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Enhancing photovoltaic module sustainability: Defect analysis on partially repaired modules from Spanish PV plants

M.B. Nieto-Morone [a,b,*], F.G. Rosillo [a], M.A. Muñoz-García [b], M.C. Alonso-García [a]

[a] *Unidad de Energía Solar Fotovoltaica, Departamento de Energía, CIEMAT. Av. Complutense, 40, 28040, Madrid, Spain*
[b] *ETSIAAB, LPF-TAGRALIA. Universidad Politécnica de Madrid, Av. Puerta de Hierro, n° 2, 28040, Madrid, Spain*

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ABSTRACT

Between 2010 and 2022, there has been a significant increase in photovoltaic (PV) solar energy installations, driven by factors such as cost reductions, technological advances, policy support and innovative financing approaches. However, this rapid growth has created a significant challenge in the form of increased PV waste generation, coinciding with global commitments to achieve carbon neutrality by 2050. The potential for reuse of decommissioned PV modules represents an environmentally sustainable way forward that requires a comprehensive assessment of technical, economic, environmental and regulatory considerations. This study focuses on evaluating the impact of defects in partially repaired PV modules from Spanish installations on their power output and efficiency, with the aim of developing strategies to increase reuse and reduce environmental impact. The research focuses on 23 crystalline silicon modules and uses established techniques to evaluate their operational condition, detect defects and assess potential safety risks. Among the defects observed, moisture-induced degradation (MID) emerges as the most prevalent, followed by cracked cells and disconnected areas in cells across different technologies. Notably, despite the presence of defects, approximately 87 % of these modules have a power loss of less than 20 %.

1. Introduction

According to Renewable Energy Agency (2023), photovoltaic solar energy installations experienced outstanding growth during the 13-year period from 2010 to 2022, showing a remarkable twenty-sixfold increase. This substantial expansion was driven by cost reductions facilitated by technological advancements, accelerated learning curves, strong policy support and the introduction of new financing approaches. The widespread deployment of photovoltaic (PV) systems presents a significant challenge for the future, which is the large quantities of PV waste that will result from the decommissioning of large numbers of PV modules over the next few decades, coupled with the global commitment to carbon neutrality by 2050.

Several studies have estimated the mass of PV waste generated in the European Union (EU) and China for the years 2030 and 2050 (Liu et al., 2023; Nieto-Morone et al., 2023). These reports indicate that the EU will have to manage a cumulative PV waste mass of 2.5 M tons in 2030 and 22.3 M tons in 2050. Moreover, China is projected to have a similar amount of PV waste mass to the EU in 2030 but is expected to exceed it by 66 % in 2050. As this prospect approaches, it is highly relevant to consider innovative strategies beyond conventional recycling techniques to address the end-of-life phase of PV modules. It is essential to distinguish between end-of-life modules and those that remain operational and could yield income or tax benefits if sold or reused for second-life applications based on their performance. Alternatively, module recycling and disposal may impose significant economic and environmental costs (Komoto et al., 2018; Libby and Shaw, 2018). Regarding material composition, approximately 95 % of the components found in solar modules can be recycled. Considering the typical lifespan of solar panels is roughly 25 years, a substantial number of solar panels worldwide are nearing the end of their operational lives.

The possibility of reusing decommissioned PV modules offers a promising prospect for establishing sustainable and lasting reuse practices. However, a thorough examination of complex technical, economic, environmental, and regulatory factors is required to navigate the complex universe of reuse of end-of-life PV modules. As the installed capacity of photovoltaic systems continues to increase, effective management of the electronic waste generated by PV modules reaching the

* Corresponding author. Unidad de Energía Solar Fotovoltaica, Departamento de Energía, CIEMAT. Av., Complutense, 40, 28040, Madrid, Spain.
E-mail address: mariabeatriz.nieto@ciemat.es (M.B. Nieto-Morone).

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end of their operational life is becoming increasingly necessary.

In response to this challenge, the European Union (EU) introduced Directive 2012/19/EU aimed at regulating the handling of Waste Electrical and Electronic Equipment (WEEE), which includes provisions explicitly addressing the recycling of PV modules. This directive includes the principle of extended producer responsibility (EPR), which mandates that PV module manufacturers are responsible for disposing and treating their products at the end of their operational lifespan. The regulation also forbids mixing PV panels with other types of waste, such as demolition materials. It requires silicon-based modules to be handled separately from those that use different technologies (European Parliament, 2012).

At the global level, the Basel Convention (United Nations Environment Programme, 1998), established in 1989, sets out rules for the international shipment of various types of waste, including electronic waste. Within the European Union (EU), the Waste Shipment Regulation of 2006 (European Parliament, 2006) which originally dates back to 1993, sets out the guidelines for cross-border waste shipments within, into, and out of the EU, acting as the European implementation of the Basel Convention. To prevent the misuse of repaired modules, legislation on the adequate preparation and reuse of PV modules requires establishing clear conditions for their preparation and reuse. The export of real PV module waste under the guise of labelling it as 'used' modules, a common illegal practice in the electronic waste sector, is an illustrative example of such misuse (Kiddee et al., 2013).

A comprehensive evaluation of the potential applications for second-hand PV modules unveils a dynamic and varied landscape. Currently, high-income economies are highly inclined towards specific scenarios. These include replacing faulty PV modules to maintain systems that still benefit from feed-in tariffs. This approach is also an economically viable means of extending the life of PV systems. In contrast, low-income countries are increasingly exploring using second-hand PV modules to construct new, small-to-medium-sized PV systems, particularly in off-grid or remote areas. These modules usually stem from large-scale power plants that may have withstood severe environmental conditions or transitioned away from feed-in tariff incentives. (van der Heide et al., 2022).

However, a notable obstacle in this sector is the lack of clearly defined technical and legal measures for assessing the suitability of PV modules that have the potential to be re-used. This scarcity of guidelines is compounded by the absence of comprehensive global policies addressing the management of PV waste and mitigating the environmental impact worldwide. It is, therefore, imperative to improve economic feasibility and practicality, achieve high recovery rates, and enhance environmental performance (Chowdhury et al., 2020).

Distinguishing between a viable PV module and electronic waste is not as trivial as assessing typical consumer electronics. It is imperative to establish a protocol for evaluating the features of a PV device. The working committee of "IEC TR 63525 ED1: Reuse of PV modules and circular economy" is currently developing a standard protocol for assessing the characteristics of reusable PV to promote the creation of a robust and sustainable market for their reuse.

Therefore, to build confidence and create opportunities for re-use PV markets, it is essential to understand and practically validate the performance, reliability, and safety of re-use PV modules. IEC 61730 (International Electrotechnical Commission, 2006) based high-voltage test is a common practice among repair service providers. As a result, each refurbished PV module is electrically characterised following this standard qualification. But the re-certification of repaired panels is still a long way off. The PV industry has accumulated significant expertise in addressing module reliability concerns, primarily through "design qualification" and "type approval" testing protocols conducted in controlled laboratory environments by International Electrotechnical Commission (IEC) standards. Consequently, the current framework for PV qualification testing does not offer a precise evaluation of the actual lifespan of PV modules, nor does it establish connections with specific repairable fault modes for conducting comprehensive assessments of second-life PV modules and their subsequent re-certification (Tsanakas et al., 2020).

In this context, this research aims to investigate the impact of defects in partially repaired PV modules on power output and efficiency loss. By understanding these effects, we aim to contribute to developing strategies for improving the reuse of PV modules, reducing electronic waste mass, and minimising the environmental cost associated with their lifecycle. The present study is an important preliminary step in the wider effort to facilitate the reuse of PV modules. Focusing specifically on 23 crystalline silicon (c-Si) partially repaired PV modules, including three distinct models decommissioned from working Spanish PV plants, this research employs a comprehensive standardised approach. It integrates visual inspection, electrical testing, electroluminescence imaging, and thermal imaging techniques to thoroughly evaluate the functional status of these modules and define the nature and extent of defects that persist post-repair. An in-depth examination of these defects holds the potential to substantially enhance the performance and lifespan of PV modules substantially, thereby boosting the overall sustainability of solar energy generation. Therefore, the meticulous characterisation of partially repaired PV modules assumes paramount importance in the pursuit of achieving reusable conditions, as it helps to determine not only their functional status but also identify potential safety hazards.

The study is structured as follows: Section II explores the materials and methodologies used in the analysis. Section III outlines the failures identified through the application of standardised techniques. Section IV provides a discussion and analysis of the results, and Section V completes the study by presenting the conclusions drawn from the research conducted.

2. Materials and methods

2.1. Tested PV modules

A Spanish company focused on repairing photovoltaic modules assesses whether the module can be repaired and if the cost of repair is outweighed by the expense of purchasing a new module, all from an economic perspective. The types of defects that are considered repairable are: damaged diodes, junction box replacement, minor damage to Tedlar, and broken or burnt cells. Our study material consists of 23 partially repaired modules purchased from this company in order to evaluate the restored power capacity achieved through these partial repairs. These modules have been in operation for a maximum of 12 years before decommissioning due to failures.

Three different module types were evaluated for the characterisation of partially repaired PV modules. A total of 23 PV modules were subjected to the qualification tests of the IEC 61215 (International Electrotechnical Commission, 2015) standard, i.e.: Visual inspection (MQT 01), Determination of maximum power (MQT 02), Insulation test (MQT 03), Wet leakage current (MQT 15), as well as electroluminescence and infrared imaging. Due to the modules' age, the insulation test conditions utilised in this study adhered to the 2015 version of the 61215 standard. The present standard's conditions are tailored for new modules.

The set of modules analysed consists of 5 monocrystalline Si, m-Si modules, referred to as type A, 5 p-Si modules, or type B, and 13 m-Si modules from another manufacturer, which fall under type C. Technical and electrical characteristics are shown in Table 1 and Table 2.

2.2. Visual inspection

To identify any visual defects, all 23 modules undergo optimum irradiance conditions, guaranteeing the lighting conditions required by the IEC 61215 standard Module Quality Test 01 (MQT 01) (International Electrotechnical Commission, 2005). Photographs of each module, both front and back, and any detected anomalies such as cracks, bubbles, and delamination were taken. Their position within the module was also

Table 1
Mechanical data corresponding to the three PV modules typologies evaluated.

Mechanical data	Type A	Type B	Type C
Length (mm)	1680	1660	2000
Width (mm)	990	990	1000
Thickness (mm)	50	50	50
Weight (kg)	24	21	25
Bypass diode	yes	yes	Yes
Modular construction	glass -polymer backsheet	glass – polymer backsheet	glass -polymer backsheet

Table 2
Electrical nominal parameters of the three module types analysed.

Nominal parameters	Type A	Type B	Type C
Tech.	m-Si	p-Si	m-Si
N° Cell	60	60	72
Isc (A)	8.20	8.06	8.36
Voc (V)	36.4	36.0	46.98
Pmax(W)	215	205	280
Imax (A)	7.48	7.39	7.81
Vmax (V)	28.8	27.7	35.89

documented.

2.3. Insulation test and wet leakage current test

Both IEC 61215 standards, MQT 03 and MQT 15 Module Quality Test, evaluate the insulation of the module under dry and wet atmospheric conditions, respectively. The two tests were conducted in accordance with IEC 61215 using a Chroma 19050 Series electrical tester with an accuracy of reading of ±4 % of the output with a load line and a multi-step function, which enables users to perform other tests. As stated in the standard, for the MQT 15, the shallow receptacle must contain a solution that meets specific electrical resistivity conditions. To confirm that the solution used met these criteria, the mixture's electrical conductivity was measured using a Mettler Toledo SevenMulti S470 pH and conductivity meter, which has a conductivity resolution of 0.001 μS/cm to 200 mS/cm.

2.4. I–V curve measuring

Information on the electrical parameters was acquired from solar modules under simulated light irradiance conditions in a flash-type solar simulator, Pasan Sun Simulator Class A. The measurements were conducted under Standard Test Conditions (STC) as per IEC 61215-2 standard; this is 25 °C of temperature and an irradiance of 1000 W/m^2, with an accuracy on tension and current of ±0.2 % at 25 °C.

2.5. Electroluminescence imaging

The Electroluminescence Images (EL) were captured following the IEC 62446-4 (International Electrotechnical Commission, 2021) standard and IEA report (Ulrike et al., 2018) specified method, including EL characterisation under Isc and 10 % Isc forward bias conditions in a dark room.

EL images were obtained using an Owl 640 II InGaAs digital camera with a resolution of 640 x 512 pixels, a DC Power supply SM 70 V-22 A with an accuracy on the output of ±0.5 %, and a computer with suitable data acquisition and processing software. A thermocouple and a voltmeter recorded the module's temperature and the voltage at the connections, respectively.

2.6. Infrared thermography imaging

For the infrared thermography (IR) technique, the camera measures the near-infrared electromagnetic radiation emitted from an object whose temperature is above absolute zero in the wavelength range of 8–12 μm. The incident radiation in the PV module is converted into electricity and heat; changing the current flow conditions allows it to register temperature changes due to irradiance fluctuations and create distinct cell temperature patterns that reveal more precise details of any failure. Similar procedures were implemented by (Waqar Akram et al., 2019) and (Bhoopathy et al., 2018).

IR images were taken using a FLIR SC640 Thermal Imaging camera with an accuracy of temperature reading of ±2 °C or ±2 %, a focal plane array of 640 x 480, and a thermal sensitivity of 60 mK at 30 °C. The analysis was carried out outdoors by taking images in three operating conditions. The first image was taken with no current flowing. Secondly, a photo was taken of the module operating near its maximum power point under the irradiance conditions of the experiment, and the third image was taken when the module was operating under short circuit conditions.

3. Results

3.1. Visual inspection

Fig. 1 shows some images from the visual inspection of the PV modules. The failures are identified according to the classification suggested by Ref (Kontges et al., 2018)

According to Kontges et al. (2018), the loss in power can take different shapes, for example, exponential-shaped, linear-shaped, step degradation, and saturating power loss over time. This categorisation delineates the progression of power loss from the initial level to a specific point in the operational lifespan of a PV module. Regarding the defects identified during the visual inspection that follows this classification (Kontges et al., 2018), Fig. 2 depicts their impact on power loss and each corresponding category.

Fig. 2 compares the results of module types A and C due to the similarity of their technologies and results. Type B, which is not included in Fig. 2, only exhibited an 80 % occurrence of exposed welds on the backsheet and no other visible anomalies. This irregularity results from the repair process and not a module failure. The completion of the repair process in this set of modules remains outstanding. The exposed welds are also found in types A and C, with percentages of 83% and 92%, respectively.

The results show that the modules exhibit optical degradation due to delamination and discolouration of the encapsulation. Delamination at the cell interface can be classified into two main types: front-side and backside delamination. Backside delamination usually appears as surface bubbles, which could cause the formation of hotspots, leading to a decrease in the system's energy output. In contrast, front-side delamination displays a distinct grey appearance when it arises at the cell interface (Meena et al., 2020).

Fig. 3 illustrates the presence of trapped moisture alongside corrosion and oxidation in the metal grids surrounding the solder joint. This effect is called Moisture-induced degradation, MID (Jeffries et al., 2021; Kim et al., 2013; Peike et al., 2013). This failure is mainly attributed to the dissolution of lead and tin in the presence of moisture and acetic acid, which is generated by photo-degradation of EVA encapsulant and cannot leave the module (Kraft et al., 2015; Oreski et al., 2019). The degradation mechanism of EVA starts with deacetylation followed by an oxidation and fragmentation of the main chain of vinyl acetate. (Czanderna, 1996) (see Fig. 3).

3.2. Insulation test and wet leakage current test

The PV's encapsulation system is purposely designed to insulate its electrical circuitry from the surrounding environment, minimising any potential hazard. Roy (2015) carried out dry and wet insulation tests to characterise the resistance to current flow in both conditions and

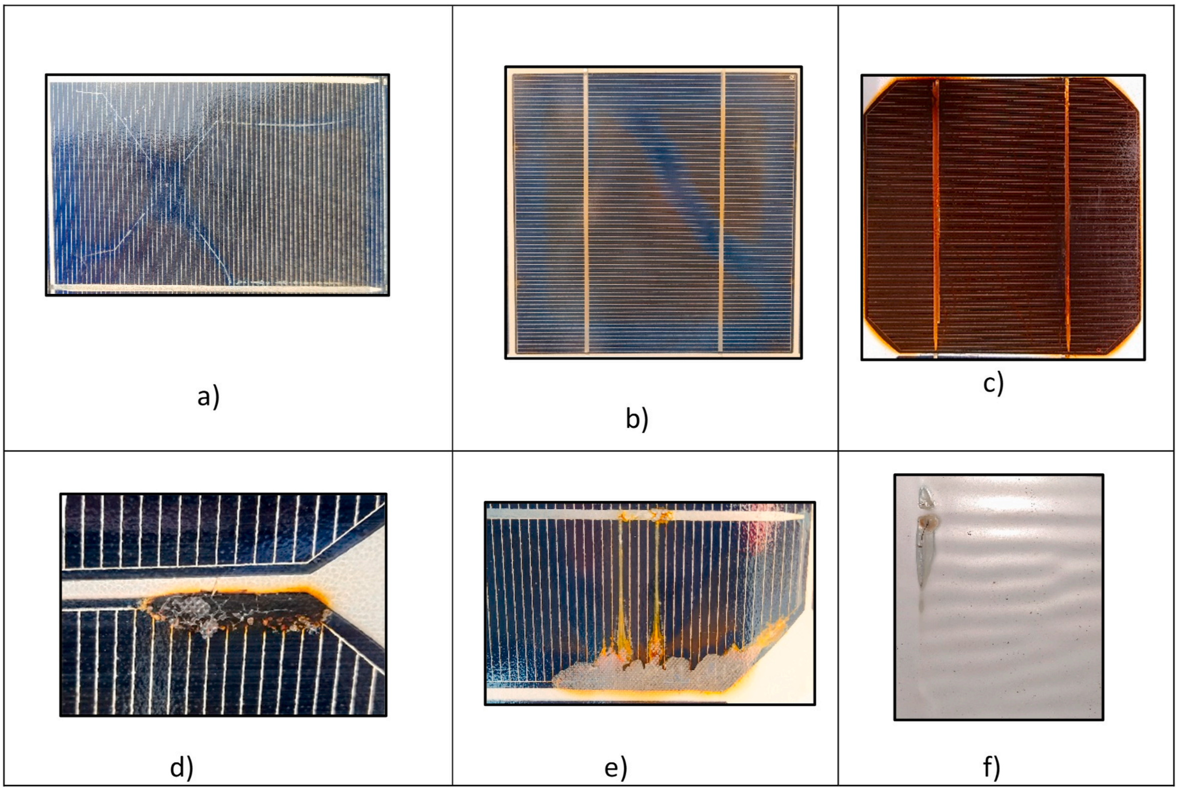

Fig. 1. a) Snail trails. b) Browned EVA and broken cell. c) Burnt cell. d) and e) Delamination and corrosion as a consequence of EVA degradation. f) Bubbles formation, cracking and burn in the backsheet.

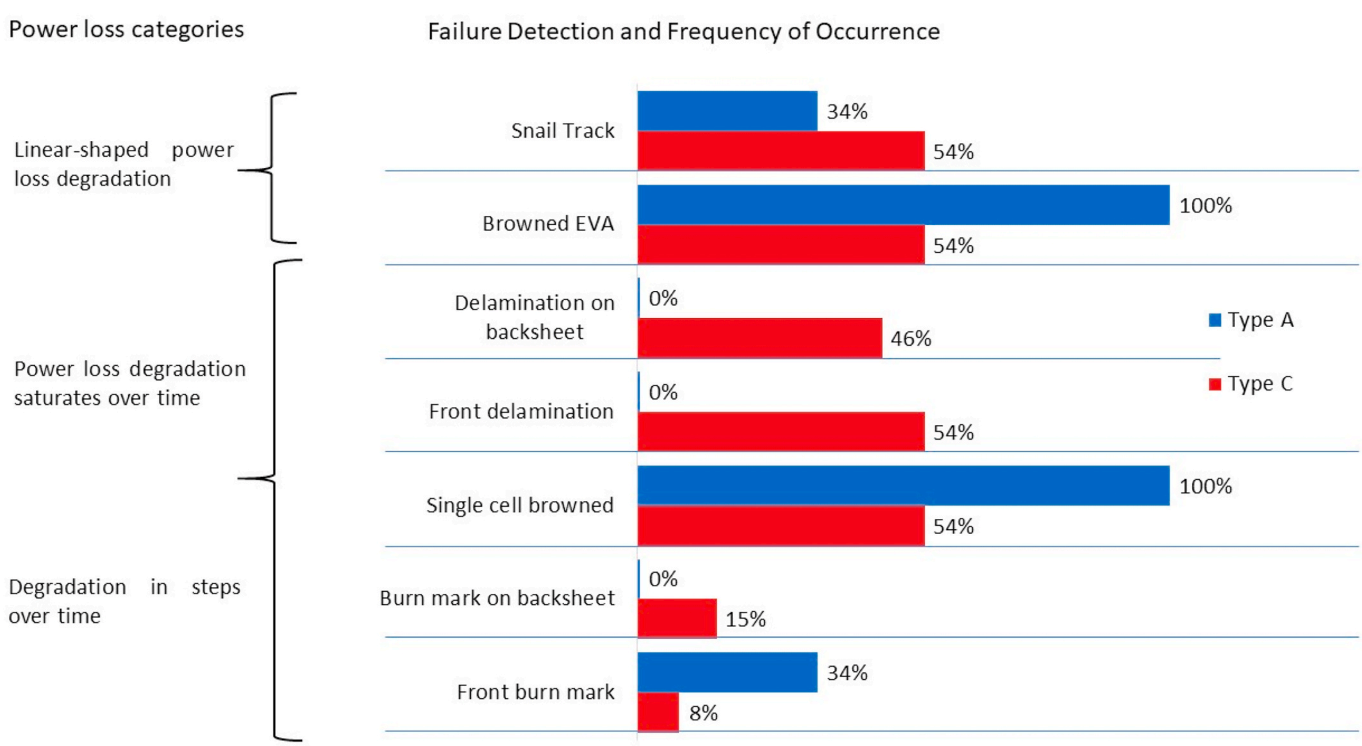

Fig. 2. *Failures detected after visual inspection test relationship with power loss categories according to* (Kontges et al., 2018) *in type A and C m-Si modules.*

concluded that when backsheet absorbs some water, the resistance decreases. This conclusion is coincident with our findings, which indicate that PV modules can pass the dry insulation test but fail the wet leakage current test, as highlighted in Fig. 4, which leads to a safety key issue.

These results are consistent with the evidence found by visual inspection, where it was possible to detect micro-cracks in the backsheet

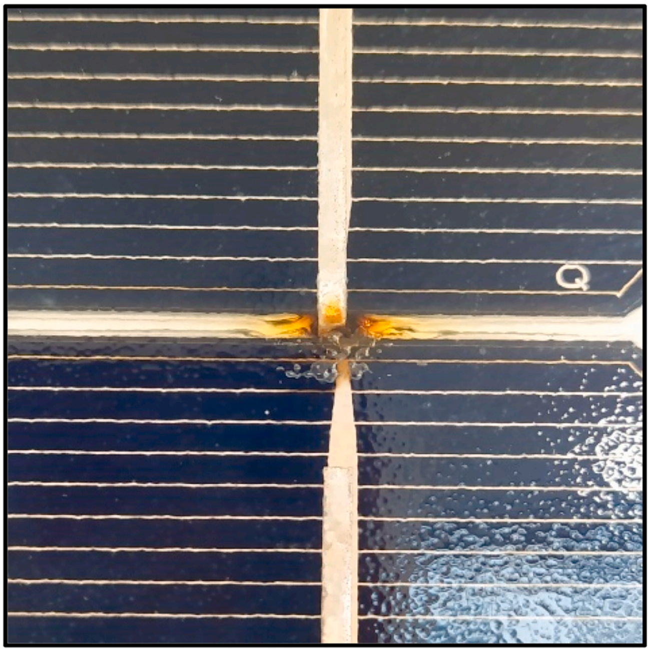

Fig. 3. Image of moisture-induced degradation of EVA and corrosion within the metal grids.

and/or exposed welds. Backsheet cracks act as pathways for ultraviolet radiation, oxygen and moisture ingress. These elements can lead to the degradation of encapsulating materials, erosion of metallisation, and significant declines in insulation resistance (Nordmann et al., 2014)

All modules analysed exhibit exposed welds on the backsheet (due to bus bar interruption repair). This condition is not a failure due to the degradation of the module itself but rather a result of the subsequent partial repair, which caused the insulation to fail, making electrical isolation impossible. To fix the insulation of these modules, it is necessary to continue with the backsheet repair, sealing the exposed solder joints and re-testing the modules for wet leakage current.

Among the three types evaluated, 96 % of the PV modules meet the levels specified by IEC 61215, surpassing the 40 MΩ m^2 threshold for the dry insulation test. However, only 1 out of the 23 modules passed when subjected to the wet leakage current test. Upon a technology-specific analysis within the set of analysed modules, it is observed that the m-Si technology complies with the standard specified in the norm. Nevertheless, it is important to note that this compliance is not necessarily linked to the type of technology employed but rather associated with the degradation of the backsheet, a common factor across all three module types. This degradation has also been reported by other field studies (Pascual et al., 2023).

3.3. I–V curve measuring

Fig. 5 a, b and c illustrate the degradation in Pmax, Voc, and Isc due to increased series resistance, low shunt resistance and reduced fill factor for a selection of modules.

Fig. 5a shows an I–V curve indicating a degradation in the electrical parameters from their nominal values. The decrease in Isc and a substantial reduction in Pmax and fill factor (FF) can be attributed directly to electrical mismatches between cells in the photovoltaic module. The electrical mismatches may include disconnected cells, interrupted string interconnection ribbons or busbars.

Metal grid corrosion, optical degradation, and Potential Induced Degradation (PID) caused by moisture ingress are the leading causes of series resistance losses and, as a result, power degradation. This degradation caused by moisture ingress is called Moisture induced degradation, MID (Segbefia et al., 2021a, 2021b). Fig. 5b is an I–V curve of another module of type C showing this phenomenon. In a standard photovoltaic system, there is usually a high voltage difference between the active circuit and the module frame at both ends of the string. This disparity can lead to the occurrence of leakage currents within the module assembly, potentially resulting in a reduction in the efficiency of PV modules (Luo et al., 2017). PID is a failure mechanism that occurs in operational PV modules. It is a crucial factor triggered by external conditions that tend to accelerate the degradation process when exposed to hot and humid conditions, resulting in significant power loss and substantial degradation. The PID effect induces cell shunts, leading to the degradation of Voc and FF. This particular MID effect will be detected with electroluminescence characterisation in section 3.4.

The I–V curves of the types A and B modules showed no obvious anomalies, but they did show a reduction in power, although to a lesser extent than the C modules. Fig. 5C is one of the curves obtained for type B modules. The remaining I–V curves for all technologies are shown in Supplementary Data.

3.4. Electroluminescence imaging

The Electroluminescence (EL) technique is a valuable non-destructive inspection method for identifying and distinguishing different photovoltaic (PV) module failure modes. It enables observation of defects and their correlation with different stages of the PV module's lifespan. Moreover, EL imaging is reliable for quantifying resistive losses in aged PV modules that have encountered issues, such as cracks and damaged metal grids.

The EL technique led to the identification of the presence of micro-cracks and darker areas on the periphery of the solar cells on 73.3 % of the analysed PV modules. These microcracks serve as pathways for moisture infiltration, causing enhanced degradation along cell perimeters. This leads to darker zones where the degraded regions exhibit minimal or no electron conduction (Segbefia et al., 2021a, 2021b). While this type of degradation (dark regions) predominantly occurs near the edge of the modules (Segbefia et al., 2023), we also observed the

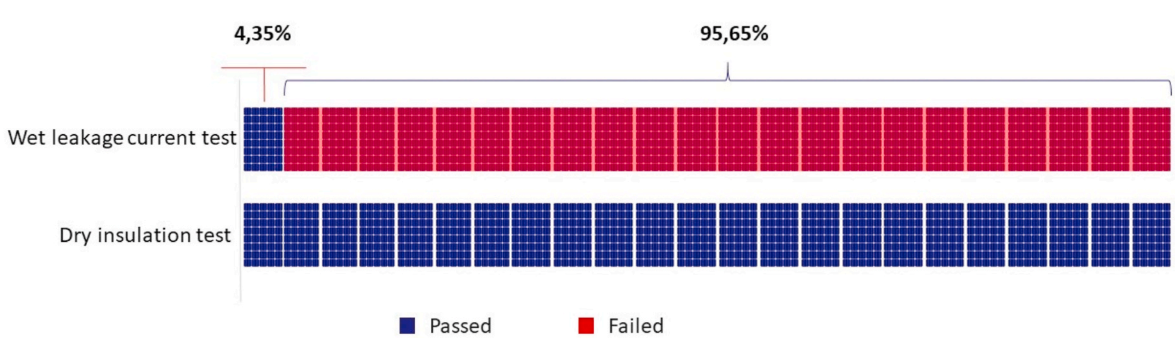

Fig. 4. Of the 23 PV modules evaluated, all 23 passed the dry insulation test, while only one passed the wet leakage current test.

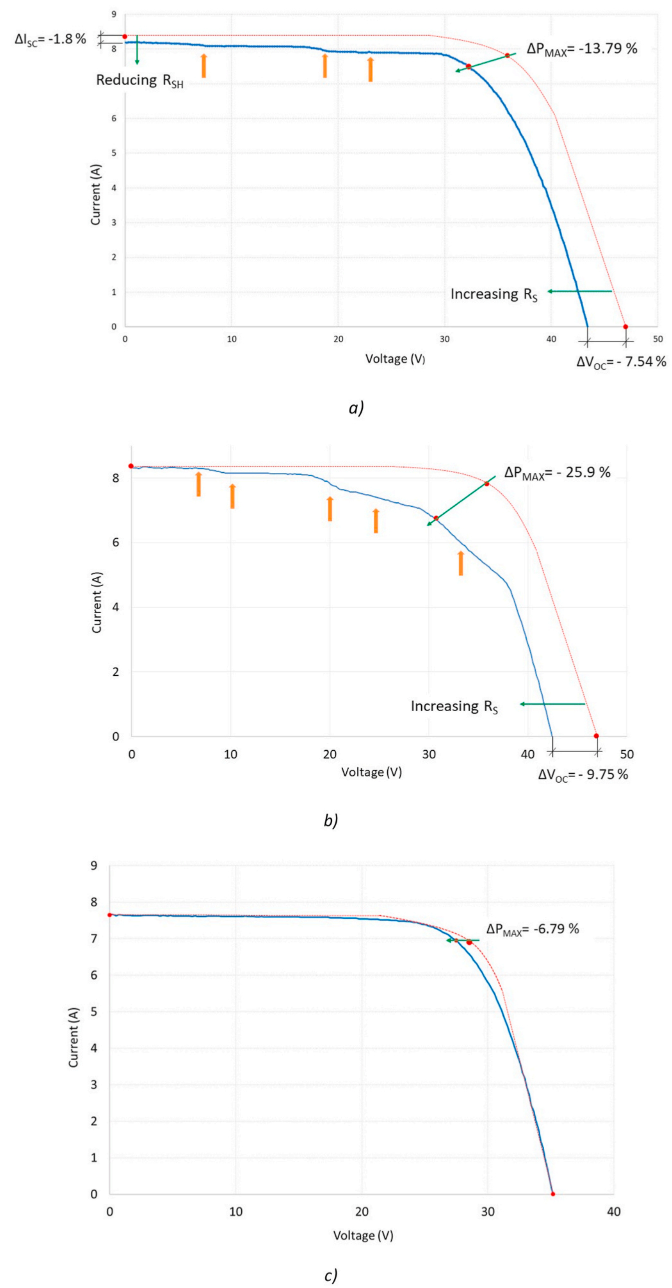

Fig. 5. I–V curves of a set of modules showing degradation in Pmax, Isc and Voc. a) Type C module exhibits a decrease in Isc, Voc and Pmax. b) The type C module shows a decrease in Voc and Pmax, and the change in slope indicates PID (Kontges et al., 2018) c) The type B Module presents a reduction in Pmax.

impact of moisture penetration through microcracks and its degradation effects elsewhere. Our findings align with other reports, as evidenced by (Kajari-Schröder et al., 2012). It can be seen in Fig. 6 an example of this type of failure, the moisture-induced degradation, MID, explained in section 3.1.

Other failures, such as finger interruptions, cell cracks and short-circuited busbars, were also detected using electroluminescence imaging because of the reduced luminescence from these defective areas. Fig. 7 presents the results we obtained after analysing the modules of the three types of modules.

Some cracks do not interrupt the current flow, while others electrically insulate the region in the cell. The non-disruptive cracks have been denoted as "A", while the electrically insulated areas are indicated as "B" in Fig. 8. Although both images display cracks labelled as "A," they exhibit different patterns. In photo a), the crack pattern is branched, while in photo b), it may be attributable to impacts on the module. The cell marked as "C" is entirely disconnected from the circuit and is bypassed because of a reparation. The "D" faults are broken fingers, which are similar to other cases documented in the literature and originate during soldering (Spertino et al., 2015).

Inadequate soldering, thermomechanical stresses, or the presence of hot spots can damage or deteriorate the connecting ribbons between the solar cells or the busbars, resulting in a mismatch in the PV module's electrical parameters. Fig. 9 shows an EL image of a module exhibiting several examples of this failure.

3.5. *Infrared thermography imaging*

Fig. 10 presents the most significant temperature differences observed between operating near maximum point and short-circuit operating conditions were around 17 °C in the marked area “A”.

Hotspots are a prevalent problem that occurs during the operational lifespan of a photovoltaic module. These hotspots, localised heating effects, occur when one or more solar cells in a module exhibit a significantly lower short-circuit current than those in the same module's series string. This situation arises when the cell is partially or entirely shaded, damaged, or experiencing electrical mismatches (Alonso-García et al., 2003). When defective, a cell is forced to carry a higher current than its generating capacity when it is non-defective. This results in the cell becoming reverse-biased or entering the breakdown phase and subsequently consuming power instead of generating it. The reverse-biased cell then dissipates energy in the form of heat, leading to a significant decrease in the efficiency of the photovoltaic whole module. An increase of 10 °C in the surface temperature of the cell can cause a reduction of approximately 4 % in power output, commonly referred to as a "light hot spot", according to (Acciani et al., 2010). Furthermore, an increase of 18 °C can lead to a reduction in power output of up to 10 %, typically known as a "strong hot spot".

Under this categorisation, thermographic images revealed "strong hot spots" in a percentage of 4.35 % of the examined modules operating near their maximum power point, whilst 2.3 % presented strong hot spots during short-circuit operating conditions and 74 % displayed “light hot spots”. In this last group, we found that 47 % had featured high temperatures in the junction boxes, attributable to the diode's activation and further energy dissipation. Furthermore, all photovoltaic modules in their operating point condition exhibited a temperature pattern that closely resembles the one described in (Ulrike et al., 2018), where the solar cells situated near the junction boxes typically operate at temperatures 3 °C higher than those located in other parts of the cell matrix.

4. Discussion

By gathering all the diagnostic methods for each module type, an overview of module failures can be obtained, and our findings can be validated against those of other studies. This facilitates the objectivity and comprehensibility of our results.

Failures in PV modules range from broken cells, mismatch faults, problems with junction boxes, diodes, ground and arc faults to moisture induced degradation or isolation failures. This study conducted a thorough diagnosis of 23 partially repaired modules. The faults were categorised based on their contributions to module degradation, which includes optical degradation, electrical degradation and mismatches, and non-classified defects. This categorisation system was first introduced by Tsanakas et al. (2016), and several other studies have been carried out in order to characterise fault in PV modules in particular cases (Aghaei et al., 2022a; Haque et al., 2019; Santhakumari and Sagar, 2019; Triki-Lahiani et al., 2018; Tsanakas et al., 2016; Waqar Akram et al., 2022).

The typical signs of optical degradation include visible changes that

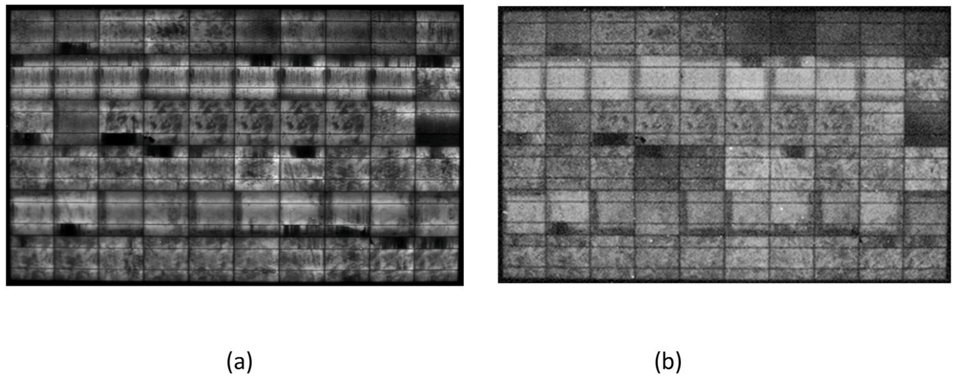

Fig. 6. Electroluminescence images of m-Si taken under (a) Isc and (b) 10 % of Isc forward bias conditions exhibiting MID.

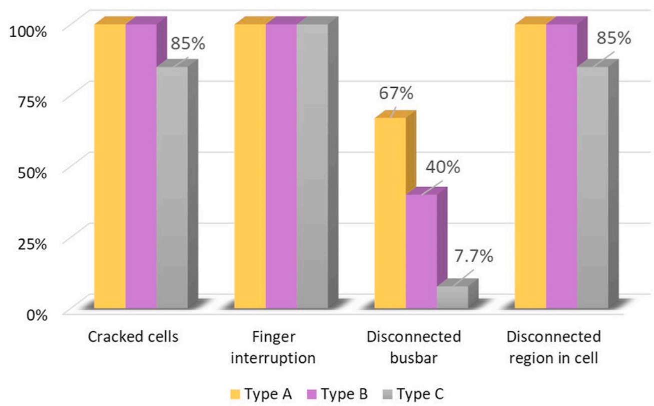

Fig. 7. Percentage of modules affected by the defects revealed in the electroluminescence images. Bars without labels have a failure occurrence rate of 100 %.

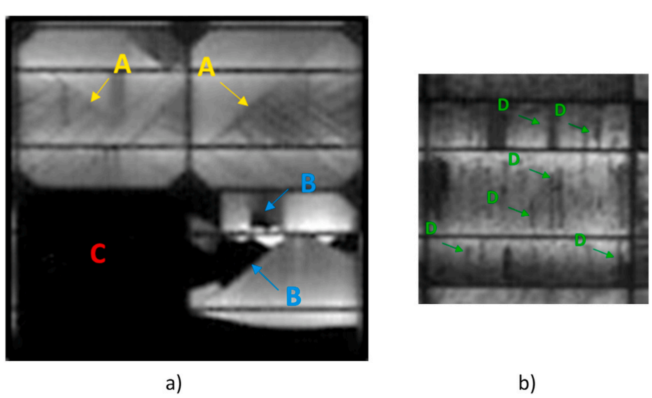

Fig. 8. Different failures detected with EL. a) Dendritic or branched cracks denoted by "A". Deep cracks disconnecting a region in the cell denoted by "B". Disconnected cell denoted by "C". b) Broken fingers denoted by "D".

are detectable through a visual inspection. This degradation leads to undesirable effects such as increased optical reflection and reduction of the solar flux penetration, resulting in decreased electric current and power output from the defective PV module.

With regard to optical degradation, i.e. bubble formation or delamination and glass breakage, it has been shown that these anomalies can cause a significant reduction in electrical parameters and even have the potential to cause temperature differences of 5 °C or more between faultless and defective cells. It is also important to note that this type of degradation often leads to a reduction in power of up to 4 % (Tsanakas et al., 2016). In our study, out of all the modules examined, 30.43 % displayed front delamination, and 26.1 % had backsheet delamination, with no instances of glass breakage. However, the affected area for each failure was minimal, approaching only 0.25 % of the module. Therefore, we can conclude that the reduction in power is not attributable to optical degradation.

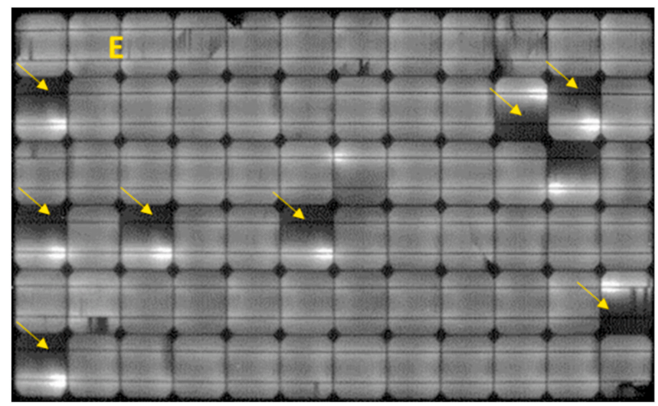

Fig. 9. Several disconnected busbars in a module type C. Note that as one of the two busbars in each defective zone is active, then the current flows.

Visual inspection of one module type C, shown in Fig. 2, revealed snail tracks and broken and possibly burned cells. As explained in section 3.4, a reduction in current flow is expected when a major insulation crack occurs. According to Aghaei (2022a, 2022b), cracking and chalking on the backsheet are among the most common PV module degradation modes. However, although backsheet delamination is present, the diagnostic results from our set of 23 modules indicate that cracked cells with compromised conductivity are the prevailing defect across all three types of modules. Our findings align with those of other similar studies, such as the research conducted by Akram et al. (2020), Schuss et al. (2016), and Luo (2021). They reported power losses in modules due to cell cracks with isolated zones or inactive cells, as well as interrupted busbar connections.

A study conducted by Iqbal et al. (2022) compared the degradations of monocrystalline and polycrystalline modules under identical conditions. It was observed that both types exhibited a noticeable darkening originating from the busbars. However, the polycrystalline modules experienced greater degradation. In this instance, despite variations in operating conditions and geographical locations, there is no evidence of busbar darkening across any of the three types of modules assessed in our work. This leads to infer that there has been no Sn migration from Pb-containing or Pb-free solder joints, except in a few small regions where corrosion has occurred.

Several works have studied the types of cell cracks with

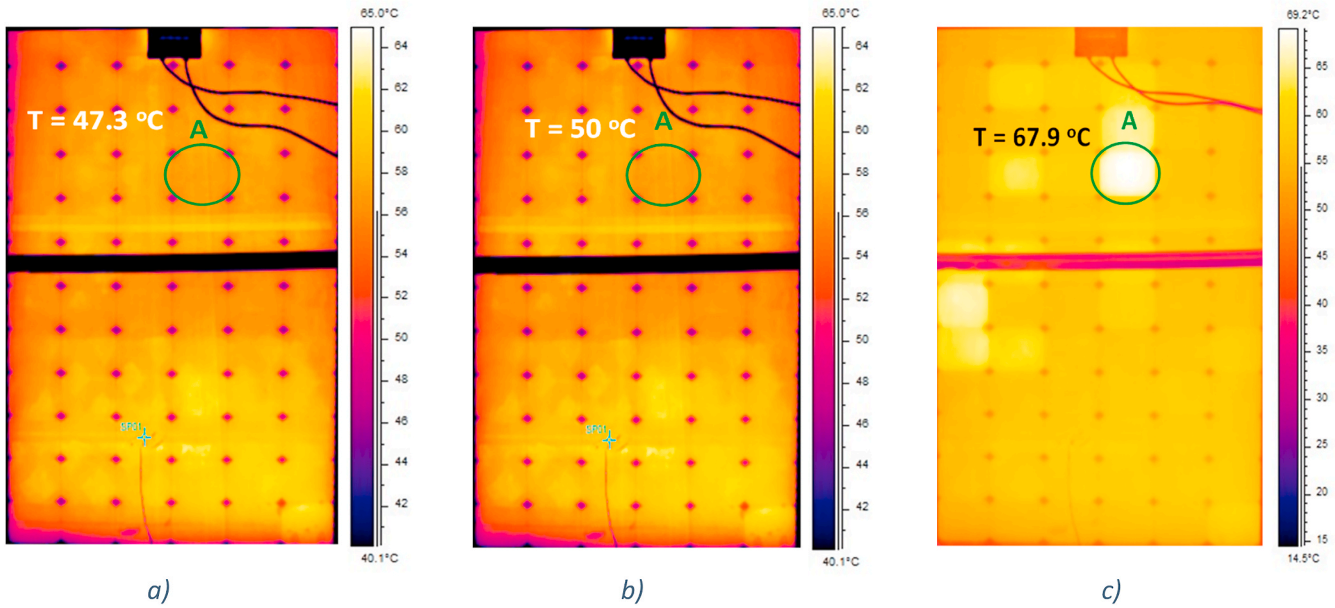

Fig. 10. Infrared thermographic images of a PV module operating in a) open circuit, b) near maximum power point, c) short circuit. The encircled region marked "A" corresponds to the maximum temperature area. Test conditions: Irradiance 923 W/m^2, T_r = 20 °C.

electroluminescence and classified them as multidirectional, diagonal, parallel, and perpendicular to busbars. These papers indicate that while the cracks may not cause cell disconnection, they can develop resistance to current flow when operated continuously. Additionally, the papers have determined that cracks parallel to the busbars are critical because they decrease the current flow (Dhimish et al., 2017; Kajari-Schröder et al., 2012). As shown in Figs. 8 and 11, our analysis revealed that the cracks in our study mainly allow current conduction, with the most common direction of crack occurrence being diagonal (40.21 %), while cracks perpendicular or parallel to the busbars accounted for only 22.7 %.

Infrared thermography images of module type B are given in Fig. 12, which shows the image captured in maximum point operating conditions and the image in short circuit conditions. The temperature gradient between the marked areas is presented and is consistent with the defects detected in this module. Note that AR03 sector is associated with a cell

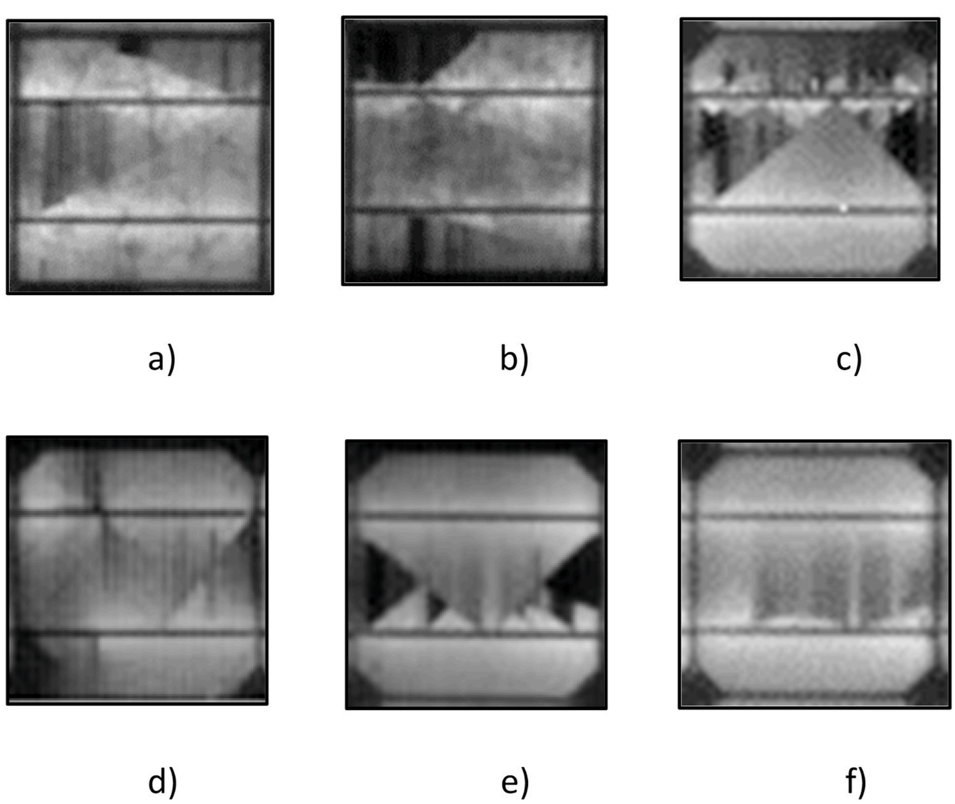

Fig. 11. a), b), c), d), e) Diagonal cell cracks. a), c), e), f) Parallel and perpendicular. d), e) Multidirectional cell cracks.

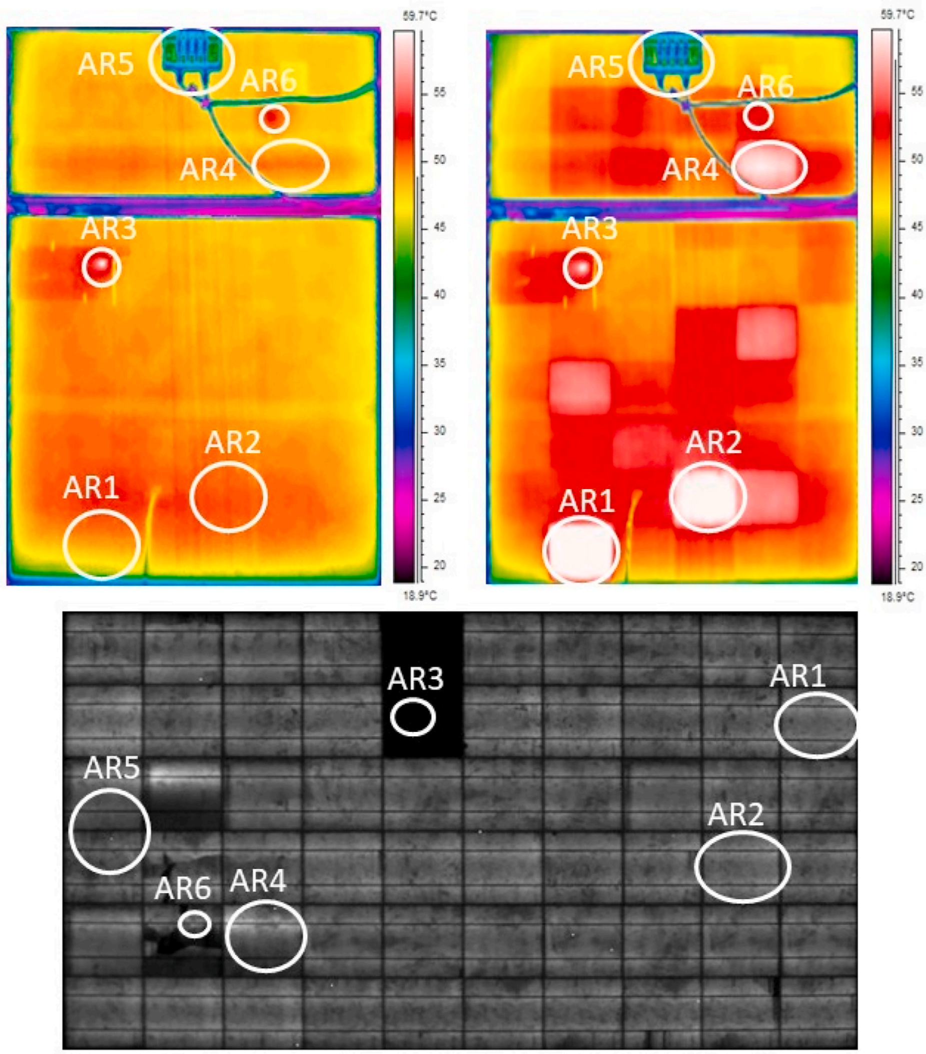

Fig. 12. Images of IR thermography and EL of a module of type B show a maximum temperature difference of 11.2 °C between the marked regions temperature during the operating point and its temperature at short-circuit conditions.

that has deviated from its normal operation, which implies that the heat generated in this region does not originate from the intrinsic activity of the cell itself but is the result of the sum of heat transfers from both the front glass and the rear busbar, the latter soldered to repair and bypass the cell.

Fig. 13 presents a relation between the failures spotted in visual inspection, I–V measurement, EL, and IR images.

A decrease in open circuit voltage may be due to cell interconnection interruptions, cell cracks with isolated zones, or PID. Although the curve does not display a stepped evolution, an IR image indicates high temperature around the junction box, which suggests that the diode could be activated due to significant electrical mismatches of the cells evident in both the EL image and the I–V curve itself.

A summary of the identified faults and their frequency for each of the examined module categories is displayed in Fig. 14 below.

Regarding the reduction in power, 80 % of polycrystalline modules of type B have experienced a peak power reduction of less than 10 %, based on our findings. This is also applicable to monocrystalline modules of type A. In contrast, type C modules demonstrated a distinct outcome, as depicted in Fig. 15. This decline is attributed to their higher susceptibility to degradation due to Moisture-induced degradation (MID), as evidenced in the EL images (refer to Appendix A for the complete set of images).

Fig. 16 shows that type C modules have the largest power loss. Even those not exceeding the −20 % threshold show a greater dispersion than the remaining types A and B. Modules of types A and B show lower power losses, with a maximum power loss of 12.5 % for type B.

Analysing the power reduction in the complete set of modules, our results show that despite the presence of defects, around 87 % of these modules exhibit a power reduction of less than 20 %, as depicted in Fig. 16.

Several factors contribute to power reduction. Among them, moisture ingress is a primary cause of degradation in PV modules. When exposed to moisture, aluminium (Al) and sodium (Na) ions have the potential to migrate from the aluminium frame and front glass into the emitter regions within solar cells and modules (Segbefia et al., 2023). This phenomenon can consequently lead to the occurrence of potential induced degradation, as it was explained before. Moisture ingress can also cause the encapsulation and silver grids to degrade, forming silver carbonates, sulfides and phosphates, which are precursors for snail tracks (Duerr et al., 2016). This effect can increase the module temperature and cause a hotspot (Dupré et al., 2015). Moreover, MID is responsible for the corrosion of metal grids.

Although all the modules examined exhibit MID and have failed the wet leakage test MQT 15, it remains unclear whether these modules could have passed the test before the partial repair because the test

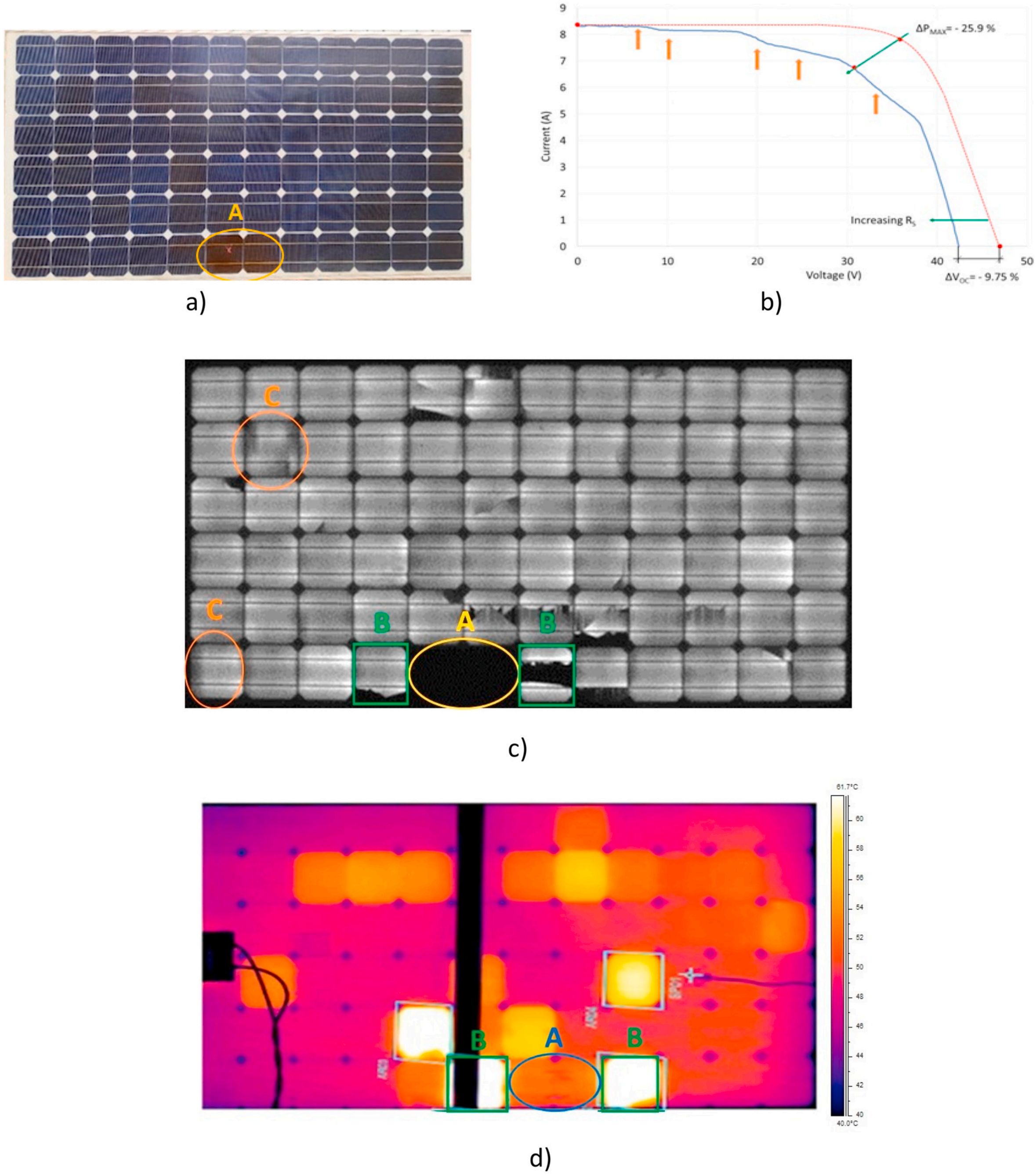

Fig. 13. a) Image captured during visual inspection of type C module showing browned and cracked cells, denoted by A. b) I–V curve with electrical degradation. c) Electroluminescence image exhibiting cracked cells, some denoted by B, MID, some denoted by C. d) IR thermography image presenting hotspots in the cracked cells, denoted by B.

couldn't be performed.

Although it is still necessary to evaluate the evolution of the efficiency over time of these modules, a test that is currently carried out, these results confirm those obtained in other studies, such as the one conducted by (Dobra et al., 2021), that shows that repair processes are almost always environmentally beneficial and economically viable compared to disposal with and without module replacement. Other studies have proven that PV panel refurbishment is more than a hundred times more effective than PV panel replacement in terms of carbon footprint (Poulek et al., 2023). This significant difference reflects the importance of considering the entire lifecycle of solar panels and the environmental impacts associated with their manufacture, transport, and final disposal.

5. Conclusions

The prospect of reusing repaired modules mitigates the necessity for new module production, resulting in reduced demand for raw materials and helps alleviate the environmental impact associated with manufacturing processes.

This study used a comprehensive standardised methodology to characterise 23 partially repaired crystalline c-Si PV modules from a twelve-year-old PV plant in Spain. Our work integrates visual inspection, electrical parameter testing, electroluminescence imaging, and thermographic imaging techniques to provide an in-depth assessment of the modules' operational condition and identify the nature and extent of defects that remain after partial repair.

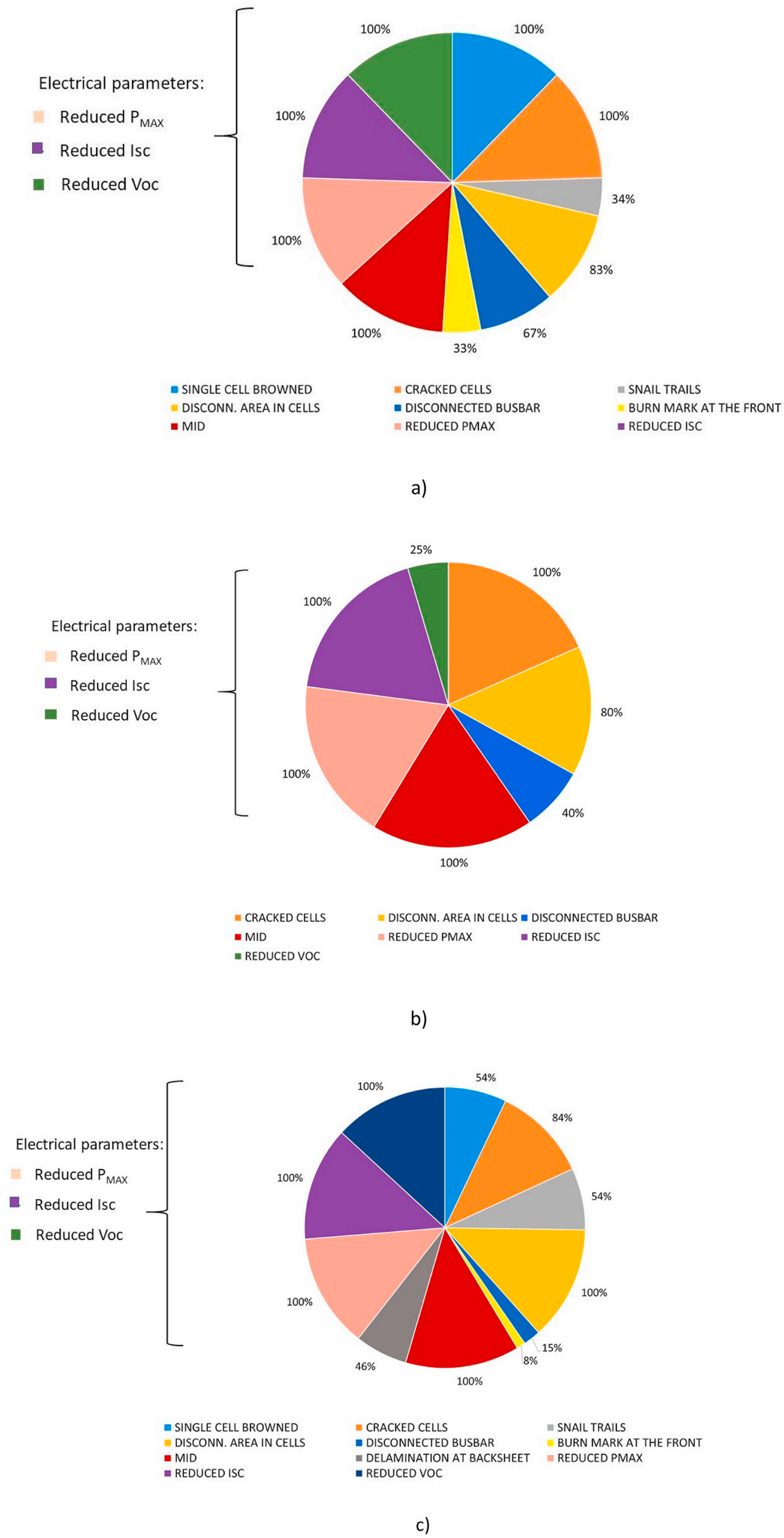

Fig. 14. a) Frequency of failures in type A modules. b) Frequency of failures in type B modules. c) Frequency of failures in type C modules.

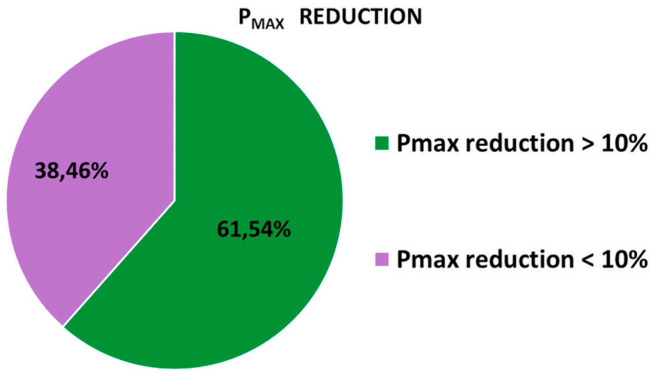

Fig. 15. Maximum Power reduction found on modules type C.

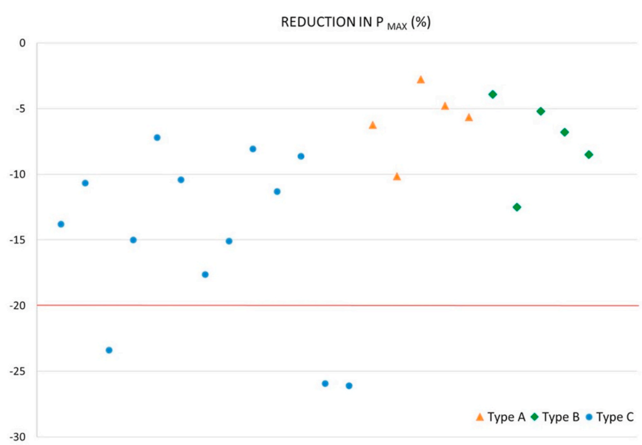

Fig. 16. Analysis of Maximum power reduction of the 23 partially repaired modules.

In terms of the type of defect with the highest frequency of occurrence across the three module types, our results indicate that moisture-induced degradation (MID) is the most common defect, followed by cracked cells and disconnected areas in cells. However, despite the presence of defects, around 87 % of these modules exhibit a reduction of less than 20 % in power.

This significant finding suggests that the repaired modules successfully meet the manufacturer's warranty criteria, indicating their potential for reuse.

This study demonstrates the feasibility of repairing some of the problems associated with solar module failures and recovering module power production. In contrast, other unresolved module defects (excluding insulation) do not entirely wipe out the value of the repaired modules.

However, it is essential to rigorously characterise the modules by implementing a protocol that we consider needs to be different from that of new modules. Additionally, it is necessary to raise awareness regarding international standards, i.e. Cradle-to-Cradle certification (What is cradle, 2020), as this has the potential to stimulate the market demand for second-hand modules with improved sustainability and circularity attributes.

Following these protocols would guarantee the long-term viability and safety of the reused modules.

CRediT authorship contribution statement

M.B. Nieto-Morone: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **F.G. Rosillo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **M.A. Muñoz-García:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Conceptualization. **M.C. Alonso-García:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is attached in as Supplementary Data with the Manuscript

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142575.

References

Acciani, G., Simione, G.B., Vergura, S., 2010. Thermographic analysis of photovoltaic panels. Renewable Energy and Power Quality Journal 1 (8), 1245–1247. https://doi.org/10.24084/repqj08.634.

Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Lobato, K., Oreski, G., Reinders, A., Schmitz, J., Theelen, M., Yilmaz, P., Kettle, J., 2022a. Review of degradation and failure phenomena in photovoltaic modules. Renew. Sustain. Energy Rev. 159 https://doi.org/10.1016/j.rser.2022.112160. Elsevier Ltd.

Aghaei, M., Fairbrother, A., Gok, A., Ahmad, S., Kazim, S., Lobato, K., Oreski, G., Reinders, A., Schmitz, J., Theelen, M., Yilmaz, P., Kettle, J., 2022b. Review of degradation and failure phenomena in photovoltaic modules. Renew. Sustain. Energy Rev. 159 https://doi.org/10.1016/j.rser.2022.112160. Elsevier Ltd.

Akram, M.W., Li, G., Jin, Y., Chen, X., Zhu, C., Shauket, I., Ahmad, A., 2020. Defect detection and degradation analysis in photovoltaic modules using thermography, spectroscopy, and current–voltage measurements, and quantitative assessment of their impact. Energy Technol. 8 (7) https://doi.org/10.1002/ente.202000100.

Alonso-García, M.C., Herrmann, W., Böhmer, W., Proisy, B., 2003. Thermal and electrical effects caused by outdoor hot-spot testing in associations of photovoltaic cells. Prog. Photovoltaics Res. Appl. 11 (5), 293–307. https://doi.org/10.1002/pip.490.

Bhoopathy, R., Kunz, O., Juhl, M., Trupke, T., Hameiri, Z., 2018. Outdoor photoluminescence imaging of photovoltaic modules with sunlight excitation. Prog. Photovoltaics Res. Appl. 26 (1), 69–73. https://doi.org/10.1002/pip.2946.

Chowdhury, M.S., Rahman, K.S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S.K., Sopian, K., Amin, N., 2020. An overview of solar photovoltaic panels' end-of-life material recycling. In: Energy Strategy Reviews. Elsevier Ltd. https://doi.org/10.1016/j.esr.2019.100431, 27.

Czanderna, A.W., 1996. Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: a critical review. Pern/Sol. Energy Mater. Sol. Cell. 43.

Dhimish, M., Holmes, V., Mehrdadi, B., Dales, M., 2017. The impact of cracks on photovoltaic power performance. J. Sci.: Advanced Materials and Devices 2 (2), 199–209. https://doi.org/10.1016/j.jsamd.2017.05.005.

Dobra, T., Hilweg, M., Eder, G.C., Voronko, Y., Oreski, G., Feldbacher, S., Neumaier, L., Lenck, N., Figl, H., 2021. Environmental and economic assessment of repair solutions for cracked backsheets in photovoltaic modules. 13th International Conference on Sustainable Energy & Environmental Protection.

Duerr, I., Bierbaum, J., Metzger, J., Richter, J., Philipp, D., 2016. Silver grid finger corrosion on snail track affected PV modules - investigation on degradation products and mechanisms. Energy Proc. 98, 74–85. https://doi.org/10.1016/j.egypro.2016.10.083.

Dupré, O., Vaillon, R., Green, M.A., 2015. Physics of the temperature coefficients of solar cells. Sol. Energy Mater. Sol. Cell. 140, 92–100. https://doi.org/10.1016/j.solmat.2015.03.025.
European Parliament, 2006. *Regulation (EC) N° 1013/2006of the European Parliament and of the Council on Shipment of Waste*.
European Parliament, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE).
Haque, A., Bharath, K.V.S., Khan, M.A., Khan, I., Jaffery, Z.A., 2019. Fault diagnosis of photovoltaic modules. Energy Sci. Eng. 7 (3), 622–644. https://doi.org/10.1002/ese3.255. John Wiley and Sons Ltd.
International Electrotechnical Commission, 2005. IEC TS 61215. Crystalline Silicon Terrestrial Photovoltaic Modules- Design Qualification and Type Approval.
International Electrotechnical Commission, 2006. IEC TS 61730-2. Photovoltaic Module Safety Qualification.
International Electrotechnical Commission, 2021. IEC TS 62446-4. Ed 1. Photovoltaic (PV) Systems - Requirements for Testing, Documentation and Maintenance - Part 4: Electroluminescence Measurement of Photovoltaic Arrays.
Iqbal, N., Colvin, D.J., Schneller, E.J., Sakthivel, T.S., Ristau, R., Huey, B.D., Yu, B.X.J., Jaubert, J.N., Curran, A.J., Wang, M., Seal, S., French, R.H., Davis, K.O., 2022. Characterization of front contact degradation in monocrystalline and multicrystalline silicon photovoltaic modules following damp heat exposure. Sol. Energy Mater. Sol. Cell. 235 https://doi.org/10.1016/j.solmat.2021.111468.
Jeffries, A.M., Nietzold, T., Schelhas, L.T., Bertoni, M.I., 2021. Corrosion of novel reactive silver ink and commercial silver-based metallizations in diluted acetic acid. Sol. Energy Mater. Sol. Cell. 223 https://doi.org/10.1016/j.solmat.2020.110900.
Kajari-Schröder, S., Kunze, I., Köntges, M., 2012. Criticality of cracks in PV modules. Energy Proc. 27, 658–663. https://doi.org/10.1016/j.egypro.2012.07.125.
Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33 (5), 1237–1250. https://doi.org/10.1016/j.wasman.2013.01.006.
Kim, T.H., Park, N.C., Kim, D.H., 2013. The effect of moisture on the degradation mechanism of multi-crystalline silicon photovoltaic module. Microelectron. Reliab. 53 (9–11), 1823–1827. https://doi.org/10.1016/j.microrel.2013.07.047.
Komoto, K., Oyama, S., Sato, T., Uchida, H., 2018. Recycling of PV modules and its environmental impacts. In: 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion. https://doi.org/10.1109/PVSC.2018.8547691.
Kontges, M., Kurtz, S., Packard, C., Jahn, U., Berger, K.A., Kato, K., International Energy Agency Photovoltaic Power Systems Programme, 2018. Performance and Reliability of Photovoltaic Systems Subtask 3.2: Review of Failures of Photovoltaic Modules. *IEA PVPS task 13 : external final report IEA-PVPS*.
Kraft, A., Labusch, L., Ensslen, T., Durr, I., Bartsch, J., Glatthaar, M., Glunz, S., Reinecke, H., 2015. Investigation of acetic acid corrosion impact on printed solar cell contacts. IEEE J. Photovoltaics 5 (3), 736–743. https://doi.org/10.1109/JPHOTOV.2015.2395146.
Libby, C., Shaw, S., 2018. SOLAR PV MODULE END of LIFE: OPTIONS and KNOWLEDGE GAPS for UTILITY-SCALE PLANTS DISCLAIMER of WARRANTIES and LIMITATION of LIABILITIES NOTE Solar PV Module End of Life: Options and Knowledge Gaps for Utility-Scale Plants.
Liu, C., Zhang, Q., Liu, L., 2023. Estimation of photovoltaic waste spatio-temporal distribution by 2060 in the context of carbon neutrality. Environ. Sci. Pollut. Control Ser. 30 (12), 34840–34855. https://doi.org/10.1007/s11356-022-24487-3.
Luo, W., Clement, C.E., Khoo, Y.S., Wang, Y., Khaing, A.M., Reindl, T., Kumar, A., Pravettoni, M., 2021. Photovoltaic module failures after 10 years of operation in the tropics. Renew. Energy 177, 327–335. https://doi.org/10.1016/j.renene.2021.05.145.
Luo, W., Khoo, Y.S., Hacke, P., Naumann, V., Lausch, D., Harvey, S.P., Singh, J.P., Chai, J., Wang, Y., Aberle, A.G., Ramakrishna, S., 2017. Potential-induced degradation in photovoltaic modules: a critical review. Energy Environ. Sci. 10 (1), 43–68. https://doi.org/10.1039/c6ee02271e. Royal Society of Chemistry.
Meena, R., Kumar, S., Gupta, R., 2020. Comparative investigation and analysis of delaminated and discolored encapsulant degradation in crystalline silicon photovoltaic modules. Sol. Energy 203, 114–122. https://doi.org/10.1016/j.solener.2020.04.041.
Nieto-Morone, M.B., Alonso-García, M.C., Rosillo, F.G., Santos, J.D., Muñoz-García, M. A., 2023. State and prospects of photovoltaic module waste generation in China, USA, and selected countries in Europe and South America. Sustain. Energy Fuels 7 (9), 2163–2177. https://doi.org/10.1039/d2se01685k.
Nordmann, T., Clavadetscher, L., van Sark, W., Green, M., 2014. Analysis of Long-Term Performance of PV Systems Different Data Resolution for Different Purposes, 2014th ed. IEA.
Oreski, G., Ottersböк, B., Omazic, A., 2019. Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules. Elsevier. https://doi.org/10.1016/C2016-0-01032-X.
Pascual, J., García, M., Marcos, J., Marroyo, L., 2023. Analysis of polyamide and fluoropolymer backsheets: degradation and insulation failure in field-aged photovoltaic modules. Prog. Photovoltaics Res. Appl. 31 (5), 494–505. https://doi.org/10.1002/pip.3653.
Peike, C., Hoffmann, S., Hülsmann, P., Thaidigsmann, B., Weiß, K.A., Koehl, M., Bentz, P., 2013. Origin of damp-heat induced cell degradation. Sol. Energy Mater. Sol. Cell. 116, 49–54. https://doi.org/10.1016/j.solmat.2013.03.022.
Poulek, V., Tyukhov, I., Beranek, V., 2023. On site renovation of degraded PV panels – cost and environmental effective technology. Sol. Energy 263. https://doi.org/10.1016/j.solener.2023.111956.
Renewable Energy Agency, I., 2023. World energy transitions outlook 2023: 1.5°C pathway. www.irena.org.
Roy, J.N., 2015. Modelling of insulation characteristics of Solar Photovoltaic (SPV) modules. Sol. Energy 120, 1–8. https://doi.org/10.1016/j.solener.2015.06.036.
Santhakumari, M., Sagar, N., 2019. A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: failure detection methods and essential mitigation techniques. Renew. Sustain. Energy Rev. 110, 83–100. https://doi.org/10.1016/j.rser.2019.04.024. Elsevier Ltd.
Schuss, C., Remes, K., Leppanen, K., Saarela, J., Fabritius, T., Eichberger, B., Rahkonen, T., 2016. Estimating the impact of defects in photovoltaic cells and panels. In: 2016 IEEE International Instrumentation and Measurement Technology Conference Proceedings, pp. 1–6. https://doi.org/10.1109/I2MTC.2016.7520345.
Segbefia, O.K., Akhtar, N., Sætre, T.O., 2023. Moisture induced degradation in field-aged multicrystalline silicon photovoltaic modules. Sol. Energy Mater. Sol. Cell. 258 https://doi.org/10.1016/j.solmat.2023.112407.
Segbefia, O.K., Gerd Imenes, A., Burud, I., Satre, T.O., 2021a. Temperature profiles of field-aged multicrystalline silicon photovoltaic modules affected by microcracks. In: 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), pp. 1–6. https://doi.org/10.1109/PVSC43889.2021.9518939.
Segbefia, O.K., Imenes, A.G., Sætre, T.O., 2021b. Moisture ingress in photovoltaic modules: a review. Sol. Energy 224, 889–906. https://doi.org/10.1016/j.solener.2021.06.055. Elsevier Ltd.
Spertino, F., Ciocia, A., Di Leo, P., Tommasini, R., Berardone, I., Corrado, M., Infuso, A., Paggi, M., 2015. A power and energy procedure in operating photovoltaic systems to quantify the losses according to the causes. Sol. Energy 118, 313–326. https://doi.org/10.1016/j.solener.2015.05.033.
Triki-Lahiani, A., Bennani-Ben Abdelghani, A., Slama-Belkhodja, I., 2018. Fault detection and monitoring systems for photovoltaic installations: a review. Renew. Sustain. Energy Rev. 82, 2680–2692. https://doi.org/10.1016/j.rser.2017.09.101. Elsevier Ltd.
Tsanakas, J.A., Ha, L., Buerhop, C., 2016. Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: a review of research and future challenges. Renew. Sustain. Energy Rev. 62, 695–709. https://doi.org/10.1016/j.rser.2016.04.079. Elsevier Ltd.
Tsanakas, J.A., van der Heide, A., Radavičius, T., Denafas, J., Lemaire, E., Wang, K., Poortmans, J., Voroshazi, E., 2020. Towards a circular supply chain for PV modules: review of today's challenges in PV recycling, refurbishment and re-certification. Prog. Photovoltaics Res. Appl. 28 (6), 454–464. https://doi.org/10.1002/pip.3193. John Wiley and Sons Ltd.
Ulrike, M., Köntges, M., Parlevliet, D., Paggi, M., Tsanakas, I., Stein, joshua, Berger, K., Ranta, S., French, R., Richter, M., Tanahashi, T., 2018. Review on Infrared and Electroluminescence Imaging for PV Field Applications.
United Nations Environment Programme, 1998. Basel Convention on the control of transboundary movements of hazardous wastes and their disposal. https://wedocs.unep.org/20.500.11822/8224.
van der Heide, A., Tous, L., Wambach, K., Poortmans, J., Clyncke, J., Voroshazi, E., 2022. Towards a successful re-use of decommissioned photovoltaic modules. Prog. Photovoltaics Res. Appl. 30 (8), 910–920. https://doi.org/10.1002/pip.3490.
Waqar Akram, M., Li, G., Jin, Y., Chen, X., 2022. Failures of photovoltaic modules and their Detection: a Review. Appl. Energy 313. https://doi.org/10.1016/j.apenergy.2022.118822.
Waqar Akram, M., Li, G., Jin, Y., Chen, X., Zhu, C., Zhao, X., Aleem, M., Ahmad, A., 2019. Improved outdoor thermography and processing of infrared images for defect detection in PV modules. Sol. Energy 190, 549–560. https://doi.org/10.1016/j.solener.2019.08.061.
What is cradle, 2020. To cradle certified? n.d. Cradle to Cradle Products Innovation Institute. Retrieved November 7, 2023, from. https://www.c2ccertified.org/get-certified/product-certification.