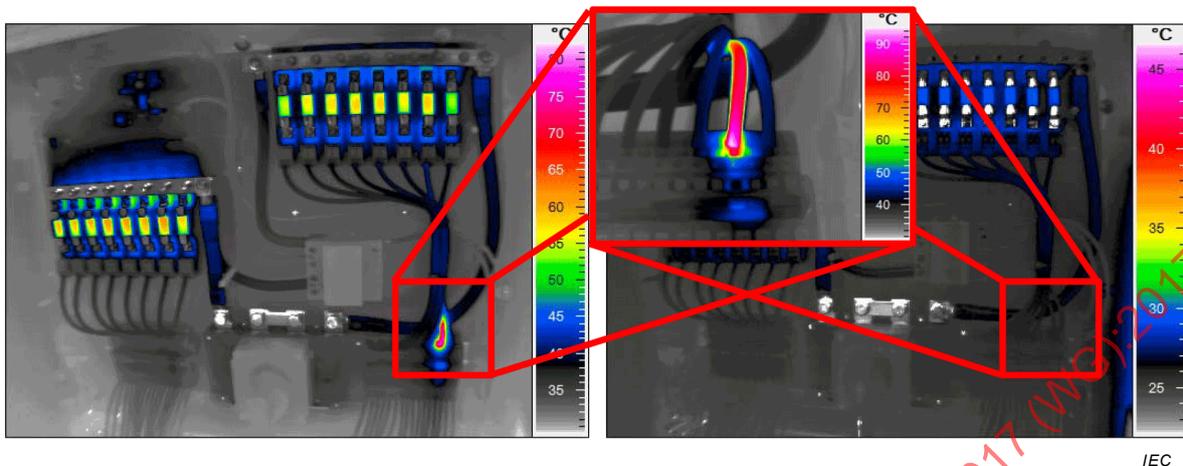


Figure 4 – Example infrared thermograms of a PV string combiner box with cables, contacts, fuses and switches before (left) and after (right) maintenance on a faulty contact

7.4 Projection of temperature differences to nominal irradiance

7.4.1 General

The following gives guidance for the extrapolation of the measured temperature difference between functioning and non/partial-functioning components under actual conditions, to the expected temperature difference under nominal in plane irradiance of the PV module, defined as 1 000 W/m². This applies for PV modules and for other BOS components for any thermal abnormality, and does not consider other conditions such as wind speed which are separately reported.

Here, thermal abnormalities are differentiated between:

- a) point abnormalities (e.g. localized hot-spots in solar cells or a fuse), and
- b) extended area abnormality (e.g. an entire warm/hot solar cell or a heat sink plate).

For temperature difference extrapolation the following formula shall be used:

$$\Delta T_2 = \left(\frac{G_2}{G_1} \right)^x \Delta T_1$$

NOTE 1 Reference for the formula: Guidelines to thermographic inspection of electrical installations; Thomas Perch-Nielsen, Jens Christian Sorensen; 1994 [1].

where

ΔT_i is the temperature difference between functional and non-functioning components under identical irradiance condition i ;

G_i is the irradiance or load (DC current) at condition i ;

Index $i = 1$ is the value at actual/partial irradiance/load (see Table 3 for minimum required partial irradiance/load conditions);

Index $i = 2$ is the value at nominal load/temperature (100 % irradiance/load condition);

x is the exponential factor, considering different shapes of abnormalities. For impact of x see Figure 5.

Since DC current load generated by the PV modules is proportional to irradiance and if the nominal current load at 1 000 W/m² is known, DC current load may be substituted for irradiance in the above formula and Table 5.

- For a point abnormality (point heat source with radial heat transport – typically up to a couple of square millimetres in size and much smaller than a cell – for example, for a 6" c-Si cell a point abnormality is typically less than 3 mm²) the following applies:

exponential factor x is typically between 1,5 and 1,8, where $x = 2,0$ represents only current induced heat from a point spot, without any heat dissipation by radiation.

NOTE 2 "6 inch cell" is an expression currently used in the PV industry; 6" corresponds to 15,24 cm. However, other similar sizes are used in the PV industry as well.

- For extended area abnormality (lateral extended heat source – typically of the size of one or more cells) the following applies:

exponential factor x is typically $x = 1$ and therefore represents a linear dependence of temperature on irradiance / current load.

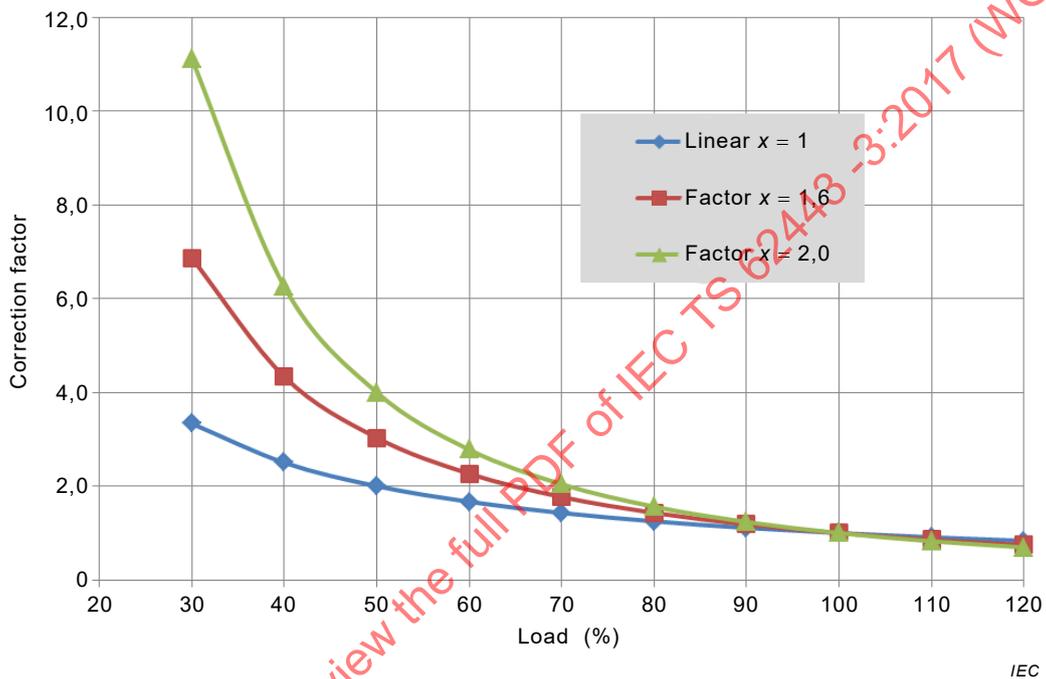


Figure 5 – Graphic representation of the correction factor for temperature differences to nominal irradiance/load conditions as a function of the relative irradiance/load

For convenience, the exponential factor x and the irradiance/load terms can be combined into a "correction factor", to directly extrapolate ΔT from the measured to the nominal condition. Values for these correction factors for point abnormalities and extended area abnormalities of PV modules and BOS components can be found in the corresponding columns of Table 5 and graphically shown in Figure 5.

$$\text{correction factor} = \left(\frac{G_2}{G_1} \right)^x$$

Table 5 – Example correction factors for temperature differences to nominal load conditions based on formula above and Figure 5

Fraction of rated irradiance / current load %	Point abnormality		extended area abnormality (x = 1,0)	
	PV modules (x = 1,5)	Other BOS (x = 1,6)	PV modules	Other BOS
30	NA	6,9	NA	3,3
40	NA	4,3	NA	2,5
50	NA	3,0	NA	2,0
60	1,7	2,3	1,7	1,7
70	1,4	1,8	1,4	1,4
80	1,3	1,4	1,3	1,3
90	1,1	1,2	1,1	1,1
100	1,0	1,0	1,0	1,0
110	0,9	0,9	0,9	0,9
120	0,8	0,8	0,8	0,8

7.4.2 Modules

For a simplified inspection, 7.4 does not apply since only IR patterns as given in Annex C shall be used for interpretation of abnormalities.

For a more detailed inspection absolute temperatures are important. For a detailed inspection, maximum temperatures, temperature differences and temperatures gradients shall be evaluated. Qualified personel are required as per Annex B.

Guidance for normalizing temperature differences for module abnormalities is given in 7.4.

A clear differentiation shall be made between point and extended area abnormalities.

The detailed evaluation shall consider also additional observations such as DC current load measured at the abnormality, soiling (homogenous or partial), possible mechanical stress (e.g. due to installation, thermal cycling, or snow loads), previous inspections, and material properties of the components.

At least the following normative references shall be taken into account, e.g. for operating conditions, expected temperatures and temperature limits given by the used materials:

- IEC 61730-1, *Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction*
- IEC 60216-2, *Electrical insulating materials – Thermal endurance properties – Part 2: Determination of thermal endurance properties of electrical insulating materials – Choice of test criteria*
- IEC 60216-5, *Electrical insulating materials – Thermal endurance properties – Part 5: Determination of relative thermal endurance index (RTE) of an insulating material*

Based on the results, a classification of each abnormality according to 7.3 and Table 4 shall be done. Examples of corrective actions for PV modules are specified in Annex C.

7.4.3 Other BOS components

The BOS component inspection includes, but is not limited to, cables, contacts, fuses, switches, inverters and batteries.

General guidance for normalizing temperatures for BOS components is given in 7.4. A clear differentiation shall be done between point and extended area abnormalities. For evaluation the component shall be stressed with at least 30 % of its nominal maximum rating in its application, recommended is more than 60 %, per Table 3.

Based on the results, a classification of each component according to 7.3 and Table 4 shall be done. Corrective actions for BOS components depend on component. Guidance can be found in the following references and in manufacturers documentation:

- Cables:
 - Future IEC 62930, *Electric cables for photovoltaic systems with a voltage rating of 1,5 kV d.c.*
- Fuses:
 - IEC 60269-1, *Low-voltage fuses – Part 1: General requirements*
- Inverters:
 - IEC 62109-1, *Safety of power converters for use in photovoltaic power systems – Part 1: General requirements*
 - IEC 61095, *Electromechanical contactors for household and similar purposes*
- Switchgear:
 - IEC 61439-1, *Low-voltage switchgear and control gear assemblies – Part 1: General rules*
 - IEC 61095, *Electromechanical contactors for household and similar purposes*

8 Inspection report

The inspection report shall contain the following information:

- a) name of the PV expert, thermographer and of the attending persons,
- b) type, including make and models, of the camera system,
- c) day and time of the inspection,
- d) location of the inspection,
- e) scope of inspection as contracted:
 - 1) with type designation of components,
 - 2) efficiency of PV module, nominal rating of BOS component,
 - 3) listing of all inspected components,
 - 4) mounting:
 - i) Modules: type of mounting (e.g. roof mounted: parallel, tilted, in roof; greenfield installation; orientation; inclination).
 - ii) BOS component location (e.g. roof, conduit, open-air).

NOTE Modules with higher efficiency will reach lower normal operating absolute temperature values.

- f) environmental conditions:
 - 1) air temperature, in °C,
 - 2) wind speed, in Bft or m/s and direction,
 - 3) cloud coverage, in okta and type of cloud,
 - 4) irradiance in plane of module, in W/m²,

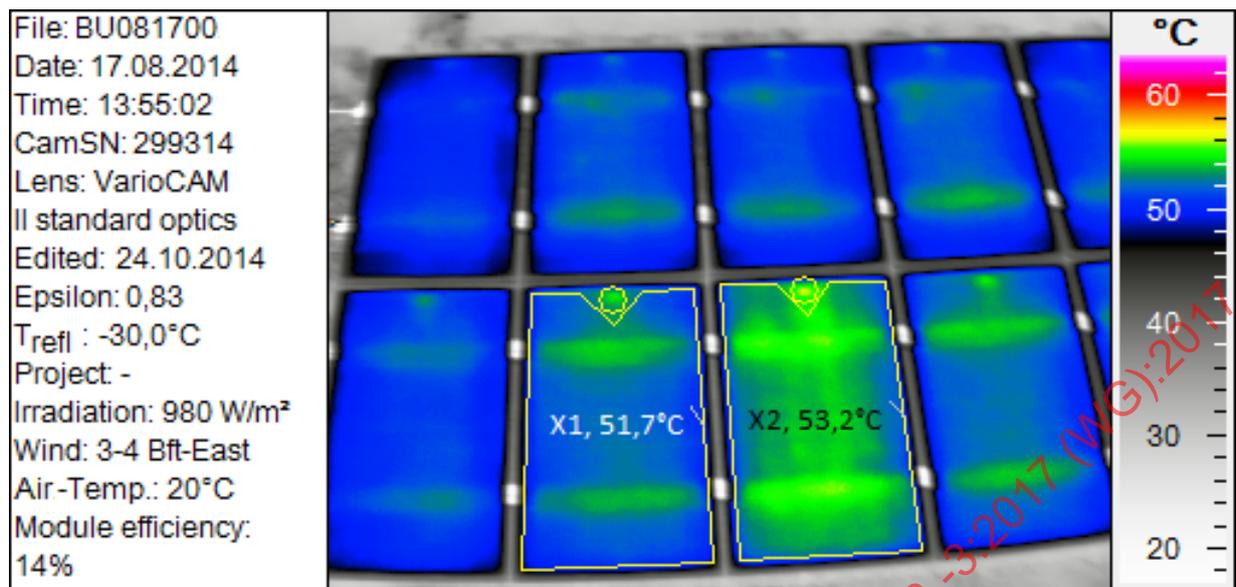
- g) soiling of component (mainly important for PV modules) with photos as evidence,
- h) description of the inspection procedure,
- i) listing of the identified thermal noticeable spots with identification of their position inside the PV plant, using at least 2 of the possible identifications for each item:
 - 1) PV modules:
 - i) serial number,
 - ii) a photograph which shows the position of the module in the array (for small installations only),
 - iii) X-Y coordinates with clear identification of column and row,
 - iv) marking in the system documentation (string or table/roof plan),
 - v) permanent marking of the module on site.
 - 2) Other BOS:
 - i) serial number,
 - ii) marking on a photograph clearly indicating the location within the photo, and clearly identifying the location of the photo,
 - iii) X-Y coordinates with clear identification,
 - iv) marking in the system documentation,
 - v) permanent marking of the component on site,
- j) recommendation for the next periodic inspection, if different from the 4 year cycle,
- k) recommended actions based on classification of the abnormalities,
- l) summary of the results.

For thermal abnormalities within a module, the thermographic image shall show at minimum one whole module, pointing out the position of the junction box and the lower edge within the installation. Additional thermographic images of detailed views may be added for further clarification (See Clause A.3).

The following details shall be given for every thermographic image:

- m) exact description of the object,
- n) file name, date and time of taking the thermographic image,
- o) camera system with serial number and lens,
- p) used emissivity and recorded reflected-temperature (T_{refl}),
- q) exact description of the location in the PV plant, which allows the customer the clear identification of the abnormality,
- r) in case immediate action is required (see 7.3), a photo with sufficient resolution to visually distinguish the details in the thermographic image shall be provided,
- s) for detailed inspections, temperatures (T_{atm} , objects) or temperature difference at the thermal abnormality, preferably in comparison to the temperature of an regular spot,
- t) conclusions and recommendations for further actions.

An example including a polygon evaluation is given in Figure 6. The details may be recorded within the image file itself, or separately.

**Key**

right: color scheme of temperature, center: IR image, left: image information like file name, date, time, used equipment with setting, ambient conditions like T_{refl} , T_{atm} , irradiance, wind speed and project information such as module efficiency

Figure 6 – Example of image reporting

Annex A (normative)

Inspection procedure explanations

A.1 Geometric resolution of the camera

All PV modules, including those observed at the most unfavourable angle of 30°, shall be recorded with a minimum resolution of 5 x 5 pixels per cell. In the case of thin film based modules, in case a deviation is required, it should be discussed with the client prior to imaging and shall be noted in the report. Figure A.1 shows examples for geometric resolution with different distances and fixed IFOV on a 6" cell.

$$\text{Length of pixel on edge of PV module} = \text{IFOV} \cdot \text{Distance to PV module}$$

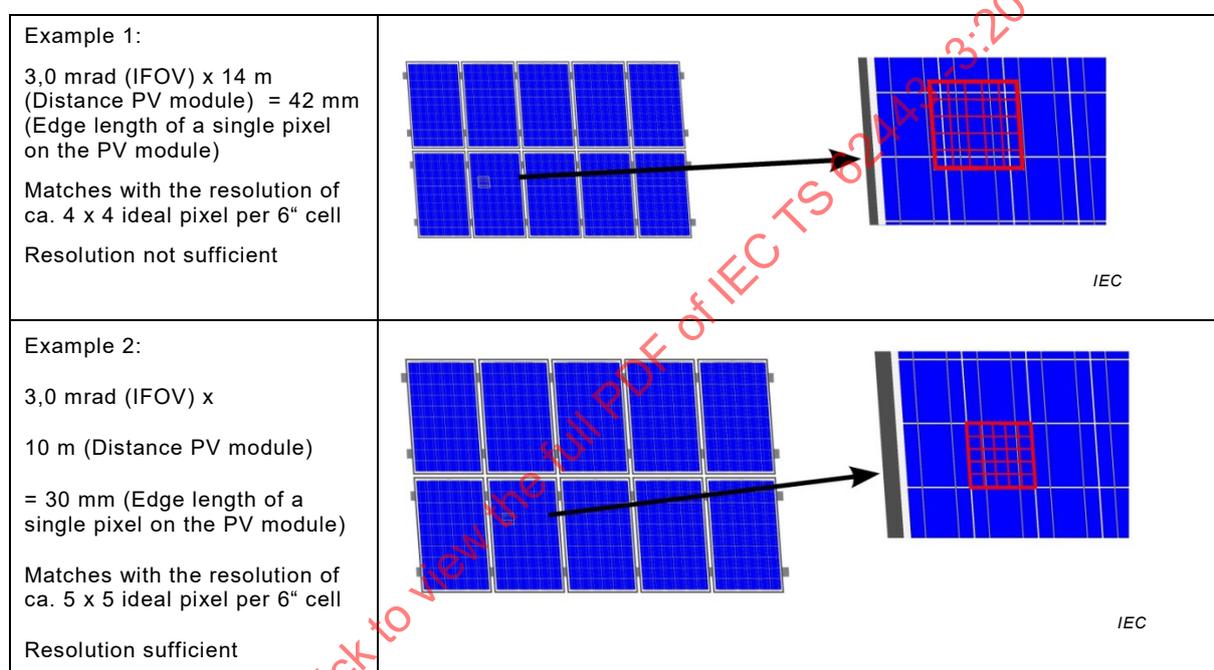


Figure A.1 – Geometric resolution of the IR camera

A.2 Angle of view

The angle of view is the angle between the module surface and the IR-camera. Ideally it is 90°. Figure A.2 explains the angle of view with $\alpha, \beta > 30^\circ$, measured starting from the module surface. The minimum angle of view of 30° should be respected to minimize effects of reflected background.

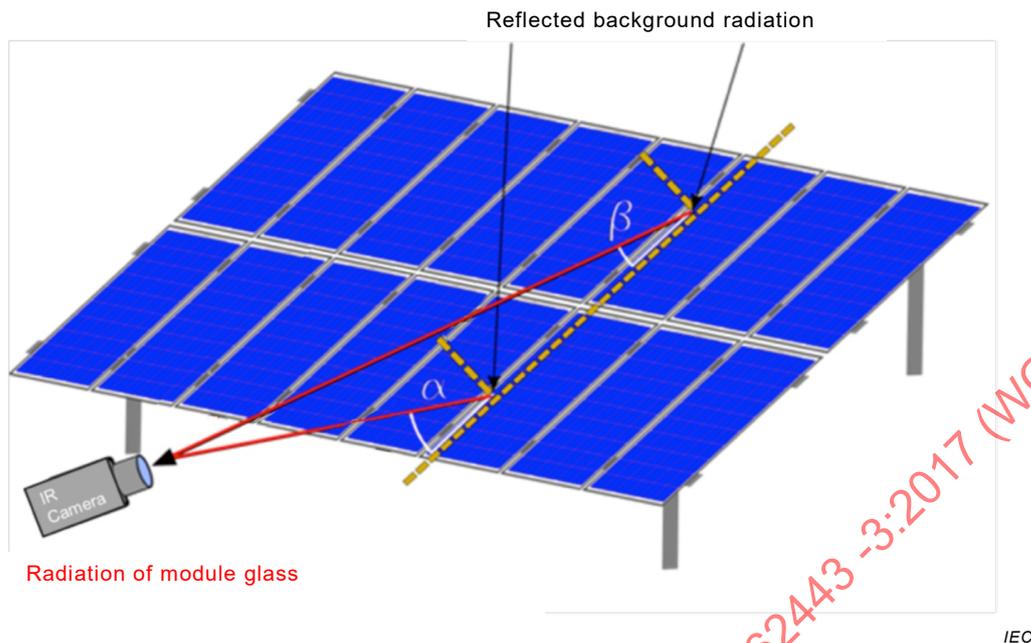
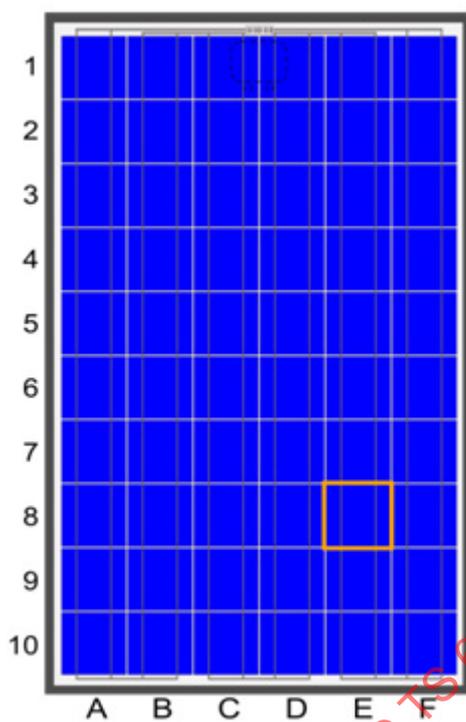


Figure A.2 – Angle of view

A.3 Matrix for cell identification

It is recommended to indicate the cells of a single module according to the following matrix. The module junction box is on top and the module is shown from the front side. An alternative if the junction box is not a clear indicator: in-laminate serial number or name plate position. In Figure A.3 the marked cell is E/8.

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Figure A.3 – View for the designation of cell position, viewed from the front of a 60-cell module, with the junction box at the top (rear side)

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Annex B (normative)

Qualification of personnel

The testing personnel shall have sufficient knowledge in electrical installations, PV plants and also thermography including the analysis of the thermographic findings in electrical systems, in particular:

- a) sufficient knowledge to be able to work in electrical installations has to be proven,
- b) sufficient knowledge to document PV power plant related findings in accordance to requirements stated in Clause 5 and to relevant standards (e.g. IEC 62446 series),
- c) knowledge and skill in electro thermography has to be assured by the proof of a qualification and a certification. A certificate according to ISO 9712 can serve as confirmation.

For the simplified thermographic inspection during the commissioning of a PV plant, the technician shall have the knowledge of the basic functionality of a PV plant. Furthermore, sufficient knowledge regarding the thermographic measurements shall be present. It is recommended that an education, like a level 1 certification according to ISO 9712, or equivalent should be proven.

Access to the electrical installation, like opening enclosures with access to electrically live parts shall be restricted to electrically qualified persons.

Only in the case that the personnel has appropriate knowledge of the functionality of a PV plant, a two days training session of the basics of thermography and the thermographic characteristics of PV plants will be adequate for the commissioning of the PV system. Training on the IR camera, provided by the manufacturer, is not sufficient.

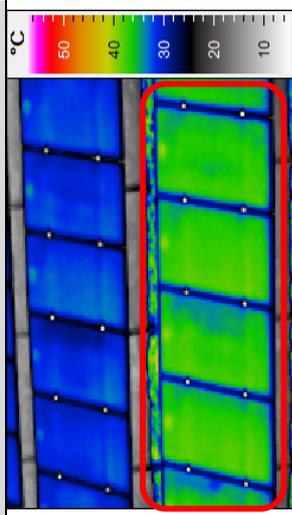
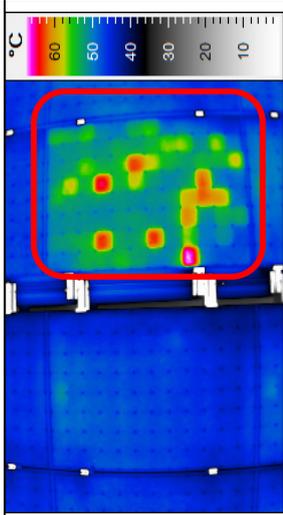
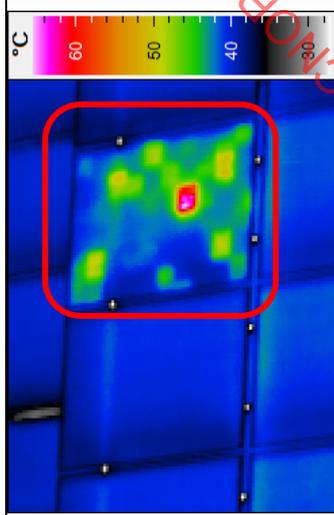
For the detailed thermographic inspection, the authorized expert for PV plants shall have in-depth understanding of the PV system, related failure modes, and thermographic imaging. The thermographic expert should have a qualification equal to level 2 electro thermography according to ISO 9712, and minimum shall have level 1 certification.

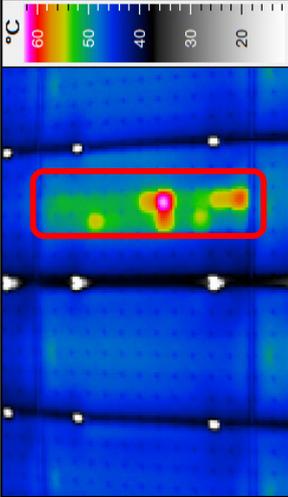
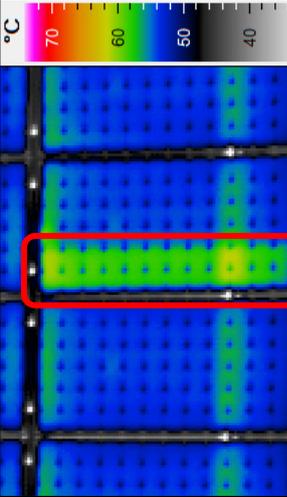
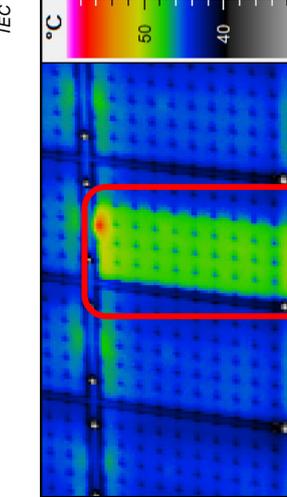
In case the purpose of the planned inspection of the system is the prevention of fire hazards, the testing personnel should be independent (no personnel of the owner or operator).

The proof of eyesight may be done non-recurring according to ISO 9712.

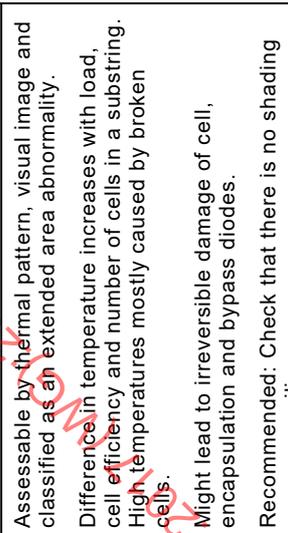
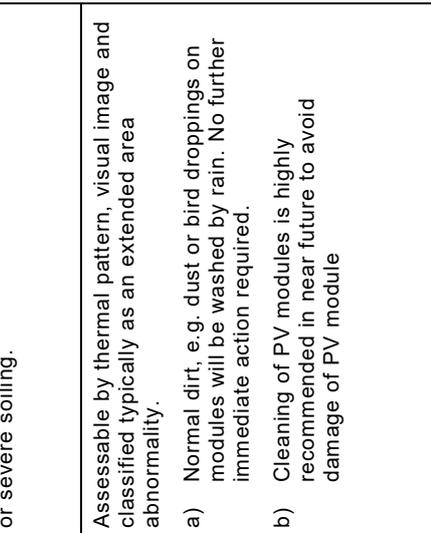
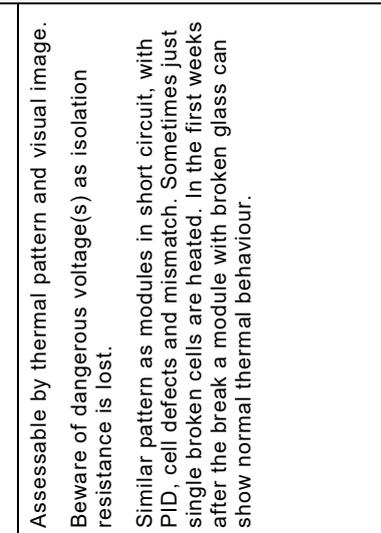
Annex C
(normative)

Matrix for thermal abnormalities of PV modules

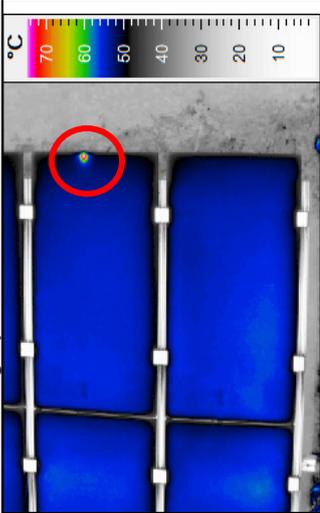
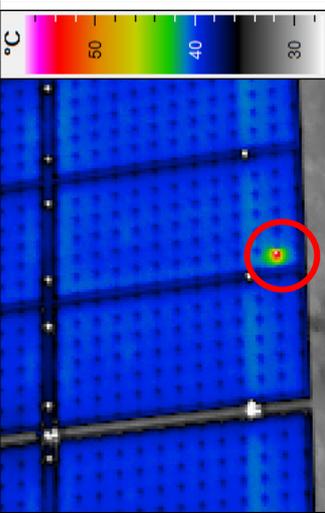
Example 1 – 3: Strings and modules	Category	CoA	Temperature difference to normal operating device at 1 000 W/m ² (ΔT_2)	Thermal pattern, definition and additional information of abnormality
	<p>Modules in open circuit (crystalline Si and thin film)</p>	2	<p>2 K to 7 K (at 15 % module- efficiency typically 4 K to 6 K)</p>	<p>Assessable by thermal pattern and classified as a extended area abnormality. The module surface is homogeneously heated. ΔT of the junction box is similar to operational state. Recommended: check module, state of operation of inverter, and condition of cabling, connectors, and fuses.</p>
	<p>Module in short circuit (crystalline Si)</p>	2	<p>Averaged 2 K to 7 K over module surface (at 15 % module- efficiency typically 4 K to 6 K)</p>	<p>Assessable by thermal pattern, visual image and classified as a extended area abnormality. Similar pattern as with broken front glass (check isolation resistance), PID, cell defects and mismatch. Recommended: check module and cabling.</p>
	<p>Crystalline Si module with broken front glass (crystalline Si)</p>	3	<p>Averaged 0 K – 7 K over module surface (at 15 % module- efficiency typically 0 K – 6 K)</p>	<p>Assessable by thermal pattern and visual image. Beware of high voltage as isolation resistance is lost. Similar pattern as modules in short circuit, with PID, cell defects and mismatch. Sometimes just single broken cells are heated. In the first weeks after the breakage, a module with broken glass can show almost normal thermal behaviour.</p>

Example 4 – 6: Substrings within module	Category	CoA	Temperature difference to normal operating device at 1 000 W/m ² (ΔT_2)	Thermal pattern, definition and additional information of abnormality
	Substring in short circuit (crystalline Si)	2	Averaged 2 K to 7 K higher than substring (at 15 % module- efficiency typically 4 K to 6 K)	Assessable by thermal pattern and classified as a extended area abnormality. At one or more substrings, easily mistaken for cell breakage or cell defects, Potential induced degradation (PID) or mismatch. Recommended: check module and bypass diodes for proper function under reverse biasing.
	1x substring in open circuit, loss of connection within module junction box or cell connector (crystalline Si and thin film)	2-3	2 K to 7 K (at 15 % module- efficiency typically 4 K to 6 K)	Assessable by thermal pattern and classified as a extended area abnormality. Part of the module surface is homogeneously heated up and heat dissipation by the bypass diode, which is operating, is visible. Temperature difference of the glass on top of the junction box containing the operating bypass diode differs with construction. Loss of contact at a cell connection might lead to a serial arc visible on the module backside surface=> CoA: 3.
	2x substrings in open circuit, loss of connections within module junction box (crystalline Si and thin film)	2-3	2 K to 7 K (at 15 % module- efficiency typically 4 K to 6 K)	Assessable by thermal pattern and classified as a extended area abnormality. Part of the module surface is homogeneously heated up and heat dissipation by the bypass diodes, that are operating, is visible. Temperature difference of the glass on top of the junction box differs with construction. Loss of contact at a cell connection (or failure of a bypass diode) might lead to a serial arc visible on the module backside surface=> CoA: 3.

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Example 7 – 9: Local abnormalities	Category	CoA	Temperature difference to normal operating device at 1 000 W/m ² (ΔT_2)	Thermal pattern, definition and additional information of abnormality
	<p>Single cell with difference in temperature (crystalline Si)</p>	<p>a) 2 b) 3</p>	<p>a) 10 K – 40 K average value over the cell area b) > 40 K average value over the cell area</p>	<p>Assessable by thermal pattern, visual image and classified as an extended area abnormality. Difference in temperature increases with load, cell efficiency and number of cells in a substring. High temperatures mostly caused by broken cells. Might lead to irreversible damage of cell, encapsulation and bypass diodes. Recommended: Check that there is no shading or severe soiling.</p>
	<p>Module with cells shaded by dirt (crystalline Si and thin film)</p>	<p>a) 1 b) 2</p>	<p>a) if location with lots of rain and ΔT a few K b) if location with basically no rain and $\Delta T > 40$ K</p>	<p>Assessable by thermal pattern, visual image and classified typically as an extended area abnormality. a) Normal dirt, e.g. dust or bird droppings on modules will be washed by rain. No further immediate action required. b) Cleaning of PV modules is highly recommended in near future to avoid damage of PV module</p>
	<p>Thin film module with broken front glass</p>	<p>3</p>	<p>Averaged 0 K – 7 K over module surface (at 10 % module- efficiency typically 0 K – 4 K)</p>	<p>Assessable by thermal pattern and visual image. Beware of dangerous voltage(s) as isolation resistance is lost. Similar pattern as modules in short circuit, with PID, cell defects and mismatch. Sometimes just single broken cells are heated. In the first weeks after the break a module with broken glass can show normal thermal behaviour.</p>

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Example 10 – 12 Local abnormalities; Evaluation only by experienced PV – thermographers	Category	CoA	Temperature difference to normal operating device at 1 000 W/m ² (ΔT_2)	Thermal pattern, definition and additional information of abnormality
	Transfer resistance at cross-connections of a thin film module	2-3	>10 K	Assessable by thermal pattern, visual image and classified as a point abnormality. Difference in temperature increases with load, caused by increased contact resistance e.g. due to bad soldering. Personal review by a PV expert or thermographer level 2 or equivalent is recommended.
	Transfer resistance at cell connections of a crystalline Si module	2-3	>10 K	Assessable by thermal pattern, visual image and classified typically as a point abnormality. Difference in temperature increases with load, caused by increased contact resistance e.g. due to bad or no soldering. Could also be caused by a broken ribbon or a missed solder point between ribbon and cross connector. Personal review by a PV expert or thermographer level 2 or equivalent is recommended.
	Heated module junction box (crystalline Si and thin film)	2-3	≥ 3 K higher temperature compared to nearby junction box	Assessable by thermal pattern, visual image and classified typically as a point abnormality. Temperature difference increases with load caused by increased contact resistance within the junction box. Alternatively it could be caused by low resistive bypass diodes that carry a significant current although they should be biased in reverse direction. Personal review by a PV expert or thermographer level 2 or equivalent is recommended. Be aware of high voltages.

Source: HaWe Engineering GmbH.