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Edition 1.0 2018-08

TECHNICAL SPECIFICATION

colour inside

Photovoltaic devices –
Part 13: Electroluminescence of photovoltaic modules

IEC TS 60904-13:2018-08(en)

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COMMISSION

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FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

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

IEC TS 60904-13, 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
82/1292/DTS	82/1424/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 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,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

PHOTOVOLTAIC DEVICES –

Part 13: Electroluminescence of photovoltaic modules

1 Scope

This part of IEC 60904 specifies methods to:

a) capture electroluminescence images of photovoltaic modules,

b) process images to obtain metrics about the images taken in quantitative terms, and

c) provide guidance to qualitatively interpret the images for features in the image that are observed.

This document is applicable to PV modules measured with a power supply that places the cells in the modules in forward bias.

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 TS 61836:2016, *Solar photovoltaic energy systems – Terms, definitions and symbols*

3 Terms and definitions

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

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

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

3.1
electroluminescence
EL
emission of optical radiation resulting from the application of electrical energy

3.2
open circuit
electrical circuit that has a break, or “open”, somewhere in the conductive path

Note 1 to entry: A module or laminate exhibits an “open circuit” if defective or damaged so that no current can flow through it when attached to an external circuit at the module electrical connection points.

Note 2 to entry: A PV module itself is in open circuit condition if one or both of the module electrical connection points are not connected to anything or current is not flowing as defined in IEC TS 61836:2016, 3.4.57.

3.3
forward bias
forcing current flow with a power supply where the leads are connected to those of the same polarity (+ and -) on the sample

3.4
barrel distortion
distortion in the image whereby rectangular features in an image appear expanded, as in a curved barrel wall

3.5
vignetting
reduction of an image's brightness at the periphery compared to the image center

4 Imaging

4.1 Apparatus

4.1.1 Electroluminescence imaging camera

4.1.1.1 Camera detector

Detectors are typically light-sensing pixels consisting of charge coupled devices (CCD) or complementary metal oxide semiconductor (CMOS) devices arranged in a focal-plane array. They may be cooled, usually with thermoelectric cooling, to achieve better signal-to-noise ratio by means of reducing device dark current originating from thermally generated charges. Semiconductor light absorber materials in the detector shall be sensitive to the EL emission of the device under test. Example semiconductor light absorber materials and their useful wavelengths of detection for PV module characterization are given in Table 1. The spectral response for some semiconductor detectors is given in Figure 1. The typical emission spectrum for Si, ZnO/CdS/Cu(In,Ga)Se_2 (CIGS) and CdS/CdTe heterostructure solar cells are given in Figure 2. The signal strength obtained during EL measurements will be proportional to the product of the spectral response and the emission. For a given EL signal from a sample, a greater spectral response at the wavelength of interest will typically permit a shorter exposure time. Spectral response of Si detectors to Si cell PV module EL emission is relatively low. Commercial Si detectors frequently offer the best resolution, but spectral response of silicon detectors is typically compromised as a result.

Table 1 – Detectors and their applicable wavelengths

Detector	Sensitive wavelengths µm
Ge	0,8 to 1,7
InGaAs	0,7 to 2,6
Si	0,3 to 1,1
InAs	1,0 to 3,8

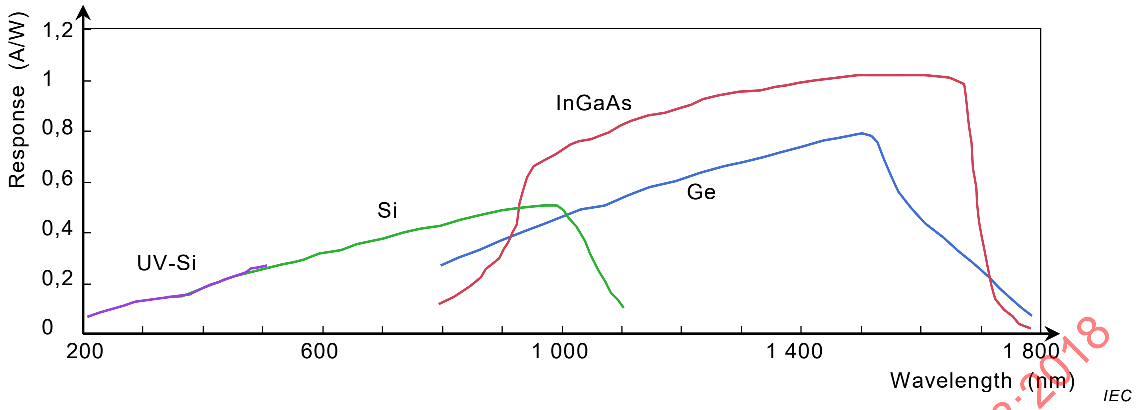


Figure 1 – Various semiconductor detector materials and their absolute spectral response [1][1]

Relevant parameters in choosing detectors include number of pixels, noise, quantum efficiency at the wavelength of interest, and dynamic range. This document contains provisions for various image resolutions. Choice of camera to obtain images that meet the sharpness classes given subsequently in 4.2.3 is made with respect to its imaging sensor and lens, with consideration to working distance (WD) and field of view (FOV). Theoretically, camera sensor resolution translates one-to-one with the image resolution. The resolution of an image in one of the dimensions (length or width) of an orthogonal array of pixels is the number of pixels in the image in that dimension.

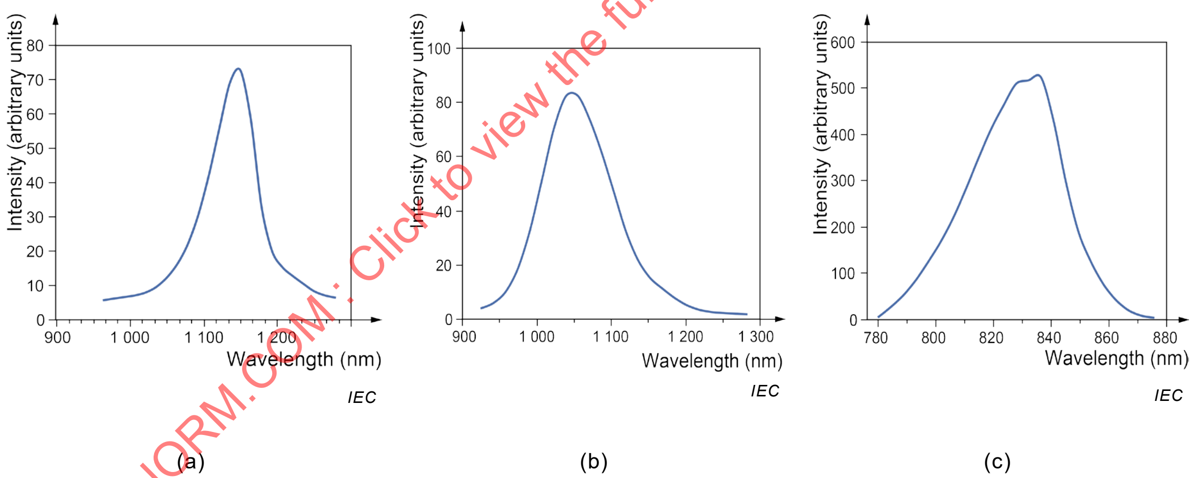


Figure 2 – Electroluminescence emission spectra for (a) Si, (b) ZnO/CdS/Cu(In,Ga)Se_2 (CIGS) [2], and (c) CdS/CdTe [3]

Sensor resolution = Image resolution = FOV/smallest image feature

For example, if it is desired to image features of 2,5 mm onto a pixel and the length of the module to be imaged (corresponding to the FOV) is 1 600 mm, the sensor resolution (in pixels) required in this dimension is 640. This example implies the camera being in focus and neglects image sharpness considerations (see 4.2.3).

1 Numbers in square brackets refer to the Bibliography.

The camera response function (CRF) relates the actual quantity of light impinging on each element of the sensor array to the pixel values that the camera outputs. When the same object is captured at different exposure times but with an otherwise identical camera setup, a non-linear CRF causes the resulting image intensity distribution to exhibit nonlinearity, even after application of a correction for exposure time. Therefore, when analyzing image intensities, either the linearity of the CRF needs to be assured (basic methods are commonly found in the camera literature), or a correction for non-linearity needs to be performed using image processing. Scientific grade Si or InGaAs-based sensors are often linear or have a correction for non-linearity embedded. Neglecting non-linearity will cause erroneous results when applying procedures for image correction that are given in Annex A or any quantitative analysis.

To obtain maximum image resolution and electroluminescence signal, the optical axis of the camera is placed perpendicularly and as close as possible to the module face to image the solar cell or module area. Images captured at the highest resolution may require a longer exposure time and time to transfer from the camera and process. Binning features may exist to combine pixels for lower resolution and shorter image processing times. Gain feature may exist to amplify the signal of the EL image.

4.1.1.2 Lens

Lenses shall be free of absorption filters or coatings that remove the infrared near the band-gap of the semiconductor material to be examined. Optical glass is generally suitable, however Ge lenses will be necessary for measuring EL from the very low band gap materials (under 0,6 eV). Lenses vary from telephoto to wide-angle in focal length. Choice will depend on the specific application and geometric considerations when capturing the image. Wide-angle lenses that have short focal lengths used in conjunction with the higher resolution cameras capture a larger FOV. The camera may be placed much closer to the subject, which is useful when space is constrained. Some wide-angle lens optics however cause undesirable barrel distortion in the images that will require correction by post-processing. Lenses with longer focal lengths generally have less barrel distortion and can therefore more accurately image a module, whereby the resulting images may require little or no correction by post processing. Lenses may feature components that correct for the difference between visible and infrared wavelengths, which can aid in focusing.

Lenses typically have an aperture with the size referred to by a f-number. Ignoring differences in light transmission efficiency, a lens set to a greater f-number has less light gathering area and projects less electroluminescence signal to the image sensor. Depth of field increases with increasing f-number. Image sharpness is related to f-number through two different optical effects; aberration, due to imperfect lens design, and diffraction, which is due to the wave nature of light. Many wide-angle lenses will result in significant vignetting at the edges of the image when using a smaller f-number.

4.1.1.3 Filters

Filters on the camera lens may be used to help cut light of extraneous wavelengths from being detected. 850 nm to 950 nm long-pass filters may be used when imaging near band-edge EL from modules with silicon cells.

4.1.2 Dark room imaging studio or environment

A darkened environment is favored for high quality images. Precautions should be taken to eliminate stray light entering the imaging studio, such as with use of hard walls, curtains, baffles, and sealing of any gaps with material that are of light absorbing nature (black). If a filter is used on the camera, then LED lighting may be used that emits light only in the spectrum that is cut by the filter. For non-laboratory measurements, minimize extraneous light when possible. For example, perform measurements at night. If stray light is present, an image subtraction procedure will be required, as discussed in 4.1.5.2.

Fixed mounting of the camera and a mount for the module(s) to be imaged are required so that the camera and the module positions are absolutely stable.

Laboratory measurements, for consistency in achieving qualitative or quantitative comparisons, should be performed with the module maintained between 20 °C to 30 °C. Temperature should be obtained with a temperature sensor accurate to within 1 °C placed on the module rear (the side not being imaged) and installed in a manner that does not interfere with the imaging. It may however be necessary to obtain EL images with the module at temperatures outside of the prescribed range to evaluate the effect of temperature or when it is not possible to maintain the module temperature within the prescribed range. For such measurements, the module temperature shall be noted and indicated as being performed “outside of the standard testing condition” (See Clause 6). The final temperature, measured within 15 s of the end of the image capture, shall be recorded for module temperature reporting requirements.

For highly accurate work, the module temperature may be stabilized by passing current until the temperature reaches equilibrium. The comparison of two images taken in sequence may be performed to see if both the module temperature and the camera detector (also affected by temperature) is stable by employing image histograms defined in Clause 5.3.8 and Formula C.1. The module may be considered stabilized if the absolute difference of the image intensity histogram of sequentially captured images is below 0,02 in each bin, where for this analysis, each bin width is 5 % of the EL intensity range captured from the module area (not including the background, area with no cells, or defective pixels).

For repeated measurements on a single module type under condition where the room temperature is maintained within a range of 5 °C, the module stabilization time may be determined by passing current until the temperature reaches equilibrium. EL imaging shall commence after thermal stabilization, and the module temperature shall be recorded. The waiting time required for the module to thermally stabilize shall be validated on at least one module of the same type, after which stabilization may be based on waiting time (and not direct temperature measurement) for future measurements of the module type. Images with the module temperature outside of the range of 20 °C and 30 °C shall be noted as being performed “outside of the standard testing condition.”

NOTE 1 EL images obtained at different temperatures, including within the range of 20 °C and 30 °C, lead to different visibility of defects, such as those due to shunting and partially disconnected regions of broken cells because of thermal coefficient of expansion mismatches.

NOTE 2 Due to factors including module positioning and poor connections in the cell (e.g. cracks), grid fingers and interconnects, some EL signal may change, even when measurements are repeated at the same temperature.

4.1.3 Power supply

An electric DC power supply capable of applying I_{SC} of the module or a series string of cells or modules to be imaged is required. The power supply shall be able to provide sufficient voltage to achieve I_{SC}. Depending on the module technology, the required voltage may be approximately equal to the open circuit voltage V_{OC} of the module, but it may be significantly higher for some PV modules, such as those based on thin-film technology.

Measuring voltage during application of DC current through the module for EL imaging gives additional information about the condition of the module including the existence of shunt resistance reduction (lower voltage is measured), series resistance (higher voltage is measured), and correct connection to the module, but its measurement is optional. For accurate voltage measurement reporting, cabling from the module leads shall be of sufficient gauge to maintain less than 2 % voltage drop over the leads, or alternatively, a four-wire configuration shall be used to separately supply current and measure voltage at the connectors of the module(s) under test.

4.1.4 Computer interface with camera and power supply for image capture

Computer control of the power supply and camera so that pre-programmed currents can be quickly applied and coordinated with image capture are optional equipment that will provide speed and improve accuracy of the imaging of module EL. Further if the image and its capture settings are programmatically transferred into a file on the computer, it can aid in automatically recording image parameters for reporting requirements described in Clause 6.

4.1.5 Image processing and displaying software

4.1.5.1 Assignment of image colours

The image is transferred electronically from the camera to a computer for saving and maintaining in raw image format for subsequent display and image post-processing. Computer software should load EL image files, assign colours or a grey scale to each signal level measured within the PV module and any regions of interest. In the case of a colour image, a legend to indicate the meaning of the colours or levels shall be provided. Lowest EL signal shall be represented by black and the highest EL signal in the image should be represented by white; however, the image data of the active cell area shall not exist in the upper extreme to avoid detector saturation except where unavoidable (see 4.2.2.3). The colours in the scale between these extremes are not defined herein, but there should be no possibility of misinterpretation by re-use of similar colours to represent multiple signal levels or by the highlighting of areas where there are in fact no features; i.e., the number of colors should be minimized.

4.1.5.2 Software capabilities

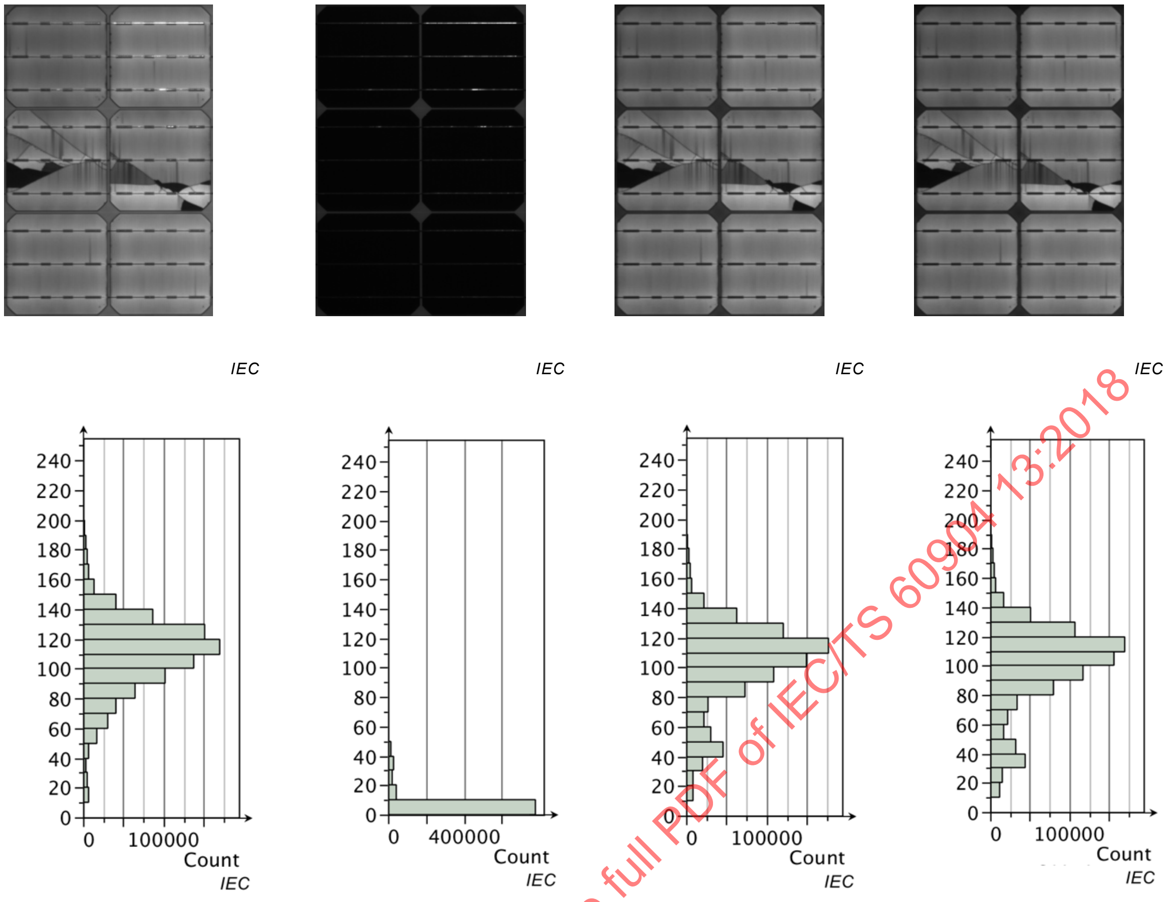
Software should produce histograms in counts versus EL signal level bin to quantitatively interpret the images for features that are observed.

Basic software features that will be helpful, depending on the nature of the original image, for post-processing of images in the application of this document include:

- Level range adjustment
- Cropping the image to the region of interest
- Determination of EL signal level at any given point on the image
- Frame subtraction: Uniform subtraction of noise signal including from dark current or stray light, such as by subtracting the signal when the module is unpowered. An example of results from this procedure is given and explained in Figure 3. This may be performed with image processing software or in signal processing software, including with pulses of forward bias current applied cyclically.
- Dead pixel removal
- Single time effects removal
- Dark current variations (variation in CCD sensitivity and offset)
- Barrel distortion
- Vignetting

Fundamentals of image processing may be found in published literature. [4] [5]

When programming for operations on images involving matrix calculations (e.g., signal-to-noise ratio calculations, vignetting corrections), cast the data to double-precision floating point variables to prevent numerical errors. For saving images after performing calculations, image files may be reconverted to their original bit depth.



a) Image of powered module with stray light

b) Image of unpowered module with stray light

c) pixel-by-pixel subtraction of Figures 3a) -3b)

d) Image of module in ideal dark room with same camera settings as a) and b)

Figure 3 – Example of frame subtraction given in Figure 3a) to Figure 3c), with images taken in ideal dark room conditions given in Figure 3d)

Under stray light, areas where the pixels become saturated shall be discarded. The exposure duration is preferably limited such that the pixels do not approach saturation. Image quality for subtraction of stray light purposes is significantly improved with cameras having greater dynamic range. The noise level is however greater in the case of images taken with stray light after frame subtraction than images taken without stray light.

4.1.6 Safety and handling

EL imaging of photovoltaic modules with insulated cables and connectors (as is recommended) does not generally involve risk of exposure to live electrical wiring hazards, however any electrical safety protocols should be taken according to the specific circumstances.

Handle PV modules and laminates with care when moving them into position for imaging as to not cause damage that will introduce new features or artifacts in the module image.

4.2 Procedure

4.2.1 Camera settings and positioning

4.2.1.1 Calibration

The camera should be in calibration according to any procedures specified by the manufacturer. Time and date should be properly entered in the camera or image recording computer if the functionality exists so that images may be later related to the time and date captured.

4.2.1.2 Angle from normal of module plane

Angle of view relative to surface is preferably normal with respect to the module surface to be imaged. The maximum angle of view from module normal should be less than 50°. Emissivity adjustment for angle is required if it is greater than 50°.

The principal light facing side of the module is imaged. However, it may be advantageous to image bifacial modules from the opposite side as well.

4.2.2 Camera settings

4.2.2.1 General practice

For routine measurements, the image intensity for the camera at each forward bias current level may be optimized by adjusting the total exposure time, aperture *f*-number), or by gain adjustment after a survey of modules of the type to be examined is made, and then kept consistent. If changes need to be made to achieve the desired image intensity, exposure time shall be adjusted and the change recorded. See 4.2.2.3 for guidelines regarding image intensity.

4.2.2.2 Recommended camera settings (focus, gain *f*-number)

A first, rough focus, may be performed by viewing in the visible light regime, but fine focus shall be optimized to the wavelength of the EL signal to be imaged. This can be simplified by using IR-corrected lenses. In this case the focus setting is the same for the EL and visible images. Focus shall be sufficient to resolve the features according to the desired level of sharpness defined in 4.2.3. An algorithm is given in Annex B that may be used for computing the optimum lens focus position.

Other recommended settings are as follows:

Gain setting shall be set to obtain optimum pixel depth resolution of module to be imaged.

f-number shall not be changed between images to be compared. If an adjustable *f*-number is available, choose the lowest *f*-number by default when imaging samples that are centered in front of the camera with the optical axis passing through the center of the module. A different *f*-number may be selected and fixed if it is deemed to produce optimized results, such as to decrease vignetting, increase sharpness, and increase the depth of field for imaging with an oblique view of the module face.

4.2.2.3 Image intensity

Optimized images will have less than 5 % area around the perimeter of the module not producing luminescence. The exposure shall be optimized (increased) to achieve maximum signal to noise ratio, but limited such that pixels in the image are not saturated. Single time effects and random noise are not counted in this analysis of pixel saturation.

4.2.2.4 Comparisons of modules

Various module types and degradation processes may show differing EL behavior. For easy comparison of a degraded module to an undegraded module, image the degraded module at the original condition and optionally, with settings reoptimized for the degraded condition. Only the exposure time may be used for the readjustment when comparing undegraded and degraded modules in this way. The current shall not be changed. Perform any required image frame subtraction (4.1.5.2) before additional post processing. When visual comparison is desired for modules imaged with different exposure times, the intensities of the pixel may be scaled in post-processing by inversely scaling the pixel intensities by the exposure time and the modified image labeled as such. The brightest image intensity in such comparisons shall be set according to 4.2.2.3.

4.2.3 Sharpness determination and classification

4.2.3.1 General

The sharpness (S [mm]) is used as the index of the resolvable object size in the image obtained by a camera, its settings, and the WD. It is the minimum real dimension that still provides a contrast of 50 %. Sharpness is dependent on the pixel dimension, the linear distance on the module sampled by a pixel, and it includes the effects of image blurriness. A method for determining and classifying image sharpness is defined here. Comparisons for quality of module(s) shall be made between images of similar sharpness classes.

4.2.3.2 Sharpness measurement

The hereinafter described 'V-cut' measurement involves calculation of the intersection angle α and distance r_{50} from two edge lines L_1, L_2 created by an opaque mask on top of the luminescent surface. To convert pixels into mm, which will be necessary to obtain the value of r_{50}, a conversion factor between millimeters of length on the module and pixels in the image shall be obtained. It can be obtained from an object of known dimension in the image such as a cell or the module. The formulas needed for the sharpness determination are detailed in Formula (1) through Formula (3).

NOTE This method is a modified version of the spoke target, also known as the Siemens star and sector star target, based on a pair of lines (black-white-black group). Here it is modified such that only the bright field is examined.

Two edges are created on an EL image of a monocrystalline silicon PV module. This can be achieved with thin metal plates or opaque (e.g. aluminum film) tape over the luminescing region as illustrated in Figure 4. The angle α between both edge lines should be between 3° and 6°. For an example edge length of 10 cm, this corresponds to a distance of about 0,5 cm to 1,0 cm between both edges at the open end. The edge lines run through the local maxima of an edge gradient image G_{Edge} (Figure 5). The Sobel operator discussed in Annex B may be used to determine G_{Edge}, though the Find Edges function in the public domain software ImageJ, or simple linear derivatives may also be used. The middle line L_2 goes from intersection p_0 of L_1 and L_3 to point p_2, in the middle of p_1 and p_3. From all plotted EL image intensity values along L_2, the distance r_{50} is measured from p_0 to that point on L_2 where the image intensity equals the mean between the dark and bright EL intensity plateau $(EL_{\text{low}}, EL_{\text{high}})$ as in the example in Figure 6. The line lengths between points p_0 and p_1, for example, are indicated by $\overline{p_0p_1}$ in Formula (2).

To reduce the measurement uncertainty, this measurement shall be repeated at least five times at different rotation angles and device positions. Finally, S shall be calculated from the median of all individual results, where the angle α is in radians and the length r_{50}, mm on the module surface.

$$S = 1{,}35 \cdot \alpha \cdot r_{50} \qquad (1)$$

$$\alpha = \arccos\left(\frac{\overline{p_0p_1}^2 + \overline{p_0p_3}^2 - \overline{p_1p_3}^2}{2 \cdot \overline{p_0p_1} \cdot \overline{p_0p_3}}\right) \qquad (2)$$

$$G_{Edge} = \sqrt{G_x^2 + G_y^2} \qquad (3)$$

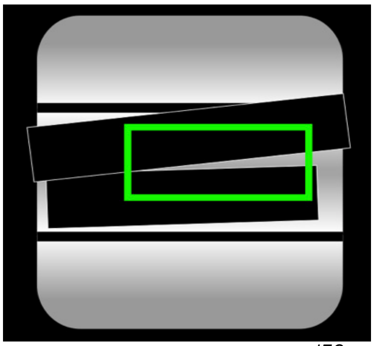


Figure 4 – EL image with introduced two edges using aluminum tape

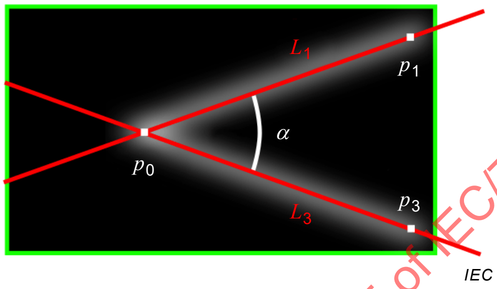


Figure 5 – Edge gradient image G_{Edge} from the Figure 4 EL image's first derivative in orthogonal direction $G_{x,y}$

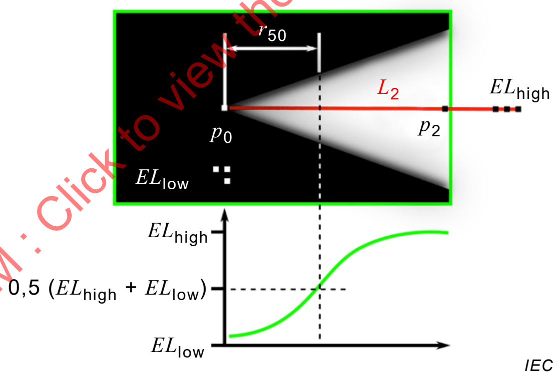


Figure 6 – Excerpt of the EL image of Figure 4 and plot of image intensity values along line L_2

4.2.3.3 Sharpness classes

Three sharpness classes for intercomparing EL images are defined for application in practice as follows, with S:

a) less than or equal to 1,5 mm,

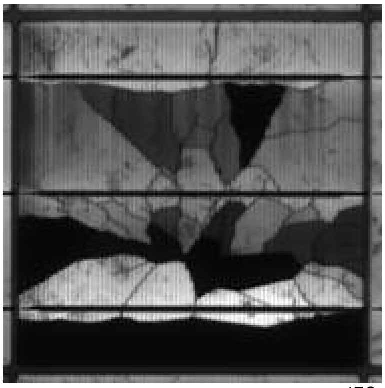
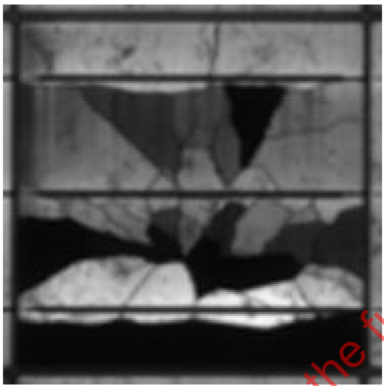
b) less than or equal to 5,0 mm,

c) and less than or equal to 15,0 mm.

4.2.3.4 Examples of images in sharpness classes

Examples of the sharpness classes are given in Table 2. In images of PV modules, the sharpness may be limited by the diffusion length of the semiconductor material in the cells of the module under test.

Table 2 – Sharpness classes, examples of images meeting the criteria of the classes, and examples of distinguishable features

Sharpness class	Image example	Examples of distinguishable features
a) Less than 1,5 mm	 IEC	Grid fingers (depending on finger width) Crack structure clearly distinguishable
b) Less than 5,0 mm	 IEC	Effects of disconnected grid fingers Type A and B cracks
c) Less than 15,0 mm	 IEC	Busbars Isolated regions Type C cracks Areas of reduced lifetime
See Annex C for definitions of crack types A, B, and C.		

4.2.4 Imaging

4.2.4.1 Preparation and setup – General

If the module may be moved, place it securely in position for imaging. Modules may be imaged on the front (normally sun-facing side). Bifacial modules may additionally be imaged from the rear.

Make all necessary preparations according to 4.2.2 above, including preparations for camera settings, focusing, angle, image framing and where possible, a darkened environment.

4.2.4.2 Electrical connection

Connect the (+) and (-) electrical leads from the DC power supply to the sample, matching the (+) lead of the power supply with the (+) of the sample. Ties or tape may be used to attach the leads so that they minimize interference with the camera's view of the sample.

4.2.4.3 Biasing and imaging

Imaging is taken at two bias currents sequentially for maximum information retrieval, followed by an image with module disconnected, (i.e. a background image) for the case when frame subtraction will be performed (4.1.5.2).

- I_{sc}
- $0,1 \times I_{sc}$
- $0 \times I_{sc}$ – background images

Exposure time may be optimized according to 4.2.2.3 for each bias current applied. See 5.2 for interpretation of the images obtained at each of the bias current levels. Apply I_{sc} forward bias to the module; voltage should be applied as necessary, but not to exceed that specified by the module manufacturer for electrical loading of the module or the limits necessary for laboratory safety. Take the EL image and switch off the forward bias current after image capture. Repeat procedure for the $0,1 \times I_{sc}$ (low current) image. Omission of one of the bias current levels shall be listed as a process deviation when reporting the results (See Clause 6). Finally, a background image is taken at the same exposure time as the electroluminescence images when frame subtraction will be performed for the removal of stray light effects. If different exposure times are used, multiple background images have to be taken for all used exposure times.

If there is no current through the circuit, there may be an open circuit within the module in which case alternate procedures or characterization techniques outside of the scope of this document may be necessary. Additionally, some modules such as those intended to be connected in parallel may contain diodes in series that may prevent current flow.

In some modules, series resistance behavior of the module in the dark may require high voltage to achieve the magnitude of I_{sc}. Consult with the module manufacture on any limits for application of voltage. Note any deviations to the bias currents applied from those specified in this Clause and maintain consistency of the applied bias currents for testing of the module type.

Tabulate the module model and serial number, image capture settings which may include pixel binning, gain, aperture, integration time, working distance, and focus setting, image number, currents and voltages, and any comments based on observations about the image during image taking for inclusion in Clause 6.

4.2.5 Image correction

After image acquisition, images are corrected to achieve, characterize, and optimize desired image quality. Image corrections are essential if images will be analyzed quantitatively. These image corrections are:

- frame subtraction
- vignetting correction

Frame subtraction of the background image from the electroluminescence image is performed on pixel-by-pixel basis. Note that the background image has to be taken at exactly the same conditions (including f number, position, exposure time) as discussed in 4.2.4.3.

Procedures for vignetting calibration and correction are given in Annex A.

4.3 Image signal-to-noise ratio

4.3.1 General

Signal-to-noise ratio (SNR) is included in this document because it is an important factor in image quality affecting the ability to distinguish electroluminescent features.

The EL signal is distorted by multiple noise sources: dark current or thermal noise which is caused by the thermal energy of electrons in the camera sensor, photon- or shot noise due to statistical fluctuations in the number of photons emitted from an object and other sources produced by the electronics, like readout noise, amplifier noise and quantization noise. The SNR categorizes the ratio of usable to unusable signal. Its inverse is directly related to the relative uncertainty of pixel brightness.

The SNR is determined using three images of a module type of that to be analyzed for imaging at each current bias level applied according to 4.2.4.3. The images shall be obtained according to the procedure in 4.3.2 and analyzed according to the calculation described in 4.3.3.

SNR class can be obtained from the EL signal of the active area of a reference module (REF) and applied when reporting EL images of other modules captured using a given camera if:

a) the average pixel intensities corresponding to the active area of the other modules are equal to or greater than that of REF, and

b) the gain (or ISO speed setting) of the camera is not changed.

4.3.2 Imaging procedure

a) Place and prepare the module and camera for measurement according to 4.2, in a manner characteristic in every way of the setup that is to be used for the purposes of reporting according to this document. The images obtained for the SNR determination may also be selected for Clause 6 EL image reporting purposes. Background area of the module should be excluded—the image should contain principally the active cell area. Neither the camera nor the module may move during the capture of the images for application of this procedure. If there is slight motion, then manual image translation shall be implemented so that the images align exactly on a pixel-by-pixel basis.

b) Apply forward bias current through the module until the module temperature is in steady state and then sequentially take two EL images, EL_1 and EL_2, at the same forward bias current as to be used for the obtained image for study, where EL is an uncompressed grey scale pixel array. The data type for calculation shall be casted at a minimum of twice the bit resolution of the captured images using floating point, preferably double precision 64-bit floating point, to prevent numerical errors.

NOTE Many common image formats store image intensities using unsigned integers. This ensures low memory usage but can cause integer overflow on arithmetic operations. It is therefore critical to cast images for calculation purposes to a high bit depth, e.g., 64-bit (double precision) floating point variables. Example code which shows the effects of precision on the SNR calculation is given in [6].

c) Take a background image of a module EL_{BG}, where the module is in open circuit using the same camera and imaging parameters.

d) Repeat for each bias current to be imaged.

4.3.3 Analysis

The following ratio of signal to noise is used to determine the SNR, averaged for the imaged scene, SNR_{50}:

$$SNR_{50} = \frac{\sum_k \left(0.5 \cdot \left(EL_1(k) + EL_2(k)\right) - EL_{\mathrm{BG}}(k)\right)}{\sum_k \left(|EL_1(k) - EL_2(k)| \cdot \sqrt{0,5} \cdot \left(\frac{2}{\pi}\right)^{-0.5}\right)} \quad (4)$$

All image operations for images EL_1, EL_2 and EL_{BG} are done pixel by pixel (k) in the corresponding image arrays, and then summed for determination of the ratio. The signal is defined as the average of both EL images, EL_1 and EL_2, reduced by the background image EL_{BG}.

NOTE The noise level is obtained from the average absolute deviation (AAD) of both EL images. The AAD has a higher stability towards outliers and can be scaled to a root mean square deviation (RMS) through the constant $\left(\frac{2}{\pi}\right)^{-0,5}$. Because the noise level is taken considering a noise difference of two images, the factor $\sqrt{0,5}$ scales the sum of variances.

4.3.4 SNR criteria

Guidelines for minimal acceptable SNR depend on the measurement application. These minimum SNR are defined into classes as follows:

a) Laboratory measurements: $SNR_{50} \geq 45$

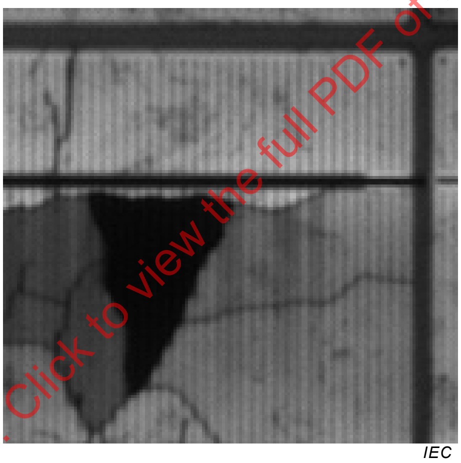
b) Industrial and process control: $SNR_{50} \geq 15$

c) Outdoor measurements: $SNR_{50} \geq 5$

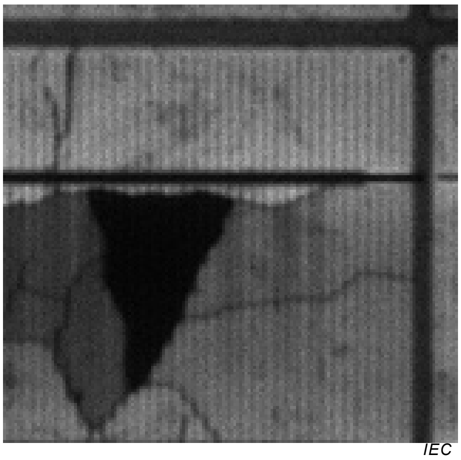
Determined SNR for images obtained in this document shall be reported per Clause 6.

Examples of images at these SNR_{50} thresholds are given in Figure 7.

a) $SNR_{50} = 45$



b) $SNR_{50} = 15$



c) SNR_{50} = 5

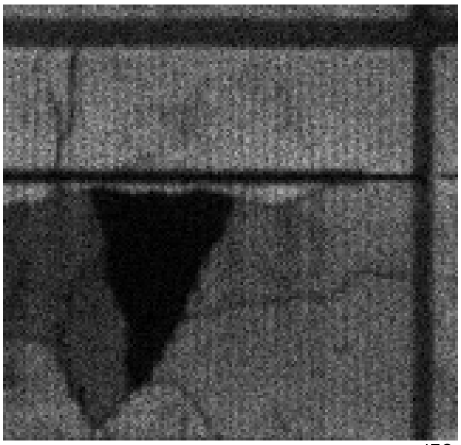
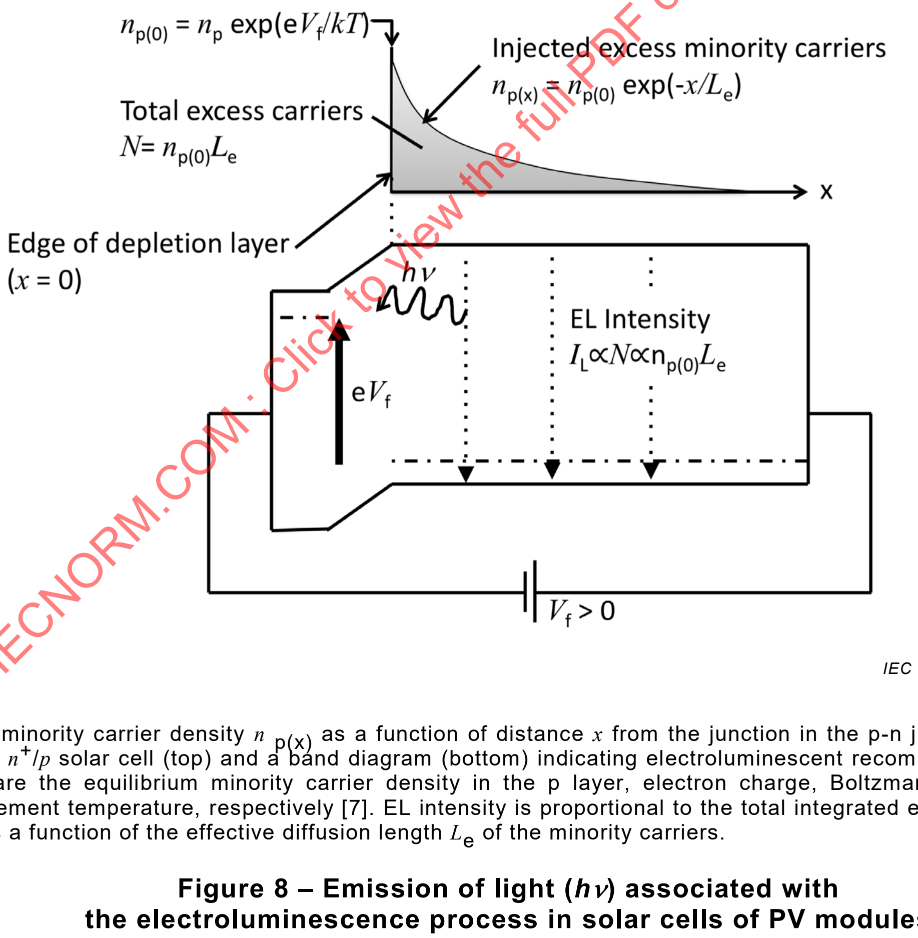


Figure 7 – Images of regions of multicrystalline silicon solar cells with three SNR_{50} values as labeled

5 Evaluation of EL images

5.1 Principles of electroluminescence



Excess minority carrier density $n_{p(x)}$ as a function of distance x from the junction in the p-n junction of a front junction n^+/p solar cell (top) and a band diagram (bottom) indicating electroluminescent recombination. n_p, e, k, and T are the equilibrium minority carrier density in the p layer, electron charge, Boltzmann constant, and measurement temperature, respectively [7]. EL intensity is proportional to the total integrated excesses carriers, which is a function of the effective diffusion length L_e of the minority carriers.

Figure 8 – Emission of light ($h\nu$) associated with the electroluminescence process in solar cells of PV modules

EL fundamentally occurs because of electronic transitions between states in the semiconductor material (Figure 8). This document focuses primarily on the signal of the near-band edge luminescence (and not deep-level luminescence and other effects due to electrical arcing or impact ionization). Near-band edge recombination associated with EL requires both an electrically injected electron and a hole for the transition to occur. Majority carriers, the type depending on the type of the semiconductor, will generally be in abundant supply. Minority carriers that are injected with electrical bias will exist to an extent depending on the bias current supply that pumps the excess minority carriers, the ability for the current supply to move across the device (modulated by series resistance), and the alternative, non-luminescent recombination paths, which reduces the effective diffusion length of minority carriers and reduces the supply of carriers available for the near band-edge EL signal.

5.2 Image interpretation

5.2.1 Series resistance

Areas where current flow is limited by series resistance will show a reduced EL signal because of the lack of supply of injected carriers at those regions. Conversely, for a given net current supplied to the device, areas of reduced resistance to current flow will have higher numbers of injected carriers flow there and generate a higher EL signal. In the absence of effects of varying minority carrier diffusion length, the EL signal will vary with the voltage potential across a cell in a module. Assuming other parameters are not changing, the voltage between two points (x_1 and x_2) associated with series resistance in an EL image is related to the logarithm of the EL intensities $K(x_1)$ and $K(x_2)$ at these points multiplied by the Boltzmann constant k and the temperature T in Kelvins as:

$$\Delta V(x_1,x_2) = kT \cdot (\ln(K(x_1)) - \ln(K(x_2))). \qquad (5)$$

5.2.2 Minority carrier lifetime and diffusion length

At forward bias currents not significantly limited by series resistance, EL signal is proportional to the effective diffusion length.

5.2.3 Shunt resistance

Shunts through the p-n junction of a cell provide alternate recombination paths to the near-band edge recombination responsible for EL signal. High currents applied to the device (such as I_{sc}) may saturate leakage paths associated with shunts, thus the cells in a module may appear bright except at the shunt locations. When current applied to the device is reduced (such as $0{,}1 \times I_{sc}$) then unsaturated shunt paths may (depending on the extent) reduce overall minority carrier density and overall cell EL.

5.2.4 Assignment of root cause

While defects such as cracks are seen in EL with an easily recognizable signature pattern, it is not always possible to assign a specific physical phenomenon using EL images taken at a unique forward bias current and temperature. Signals taken at two bias currents and combined with infrared thermography, photoluminescence, or laser-beam induced current methods can be used to further deconvolute various root causes of EL signal variation across module surfaces. Some generalizations for determination of class of defects are as follows:

- Shunts or areas of non-luminescent recombination will be seen as dark areas with higher bias currents applied, whereas whole cells will appear darker with lower bias current.
- Contrast due to variations in series resistance will be low at low bias current, but increased contrast will be seen at higher bias current.

5.3 Histogram-based analysis of the electroluminescence signal

5.3.1 General

This subclause describes quantitative metrics of module quality that can be extracted from the statistical distribution of intensity data in EL images [8]. These methods, except where noted, do not fundamentally inform about the underlying mechanisms that may be affecting the module quality. Any or all of these analyses may optionally be applied to extract quantitative metrics, which provide indicators of the consistency or variability in the EL image of the module(s). A consistent, narrow distribution is desirable.

Creation of histograms and their derived statistic from the images of the module active area(s) and image analysis software will be generally required for application of these techniques. The histograms consist of counts of pixels at each EL intensity bin. These techniques should be applied only to the active area of the module(s). Irrelevant areas of the background shall be minimized during imaging, cropping, or through other digital analyses of the EL distribution.

A reference module free of known defects is useful for comparison against degraded modules of the same type. Any degraded module shall reference and replicate this same image capture processing condition as the reference module; however, the exposure time may be adjusted to achieve the desired signal level as discussed in 4.2.2.3.

5.3.2 Image information

Complete details about module(s) model and serial number, image number, current, voltage, module temperature, camera settings, and any comments observed about the image during image capture shall be noted.

5.3.3 Bias current effects

When compared, images shall be performed at nominally the same bias current levels.

5.3.4 Analysis of intensity distributions

The widths of histograms of the intensity distributions at 0,1 and 0,5 maximum may be compared [8]. Bimodal distributions, or other multi-peak distributions shall be noted. Thresholds for separation of the distributions may be required for application of analyses, such as in Annex C.

5.3.5 Variance

In this analysis the mean EL signal of all pixels of the module image is computed and the variance is calculated as the average of the squared differences from the mean. A higher variance means greater variation of EL across the module(s).

5.3.6 Kurtosis

Kurtosis is an indicator of existence of tails to the distribution, a high kurtosis indicates there are extremes in EL signals from the module.

5.3.7 Skewness

Skewness indicates a tail to the distribution that is predominantly either positive or negative. A skew to the negative side is an indicator of regions of lower EL.

5.3.8 Pixel (or area)-weighted electroluminescence relative to an ideal module

The difference of the relative histograms between the module under test and the ideal (reference) device of the same type is computed. For this purpose, both histograms have to be divided by their respective device area in square pixels. The sign and magnitude of the elements in the resulting array plotted as a function of EL intensity is the relevant metric. A specific technique for analyzing extent of cell cracking developing on this method is given in Annex C.

6 Reporting

A report of the testing with measured performance characteristics and details of any failures and re-tests is prepared by the test laboratory or agency. The report shall contain the detail specification for the module. Each test report shall include at least the following information:

a) a title;

b) name and address of the test laboratory and location where the tests were carried out;

c) unique identification of report and of each page;

d) name and address of client, where appropriate;

e) description, characterization, condition, and identification of the item tested;

f) date of receipt of test item and date(s) of test, where appropriate;

g) identification of measurement equipment used, including camera, detector, and lens and type;

h) information, either by referencing the appropriate clauses of this document, or additional information as needed, describing the applied image corrections, including but not limited to handling of single time events, stuck pixels, and background removal, enhancement with filters or other manipulations of the raw image file;

i) reference to sampling procedure, where relevant;

j) determined sharpness and sharpness class, SNR_{50} and SNR class, and corresponding application category for the imaging conditions and if evaluated specifically for the module imaged or the REF module;

k) exposure time, WD, gain (or ISO speed setting), f-number of aperture;

l) any deviations from, additions to or exclusions from the test method, and any other information relevant to the specific test, such as environmental conditions;

m) images (pre- and post-processed, as applicable) obtained during the examinations and derived results supported by tables, graphs, histogram data, sketches as appropriate showing module orientation when mounted in arrays (Figure 9 shows a scheme for referencing particular cells in movable modules);

n) current and voltage (if measured) applied on the module under test, module temperature, camera settings, working distance, imaging angle (degrees from normal), and nominal ambient light conditions;

(a)

1,A	1,B	1,C	1,*j*
2,A	2,B	2,C	2,*j*
3,A	3,B	3,C	3,*j*
4,A	4,B	4,C	4,*j*
5,A	5,B	5,C	5,*j*
6,A	6,B	6,C	6,*j*
7,A	7,B	7,C	7,*j*
i,A	*i*,B	*i*,C	*i*,*j*

(b)

1,*j*	2,*j*	3,*j*	4,*j*	5,*j*	6,*j*	7,*j*	*i*,*j*
1,C	2,C	3,C	4,C	5,C	6,C	7,C	*i*,C
1,B	2,B	3,B	4,B	5,B	6,B	7,B	*i*,B
1,A	2,A	3,A	4,A	5,A	6,A	7,A	*i*,A

The default position, when the module is movable shall be the junction box (or if no junction box, the positive connector) on the left or top (typically on the backside of the module).

Figure 9 – Scheme for labeling position of cells in a module viewed from the light-facing side according to coordinates (*i,j*) in portrait orientation (a) or rotated into landscape orientation (b), which shall be indicated if applicable

o) any failure, with position in module and type of defect;

p) a statement of the estimated uncertainty of the test results, including SNR information (where relevant);

q) a signature and title, or equivalent identification of the person(s) accepting responsibility for the content of, and the date of the report;

r) where relevant, a statement to the effect that the results relate only to the items tested;

s) where relevant, a statement that the report shall not be reproduced except in full, without the written approval of the laboratory.

Annex A
(normative)

Procedures for image correction

A.1 Dark current and stray light removal

Dark current or stray light effects of all taken images shall be removed before other corrections (e.g. vignetting) can be determined. This can be done with subtracting every image by an image taken with the module unpowered (frame subtraction). See 4.1.5.2 and 4.2.5.

A.2 Vignetting

A.2.1 Vignetting correction

Vignetting is the phenomenon whereby intensity of the image falls toward the edges of an image taken by a camera. There is an effectively reduced area of camera aperture for light entering obliquely. Some cameras (or their associated software) may have vignetting correction built in. If left uncorrected, vignetting can be confused for degraded emission from cells in the module that are toward the edges and corners. The following analysis, for simplification, assumes the module to be imaged is placed normal to and centered directly in front of the camera. A theoretical description of the correction for the loss of light due to vignetting is given, followed by the applicable method for correction.

A.2.2 Vignetting as a function of angle from the optical axis

Images (after processing for frame subtraction) are divided by the $i \times j$ matrix Z_{vig} on a pixel-by-pixel basis to correct for the influence of the distance from the optical axis on the intensity [9]. This matrix can be theoretically derived—it describes the loss of light on the image plane due to vignetting:

$$Z_{vig} = A \cdot (1 - \alpha \cdot D) \tag{A.1}$$

$$A = \frac{1}{\left(1+\left(\frac{D}{f}\right)^2\right)^2} \tag{A.2}$$

$$D = \sqrt{(x - x_0)^2 + (y - y_0)^2} \tag{A.3}$$

Where f is the focal length, α is the empirically determined geometric vignetting factor and the matrix D gives the distance from the optical image centre (x_0, y_0) for the pixels (x, y), given in Cartesian coordinates. The operator (·) multiplies pixel-by-pixel: If C=A·B, then the pixel value at index $(i \times j)$ $C_{i,j} = A_{i,j} \cdot B_{i,j}$.

A.2.3 Correction for vignetting

The drop in intensity from image centre to image corner shall be corrected.

Extent of vignetting may be determined empirically with images using either:

a) a single cell module of with the cell type of interest, sequentially moved over the object plane (up to and including the extremes of the field of view) in an array of 9 by 9, or,

b) an average image of at least 15 images of module of the cell type of interest, imaged directly in front the camera lens normal to the camera optical axis. No gap should be introduced between camera lens and device. For every image, the device should be moved slightly (including a rotation) to average out inhomogeneity. A single cell module is useful for this procedure.

With images obtained by either of the above methods, a formula or matrix of the resulting intensity surface with any fall-off of intensity toward the image edge compared to that of the intensity at the centre shall be obtained and used as the divisor to correct (normalize) for vignetting when performing EL imaging of modules. A correction matrix may be determined numerically with the above collected images. Images collected for correction of vignetting (i.e., for creation of the correction matrix or equation) are divided by a representative image maximum. This maximum can be obtained from the median of the brightest 5 x 5 pixel area, which associated with vignetting theory, is in the vicinity of the optical axis of the camera. A correction matrix in the form of Formula (A.1) may be a useful form of the equation to apply as a starting point, but should be verified and adjusted as necessary to obtain images void of vignetting for the particular camera and imaging setup. The same correction matrix or equation shall be used for subsequent EL images that will be compared with one another when imaged with a given camera, lens, and f-number.

Annex B
(informative)

Focus

B.1 General

Focus should be optimized to obtain the desired image sharpness class in 4.2.3.

B.2 Application of the Tenengrad function and Sobel operator

The algorithm described in this Annex may be used to electronically determine the optimum lens focus.

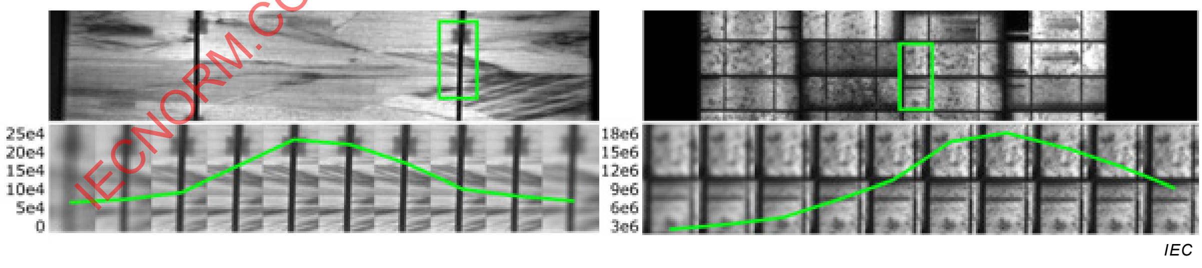
The optimum focus level can be determined by evaluating the image sharpness of a series of images. A relative measure for image sharpness is:

$$Tenengrad\ (EL_z) = \frac{1}{N}\sum_{k=0}^{k=N}\left({G_x}^2 + {G_y}^2\right) \qquad \text{(B.1)}$$

Where G_x and G_y are the first derivatives (the image intensity gradients) in the orthogonal directions in the images. To reduce the influence of noise, the Sobel operator, a combined Gaussian smoothing and differentiation operation, is used. Herein every image pixel is convolved using a 3 x 3 kernel depending on the direction (*x*,*y*) as follows:

$$G_\mathrm{x} = \begin{bmatrix} -1 & 0 & +1 \\ -2 & 0 & +2 \\ -1 & 0 & +1 \end{bmatrix} \cdot EL \text{ and } G_\mathrm{y} = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ +1 & +2 & +1 \end{bmatrix} \cdot EL \qquad \text{(B.2)}$$

The image is focused if $Tenengrad\ (EL)$ is at maximum. The absolute $Tenengrad\ (EL)$ value depends on the imaged scene and doesn't allow for conclusions about the absolute image sharpness. $Tenengrad\ (EL)$ may be calculated using the full image or a region of interest (Figure B.1). As long as focusable details are included in the image, the maximum point will indicate the best focus.



The green square indicates the region of interest for the calculation. At the bottom of each image, the calculated *Tenengrad* (*EL*) is shown over corresponding images produced at different focuses.

Figure B.1 – EL image of a solar cell (left) and a silicon module (right)

Annex C
(normative)

Quantifying solar cell cracks in photovoltaic modules

C.1 General

The method described herein is for quantifying cell cracks in photovoltaic modules that can be used as a diagnostic tool to rate cell damage, specifically by cracking, especially of modules after manufacture, transportation, installation, and field exposure [10].

Solar cell cracks can occur during manufacturing, mechanical stress sustained during module transportation, installation of the photovoltaic (PV) module, wind and snow loads, and thermal stresses.

C.2 Cell crack modes

Three cell crack types are distinguished [11] and illustrated in Figure C.1.

a) Mode A cracks: cell micro-cracks that appear as line defects in EL images that do not remove active cell area from the cell or cause significant cell power loss.

b) Mode B cracks: cracks that delineate partially electrically disconnected regions. These regions exhibit high contrast in EL images produced with I_{sc} applied current, but reduced contrast when 0,1 × I_{sc} is applied.

c) Mode C cracks: cracks that delineate essentially electrically disconnected regions from the remaining module electrical circuit. Appearing dark (background noise only) with either I_{sc} or 0,1 × I_{sc} bias current applied, these regions cause power loss, and in some cases lead to reverse biasing of the solar cells and hot-spots.

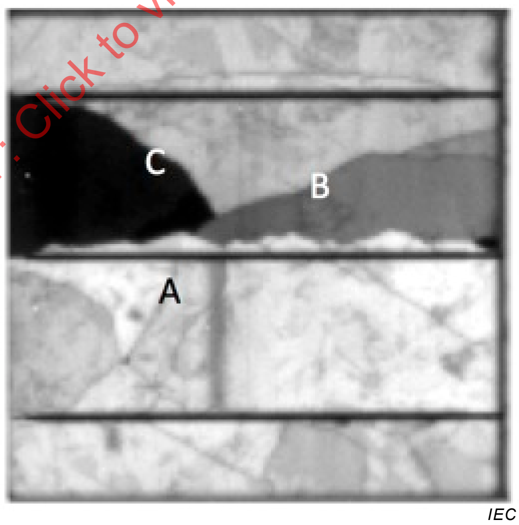


Figure C.1 – Single cell region of a module with 0,1 × I_{sc} applied showing crack types, as labeled

The quantification technique described herein is applicable to determine the area fraction affected by mode B and mode C cracking.

C.3 Basis of cell damage quantification

Histograms of EL images that have been corrected for vignetting, cropped to the active cell region are created and used as the metric for evaluation. The intensity histograms consist of counts p_M (i) as follows (Formula C.1).

$$p_{\mathrm{M}}(i) = \frac{n_i}{n}, \quad 0 \le i \le L \tag{C.1}$$

where i is the gray level of a pixel—proportional to the EL intensity detected from the corresponding location of the module, n_i is number of occurrences of gray-level i, n is the total number of pixels in the image, L is the number of gray levels of EL intensity values that can be recorded and represented by the EL camera normalized to the maximum level. Normalization is necessary to be able to compare histograms of EL images taken with different cameras.

Using I_{sc} forward bias current, bimodal distributions will normally be seen in such histogram distributions of EL pixel count by intensity bin. The higher intensity peak consists of normally performing active cell area, and the low EL (LEL) regions will include, depending on the module, reflected EL emission at regions between cells, metallization, and regions of active cell that have reduced performance. In the case of modules with additional cell damage, those damaged regions will be responsible for increased pixel counts in the LEL intensity region.

Histograms derived from the EL images of modules having cells with suspected damage are compared to a histogram obtained from ideal (best-in-class) undamaged modules of the same type to obtain a metric for that damage.

An example of a series of histograms for the best-in-class modules (marked by module STC power performance of P_{max} = 100 %) and module states with broken cells as indicated by lower P_{max} values is shown in Figure C.2, obtained with I_{sc} forward bias current.

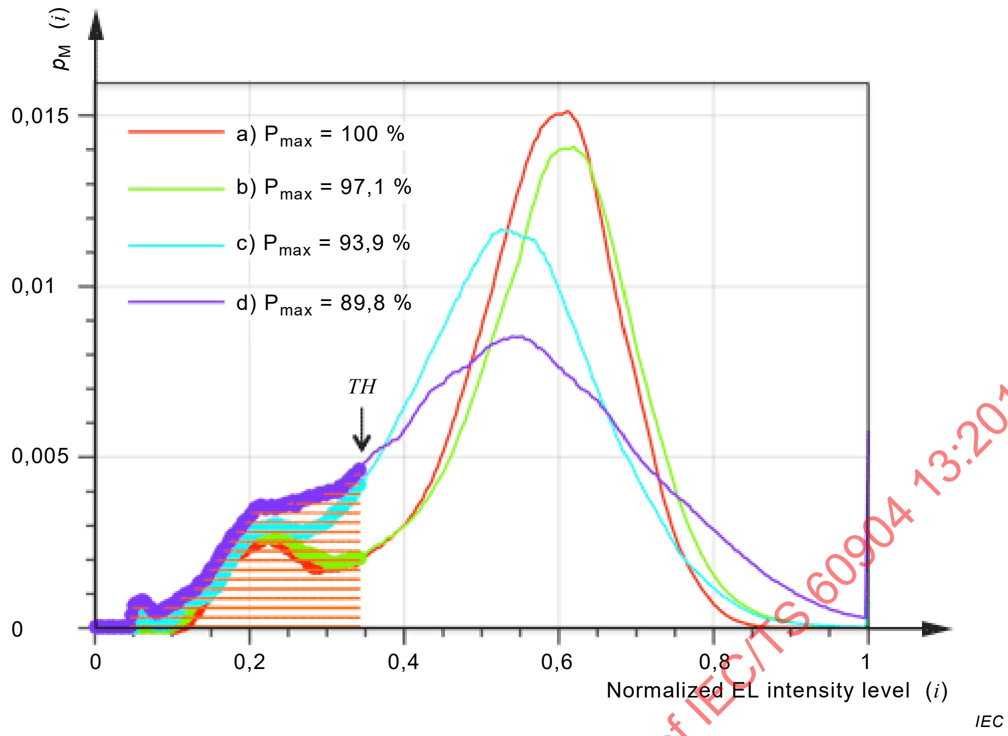
Histograms derived from the EL images of a module type under study obtained with I_{sc} current are first analyzed to define the LEL region for that module type. Defining the threshold value TH that defines the upper limit of the LEL region can be achieved in two ways.

a) Analyzing the EL images of the module type and determining an EL intensity value just below the level contrasted by a mode B cell crack (existence of mode B cracks will be necessary to determine this). A mode B crack threshold can be considered as the most benign crack that still produces a contrast in EL intensity across it with $0{,}1 \cdot I_{sc}$ bias current.
b) Use an image-segmentation algorithm that calculates an optimal threshold value that separates the two Gaussian sub-distributions of $p_M(i)$, such that their combined intra-class variance is minimized to distinguish active emitting cell area from background. A best-in-class module shall be used for this analysis.

   Where there are two or more different cell intensities, for example, from differing material quality, emissions from those various cell types shall be combined and considered a single sub-distribution for separating from the background. Cropping the image to include only the class of cells in the module of the lowest characteristic luminescence for determination of threshold can permit more accurate determination of TH.

NOTE Otsu method [12], for example, may provide a suitable image-segmentation algorithm.

Derived TH value obtained from the module type and imaging conditions (this includes current bias, exposure level, camera focus and position, ambient light noise or dark frame subtraction) should be kept constant in subsequent measurements for a given module type.



The low electroluminescence (LEL) region that exists below the threshold intensity (TH) is shown hatched. The data was obtained with I_{sc} forward bias current.

Figure C.2 – Example of normalized EL intensity histograms calculated from the EL images of modules with various levels of cell cracking and resulting power degradation, indicated by P_{max}

Once TH has been determined to be used for images of a given module type obtained using I_{sc} forward current, it will be necessary to calculate the total percentage of low EL intensity region, LEL_M, by integrating the sub- TH EL intensity distribution (number of pixels) from $p_M(i)$, per Formula (C.2) for each module:

$$LEL_M[\%] = 100\sum_{i=0}^{TH} p_M(i) \cdot \tag{C.2}$$

The total percent area degraded for a module, D_M, is calculated by determining the difference in LEL_M, for the degraded module in question, and LEL_{Mo}, that pixel count below TH intensity for the best-in-class module determined also using Formula (C.3), as follows:

$$D_{M\_BC}[\%] = LEL_M - LEL_{Mo} \cdot \tag{C.3}$$

The total percent area of a module degraded by mode B and mode C cracks is obtained with EL images obtained with I_{sc} forward bias current using Formula (C.3) and is referred to as D_{M_BC}.

Total percentage area degraded by C mode cracks is obtained with EL images using 0,1 × I_{sc} current and Formula (C.4) and is referred to as D_{M_C}. For images obtained using 0,1 × I_{sc}, corresponding TH_C shall be separately determined for each image to calculate D_{M_C}. The region below TH_C shall be defined as dark areas of mode C cracks. Typically, there will be an increase in intensity corresponding to real EL intensity emission, which is the threshold TH_C. Alternative methods for compute TH_C can be found in the literature [13].

The TH_C value in cells without any mode C cracks should exist where the histogram count starts to increase.

$$D_{M\_C}[\%] = 100\sum_{i=0}^{TH_C} p_{M\_C}(i) \tag{C.4}$$

The area of the module affected uniquely by mode B cracking, D_{M_B}, is obtained with (C.5) as follows:

$$D_{M\_B}[\%] = D_{M\_BC} - D_{M\_C}. \tag{C.5}$$

The D_M parameter is designed to quantify the increase in low EL intensity regions due to cracking relative to a best-in-class module. It will not be able to exclude nor properly quantify other solar cell defects and degradation modes, such as cell shunting. These may be distinguished before performing this analysis referencing Annex D.

C.4 Procedure

a) For each module type, obtain EL images using the methods in the body of this document, including for I_{sc} and 0,1·I_{sc} forward bias current:

   – a best-in-class module (such as an un-stressed control), and

   – modules for the quantification of cell crack damage.

   Images should be taken under the same optical conditions and same image processing procedures (including the same cropping to the active cell circuit) and parameters. There will be two separate exposure times according to images obtained with I_{sc} and 0,1·I_{sc} forward bias current.

b) Determine based on qualitative criteria given in Annex D, if the mode of degradation is primarily by cell cracking. Do not apply this procedure to modules that exhibit degradation that is not essentially due to cell cracking.

c) Calculate histograms, $p_M(i)$ for all images (Formula C.1).

d) Determine TH for images obtained at I_{sc}, and LEL_{Mo} based on the best-in-class modules, which will be fixed for images of a given module type obtained with I_{sc} forward bias current.

e) For each module for which damage is sought to be quantified,

   – determine D_{M_BC} using images obtained with I_{sc} forward bias current (Formula C.3);

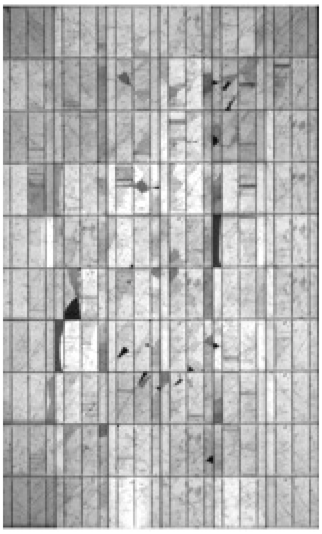
   – choose TH_C for each module for images obtained with 0,1·I_{sc} forward bias currents;

   – determine D_{M_C} using images obtained with 0,1·I_{sc} forward bias current (Formula C.4);

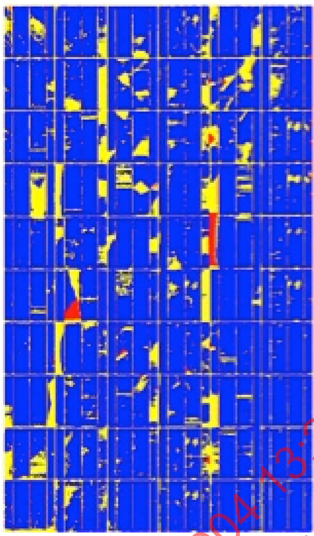
   – determine D_{M_B} using (Formula C.5).

f) For each module, report damage (percent) of mode B cracking D_{M_B} and mode C cracking D_{M_C}, in addition to the requirements of Clause 6.

Optionally, but highly beneficial for interpretation, when locational information of each pixel can be tracked in software during the analysis, display an image for each module where pixels counted toward D_{M_B} and D_{M_C} are regionally shown by contrasting colors. See the example of Figure C.3.



(a)



(b)

Mode B cracks are shown as yellow (area fraction D_{M_B} = 9,04 %) and mode C cracks are shown as red (area fraction D_{M_C} = 1,85 %).

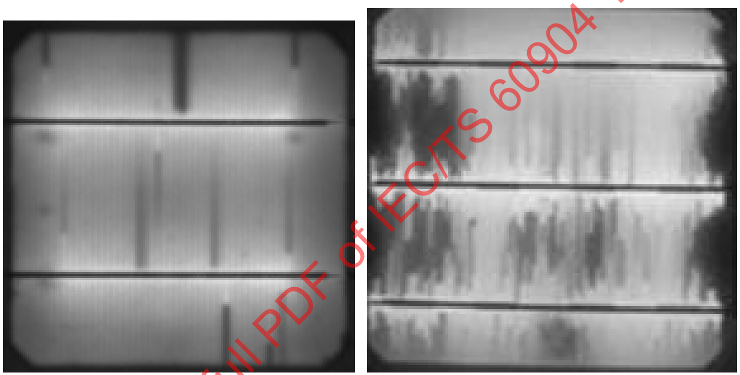
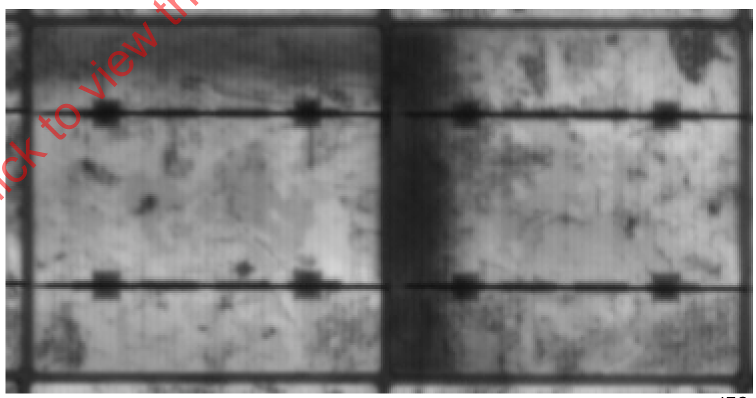
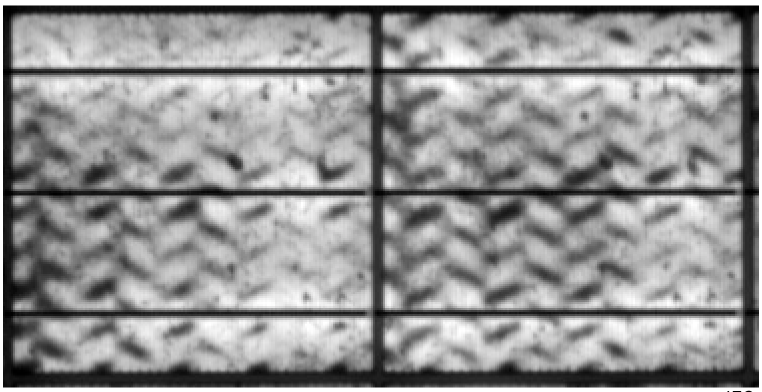
Figure C.3 – Example of quantifying solar cell cracks in photovoltaic modules: (a) EL image produced with 0,1· I_{sc} forward bias current, and (b) image of regions considered damaged

Annex D
(informative)

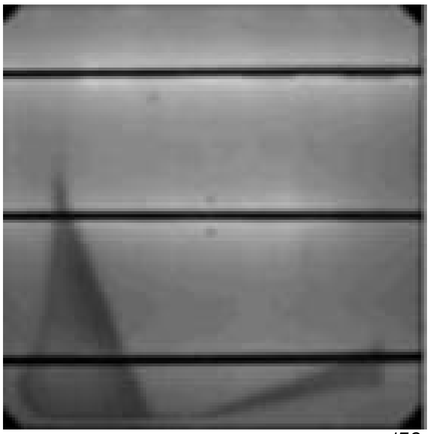
D.1 Qualitative interpretation of electroluminescence images crystalline Si PV modules

This annex should be used along with the information in 5.1 and 5.2 for understanding the root cause, and 5.2.4 for understanding the current bias level dependence of defects causing shunts or manifesting in areas of higher series resistance, see Tables D.1 and D.2.

Table D.1 – Descriptions of observables, features, and known causes, along with electroluminescence images for crystalline Si modules

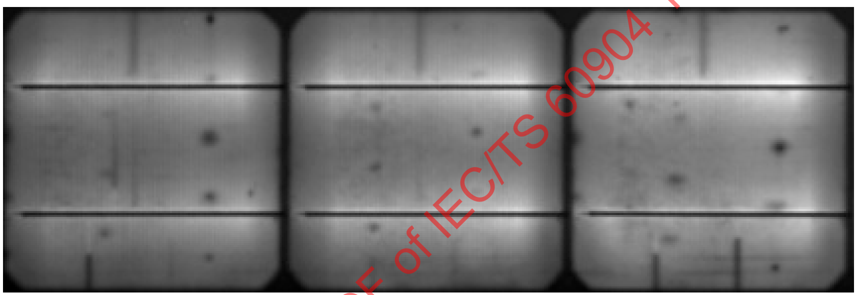
Defect type and prognosis	Image
Missing, broken, or delaminated grid finger lines. Missing or broken grid fingers (confirmable by visual inspection) are generally stable and their influence is captured in the efficiency of the cell. Grid finger adhesion may continue to degrade over time, degrading the cell and module performance.	 IEC
Reduced lifetime–cast silicon origin. Existing over particular grains or regions of the ingot that contain elevated defect or impurity concentrations. They are generally stable over time and their influence is largely captured in the initial efficiency of the cell and module.	 IEC
Belt marks. Developed during cell firing, they are generally stable over time and their influence is captured in the initial efficiency of the cell and module.	 IEC

Adhered wafers during processing. Areas of poor contact resistance or improper junction formation during cell processing. They are generally stable over time and their influence is captured in the initial performance of the cell and module.



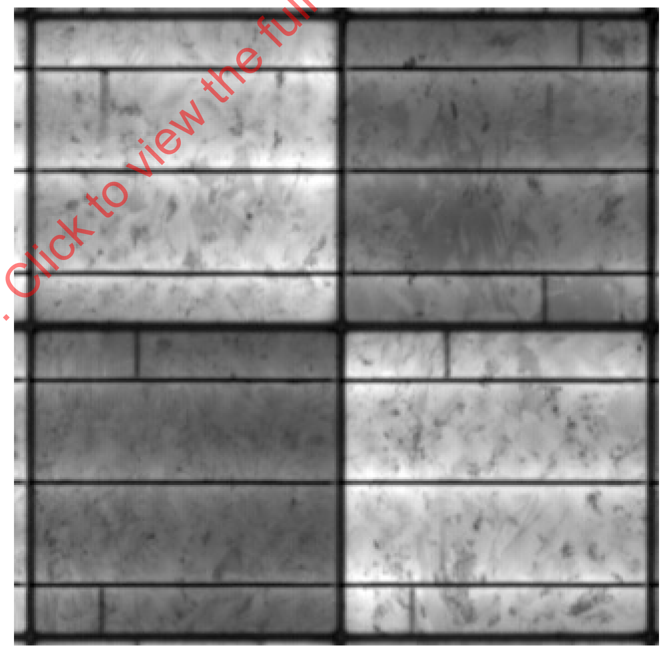
IEC

Wafer/cell contamination. Localized areas of low EL signal, especially when systematic from cell to cell, may be assignable to wafer/cell contamination by handling equipment. Alternatively, localized shunting due to material (such as contact metallization paste) contamination. They are generally stable over time and their influence is captured in the initial efficiency.



IEC

Cell-wide lower minority carrier lifetime. This may occur from lower minority carrier lifetime based on the position of the wafer in the ingot that it came from and impurities in the wafer inherently contained. Such defects may be alternatively associated with cell shunting. Grid finger breakage is also seen in this image.



IEC