

Nomenclature and description of Electro-Luminescence (EL) observations: cell cracks and other observations

Bengt Jaeckel^{1,*} , Matthias Pander¹ , Paul Schenk¹, Aswin Linsenmeyer², and Jochen Kirch³

¹ Fraunhofer Center for Silicon Photovoltaics CSP, Otto-Eissfeldt-Str. 12, 06120 Halle (Saale), Germany

² Sunset Energietechnik GmbH, Industriestr. 8-22, 91325 Adelsdorf, Germany

³ Ing.-Büro Jochen Kirch, Lindenweg 18, 86925 Leeder, Germany

Received: 30 June 2024 / Accepted: 4 November 2024

Abstract. Crystalline silicon solar cells were, are and will continue to dominate the Photovoltaic PV module market. In the past decade, significant efforts have been made to better understand and characterize observations using Electro-Luminescence (EL) to investigate the appearance of c-Si solar cells. While standards have been developed, a clear definition of the nomenclature for observations in EL images is still missing. Within the project PV-Riss, a group comprising manufacturers, advisory experts and research facilities worked on an overview of various observations found in the literature (typically of Al-BSF and PERC cells). The individual observations were categorized into four main categories, namely: 1) single cracks, 2) multi-cracks, 3) anomalies in the electrical circuit and all others into 4) miscellaneous. Each category includes several subcategories to include most relevant observations within EL images. These categories can be applied to all existing and new cell types and are independent on the size (ranging from “old” 4” to new M/G12), shape (full, half, third, x-cut), material (mono, multi), or cell technology (AlBSF, PERC, TOPCON, HJT, IBC, Perovskite on Si), as well as of the PV module design (size, glass/backsheet, glass/glass, internal wiring of the electric circuit). Along with a detailed description of observations in EL images, several important definitions are provided that are essential for general understanding, nomenclature, and the mapping of observations to ensure clear and comprehensive communication and reporting. Following the definition of most relevant observations, key observations will be discussed within a classification proposal. This classification proposal aims to facilitate future discussions and to assess EL observations, combining the risk of power loss that exceeds warranty with the probability of potential electrical safety risk.

Keywords: Electro-Luminescence / silicon solar cells / cracks / degradation / classification

1 Introduction

Electroluminescence (EL) imaging, first introduced in 2006 by Fuyuki [1], is widely used in the PV industry, from end-of-line, laboratory and even field testing. Setups vary significantly, ranging from high-resolution laboratory images (general setup still applies as in [1]) to images captured using drones [2,3]. EL imaging is particularly relevant for inspecting PV modules with crystalline wafer-based Silicon (c-Si) cells, however, it can also be applied to thin-film technologies. Herein the focus is only on c-Si, as it accounts for over 90% of the PV market in terms of installation and manufacturing capacity [4,5]. Various stakeholders in the industry maintain different failure catalogs [6–11]. However, a preliminary round robin

within the project consortium [12], consisting of members well familiar with the EL-technique, revealed that with increasing complexity of observations different terminology and evaluations of the observations make a reliable comparison very difficult.

Electroluminescence images can provide different insights into the health status of PV modules. The interpretation of these observations clearly depends on the time the image was captured (factory vs e.g., years in the field). The most relevant questions are: What are the observations? How should they be named and classified? And finally, how should they be rated according to their criticality? The first two points are a major focus of the paper. Rating criticality significantly depends on the time the image was taken, the duration of operation and the type of system. For instance, a large-scale power plant may be assessed differently in terms of risk of fire or electrical shock compared to a critical infrastructure building like

* e-mail: bengt.jaeckel@csp.fraunhofer.de

hospitals. Furthermore, final conclusions and recommendations often require more in-depth information, such as results from flash-testing and IR thermography.

Generally, EL images can provide information for cell cracks, the quality of electrical interconnections, the state of degradation, and other manufacturing and operation related anomalies. EL is typically used in manufacturing, consulting work and in the laboratories to detect cell cracks. However, in some cases, cracks can be detected and visualized with the naked eye, particular in the case of so-called snail tracks [13–15].

Cell cracks can occur at various points in the value chain, including production, transportation, installation or operation due to mechanical stress or high temperature fluctuations. The severity assessment depends on crack type and cell technology. The sensitivity of a PV module design to cracking is tested in a standardized manner as part of certification [16] or through additional tests such as extended stress tests and transportation testing [17–22]. These standards identify anomalies but do not assess potential long-term degradation and/or damage, nor do they evaluate energy yield or system safety. While cell cracks are often detected, they are rarely assessed reliably, leading to disputes between the contracting parties. As part of the normal maintenance of PV systems [23–25], imaging methods (e.g. thermography [26] or electroluminescence [27,28]) are utilized to assess a PV module's health status. Although EL-images are documented, they seldom lead to actionable conclusions.

In general system analyses, a typical procedure involves the identification of anomalies, classification, evaluation and prognosis. For PV modules, the identification of cell cracks is sufficiently reliable, however, the quality of the identification lacks consistency. There are approaches to close this gap [29]. This paper will present a generalized location mapping and nomenclature. The main results serve as the foundation for the upcoming VDE-SPEC 90031 [30] and will be incorporated into the project teams of IEC 62446-4 [27] and IEC 90904-13 [28].

The discussion will address the challenges for classification. It is important to note that knowledge for classification is typically based on long-term field exposure and laboratory tests of Al-BSF and PERC cell architectures [31–40]. Initial results for TOPCON and HJT [41–44] suggest that certain stressors are more relevant for the next generation of cells, while they are less critical for “older” cell architectures.

The still leading scientific model for the evaluation of cracks within solar cells is that of Koentges [31,32], which calculates the maximum possible crack-related separation and equates the area with the power loss. This model allows for an estimation of the maximum expected effects for power loss but must be confirmed in the laboratory in each individual case. Studies on the repeatability of power measurements reveal significant variance in the values for cracked PV modules [40]. However, there is a degree of subjectivity in the assessment, indicating a need for future research work, particular regarding half-cell PV modules and HJT/Topcon cell concepts. Furthermore, clarification

on the prognosis of potential power loss is needed as for instance dynamic mechanical load [18,45] (ML) and thermomechanical load [16] tend to cause minimal power losses when considered alone [46], without post-test stress tests like thermal cycling test. Only the combination of mechanical load with temperature cycles demonstrates the influence of mechanically induced cracks on the long-term behavior [47–49]. Correlation with field data have also only been investigated in individual cases [38,50,51]. Larger datasets of degradation rates were compiled e.g. by Koentges and Jordan and others [52–55]. While these provide a valuable overview, they lack the details necessary to link specific observation to a particular degradation rate. There remains a significant gap in scientific understanding, especially with the introduction of new PV module technologies such as multi-busbar, cut cells or designs without cell spacing. These newer concepts may exhibit significantly different susceptibility to cracking, which has not been considered in previous assessments.

The aim of this paper is not to address the newly identified knowledge gaps. Instead, it primarily seeks to establish standardized image evaluation and nomenclature for existing EL images, fostering better correspondence in future discussions.

Four main categories have been developed, and the reasoning behind them will be provided herein. As an outlook and starting point for future discussions and development a preliminary classification table will be presented.

2 Cell location nomenclature and required terms

2.1 Nomenclature for cell position in PV Module

To ensure a standardized observation description, it is essential to accurately name the exact position of the observation. Therefore, a chessboard pattern is proposed to clearly locate cells within various PV module types (see Fig. 1), including half-cut, third cut and even shingled PV module layouts (Fig. 1).

The PV module is typically imaged from the front using EL. In older PV modules, the junction box and often the nameplate are obvious locator features to align the images to the top. The columns of cells are labeled starting with “A” on the left, and the rows numbered, beginning with “1” at the top. For half-cut cell PV modules, this may not always apply. However, there are always unambiguous elements, such as nameplate or serial number markings. In a report, these unambiguous elements must be clearly stated.

2.2 Terms

For a basic understanding, it is important to use defined terms. In addition to a clear definition of the location of the observation found in an EL image, several other terms must also be clearly defined.

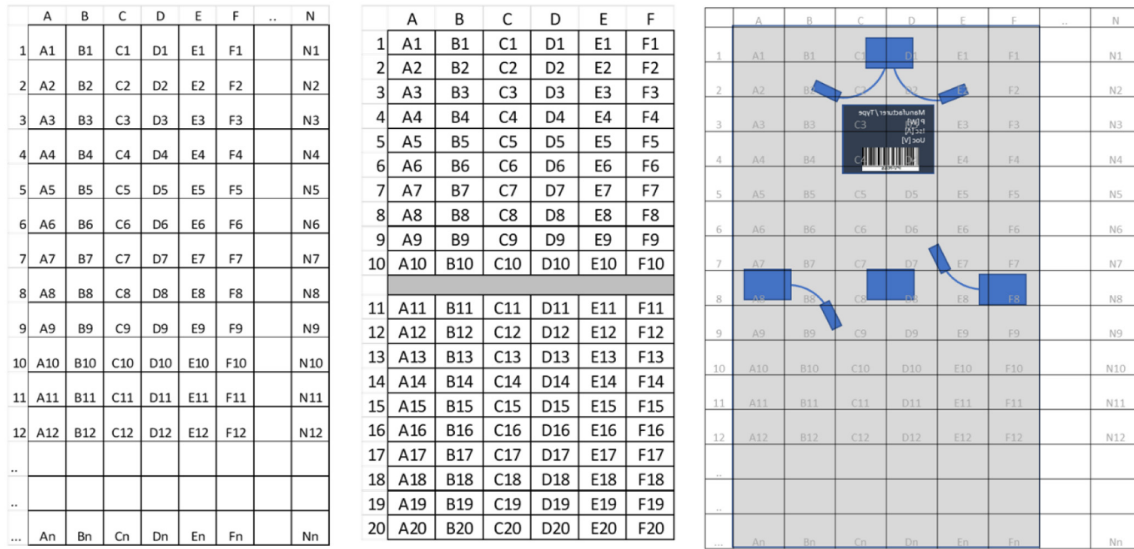


Fig. 1. Location of observations within the PV Module.

2.2.1 Crack: complete or incomplete

Generally speaking, a crack is a fracture within the crystalline silicon wafer of the solar cell, following the major crystal orientations in mono-crystalline material or along grain boundaries or through crystal grains in multi-crystalline material. A crack is not necessarily separated enough to be seen visually with the naked eye, however, a cell separation that is visible to the naked eye is definitively also identified as a crack.

For a more detailed understanding, two types of cracks are defined: complete and incomplete cracks. The differentiation is helpful for risk analysis on older PV module types with a limited number of busbars (≤ 6), as the risk for loss in active area is higher. As long as the crack is not complete, it can exhibit a relatively random future pattern, particular in multi-crystalline Si-cells.

A crack is called complete if it starts AND ends at the edge of the cell (see Sect. 3.1.1). In contrast, a crack is termed incomplete if it ends randomly on the solar cell (see Sect. 3.1.2). This definition was established as a uniform nomenclature for EL observations. It is known that for older cell types (AlBSF, 2/3Busbar designs), cracks often also stopped effectively at the busbar and/or at solder pads. However, for current technologies with significant thinner wafers and metallization, the observation of cracks stopping is rare and questionable.

2.2.2 Silicon solar cells wafers

Typically, c-Si cells are made from either mono-crystalline or multi-crystalline ingots, cut to thin wafers. Their size can vary from 4" to today's M12 (210 mm).

Mono-material: Single- or mono-crystalline Silicon wafers exhibit an almost ideal crystallographic lattice structure extending across the entire wafer. This type of material is primarily used in today's PV modules.

Multi-material: Multi- or poly-crystalline wafers consist of numerous adjacent areas (or grains) separated by grain boundaries. While the crystalline structure within is like that of mono-crystalline, the lattice orientation varies from one grain to another.

2.2.3 Observations

EL-images are used to identify various kinds of observations. In this context, the term "observation" encompasses all identifiable features in an EL-image, including cell cracks, wafer-related structures, cell manufacturing features, and aspects related to PV module manufacturing, as well as observations after use (outdoor and indoor accelerated stress testing). Observations are not necessarily defects or structures that inherently cause increased degradation rates. Additionally, some of the observations require further characterization methods (such as flash testing, IR-imaging, magnetic field imaging (MFI), photoluminescence (PL)) to identify and describe defects in more detail. For example, regarding cracks in solar cells, it is crucial to determine whether a crack is complete or incomplete to better assess its potential impact on power loss and the risk of excess heating in that specific solar cell.

3 Grouping of EL observations

The grouping of the observation into four major categories aims to facilitate faster evaluation of EL-images and the sorting of PV modules into certain classes. Training of such, typically AI-based, evaluations classes can for example be done using different open-source data bases [56–63]. Combined with the clear nomenclature from this contribution a more valuable evaluation of EL images can be made.

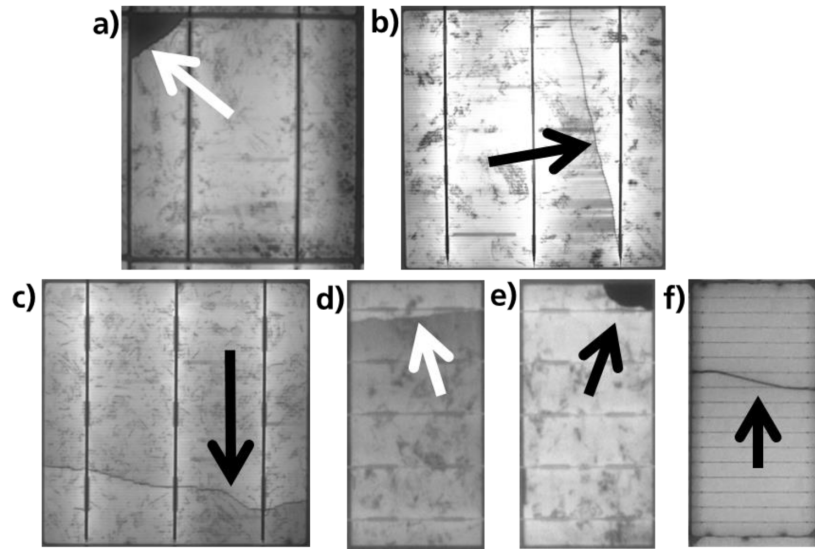


Fig. 2. Single cracks in different cell: a) to e) multi crystalline silicon solar cell, f) in a multi-busbar mono crystalline silicon solar cell.

A preliminary draft of a classification scheme is presented in [Section 4](#), it is discussed as a starting point for future discussions rather than intended to be exhaustive.

The observations are divided into four main groups: 1. single crack, 2. multiple cracks, 3. anomalies in electrical circuit, and 4. miscellaneous. Within each group, there are further gradations or subgroupings of specific observations. These four groups were developed based on the evaluation of several failure catalogues available to the consortium and years of daily work with numerous EL images from different PV module designs and stages in their service life. Initially, the focus was on observations in individual solar cells and their potential impact in serial/parallel connections in PV modules. Due to the rapid changes in cell size and number of busbars in recent years, clear conclusions for specific observations are challenging, particularly as there is a lack of experience with long-term outdoor exposure.

The first two groups deal with cracks of the crystalline silicon wafer. The distinction between single crack and multiple cracks is made for the purpose of simple risk-based sorting based on potential power loss. This approach emphasizes image processing rather than a physical criterion. For the initial counting and pre-assessment, no differentiation is made regarding the orientation, the length, or position of the crack within the solar cell. A crack parallel to a busbar will have different impact on potential power loss compared to a perpendicular crack. The risk and potential loss significantly depend on the number of busbars; therefore, this aspect is excluded from the discussion to maintain a uniformed nomenclature.

The third group deals with observations that are not cracks but can still directly impact PV module's performance. It is important to note that the potential risk for power loss or other effects, such as hot spots, varies significantly within this group of observations. For instance, finger interruptions caused by a defective cell printing mesh may have little to no impact on power and

are considered within the nameplate of the PV module. In contrast, missing or broken cell-to-cross connector joints can lead to inhomogeneous current densities within the solar cell, potentially accelerate aging (e.g. causing further disconnection) of the other remaining cell-to-cross connector joints.

The last group collects all other observations frequently found in PV modules. It should be acknowledged that this collection is based on past cell architectures, as well as an early generation of TOPCON cells, and does not claim to fully encompass future cell technologies.

For minimum image quality requirements, the definitions from IEC 60904-13 [28] were utilized. The images presented in this paper were captured using various camera systems and lenses, and the imaging current was near short circuit current (I_{sc}) under standard test conditions (STC).

3.1 Single crack

A single crack is defined as one crack within a single solar cell. Two types are possible: complete and incomplete.

3.1.1 Complete crack in a silicon solar cell

A single crack within a single solar cell that is complete. Possible root causes for this defect typically include handling of the cell and PV module or mechanical loads. The potential power loss is generally low if only a few cells are impacted (see [Sect. 4](#)). Examples are provided in [Figure 2](#).

3.1.2 Incomplete crack in a silicon solar cell

A single incomplete crack within a single solar cell is defined as one where at least one part of the crack ends within the solar cell. Possible root causes for this defect are the same as for complete cracks. While the potential power loss is still low, it is more difficult to determine. Examples are given in [Figure 3](#).

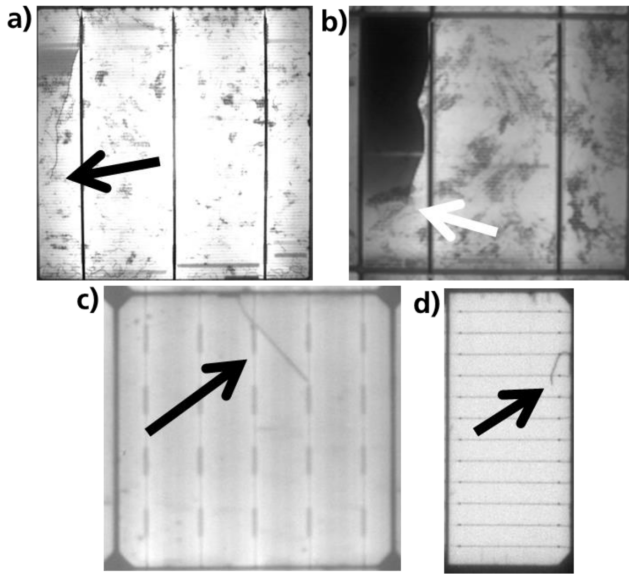


Fig. 3. Incomplete single cracks in different cells: a) and b) multi-crystalline silicon solar cell, c) and d) in a mono-crystalline silicon solar cell.

3.2 Multiple cracks

Multiple cracks are defined as the presence of at least two cracks within a single solar cell, regardless of whether they are complete or incomplete.

3.2.1 Double crack

A double crack within a single solar cell is defined as the presence of two complete or incomplete cracks. The possible root causes for this defect are the same as for single cracks. The potential power loss is higher compared to single cracks. Power loss and potential excess heating will be significantly higher for older cell technologies with two or three busbars. In contrast, for multi-busbar cells (>6BB) the risk of cell area separation is reduced. Examples are provided in [Figure 4](#).

3.2.2 Multiple crack pattern

Multiple crack patterns within a single solar cell consist of more than two complete or incomplete cracks. The possible root causes for this defect are the same as for single cracks, however, typically stronger forces are required to cause this kind of damage. The potential power loss is higher compared to double cracks. Like double cracks, the power loss and potential excess heating of the cell will be significantly higher for older cell technologies with two or three busbars. For multi-busbar cells (>6BB) the risk of cell area separation is reduced. Examples are given in [Figure 5](#).

3.2.3 Dendritic shaped crack structures (worst case of 3.2.2)

This type of crack structure can also be considered as a severe case of multiple crack patterns in terms of root cause, potential power loss, and risk for excess heating.

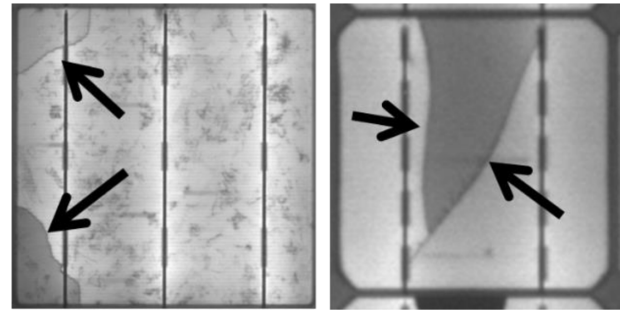


Fig. 4. Examples for double cracks. That are either two separated cracks (left) or two cracks that most likely have the same origin (right).

These dendritic or branching crack pattern typically span across the full cell (see [Fig. 6](#)) and exhibit a defined orientation, initiated by a significant load causing cell cracking. The severity (number of cracks) also depends on wafer quality. The high number of tiny cracks and the extensive overall crack area generally lead to significant power loss, which may even be critical for multi-busbar cells as these crack lines represent non-passivated edges of the wafer/cell and can decrease shunt resistance.

3.2.4 Tiny X-V-shape cracks

X- or V-shape cracks are very short cracks (<30 mm total length) within the solar cell, typically not crossing a busbar and not ending at edge of cell (see [Fig. 7](#)). These cracks often originate at the busbar, likely due to mechanical forces applied during soldering, or at the cell cut near the busbar. They usually exhibit a 45° angle relative to the busbar, which is a result of the crystal structure of the wafers.

In addition to soldering-induced X- or V-shape cracks, such cracks can also be caused by sharp tools impacting the solar cell even through the backsheet.

3.3 Anomalies in electrical circuit

Other important observations in EL images include defects (localized and extensive areas), imperfections, and features caused by the electric circuit of the solar cell or in the PV module itself. Some of these originate from production and are electrically stable, while others serve as warning signs or require exposure to environmental stress to be visible.

The groups of single and multiple cracks can be visualized through single cell images. However, some observations can't be accurately presented by such images. Therefore, this section also includes full-PV module images to better explain the observation in contrast to normal operating cells. It should be noted that some observations, such as those in [Section 3.3.4](#) could be interpreted as a large number of cracked cells with single and multiple cracks. Conversely, the EL pattern for PID, LeTID and UVID can't be viewed as a kind of string of dark cell observation from [Section 3.3.3](#) as the root cause and their development over time is entirely different.

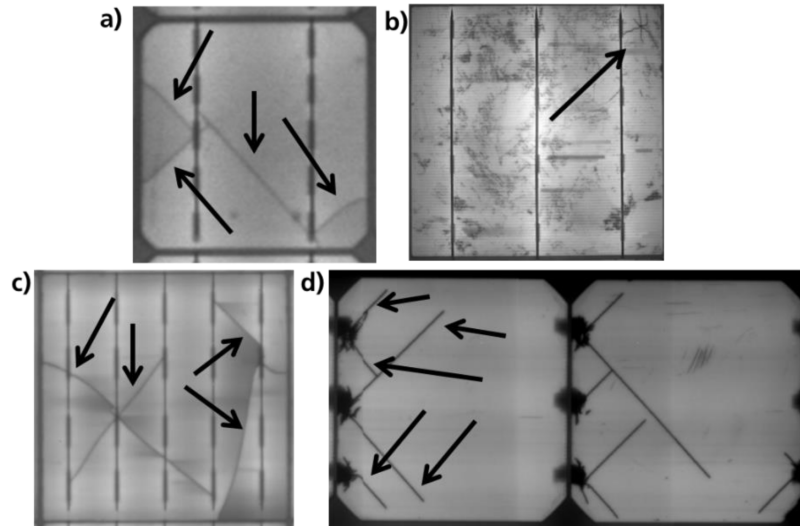


Fig. 5. Multiple crack pattern of various severity and for different cell types: a) mono 2 busbar, b) multi 3 busbar, c) mono 5 busbar cell and d) IBC cell.

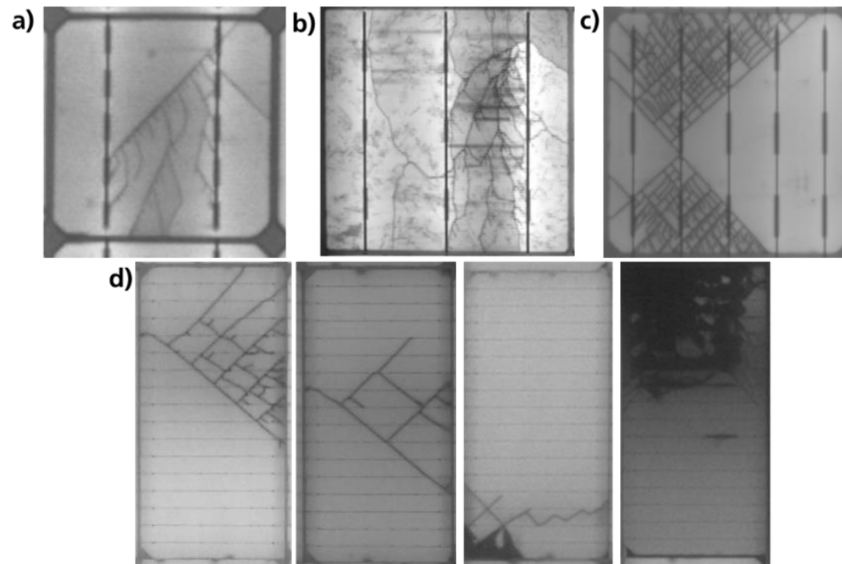


Fig. 6. Dendritic shaped crack structures for a) mono 2 busbar, b) multi 3 busbar, c) mono 5 busbar and d) different severities for a mono 16 busbar cell.

3.3.1 Finger interruptions

Solar cell grid finger interruptions appear in EL images as thin darker lines, often exhibiting a dark-to-bright gradient that varies by location. Typically, a few of such finger interruptions can be found per cell, often repeated in neighboring cells due to the manufacturing process. These interruptions are usually caused during cell manufacturing by defective printing mesh or missing paste (see for example Fig. 8a).

These finger interruptions are taken into account during cell sorting (power sorting, may lead to B-grade for optical reasons) and PV module manufacturing (power sorting, typically not visible by eye during final

visual/optical inspection, EL classification may result in B-grade product). Future power loss is very unlikely to arise from such cell printing finger interruptions.

Another cause for finger interruptions arises from soldering. If there is a misalignment between ribbon and busbar, there is a likelihood that the ribbon is “soldered” onto the fingers and rather than to the busbar. This misalignment can introduce additional stress, typically during temperature changes, leading to further finger interruptions that may not be detectable immediately after PV module manufacturing, but may become apparent after some time of use. These interruptions are illustrated in Figure 8b and can cause significant power loss over time.

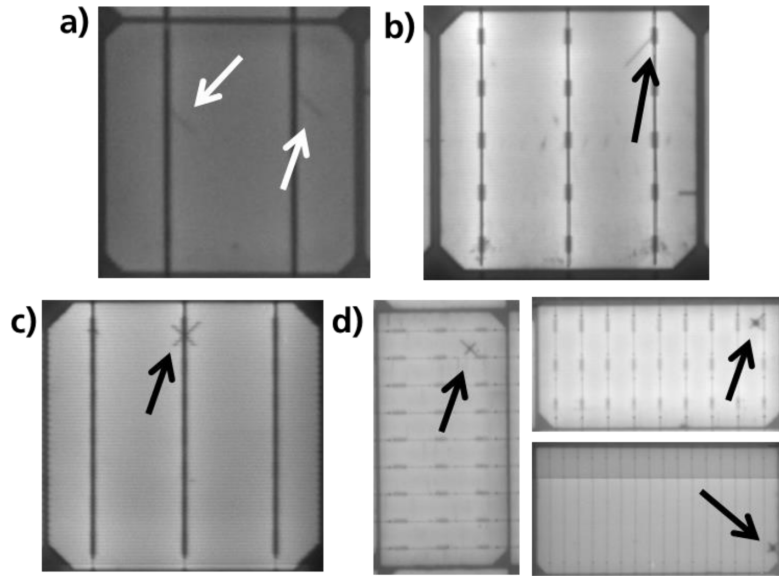


Fig. 7. Tiny V (a) and (b) or X (c) mono 3 busbar and (d) mono multi busbar shape cracks in various cell types and extensions of the crack.

3.3.2 Missing cell to cross-connector joint

In modern PV modules, the number of cell ribbons connecting to the cross-connector has increased significantly from 2-3 to over 16 for multi-busbar cells. Additionally, the number generally doubles when transitioning from full cells to half cells. As a result, the likelihood of misplacement, missing length or incorrect / missing soldering has considerably increased.

Since the contrast in EL depends on current density, it is often difficult to detect this kind of defect during manufacturing using standard EL and flash testing. The latter is unlikely to reveal this issue due to the high redundancy built into multi-busbar concepts. For more detailed analytics, magnetic field imaging (MFI) can facilitate easier detection of these failures, even in a manufacturing environment. Examples are provided in [Figure 9](#), including a sketch to illustrate the root cause.

In addition to manufacturing issues, this is a known defect that can develop after a certain time of use. Depending on the design of the ribbon and cross-connector, as well as the soldering quality, the interconnections may break due to thermomechanical stress and/or corrosion during outdoor operation. Thermal cycling tests can be employed to identify such defects, focusing solely on thermomechanical factors.

3.3.3 Completely dark cells and strings

Randomly and very rarely, completely dark cells appear in PV modules immediately after manufacturing, which should not be confused with phenomena like PID that require a certain external environmental stress to develop. Examples are given in [Figures 10a](#) and [10b](#). The root cause of this issue is a short-circuit caused by a misaligned (extra) ribbon. Notably, in [Figure 10b](#), the neighboring cells

exhibit significant current density inhomogeneities. Depending on how the short-circuit was generated, there is a high risk of excess heating, and the overall power of such a PV module is significantly reduced compared to other PV modules manufactured in the same batch.

Completely dark strings (where all cells in a substring of a PV module appear totally dark) can be observed at different stages during operation. In most cases the root cause is a shorted bypass diode, leading to a significant reduction in the power output of this particular PV module. For most PV module designs, one-third of the PV module's power output is effectively "lost" (see [Fig. 10c](#)).

3.3.4 Severe mechanical loads

Like in the previous subsection, this kind of observation is not visible immediately after PV module production. It requires a specific mechanical stress to occur. The severity of the issue significantly depends on the PV module's construction and the type of applied load, making it challenging to predict a power loss accurately. Typically, this observation can be seen as an accumulation of numerous cracked cells, combining all types from [Sections 3.1](#) and [3.2](#), often leading to inhomogeneous rerouting of currents within the PV module, including interactions with the bypass diodes.

[Figure 11](#) provides examples of three different applied loads for glass-backsheet constructions. [Figure 11a](#) shows an EL image after mechanical load test, representing severe snow loading. The power loss attributed to this image is still moderate, however, further environmental stress, such as day-night temperature cycle or cyclic loads from continuous wind gusts, is likely to exacerbate power loss. [Figure 11b](#) is a typical image after hail impact, showing a limited loss of output power. The same

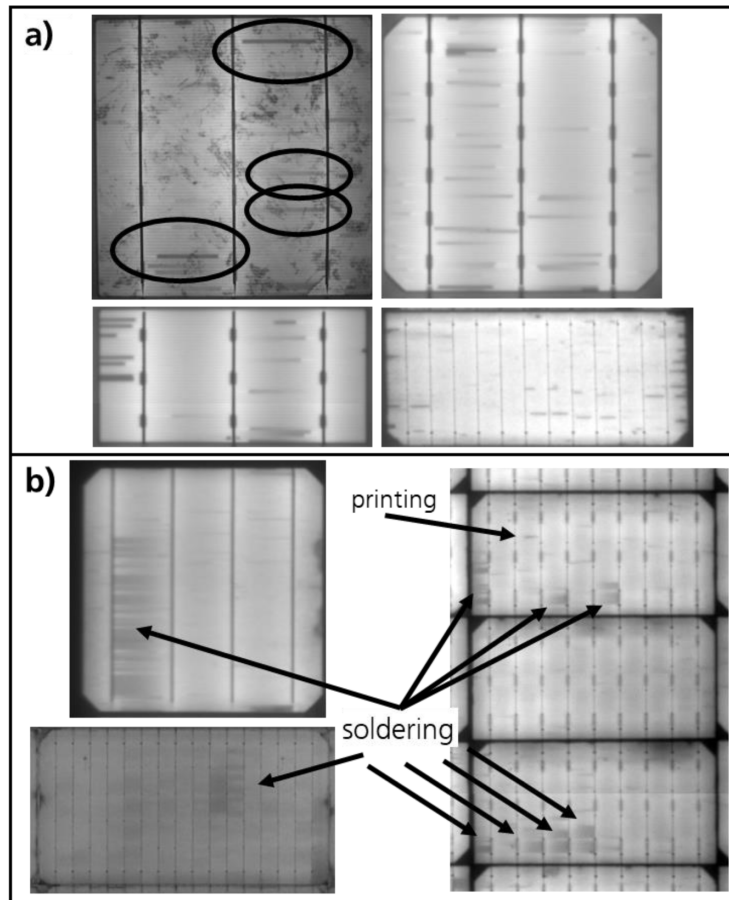


Fig. 8. Example images of finger interruptions: a) typically caused during cell metallization printing, b) interruptions at busbar possibly caused by misaligned ribbons on cell during soldering.

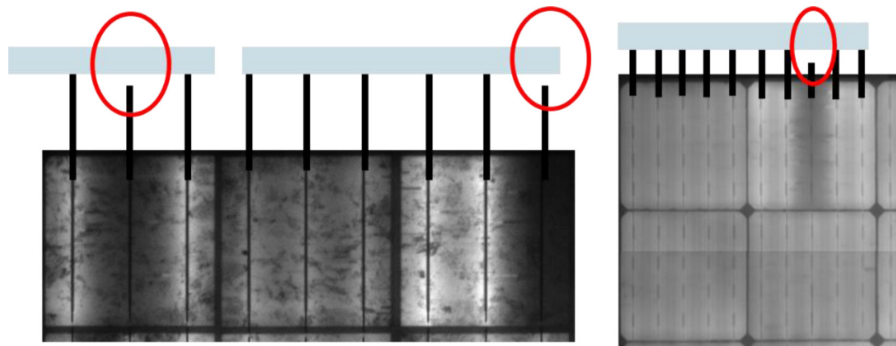


Fig. 9. Examples of missing (or broken) solder bonds to cross-connector.

reasoning (for mechanical load) regarding potential for increased power loss applies here as well. [Figure 11c](#) depicts a PV module with glass breakage resulting from an impact load test. While there is a significant power loss, this PV module also represents an electrical safety risk due to the glass breakage and must be replaced regardless.

3.3.5 PID, LeTID, UVID

This type of observation will not occur for newly built PV modules, it requires specific environmental stress to manifest. In EL imaging, PID (Potential induced degradation), LeTID (Light and elevated temperature induced degradation) and UVID (UV-induced degradation) exhibit

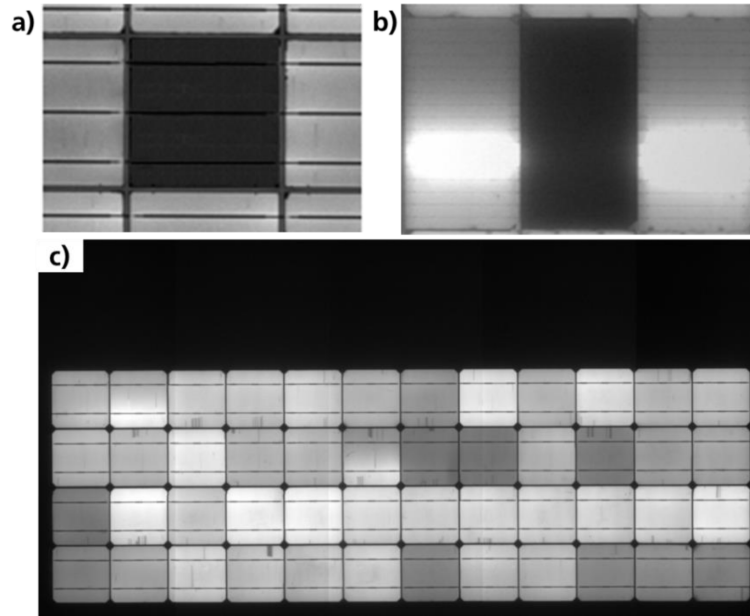


Fig. 10. Completely dark cells within the electric circuitry. a) and b): shorted individual cells within a string, c): shorted bypass diode that reduced PV module output to 2/3.

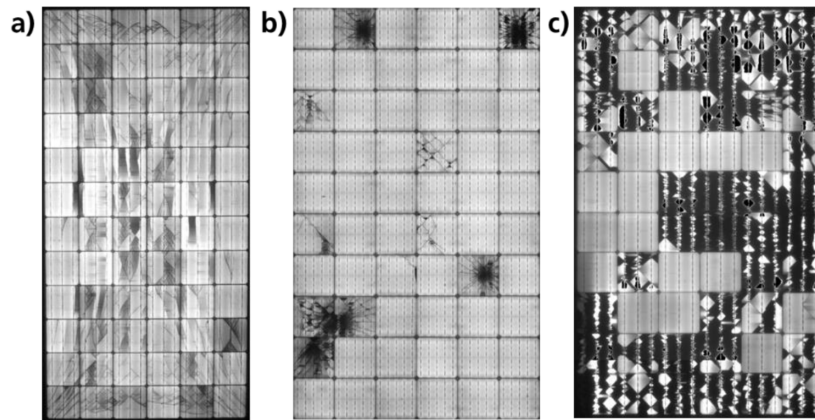


Fig. 11. Example images of a) severe homogeneous applied static load, b) Point-like loads caused by impact such as larger hail, c) severe impact with glass breakage.

very similar pattern (see Fig. 12), albeit with significant different power losses. Individual cells show a (very) homogeneous darkening, ranging from light to fully dark cells.

The different mechanisms are associated with varying different power loss and subsequently distinct root causes. PID is well known to cause significant power losses in AlBSF-type PV modules, while LeTID is associated with PERC cells, typically resulting in a few percent of power loss. UVID, a relatively new failure mode, is linked to TOPCON-based PV modules and can lead to power losses exceeding those of LeTID.

3.3.6 Pattern caused by moisture ingress

Similar to the previous subsection, this type of observation does not occur in new PV modules. It requires either extended damp-heat testing or long-term exposure of PV

module in a very warm and humid installation environment. Example images for individual cells are provided in Figure 13, where typically all cells in a PV module exhibit a similar pattern. There is generally no significant loss in open circuit voltage nor short circuit current, however, substantial fill factor losses are observed, leading to power reductions of more than 50%. The example image from outdoor exposure showed approximately 15% loss in output power.

3.4 Miscellaneous

The final section of found observations includes other common problems encountered in PV modules. Most of these are primarily “cosmetic” and do not impair the reliability of the PV modules. However, some may have implications for newer cell technologies.

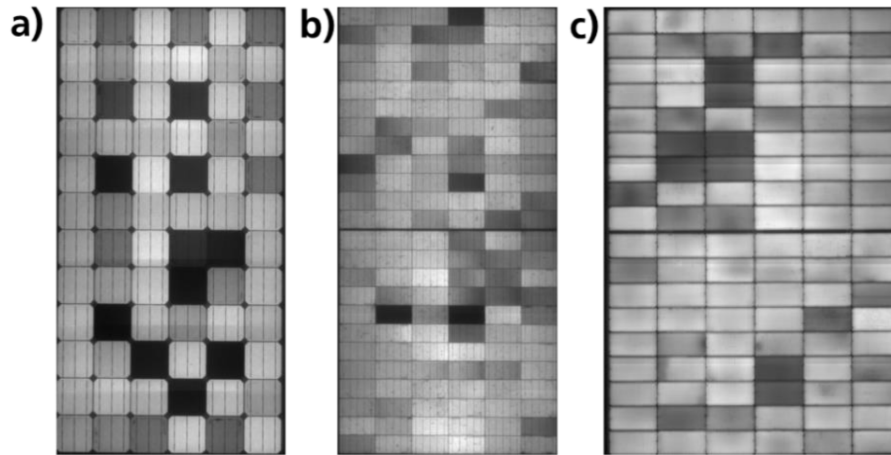


Fig. 12. Example images of a) PID from an AIBSF PV module, b) LeTID from an PERC cell PV module and c) UVID from a TOPCON-cell PV module.

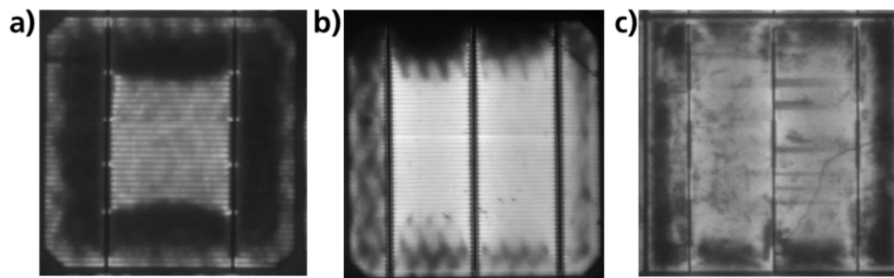


Fig. 13. Moisture induced darkening pattern: a) and b) after extended damp-heat testing, c) after ~10 years in the field.

3.4.1 Dark spots

Dark spots are tiny dark areas (in the mm-range), typically circular in shape, found within the solar cell (see Fig. 14). The observable dimension may vary depending on the current injection used for capturing the EL image (Fig. 14d). As dark spots are primarily caused during the ingoting, wafering and cell production, their impact (e.g. in terms of shunting and causing hot-spots) is generally low. Significant losses in local cell efficiency would have been detected during cell testing and sorting. However, low-grade or low-quality PV modules may contain a substantial number of dark spots, potentially leading to findings such as poor low light performance.

3.4.2 Wafer related structure

This type of observation summarizes reoccurring observations from ingot production that manifest as consistent structures in neighboring wafers. For mono-crystalline cells this observation appears as circular dark/bright rings within the solar cell (see Fig. 15a). Such pattern can't occur in multi-c-Si material, as they require a predefined ingot pulling direction and heating zones, leading to variations in contaminations within the wafer. In multi-c-Si material darker grayish areas may appear along one or two cell edges

(see Fig. 15b). For AIBSF and PERC cells, there is no known impact on long term stability. However, this may differ for next-gen cells such as TOPCON or HJT, depending on the degradation mode.

3.4.3 Belts structures

Belt-like patterns, typically spanning the full cell with varying visibility (see Fig. 16), are generally not known to have an impact on long term stability. These patterns are caused by non-optimal firing process during cell manufacturing, and any associated performance losses are considered during cell sorting. Since the root cause lies within the firing process (higher temperatures $>200^{\circ}\text{C}$), this type of observation is typically stable during use, even in high temperature climates.

3.4.4 Solar Cell “artefacts”

This type of observation encompasses various features visible in EL imaging that originated from solar cell manufacturing. These features are characterized by different shaped, often reoccurring darker and brighter areas within the solar cells. Some examples are given in Figure 17. Due to the known root cause, the impact on long term stability is considered to be low.

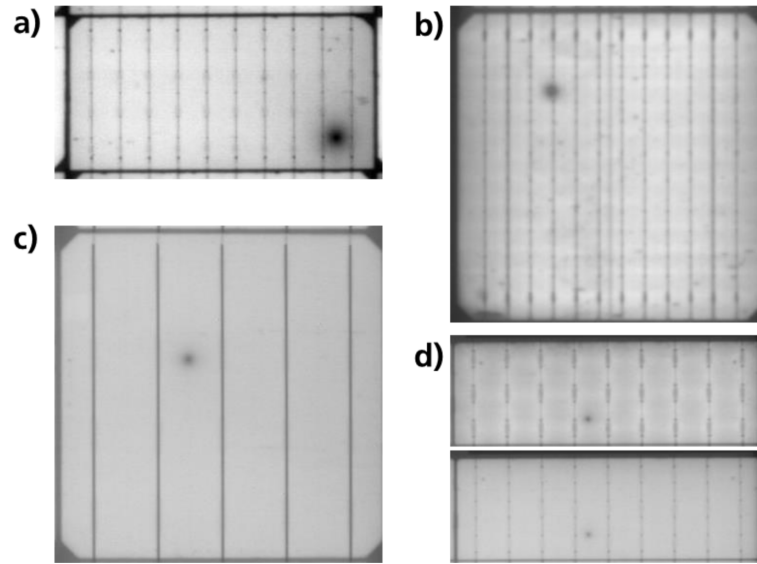


Fig. 14. Dark spots on different cell formats and cell cuts (a) to d)). d) is a third cut cell exemplarily shown with Isc-current (top) and 10% Isc current (bottom).

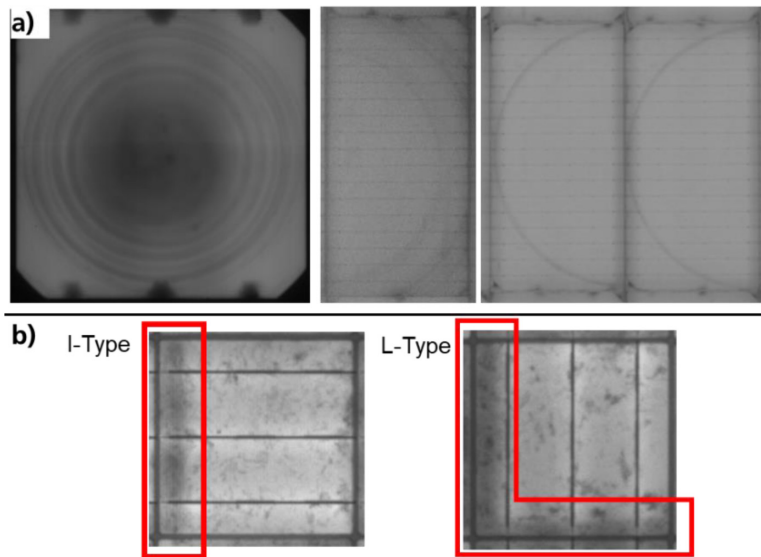


Fig. 15. a) Rings in the mono crystalline wafer, b) darker regions in multi-crystalline wafers (cells) caused by position of wafer in brick.

However, features like those in Figure 17c may have greater impact on future cell technologies, such as tandem cells, due to the potential interaction between top and bottom cell. Once such cells enter the mass market, a more accurate assessment can be made.

3.4.5 Grayish and darker areas

Grayish and darker areas can occasionally be observed on some solar cells (see Fig. 18). These areas often vary in shape, size and brightness in EL images. They may be caused by different stages during cell manufacturing, such as edge passivation. Significant edge passivation issues

can lead to potential hot-spot risks, as well as reduced solar cell efficiencies and poor low-light behavior performance. Consequently, their occurrence is relatively rare today. The impact on next generation cells is currently unknown and requires further research.

3.4.6 Scratches

The last category of observations includes scratches. These appear as artificial looking pattern with various shapes, randomly orientated across the cell, different in size and brightness. Some examples are given in Figure 19. Scratches can be induced at different stages during cell

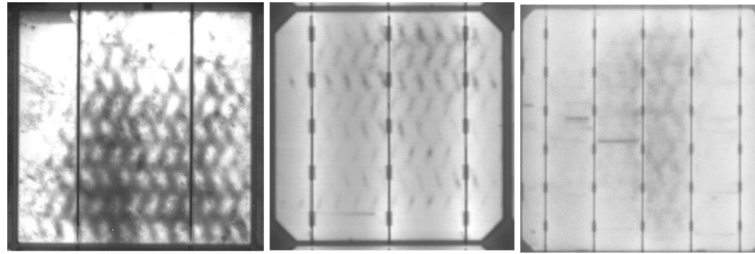


Fig. 16. Belt-like pattern, typically across the full cell.

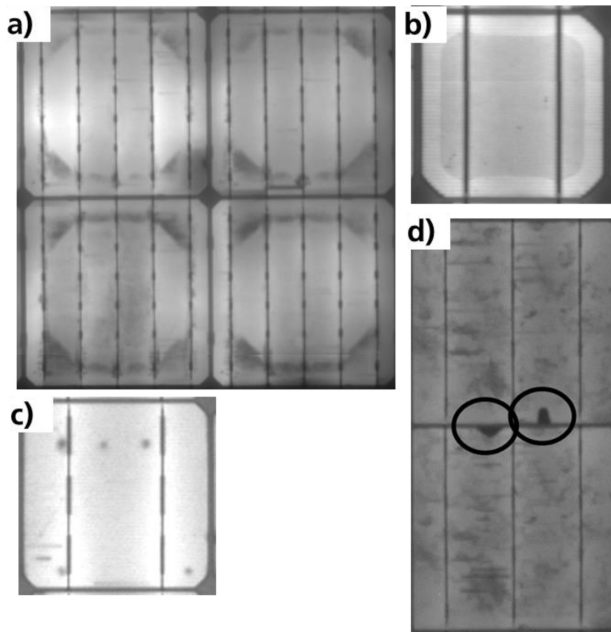


Fig. 17. Different, often reoccurring, shaped darker/brighter areas within the solar cells. a) and b) typically caused by the cell holder during e.g. ARC deposition, c) suction cups from cell handling and d) printing issue on rear side of solar cell (here AIBSF cell).

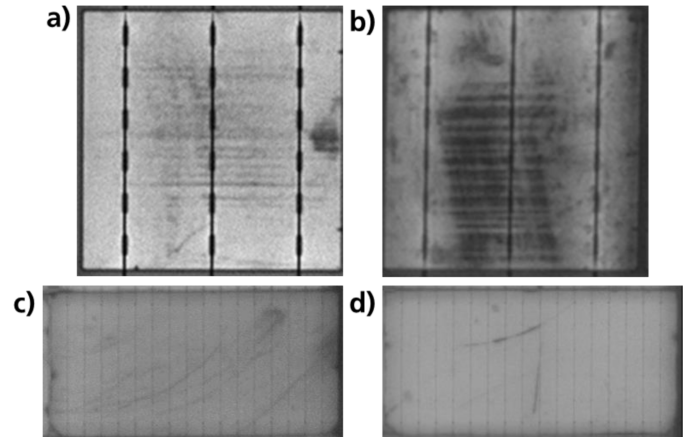


Fig. 19. Different kinds of scratches on c-Si solar cells.

and PV module manufacturing through the use of handling tools. If no cell cracking occurs during the scratching, the structure is likely stable in terms of performance. However, if the front or rear side passivation is damaged, the overall performance of the affected cell will be lower, resulting in a performance loss for the entire PV module.

4 Classification

Electro-luminescence imaging is a valuable tool for assessing the general quality of PV modules. However, classifications are primarily based on company standards, such as those used for end-of-line quality control or defined in contracts between manufacturer and buyer.

In [Section 3](#) various observations were defined, exemplified, and briefly discussed regarding their root causes and potential impacts on output power of the PV module. It is important to note that while EL can qualitatively support statements about power loss, it cannot quantify them. Numerous typically unknown influencing factors exist, such as cell technology, mechanical design of the PV module, and the encapsulation system in general. Additionally, the imaging process itself must be considered. Factors such as the setup (camera, lenses, optical filters) and injection currents (e.g. near I_{sc} or 10% I_{sc}) will affect the visibility of observations and, consequently, the conclusions drawn.

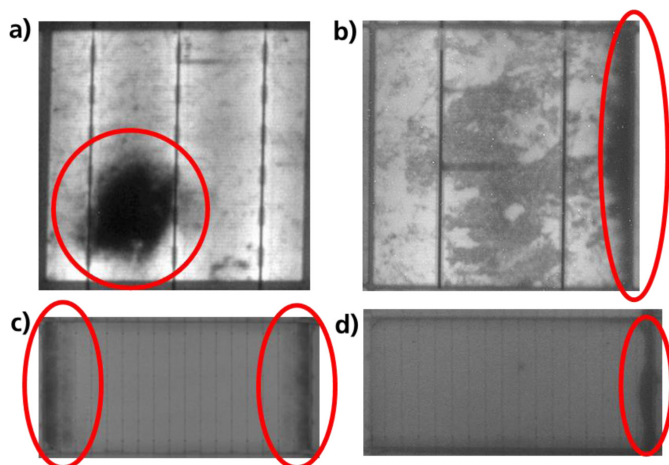


Fig. 18. Grayish and darker areas of the cell, differently shaped, different in size and brightness occurring in Mono and multi-crystalline Si cells.

Table 1. Classification proposal for selected observations; ditto always refer to the “after manufacturing” numbers.

Type of EL anomaly	After manufacturing: end of line inspection	After installation	In the field	After severe weather events
Single complete crack (Sect. 3.1.1)	$\leq 6\text{BB}$: max. 5 $> 6\text{BB}$: max. 5	Ditto	+1 per 5 years	+5
Single incomplete crack (Sect. 3.1.2)	$\leq 6\text{BB}$: max. 1 $> 6\text{BB}$: max. 5	Ditto	+1 per 5 years	+5
Dendritic crack structures (Sect. 3.2.3)	$\leq 6\text{BB}$: not allowed $> 6\text{BB}$: not allows	Ditto	Ditto	1 per PV module, follow-up inspection required
Tiny X-V cracks (Sect. 3.2.4)	$\leq 6\text{BB}$: max. 1 $> 6\text{BB}$: max. 2	Ditto	+1 per 5 years	+5
Finger interruptions per image type a) (Sect. 3.3.1)	Single finger interruptions: $\leq 6\text{BB}$: max. 20 per cell $> 6\text{BB}$: max. 30 per cell	Ditto	Ditto	Ditto
Finger interruptions per image type b) (Sect. 3.3.1)	Multiple interruptions at BB $\leq 6\text{BB}$: not allowed $> 6\text{BB}$: max. 1 per cell and 5 per 100 cells	Ditto	+1 per 5 years	Ditto
Complete dark cells (Sect. 3.3.3)	$\leq 6\text{BB}$: not allowed $> 6\text{BB}$: not allowed	Ditto	Replace PV module	Replace PV module

For general quality investigations, such as assessing cell handling or checking after strong storms, snow events, or hail, EL can be a valuable tool to initiate further investigations. Additionally, impacts related to system voltages (see Sect. 3.3.5) or significant moisture ingress can be indirectly observed as cell finger corrosion (see Sect. 3.3.6) leads to modifications in local cell surface resistance.

To establish an acceptable classification, several questions must be addressed, and a severity/ priority must be defined. The first consideration is whether the damage is critical enough to directly pose an electrical safety issue and/or harm individuals. The second consideration is the potential future development of the observation. Will there soon be an electrical safety concern or is there a risk of power loss that does not meet the manufacturer’s performance guarantees. Follow-up inspections may be required, and reclassification might be necessary after a certain period, typically 1 year for larger electrical systems [23–25], though this also depends on local regulations grid codes.

One of the next crucial questions is to determine whether the issue is an isolated case or a systematic fault that may necessitate the full replacement of all PV modules within the entire system.

The following paragraphs will discuss a few common observations. The classification will be divided based on different points in time when the EL imaging was conducted: after manufacturing (end-of-line inspection), after shipment, after installation and during operation.

Additionally, recommendations will be provided following severe weather events, such as extreme snow events, hailstorms, or floods.

A possible number of observations will be provided, “normalized” to a PV module of 100 cells, unless otherwise stated. There will be no If-then-linkage between the observations, meaning that if two observations are permissible, the stated number for each observation can occur independently. Furthermore, a distinction will be made between cells with ≤ 6 busbars (BB) and those with more than 6BB. The Threshold 6BB was chosen as it represents a sort of industry chosen barrier. Solar cells with ≤ 6 BB typically exist alongside those with ≥ 9 BB. For cells with $\geq 9\text{BB}$ the potential power loss is significantly reduced due to the redundancy of the electrical cell connections. The proposed numbers are derived from existing failure catalogues from manufactures, testing laboratories, and consultants, reflecting a baseline understanding of minimum quality levels.

The end-of-line criteria primarily aim to enhance manufacturing quality through proper handling of cell and PV module. These criteria do not yet serve as performance benchmarks. Similarly, an EL inspection after shipping can be conducted in the same manner. Transportation boxes are designed to ensure safe transport, and thus the number of observations allowed should remain unchanged.

Upon arrival on site, the installer assumes responsibility for proper handling of the PV modules, including staff training. Consequently, the liability for an increased number

of observations largely falls on the installer. Poor handling or installation practices can't be attributed to the PV module manufacturer. However, there is a possibility that additional cracks or other observations may occur during the installation process. Large and heavy PV modules can be challenging to handle, increasing the likelihood of damage. Modern glass/glass PV modules typically exhibit glass breakage rather than cell breakage. The column "after installation" is intended to address this, as it represents the next potential handover (installer to operator). Due to the lack of detailed information for discussion purposes, the number of observations allowed is maintained at the same level as after shipping.

After installation, the longest period begins: operation. During this phase, many factors can impact the performance of the PV modules, and effects of climate must be considered. General guidance on climate impact can be derived from the photovoltaic modified climate classification of Koeppen-Geiger [64,65] and proper mission profiling [66] during the planning phase of the PV power plant.

Table 1 summarizes the different periods and presents initial numbers for allowed observation. The numbers after manufacturing are based on best practices, while the others are not yet documented and should serve as a preliminary guide and starting point for clearer statements along the value chain. Follow-up discussion, including ongoing research on power loss as function of number of busbars [67] and cell technology, are expected to provide further insights and more solid arguments for reasonable limits on permissible observations.

The criteria stated in Table 1 were selected to suggest when the module should be identified as having inferior quality at the time of manufacture or to be identified as having higher risk of failure if the observation is made after certain use. It may further serve as a basis for delivery contracts between manufacturer and EPC where EL imaging is used as additional quality assurance tool. The specific tolerances can be changed depending on the number of cells and cell technology.

5 Summary

Electro-luminescence provides a powerful tool to investigate the quality of PV module manufacturing and the care taken during transportation, installation and use. It is a straightforward imaging technique that can identify trends, such as crack growth. However, the industry lacks unified nomenclature. This paper offers a detailed overview of EL observations and explicitly names them, with the results forming a key part of the upcoming VDE SPEC 90031 [30]. Both the paper and the VDE SPEC aim to support a common nomenclature for EL images and location mapping of observations.

The observations are divided into four categories for straightforward initial sorting. Each category includes more detailed descriptions and specific names. The four

categories of observations are: 1) single cracks, 2) multi-cracks, 3) anomalies in the electrical circuit and all others into 4) miscellaneous.

The naming of observations applies to all existing and new cell types, as long as they are crystalline wafer based. This nomenclature is independent of wafer/cell size (from "old" 4" to new M/G12), shape (full, half, third, x-cut), material (mono, multi), or silicon cell technology (AlBSF, PERC, TOPCON, HJT, IBC, Perovskite on Si). Even the design of the PV module (size, glass/backsheet, glass/glass, internal wiring of the electric circuit) does not affect the naming and locating observations.

EL is primarily a qualitative tool. When estimating power impact, the numbers can vary significantly and strongly depend on type of observation, cell technology and PV module design. Therefore, it is challenging to classify EL observations into clear pass / fail criteria. For future discussion and reference a few examples are discussed in Section 4.

The main observations are included in the English version of a VDE-SPEC 90031 [30]. Major parts have already been presented to IEC TC 82 WG 2. The next steps involve integrating the clear nomenclature of the VDE SPEC into existing IEC documents [27,28]. Following that, the classification matrix will be further developed and discussed within various scientific and normative groups.

Acknowledgments

The authors would like to thank Stephan Rupp (Hanwha Q CELLS GmbH) for fruitful discussion regarding the grouping of the observations and their definition. The authors would like to thank all that contributed to the Project "PV-Riss" for the fruitful discussions at various stages of the project.

Funding

The authors gratefully acknowledge the financial support by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) of the project "PV-Riss" with grant #03TN0033A.

Conflicts of interest

There are no financial conflicts of interest. There are no specific trade names or similar used.

Data availability statement

This article has no associated data generated and/or analyzed.

Author contribution statement

Bengt Jaeckel: Methodology design, data evaluation and writing of paper. Matthias Pander and Paul Scheck: result discussion and proof-reading. Aswin Linsenmeyer and Jochen Kirch: discussion, proof-reading and data sharing.

References

1. Y. N. Fuyuki, Quantitative imaging of excess minority carrier density in crystalline silicon cells by Luminoscopy, in *21st European Photovoltaic Solar Energy Conference* (2006)
2. U. Jahn, Review on infrared and electroluminescence imaging for PV field applications, Report IEA-PVPS T13-10: 2018
3. VDI 2879 SPEC, Inspection of installations and buildings with UAVs (unmanned aerial vehicles), 2018
4. ITRPV, International Technology Roadmap for Photovoltaic (ITRPV), 2024
5. Solar Power Europe, Global Market Outlook for solar power 2023–2027
6. M. Koentges, Elektrolumineszenzmessung an PV-Modulen, Photovolt. Aktuell, **7/8**, 36 (2008)
7. M. Koentges, Review on failures of photovoltaic modules, Report IEA-PVPS T13-01: 2014
8. M. Koentges, Assessment of PV modules failures in the field, Report IEA-PVPS T13-09: 2017
9. W. Herrmann, Qualification of photovoltaic (PV) power plants using mobile test equipment, Report IEA-PVPS T13-24: 2021
10. B. Jaeckel, Looking into the future, PV Mag. **10**, 46 (2013)
11. MBJ PV-Modul Bewertungskriterien, MBJ PV-modul bewertungskriterien – bewertungskriterien für die PV-modulprüfung im mobilen PV-testcenter, MBJ (2014)
12. PV-Riss, Bewertung von Zellrissen in kristallinen Silizium-Photovoltaikmodulen mittels bildgebender Verfahren, BMBK Wipano funding by PTJ, 2022–2024
13. E. Sander, Schneckenspuren, ETA Green **1**, 3 (2011)
14. S. Richter et al., Understanding the snail trail effect in silicon solar modules on microstructural scale, in *27th European Photovoltaic Solar Energy Conference* (2012), <http://www.doi.org/10.4229/27thEUPVSEC2012-4BV.3.7>
15. I. Duerr et al., Silver grid finger corrosion on snail track affected PV modules investigation on degradation products and mechanisms, Energy Pro. **98**, 74 (2016)
16. IEC 61215-series: Terrestrial photovoltaic (PV) modules – design qualification and type approval
17. IEC TR 62759-1: Photovoltaic (PV) modules – transportation testing – part 1: transportation and shipping of module package units
18. IEC TS 62782: Photovoltaic (PV) modules – cyclic (dynamic) mechanical load testing
19. IEC 62892: Extended thermal cycling of PV module
20. IEC TS 63209-1: Photovoltaic modules – extended-stress testing
21. IEC TS 63209-2: Photovoltaic modules – extended-stress testing – part 2: polymeric component materials
22. IEC TR 63279: Derisking photovoltaic modules – sequential and combined accelerated stress testing
23. IEC 62446-1: Photovoltaic (PV) systems – requirements for testing, documentation and maintenance – part 1: grid connected systems – documentation, commissioning tests and inspection
24. IEC 62446-2: Photovoltaic (PV) systems – requirements for testing, documentation and maintenance – part 2: grid connected systems – maintenance of PV systems
25. IEC 60364-7-712: Low voltage electrical installations – part 7-712: requirements for special installations or locations – solar photovoltaic (PV) power supply systems
26. IEC 62446-3: Photovoltaic (PV) systems – requirements for testing, documentation and maintenance – part 3: photovoltaic modules and plants – outdoor infrared thermography
27. IEC 62446-4: Photovoltaic (PV) system – requirements for testing, documentation and maintenance – part 4: photovoltaic modules and plants – outdoor electroluminescence imaging, project team working on document
28. IEC TS 60904-13: Photovoltaic devices – part 13: electroluminescence of photovoltaic modules
29. K. Bedrich et al., Electroluminescence imaging of PV devices: camera calibration and image correction, in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)* (2016), <https://doi.org/10.1109/PVSC.2016.7749875>
30. VDE SPEC 90031: Electroluminescence (EL) of photovoltaic modules – terms and classification
31. M. Koentges et al., Quantitative analysis of PV-modules by electroluminescence images for quality control, in *24th European Photovoltaic Solar Energy Conference* (2009)
32. M. Koentges et al., Quantifying the risk of power loss in PV modules due to micro cracks, in *25th European Photovoltaic Solar Energy Conference* (2010), <http://www.doi.org/10.4229/25thEUPVSEC2010-4BO.9.4>
33. T. Potthoff et al., Detection of the voltage distribution in photovoltaic modules by electroluminescence imaging, Prog. Photovolt.: Res. Appl. **18**, 100 (2010)
34. S. Kajari-Schroeder et al., Spatial and directional distribution of cracks in silicon PV modules after uniform mechanical loads, in *37th IEEE Photovoltaic Specialists Conference Seattle, Washington* (2011)
35. M. Koentges et al., Crack statistic of crystalline silicon photovoltaic modules, in *26th European Photovoltaic Solar Energy Conference* (2011), <http://www.doi.org/10.4229/26thEUPVSEC2011-4EO.3.6>
36. M. Koentges et al., The risk of power loss in crystalline silicon based photovoltaic modules due to micro-cracks, Sol. Energy Mater. Sol. Cells **95**, 1131 (2011)
37. S. Kajari-Schroeder et al., Criticality of cracks in PV modules, Energy Procedia **27**, 658 (2012)
38. B. Jaeckel et al., Long term statistics on micro cracks and their impact on performance, in *33rd European Photovoltaic Solar Energy Conference* (2017), <http://www.doi.org/10.4229/EUPVSEC20172017-5CO.5.6>
39. J. Arp et al., Elektrisches Schalten von Mikrocracks: Leistungsverlust: Ja, Nein, Ja (PV Symposium, 2016)
40. C. Buerhop-Lutz, Qualitätsmanagement rissbehafteter PV-Module (PV Symposium, 2019)
41. PVTech.org, TOPCon modules endure ‘significant degradation’ in damp heat testing compared to PERC, accessed 29.06.2024
42. C. Sen et al., Buyer aware: three new failure modes in TOPCon modules absent from PERC technology, Sol. Energy Mater. Sol. Cells **272**, 112877 (2024), <https://doi.org/10.1016/j.solmat.2024.112877>

43. C. Sen et al., Accelerated damp-heat testing at the cell-level of bifacial silicon HJT, PERC and TOPCon solar cells using sodium chloride, *Sol. Energy Mater. Sol. Cells* **262**, 112554 (2023), <https://doi.org/10.1016/j.solmat.2023.112554>
44. X. Wu et al., Addressing sodium ion-related degradation in SHJ cells by the application of nano-scale barrier layers, *Sol. Energy Mater. Sol. Cells* **264**, 112604 (2024), <https://doi.org/10.1016/j.solmat.2023.112604>
45. T. Silverman et al., Movement of cracked silicon solar cells during module temperature changes, in *47th IEEE Photovoltaic Specialists Conference* (2019), <https://doi.org/10.1109/pvsc40753.2019.8981150>
46. C. Buerhop et al., Evolution of cell cracks in PV-modules under field and laboratory conditions, *Prog. Photovolt.* **26**, 261 (2018)
47. J. Lincoln et al., Microcrack formation in silicon solar cells during cold temperatures, in *46th IEEE Photovoltaic Specialists Conference* (Florida, 2019)
48. C. Buerhop-Lutz et al., Influence of the module temperature on the performance and EL-image of precracked PV-modules, in *35th European Photovoltaic Solar Energy Conference* (2018), <http://www.doi.org/10.4229/35thEUPVSEC20182018-5CV.1.1>
49. C. Buerhop-Lutz et al., Performance analysis of pre-cracked PV-modules at cyclic loading conditions, in *35th European Photovoltaic Solar Energy Conference* (2018), <http://www.doi.org/10.4229/35thEUPVSEC20182018-6BO.6.6>
50. C. Buerhop-Lutz et al., Analysis of digitized PV-module/system data for failure diagnosis, in *36th European Photovoltaic Solar Energy Conference* (2019), <https://doi.org/10.4229/EUPVSEC20192019-5BO.7.6>
51. W. Muehleisen et al., Outdoor detection and visualization of hailstorm damages of photovoltaic plants, *Renew. Energy* **118**, 138 (2018)
52. M. Koentges et al., Mean degradation rates in PV systems for various kinds of PV module failures, in *32nd European Photovoltaic Solar Energy Conference* (2016), <https://doi.org/10.4229/EUPVSEC20162016-5DP.1.2>
53. D.C. Jordan, S. R. Kurtz, Photovoltaic degradation rates – an analytical review, *Prog. Photovolt.: Res. Appl.* **21**, 12 (2011), <https://doi.org/10.1002/pip.1182>
54. D.C. Jordan et al., Compendium of photovoltaic degradation rates, *Prog. Photovolt.: Res. Appl.* **24**, 978 (2016), <https://doi.org/10.1002/pip.2744>
55. D.C. Jordan et al., PV field reliability status – analysis of 100 000 solar systems, *Prog. Photovolt.: Res. Appl.* **28**, 739 (2020), <https://doi.org/10.1002/pip.3262>
56. FAU Erlangen Nürnberg EL image database for AI-Training, <https://github.com/zae-bayern/elpv-dataset/tree/master/images>, accessed 02.10.2024
57. C. Buerhop-Lutz et al., A benchmark for visual identification of defective solar cells in electroluminescence imagery, in *European PV Solar Energy Conference and Exhibition* (2018), <https://doi.org/10.4229/35thEUPVSEC20182018-5CV.3.15>
58. C. Buerhop-Lutz et al., Applying deep learning algorithms to EL-images for predicting the module power, in *European PV Solar Energy Conference and Exhibition* (2019), <http://www.doi.org/10.4229/EUPVSEC20192019-4CO.1.2>
59. S. Deitsch et al., Segmentation of photovoltaic module cells in uncalibrated electroluminescence images, *Mach. Vis. Appl.* **32**, 84 (2021), <https://doi.org/10.1007/s00138-021-01191-9>
60. S. Deitsch, V. Christlein, S. Berger, C. Buerhop-Lutz, A. Maier, F. Gallwitz, C. Riess, Automatic classification of defective photovoltaic module cells in electroluminescence images, *Sol. Energy* **185**, 455 (2019), <https://doi.org/10.1016/j.solener.2019.02.067>
61. Case Western Reserve University EL image database for AI-Training, <https://osf.io/qt5hj/>
62. A.M. Karimi et al., Automated pipeline for photovoltaic module electroluminescence image processing and degradation feature classification, *IEEE J. Photovolt.* **9**, 1324 (2019), <http://doi.org/10.1109/JPHOTOV.2019.2920732>
63. Duramat EL image database for AI-Training, <https://datahub.duramat.org/project/electroluminescence-image-analysis>, <https://github.com/hackingmaterials/pv-vision/tree/main>
64. M. Kottek et al., World map of the Köppen-Geiger climate classification – updated, *Meteorol. Z.* **15**, 259 (2006), <https://doi.org/10.1127/0941-2948/2006/0130>
65. J. Ascencio-Vasquez et al., Methodology of Köppen-Geiger-Photovoltaic climate classification and implications to worldwide mapping of PV system performance, *Sol. Energy* **191**, 672 (2019), <https://doi.org/10.1016/j.solener.2019.08.072>
66. B. Jaeckel et al., Mission profile concept for PV modules: use case middle east deserts vs temperate European climate, *EPJ Photovolt.* **14**, 39 (2023), <https://doi.org/10.1051/epjpv/2023030>
67. P. Schenk, Influence on number of busbars and cell technology on power loss after mechanical and thermomechanical stress testing, in preparation

Cite this article as: Bengt Jaeckel, Matthias Pander, Paul Schenk, Aswin Linsenmeyer, Jochen Kirch, Nomenclature and description of Electro-Luminescence (EL) observations: Cell cracks and other observations, *EPJ Photovoltaics* **15**, 44 (2024)