Solar Energy

A comprehensive review of visual inspection and detection techniques for identifying failure modes and potential defects in solar modules

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A comprehensive review of visual inspection and detection techniques for identifying failure modes and potential defects in solar modules

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Abstract-To guarantee uninterrupted and optimal power generation from photovoltaic solar energy systems, it is essential to ensure that these systems are free from any errors. Prompt detection and accurate diagnosis of solar panel faults allows for the avoidance of degradation of the PV system. Some faults can have a severe impact, potentially leading to significant human and material losses, even to the extent of causing fires in solar fields. There are various methods for detecting and characterizing faults and degradation cases in solar panels. At present, research is being conducted on one aspect through a review of the literature. Some reviews concentrate on classifying faults in solar panels, while others concentrate on detection techniques for these faults. Some reviews investigate artificial intelligence models that are applied to detect and diagnose faults in photovoltaic system units. Our paper attempts to conduct a general and comprehensive review of the various faults that occur in solar panels, as well as the traditional and modern methods that are adopted to detect these faults using artificial intelligence tools. This work allows us to address important aspects.

1. Introduction

The rapid and significant increase in global energy consumption has resulted in an increase in production rates. However, traditional energy sources are vulnerable to depletion and expose our planet to negative impacts and harmful environmental disasters. Leading countries in the field of energy have begun to explore alternative sources of energy, including solar energy. Solar energy is a significant contributor to the production of electrical energy, offering a sustainable development pathway, silent and clean production, and accessibility to all categories. In 2023, an estimated 60 gigawatts (GW) of new

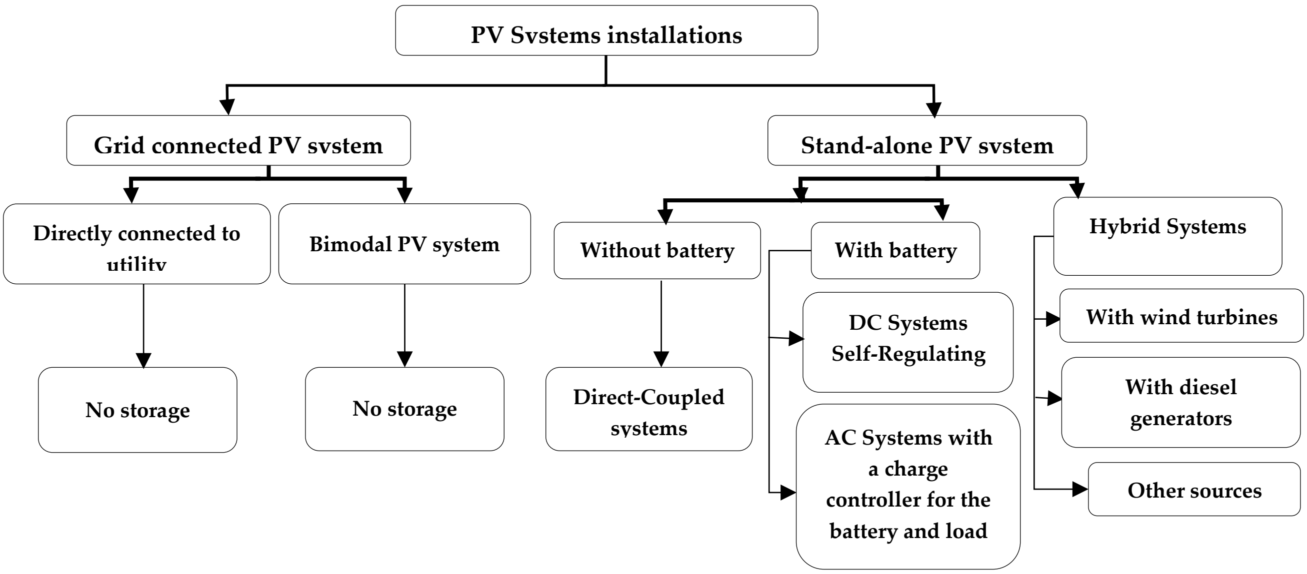


Fig. 1. Classification of photovoltaic system categories [2].

solar capacity was added to the grid in Europe, representing a 40% increase compared to 2022 [1]. The technological advancements in solar energy have facilitated the complexities inherent to construction and solar installations, while simultaneously expanding the scope of applications. Photovoltaic installations serve the function of energy conversion.

These installations comprise a number of components, each of which has been designed and is dedicated to performing a specific role, the components vary in accordance with the intended application. The general design of a photovoltaic system is dependent on the intended use, geographical location, and operating conditions. The operation of photovoltaic installations can be divided into three categories: those connected to the grid and those operating as stand-alone systems. In the first case, the electrical energy produced is used directly by users and consumers. In the second case, it is stored in batteries, in addition to hybrid systems [2] in **Fig.1**. The photovoltaic panel is the main converter and the most important component in the photovoltaic array.

It is not uncommon for electrical systems to encounter faults that impede their optimal functionality during operation. In some instances, these malfunctions can result in a complete halt in energy production. Faults in solar photovoltaic systems also have a negative impact on the system components, reducing their reliability. Consequently, researchers in the field of photovoltaic energy have recently concentrated their efforts on the development of effective fault detection and diagnosis solutions. This has resulted in a significant increase in the number of scientific publications on the various definitions and classifications of faults affecting the performance, reliability, and operational life of photovoltaic systems. Accordingly, solar system faults can be classified in accordance with a number of criteria. **Fig.2** illustrates the general hierarchy of potential faults in a photovoltaic system, based on the factors that affect it [3].

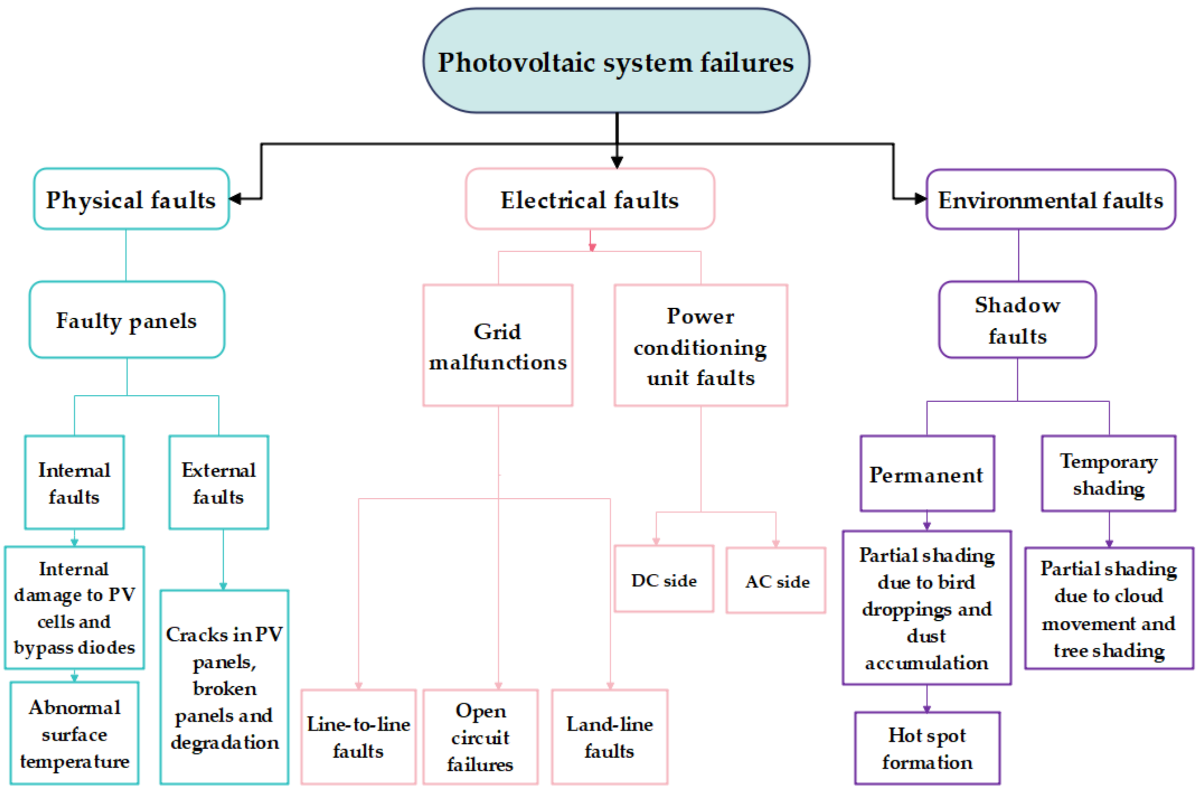


Fig. 2. Fault classification for photovoltaic systems

Proposed structure for the review

The objective of this paper is to present a methodology for the diagnosis of degradation conditions and optical failures related to photovoltaic modules. The article is structured into four key sections, which are closely interconnected. The first section provides an overview of the various types of photovoltaic systems, categorized according to their installation and connection. The second section outlines the methods and techniques used to detect faults in the electrical power system. The third section addresses the detection of faults in photovoltaic modules using visual inspection techniques, which are classified into two categories. The first category relies on the examination of electrical characteristics, while the second category employs imaging techniques, which are discussed in greater detail. The fourth section outlines some of the most prevalent faults and degradation conditions that significantly impact the performance and reliability of photovoltaic power systems.

2. PV power system failure detection techniques

In recent years, significant advances have been made in the field of solar module defect detection and diagnosis in photovoltaic systems, enabling enhanced monitoring of system performance. The International Energy Agency (IEA) has assisted the PVPS program in publishing reports that present advanced diagnostic techniques for monitoring the performance of solar power systems. These reports serve as a valuable reference for numerous research papers focusing on fault detection methods and techniques. This paper presents a discussion of the known and widely used detection and characterization techniques in the field. **Fig.3** provides a simple illustration of these techniques. During normal operation, photovoltaic panels are susceptible to a number of defects, including the accumulation of dust, the formation of micro-cracks, discoloration over time, and the emergence of hot spots. It is therefore recommended that such defects be detected and that immediate maintenance or replacement be carried out in a timely manner [4]. This will help to avoid energy loss and reduce the rate of aging and deterioration of the panels.

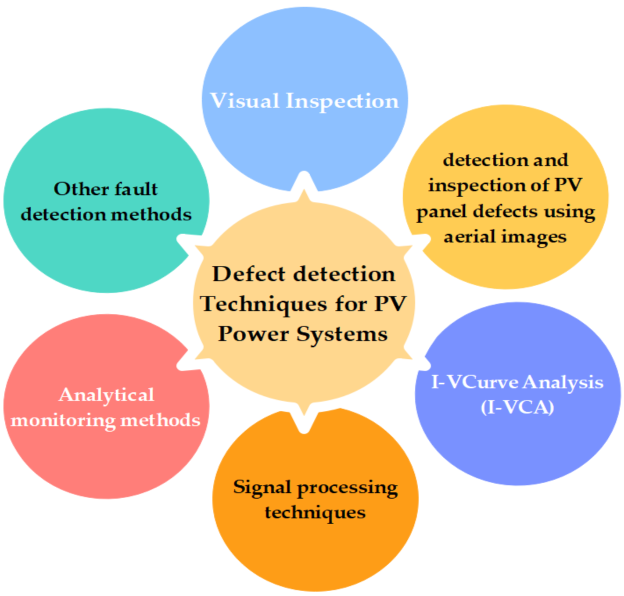


Fig.3. Techniques for detecting common failures in PV systems

The installation of photovoltaic systems in European countries is experiencing significant growth, driven by the region's robust manufacturing capacity. This has led to an increased focus on identifying and addressing potential defects that may not be fully detected during the manufacturing process. There is a growing emphasis on developing advanced fault detection techniques to ensure the quality and reliability of these systems. The aforementioned techniques are based on two distinct approaches: automatic analysis and model-based analysis. The former relies on the utilisation of data, encompassing a range of inspection methods, including infrared thermography (IR-T), electroluminescence (EL), ultraviolet fluorescence (UV-F), and photon spectroscopy (PL) [5]. In addition to inspection methods based on the analysis of voltage and current curves, techniques based on the analysis of signals imported by sensors are employed. These signals are used for measurements related to the environment, including the measurement of solar radiation and ambient temperature. The accuracy and speed of detection and diagnostic techniques (DDF) vary. Traditional methods of monitoring and analyzing the current and voltage characteristics of photovoltaic panels are time-consuming. In contrast, direct detection and accurate localization of faults are achieved by imaging techniques. The use of drone technology has facilitated the effective monitoring of photovoltaic systems. In addition to handheld cameras, In addition to techniques based on visual inspection by experts and technicians.

2.1. Aerial detection and diagnosis of defects in photovoltaic panels

The method of visual inspection of defects in photovoltaic modules using different imaging techniques has the potential to facilitate the easy and rapid identification of failure modes, which could help to ensure the maximum safety and reliability of the photovoltaic system [6],[7]. These techniques are capable of providing high-resolution image quality even in real time.

Defective areas are identified by visual inspection, and failure modes are identified by thermal imaging technique by hot spots that translate a certain degradation condition. It should be noted that not all failures of photovoltaic modules necessarily lead to overheating [8]. In light of this limitation, photovoltaic imaging techniques are used to detect micro-cracks and severed fingers [9].

By examining the photovoltaic cell directly, with the naked eye. It is common practice to perform visual inspections before and after operation, in order to check the condition of the solar panels before and after practical stress. The standards for measuring the implementation of visual inspection tests are determined by the International Agency IEC61215 and IEC61646 [10],[11].

2.2. Current-voltage (I-V) curve analysis

One of the FDD techniques for solar systems is electrical characteristics analysis. This allows the operational status of solar panels to be monitored, with the voltage and current curves coming out of the cell or group of photovoltaic panels providing the necessary data. These I-V curves provide insight into the health status of the photovoltaic system [12]. Any deviations indicate potential failure cases, such as cell glass breakage, connection failure, hot spots, or surface defects.

2.3. Signal processing methods

The field of signal processing techniques and related work is vast and multifaceted, collectively aiming to detect and diagnose faults in photovoltaic (PV) modules. The implementation of signal processing techniques does not necessitate consideration of ambient temperature or radiation. Time and frequency-related characteristics are employed to identify line faults, arc faults, and ground faults [13], or PV module output current to identify shading faults and cell aging. Panel-level data are employed to optimize PV module interconnection topologies, bridge connection (BL) and total interconnection (TCT) [14]. These methods do not necessitate the utilization of PV system parameters. Signal processing techniques may rely on time series data analysis to estimate the degradation rate of the PV system [15].

2.4. Analytical Monitoring Methods (AMM)

Analytical monitoring methods are founded upon the continuous observation of the solar photovoltaic system [16], thereby enabling the early detection and identification of faults. This approach facilitates the avoidance of failures and ensures optimal productivity and profitability. Analytical monitoring methods are divided into three sections. The first section pertains to measurements, the second to data exchange and transmission, and the last section to performance analysis. The latter has been approved by IEC 61724 [17],[18]. In accordance with the rapid advancement of technology and the proliferation of Internet of Things (IoT) applications, this innovative technology has been developed to enable the real-time monitoring of solar system performance [19].

It is based on the construction of a monitoring system that measures the energy production of solar energy systems and compares the results with those obtained from simulations [20]. This allows for the issuance of alerts in the event of a fault through the use of alarm devices. The precision of this simulation is contingent upon the accurate and specific measurement of the electrical and atmospheric parameters inherent to photovoltaic systems. The absence of analytical monitoring techniques may result in the delayed detection of faults in PV systems. A PV plant may operate at a level below its actual performance for an extended period before faults are identified, leading to a reduction in production and, consequently, revenue. FDD techniques that employ analytical monitoring typically encompass one or more of the following approaches: statistical analysis and signal processing, machine learning and real-time variability measurement.

2.5. Other methods of reliably detecting faults in photovoltaic systems

There are methods for detecting and identifying failures in solar energy systems that have not yet been classified in the platform by the Institute of Electrical and Electronics Engineers and the International Electrotechnical Commission (IEC). Through an analysis of existing literature and scientific contributions, methods have been identified and developed to assist in the detection, diagnosis, and localization of faults. The majority of these methods rely on sensors that are directly connected to specific locations and are designed to detect faults exclusively within those locations. To guarantee the reliability of the photovoltaic power generation system (PVPGS), a system has been proposed that detects discrepancies between the detection scheme and is based on the wireless sensing method (WSN), utilizing the Hampel algorithm and a set of temperature, current, and voltage sensors. Faults are identified and localized, and three categories of targeted faults are classified, including open circuit, shadow, and aging of panels, with high precision [21].

3. Detection of failures in photovoltaic modules based on visual techniques

This study focuses on the visual inspection method as a means of detecting module defects among the previously mentioned detection methods. The visual inspection process is an effective method for identifying points of degradation in solar cells and modules, allowing for the prompt detection of potential issues. This method is more accurate and effective than other available techniques [22]. This procedure involves monitoring defects before, after, or during exposure to environmental, physical, or electrical factors that could lead to degradation and failure of modules. The detection tools employed in this process rely on the use of drones, thermal cameras, electrical characteristic curves, and visual inspection (**fig.4**). These defects manifest primarily as fractures, air bubbles, discoloration, and other forms of damage. It is important to note that external influences are not the sole cause of solar module failure. Indeed, internal causes, such as faults in the junction box, have also been identified as a source of module failure. However, this method is not applicable to aged solar cells [23].

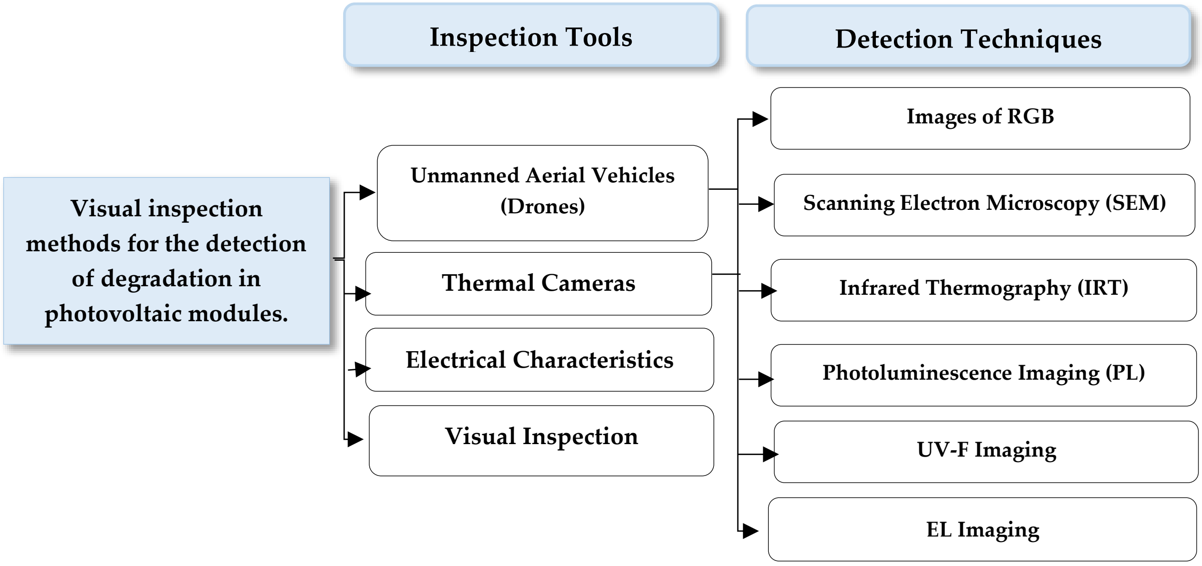


Fig. 4. Overview of visual techniques for the detection of defects in photovoltaic modules.

3.1. Electrical Characterization Technology

In order to guarantee the optimal functioning and longevity of the solar system, the imported data are subjected to an evaluation process based on electrical characterization techniques, with a particular focus on those techniques pertaining to the IV curves. This process is designed to detect and classify any electrical faults that may be present. The process of measuring and analyzing the current and voltage output curves is undertaken with the objective of translating the general operating conditions. Such curves may exhibit aberrant behavior indicative of the presence of faults and defects, including cell degradation, malfunctions in electrical components, or partial shading conditions (PSC) [24]. The latter cause unreliability and, in some cases, fires in solar energy systems. Therefore, it is of paramount importance to gain a deep understanding of solar energy behaviors through electrical modeling. To address this, a new approach has been proposed based on the innovative use of modeling algorithms with excellent performance [25]. Under real conditions and based on a careful analysis of the voltage and current curves resulting from modules and arrays, the aim is to understand the reverse bias behaviors and the complexity facing the photovoltaic system, especially the localization of power losses.

3.2. Imaging techniques in the detection of defects in photovoltaic modules.

Imaging technology has emerged as a promising solution for the rapid detection and identification of invisible defects in solar modules. It seems that technologies such as thermography and electroluminescence imaging may be particularly effective in identifying and locating manufacturing defects [26]. These methods have the potential to detect anomalies that may not be visible to the naked eye or during visual inspection. The use of these technologies has the possibility of improving the performance of solar modules and enhancing their reliability and safety [27]. Through imaging, faults can be detected and located with greater precision, which could greatly facilitate the maintenance and repair of solar installations. Imaging is an advanced method for detecting photovoltaic faults that could potentially improve the quality and durability of solar modules and enhance overall safety and security.

3.2.1. Thermal imaging technology for the detection of defects in PV modules

The conventional approach to fault detection and diagnosis in photovoltaic systems entails measuring the current flowing through the solar panels by disconnecting them from the solar array. This method is both time-consuming and labor-intensive. To address these challenges, research has been conducted to explore fast and reliable fault detection methods and techniques that do not require disconnecting the panels from the photovoltaic array. In 1990, infrared imaging was introduced as a promising technique and tool that can enable the inspection and diagnosis of photovoltaic failures [28].

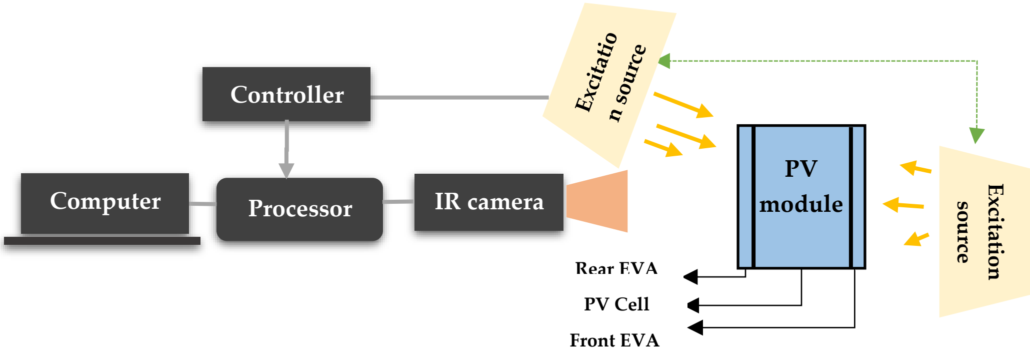
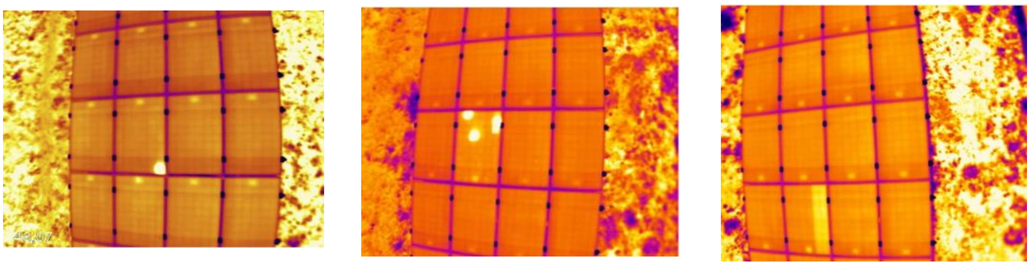


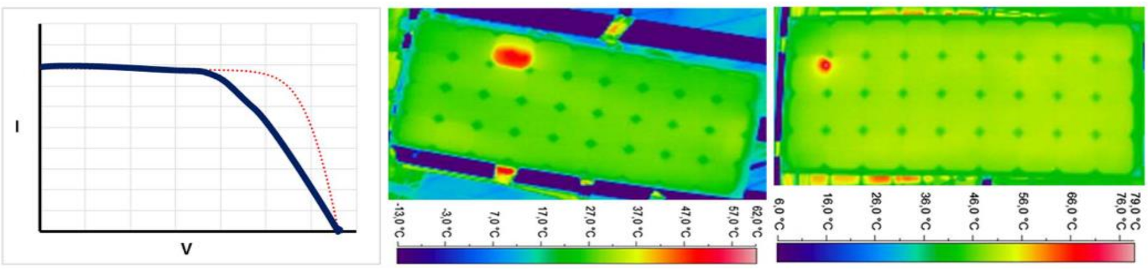
Fig.5. diagram shows the components of an IRT process used to detect defects in solar panels [29],[22].

Atypical thermal imaging setup comprises two main components: a light source and an infrared camera (Please refer to **Fig.5** for a visual representation of this configuration) [29],[22]. The underlying principle of thermal imaging in solar modules is based on the local self-heating generated in the solar cells due to various faults, such as short circuits or disconnected cables. This heat is generated as a result of the Joule effect. Faulty cells generate less current than healthy cells, which results in them being reversely polarized and resistant to current. This resistance is the cause of the temperature difference.



(a) (b) (c)

Fig.6. Infrared thermal images of PV modules show hot zones on the front of the modules. The images show (a) a defective solar panel, (b) a cracked solar panel and (c) a PV panel with an inactive sub-module (open circuit) due to a defective bypass diode [30].



(a) (b) (c)

Fig. 7. (a) I-V characteristic outputs, thermal images of an electrically mismatched PV module due to broken bus bars (b), (c) faulty soldering of bus bars [30].

The heat is generated and accumulated in a specific location, resulting in that location appearing bright and glowing during the thermal imaging process. **Fig.6, fig.7** illustrates that the hottest areas of the solar panels appear yellow due to the formation of defects in the cells, which are the source of the hot spots [30]. In the field of thermal imaging, two distinct methods are commonly used: passive methods and active methods. Passive methods (dark thermography) provide a valuable tool for quality control and detection of surface defects, especially in the context of thin-film photovoltaics. Active methods, on the other hand, are divided into four techniques: progressive heating thermography, vibration thermography, pulse thermography, and lock thermography. These techniques are used to detect and locate deep defects that lie beneath the surface. In this context, a substantial body of research has been conducted on the suitability of IRT technology in diagnosing solar panel deterioration cases, utilizing publicly available data from the Scopus database. Kandeal et al [31], investigated this literatures using *VOSview* as a tool to create a map illustrating the relationship between the primary keywords (**Fig.8**), commencing in 2016. The size and thickness of the circles and connecting lines, respectively, indicate the frequency of the words they contain.

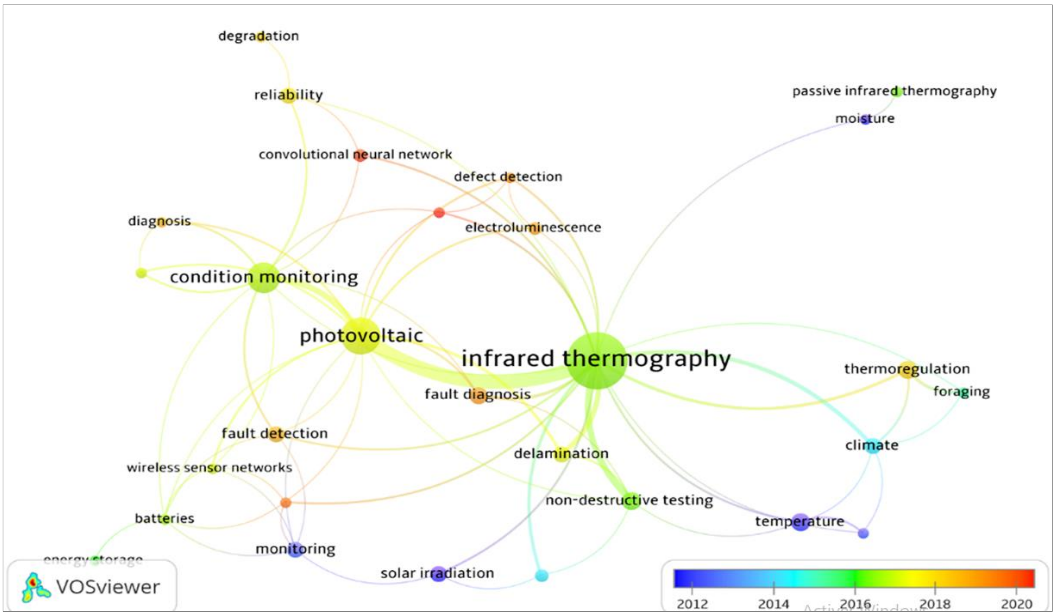


Fig. 8. The map illustrates the frequency of keywords utilized for the detection of PV module degradation through the use of IR technology [31].

3.2.2. Electroluminescence (EL) imaging technology for the detection of defects in PV modules

Electroluminescence is a photoelectric phenomenon that occurs when an electric current is passed through or a strong electric field is applied, resulting in the emission of light from the electrified materials. In solar systems, electroluminescence is achieved by supplying current to solar cells, which results in the recombination of carriers and the emission of light. This provides a direct current for EL technologies, resulting in radiation emission through the solar modules, which is then captured by 1 megapixel scientific-grade CCD cameras (Andor, Luca-R model) [32], and 640 × 480 pixel scientific-grade InGaAs camera array cameras (Sinfrared, Xeva 1.7-760 model)[33].

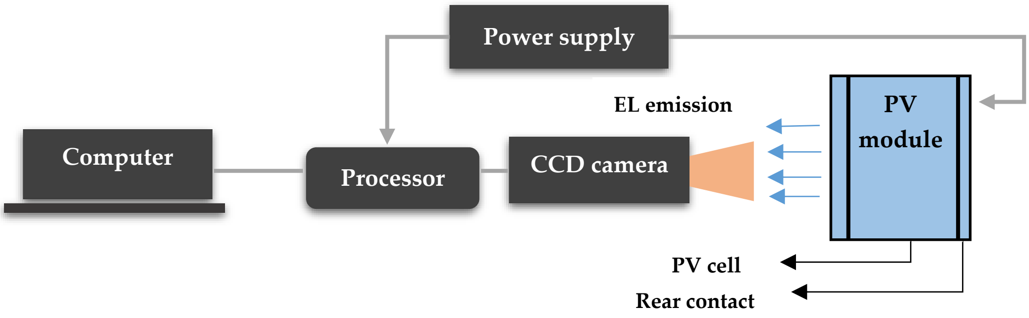


Fig.9. simplified schematic the experimental EL process for the detection of defects in a PV module [22].

The images are then arranged in a very dark environment due to the low level of radiation emitted by the solar cell, which is significantly less intense than the ambient light. As illustrated in **Fig. 9**, filters are employed prior to the camera's implementation. EL imaging is a valuable tool for detecting and diagnosing various cases of solar cell degradation, as well as classifying module defects such as Finger interruptions, electrically disconnected parts, and microcrack. It is the only technology that can effectively utilize microcrack detection. In addition to failures resulting from incomplete semiconductor processes or faulty electrical connections, EL imaging is the only technology that can detect microcracks. Images of non-defective PV cells are gray in color. Defective cells or parts appear as dark spots because they are electrically disconnected and do not radiate. **Fig.10** shows solar cell images taken by EL imaging, which clearly demonstrate the presence of cracks [34].

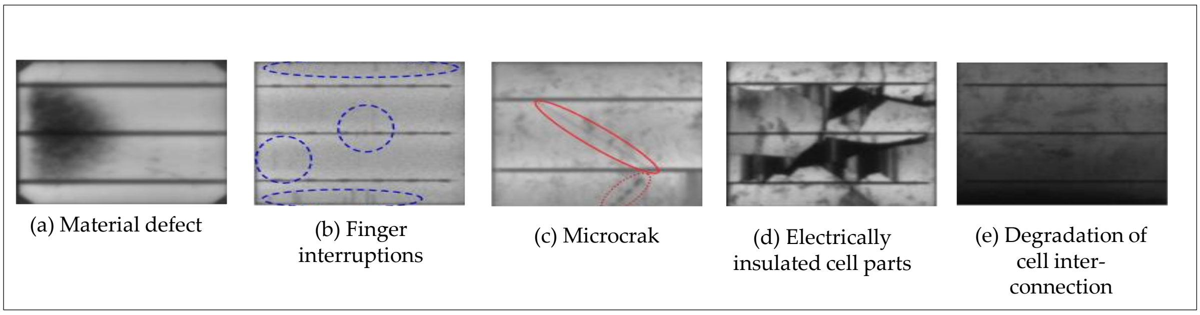


Fig. 10. Examples of solar panel failures: (a) and (b) material and manufacturing defect, (b) Finger interruptions, (c) microcracks, (d) electrical disconnection or partial breakage, (e) total degradation. Cell images are licensed under CC BY NC SA 4.0 [34].

3.2.3. UV-F imaging technology for defect detection in photovoltaic modules

Ultraviolet-F imaging (UV-F) is a non-destructive technique that has proven effective in detecting and identifying defects in solar panels, offering a valuable solution for quality assurance and monitoring. The initial proposal for this technique was made in 1997 with the objective of detecting color changes in the envelope of photovoltaic modules. UV-F technology offers an alternative to EL and PL technologies. Based on the principle of electroluminescence, UV-F technology is designed to detect defects in solar modules [35],[36]. The polymer sheet material of the solar module, often combined with additives including oxidation stabilizers, is affected by the luminescence phenomenon. During the reaction process, molecules absorb photons of light and then emit photons of a lower energy value in response to the absorbed photons [37].

In the field of solar cell spectroscopy, photovoltaic cells are exposed to UV light of a specific wavelength, which causes the molecules in the material or sample being examined to be excited. Subsequently, the excited molecules return to their original state. This process ultimately results in the emission of fluorescent light, which is then subjected to measurement and analysis. This enables the characterization of the emitted waves and the identification of different failure modes of solar panels, in particular microcracks and the breakage of solar cell glass under the influence of fluorescent waves. It is imperative that ultraviolet photographs be taken in an environment devoid of external illumination. Moreover, the cameras must be equipped with high-pass filters. **Fig.11** illustrates the general configuration for analyzing solar panels using UV technology [38],[22].

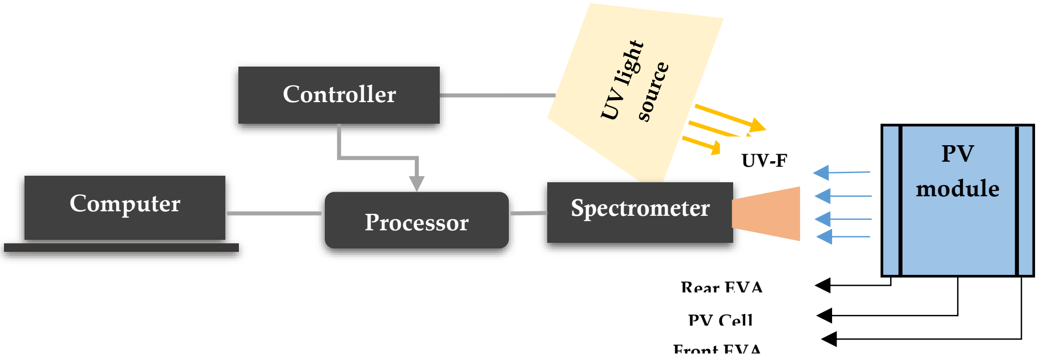
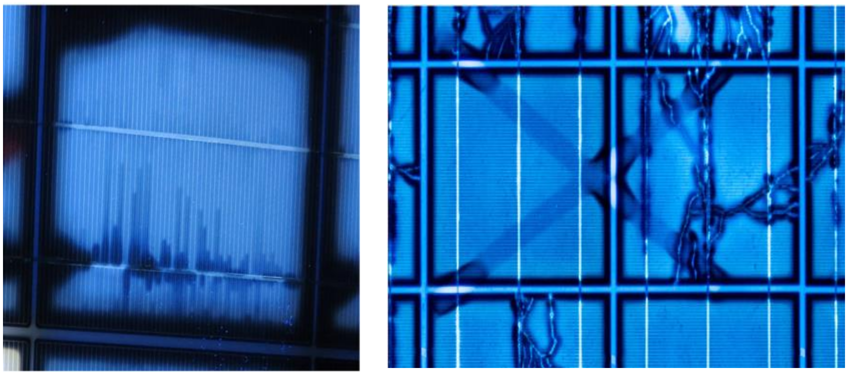


Fig.11. Ultraviolet (UV-F) imaging process to detect defects in solar panels [38],[22].

The setup comprises an optical fiber (Ocean Optics QR600-7-SR 125 BX) [39], a UV source (380 or 365 nm LED; or a 400 nm laser) [40],and a spectrometer (Ocean Optics, MAYA 2000 Pro (200-1100 nm)) [41]. [74], [75]. The results of the UV-F test for solar modules are available within 20-30 seconds. **Fig.12** demonstrates the effectiveness of UVF technology in detecting defects in PV cell images [42].



(a) (b)

Fig. 12. (a) : UVF image of a PV module with broken fingers, (b): The image of a PV module damaged by hail [42].

3.2.4. Photoluminescence imaging technology for the detection of faults in photovoltaic modules

Technologies for detecting and localizing defects in photovoltaic energy systems are experiencing a period of significant growth. This is driven by the heightened focus on monitoring solar power plants by relevant authorities, which represents a challenging yet crucial aspect of energy production. By 2027, photovoltaic energy is set to become the largest installed capacity, underscoring the importance of effective monitoring solutions [26]. Photoluminescence Imaging (PLI) is used to identify potential issues in photovoltaic modules during the manufacturing process. PLI can be performed without the need for electrical connection to the photovoltaic modules. **Fig.13** provides an illustration of the PLI process. The process is based on the combination of charge carriers with the excitation of the semiconductor material by solar radiation. A charge coupled device (CCD) camera captures the radiation emitted from the cells, which is equipped with a high-pass filter (1000 nm) to reduce noise in the images. Defective areas are indicated by a dark coloration, while healthy areas are indicated by a light coloration. PLI is an effective method for exciting semiconductors without electrical conduction, while ELI is a powerful approach for exciting semiconductors through external electrical contact [43]. The combination of these two methods offers a comprehensive overview of potential defects in solar panels.

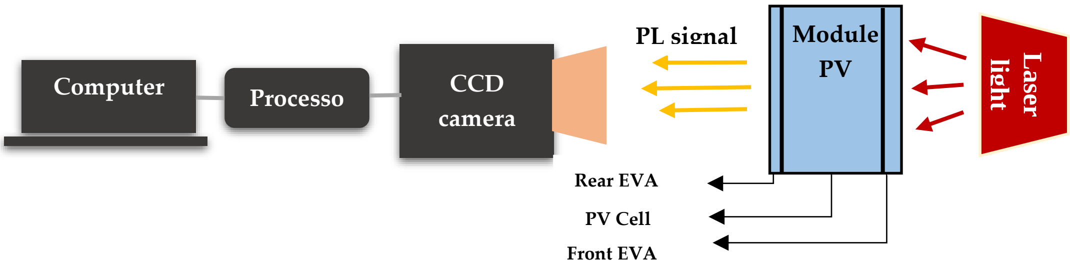


Fig.13. Components and stages the PLI process, which is used to detect defects in photovoltaic modules [43], [22].

Fig.14 illustrates the PL images of photovoltaic cells, which are analogous to conventional EL technology. This technology has been proven effective and accurate in detecting defects. Fig.14 illustrates the luminescence images of five distinct photovoltaic cells. The first row contains a conventional EL image taken when exposed to an 8 A current. The second row contains PL images of the photovoltaic cells exposed to an infrared LED array.

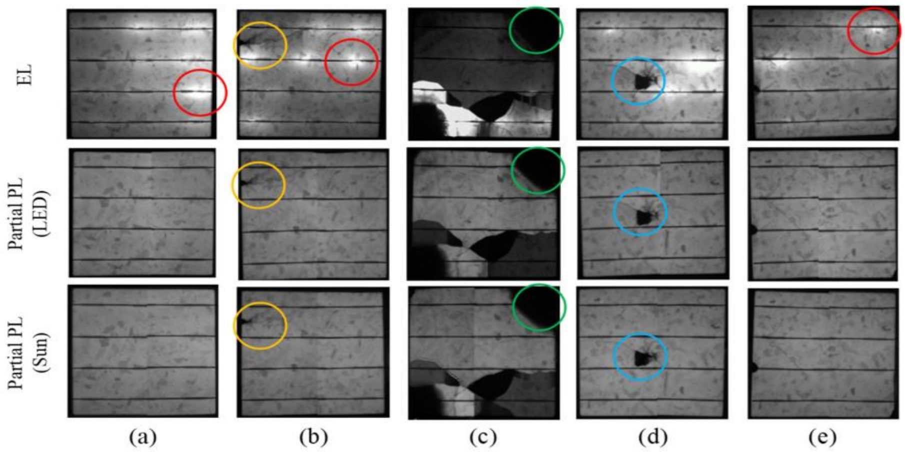


Fig. 14. Comparison of EL (8 A and 50 ms), PL imaging techniques with LED excitation (1000 W/m² and 200 ms),PL under sunlight (340-470 W/m² and 300 ms) for differentiated photovoltaic cells (a-b-c-d-e). The following symbols are used: red circles represent high-intensity current spots, yellow circles represent cracks, green circles represent inactive regions, and blue circles represent inactive regions due to cracks [44].

The third row contains PL images taken after exposure to sunlight. The images were captured within an irradiance range of 340 to 470 W/m². The PL and EL images provide valuable insight into the condition of the photovoltaic cells, offering an effective analysis that is essential for maintaining optimal performance [44]. PL images are capable of detecting disconnected and inactive parts, as well as deep defects that are not visible using EL technology. These include micro-cracks, which are particularly difficult to identify.

3.2.5. Scanning electron microscopy (SEM) imaging technique for the detection of defects in PV modules

In the field of materials science, different types of scanning microscopes have been developed for the analysis of material layers, with the objective of elucidating their internal properties. The scanning electron microscope (SEM) is one such microscope that has been employed for the detection of defects in photovoltaic modules [45]. The scanning electron microscope provides information regarding topography and structure at the nano- and micro-levels. Indeed, the issue of cracks in photovoltaic cells originates from the silicon chips themselves (**Fig.15** depicts the structural configuration of photovoltaic modules (Courtesy of Flisom, Switzerland)) [46].

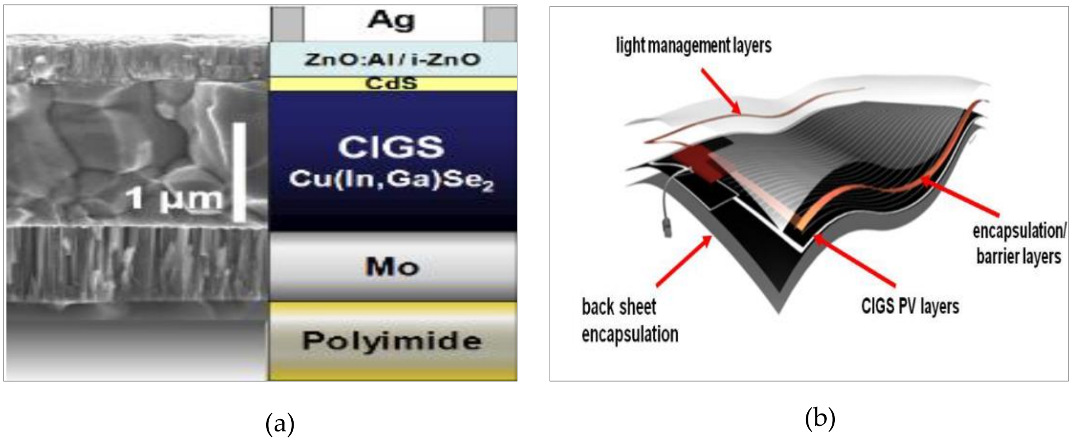


Fig. 15. Structural configuration of photovoltaic modules (Courtesy of Flisom, Switzerland), (a): A representative structure of a flexible photovoltaic module, (b): A schematic representation of a flexible photovoltaic module [46].

A beam of electrons with a high energy level is focused on the surface of the photovoltaic cells, resulting in signals that interact with the atoms in the area. This interaction provides invaluable insight into the composition and structure, which are represented by two-dimensional images in black and white [47]. This sophisticated technology enables the identification of failure modes in photovoltaic modules and the determination of external factors influencing their manufacturing defects. It provides precise, comprehensive, and expedient data regarding the locations of module defects [48].

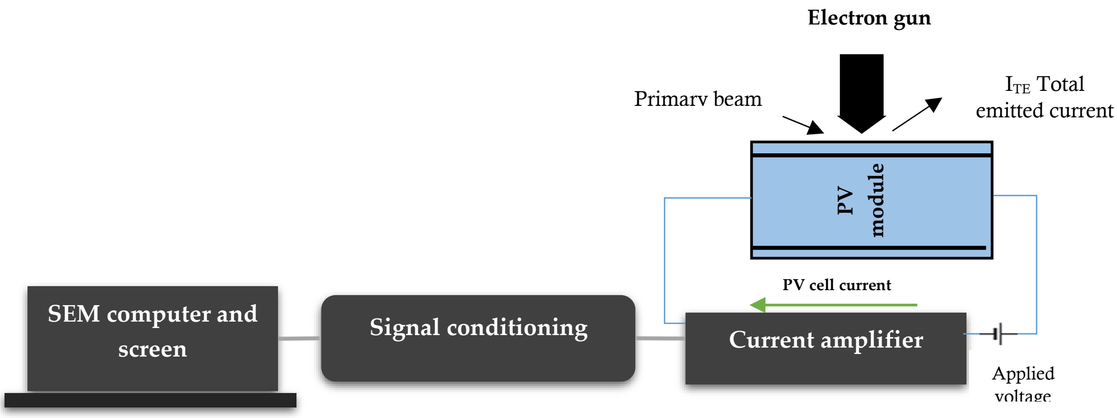


Fig.16. Simple diagram of a scanning electron microscope imaging experiment to detect defects in photovoltaic cells [22], [49].

The results of scanning the surfaces of solar panels permit a comprehensive assessment of their future production process. However, the high cost of the scanning electron microscope represents a significant obstacle to its implementation. **Fig.16** depicts a schematic representation of a scanning electron microscope (SEM) experiment designed to detect and identify defects in solar cells [49],[22].

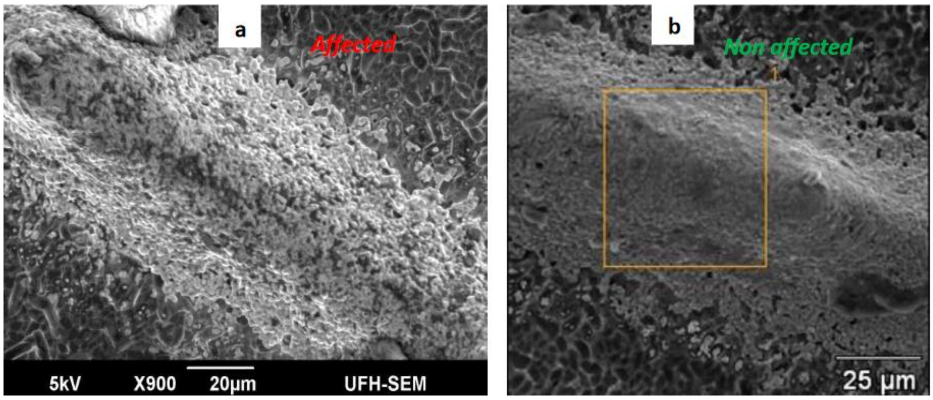


Fig. 17. Illustration a conventional SEM image of a sample of cells from grain boundaries [49],[22].

The application of scanning electron microscopy (SEM) analysis to photovoltaic systems represents an effective and reliable tool for diagnosing the degradation of multicrystalline photovoltaic cells and determining the morphology of the degraded solar cell surface [50]. In light of these considerations, a research paper was proposed that addresses the degradation cases of multicrystalline silicon cells. The objective is to study the characteristics before and after bias in order to detect hot spots [51]. The SEM technique was validated by infrared thermography, after which the morphology of the cells' surface hot spots and points was characterized. The research concluded that these spots are formed in areas with high heterogeneity and a high metal content, the scanning electron microscope images of samples from both the affected and unaffected regions are shown. The results for the grain boundary region are shown in **Fig.17**. Figure (a) represents the affected region and Figure (b) represents the healthy region.

Table.1 provides an overview of selected works and papers that include studies on the application of various visual detection techniques for the identification of defects and degradation in photovoltaic modules.

Inspection/diagnosis type	Ref	Types of failure cases
IR imaging	[52]	• Hot spots
	[53]	• Cracks • Delamination • Hotspots • Corrosion
	[54]	• Hot spot • Blind spot • Break • Crack due to fault
	[55]	• Hotspots
	[56]	• Spots hotter

	[57]	• Junction box • Broken front glass • Active bypass diode
	[58]	• Inactive cells
	[59]	• Hot diodes • Hot spots
EL imaging	[60]	• cracks • inactive regions • belt marks • horizontal gridline defects • corroded interconnection ribbons
	[61]	• Material defect • Crack • Deep crack • Microcrack • Disconnected cell interconnect
	[62]	• Material defect • Finger interruptions • Microcrack • Degradation of cell inter-connection • Electrically insulated cell parts
	[63]	• Micro crack • Cell fracture
	[64]	• cracks and breakages • Crystal inhomogeneity • Defective edge isolation • Contact grid interruptions • Shunts • TCO corrosion • Laser scribing failures • Junction box failures
	[65]	• Thick lines • Dirty cells • Broken gate • Color difference • Scratches • Paste spot
	[66]	• Solder fatigue • Cell cracking
	[67]	• Cacked cells • Snail trails • Finger corrosion or delamination
	[68]	• Hot spot cells • Cracked cells • Possible finger corrosion • Encapsulant delamination • Junction box heating • Sealing problems
	[69]	• Encapsulant discoloration • Cell breakages

UV-F imaging		• Disruptions in the finger connections • Cell defects
	[70]	• EVA degradation browning • corrosion in the busbar/interconnect ribbons • EVA/cell interface delamination • pn-junction damage • e−+hole recombination regions • breaks, microcracks • finger interruptions • passivation detected
	[36]	• hotspots • mismatched cells • power-loss-inducing cracks
PL imaging	[71]	• short-circuited bypass diodes • cracks • snail trails • ethylene-vinyl acetate degradation • interconnection failures
	[72]	• Bypass diodes fail open circuit
	[73]	• Black mist • Cross cracked • Strip cracked
	[74]	• Degradation
	[75]	• Microcrack • Dark spot/dark region
	[76]	• Failures of polycrystalline silicon chips.
	[77]	• Degradation of the defect factor Gd in solar cells
SEM imaging	[78]	• Dislocations • stacking faults
	[51]	• leakage currents • hotspot formation
	[79]	• Breakdown in the back sheet of the solar cell • Discontinuity in the cell finger • Discontinuity in the cell busbar • Breakdown in the surface
	[80]	• Delamination

4. Degradation and failure modes of photovoltaic module components

A review of the literature on the reliability of photovoltaic system components, with a particular focus on photovoltaic modules, reveals a number of potential failure modes for solar cells and panels. These include, but are not limited to, cracks, junction boxes, bypass diode breakage, bubbles, burned cells, partial shading, discoloration, cable faults, peeling, dirt, loss of backing plate adhesion, short circuits, and arc faults. Visual inspection is a key method for identifying these failure modes. Defects and degradation are the result of a multitude of factors, including manufacturing defects, environmental conditions, and aging factors. These defects and others have been classified into several categories for further analysis [81].

- Failure factors (physical factors, environmental and natural factors, electrical factors)
- The DC/AC side of the photovoltaic system, including MPPT and PV arrays.
- Module and Cable Level (Cables, Prediction Module Errors)

The degradation of a PV system is a consequence of a combination of factors, some of which are direct and others indirect. The decline in performance is a result of the degradation conditions that contribute to the system's overall deterioration. Early detection and diagnosis of failure conditions, and working to resolve them permanently and immediately, are essential to maintain the reliability of the PV system installation. This section provides a summary of the degradation conditions and major failure conditions that occur in the PV system.

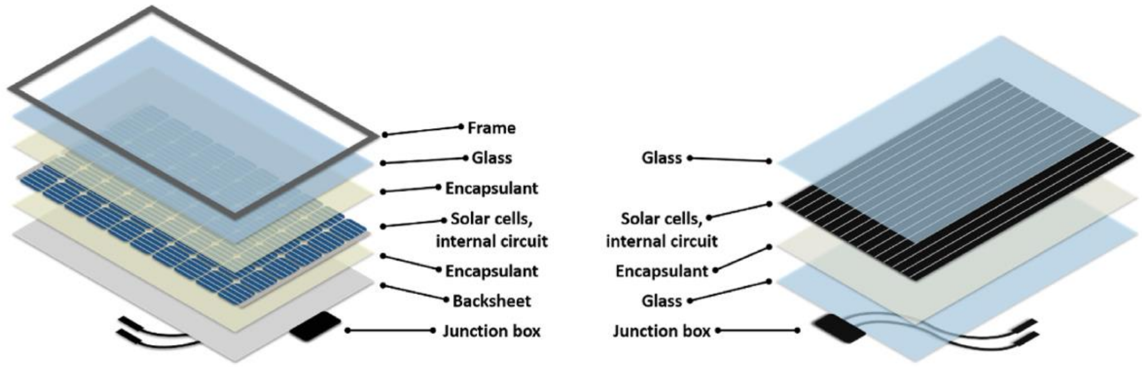


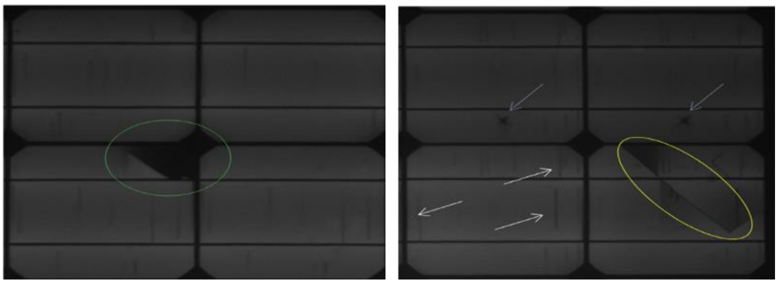
Fig. 18. The fundamental and most commonly used components of photovoltaic system modules. Crystalline silicon (a), thin films of CdTe (b) **)** [82],[83] .

4.1. Photovoltaic cell failure

The material composition of the photovoltaic cell (silicon, CIGS, CdTe, or CdS) plays a significant role in determining its resilience to degradation. However, inherent defects are inevitable, affecting all cell types. These include structural imperfections such as cracks and potential degradation (PID), as well as localized hot spots. These defects are among the most common causes of failure in photovoltaic panels. Solar cell represent one component of a PV module (are shown in **Fig. 18)** [82],[83]. The remaining components include the module packaging materials (front cover glass, back sheet), the internal circuitry (electrodes, connectors), cables, junction boxes, connectors, switching diodes, and the frame [84]. Defects in solar cells are among the most common causes of photovoltaic (PV) failure, which limits the reliability of these systems.

4.1.1. Breakage and cracking in PV cells

Solar cells are susceptible to micro-cracks and fractures due to the inherent fragility of the semiconductors they are composed of. During the initial stages of photovoltaic cell production, including welding and lamination processes, the potential for cracks to form may arise. This may continue throughout the transportation, installation, and operational stages, where thermal or mechanical stresses may contribute to the development of cracks or fractures. Second-generation cells (thin-film cells), are more vulnerable to such damage compared to silicon cells, due to their low stress characteristics. **Fig.19, Fig.20** clearly shows the crack and fracture defects of the photovoltaic cell [85].



(a) (b)

Fig. 19. Some damaged photovoltaic module cells have cracks and fractures. (a): Cell fractures. (b): Cracks, interrupted finger(white line) [85].

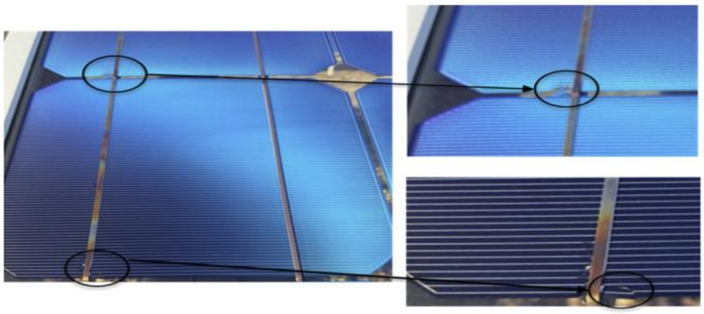


Fig. 20. Fracture and cracking defects are clearly visible in photovoltaic module cells [85].

4.1.2. Hot Spots in PV cells

A "hot spot" is an area of cells where there is a thermal anomaly, meaning the temperature of some cells is significantly higher than that of others as shown in **Fig.21** [86]. This can be caused by damaged connections, partial shading, or the accumulation of dirt in a specific location. Furthermore, the I-V curve of the various cells places an additional burden on the remaining cells, as a reverse current flows through the series, resulting in heat dissipation at different points. There are other factors that contribute to the formation of hot spots, including partial aging of the cell, defective bypass diodes, mismatch of panels in the series, and insufficient ventilation. These issues result in reduced efficiency of photovoltaic panels and, in some cases, pose a fire hazard.

To address these challenges, various solutions have been proposed [87], including an electronic device with a lightweight and effective design for detecting and identifying hot spots in photovoltaic modules[88].

Fig. 21. Locations of hot spots of damaged cells in photovoltaic modules [86].

4.2. Photovoltaic modules failure

4.2.1. Peeling and delamination of the layers of photovoltaic modules

The environmental factors of hot and humid climates have been identified as a significant contributor to the degradation of solar modules, particularly in relation to the composition and structure of the modules themselves. Additionally, the quality of the adhesives utilized in the manufacturing process has been found to be a potential source of weakness in the overall durability of the modules. The combination of high temperatures and humidity, in addition to manufacturing defects, can result in a loss of adhesion between the layers of a solar panel. The coating may separate from the glass or the glass and the cell material or with the backing layer, resulting in water leakage, moisture entering between the layers, and contamination of the photovoltaic modules. This type of degradation leads to a continuous decrease in efficiency as evidenced by a power loss of up to 4% and a degradation of the safety class A rating at a single air/polymer interface [89],and may be a cause of greater risks. Detachment defects are detected by visual inspection or advanced imaging techniques. **Fig.22, fig.23** provides further illustration of the process of separating the components of the modules [90],[91].

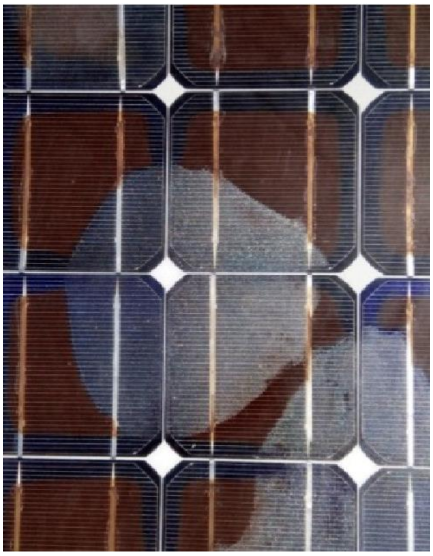
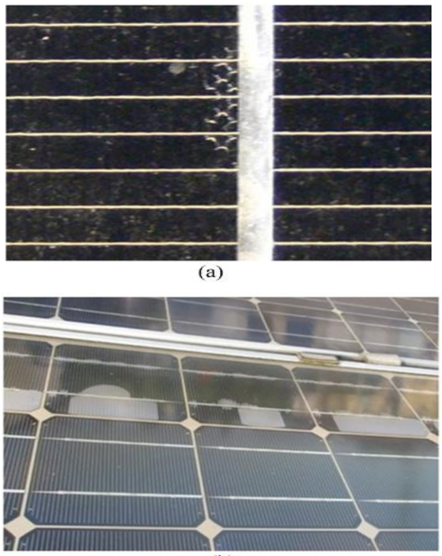


Fig. 22. A delamination of the solar panel [90].



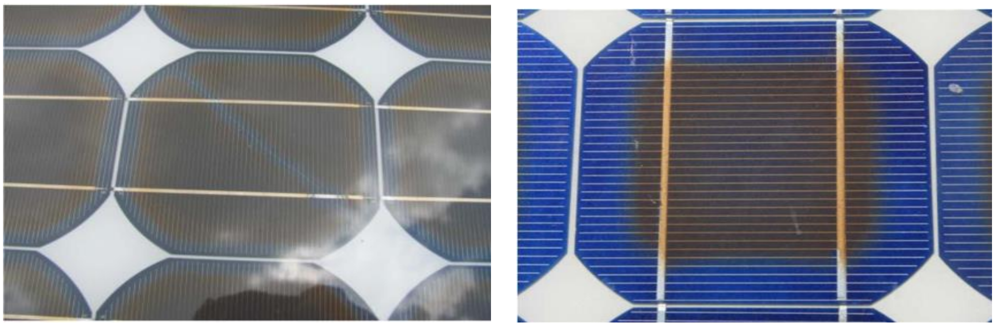
(a)

(b)

Fig. 23. The image shows the adhesion delamination between the front cover glass and the coated material, (a) shows the beginning of the separation process, (b) shows a significant delamination [90].

4.2.2. PV Module Discoloration

One of the most prevalent defects observed in photovoltaic modules is discoloration. This phenomenon can be attributed to oxidation reactions and alterations in the physical properties of the coated materials. These alterations are the result of a chemical reaction between water, ultraviolet radiation, and the materials at temperatures exceeding 50°[92].



(a) (b)

Fig. 24. (a): discoloration and cell cracking in BP Solar c-Si modules, (b): example of a discolored EVA composition [93],[94].

The chemical decomposition of the chromophores incorporated into the polymer composition results in a change in color to yellow, with an increase in color intensity as temperature rises. This phenomenon results in the color of the cells turning brown, thereby creating a color difference on the surfaces of the solar panels, as illustrated in **Figu.24** [93],[94]. This, in turn, results in a discrepancy in the transmittance of solar radiation and a reduction in light absorption in damaged areas, which accelerates the life cycle of photovoltaic modules and leads to premature aging and a loss of output power. Furthermore, this can result in additional failure modes, such as peeling and cracking.

4.2.3. Junction box failure

The photovoltaic modules feature a crucial component on the reverse side, which plays a pivotal role in ensuring the dependability of the photovoltaic system. As illustrated in **Fig.25** [95], the junction box is installed behind the module and on the edge. The junction box's primary function is to safeguard the communication components and the array of wires connecting the photovoltaic modules and external stations.

Fig. 25. The failure condition of the junction box is indicated by corrosion and loss of adhesion in the PV modules at the PNK (a) and Babuin (b) solar plants [95].

Failure can result from corrosion caused by moisture, improper installation on the back of the panel, or inadequate sealing due to poor manufacturing [89]. In addition to the most critical cause, which is the failure of internal arcs due to wires, leading to electrical short circuits and fires, resulting in human and material losses, unreliable welding connections are also a contributing factor to junction box failure.

Fig. 26. Junction box degradation: The left image shows an open junction box, the middle image shows a poorly connected junction box, and the right image shows a junction box with poor wiring [89].

4.2.4. Failure of the bypass diodes

The integration of bypass diodes, in conjunction with blocking diodes (BBD), represents an optimal solution for the avoidance of energy loss resulting from partial misalignment [96], mismatch of solar cells, or the presence of contaminants. This is achieved by their incorporation into the photovoltaic cell string [97]. Bypass diodes resist reverse bias (**fig.27.a** and **b** for illustration), which can be classified as either reverse voltage protection (BpDs) or reverse current protection (BkDs) [98]. This is achieved by allowing the current to bypass the faulty cell and flow to other healthy cells. To ensure the proper operation of these diodes integrated into photovoltaic systems, it is essential to adhere to specific conditions, including the use of compatible modules and circuit parameters, as well as the implementation of appropriate assembly techniques during the manufacturing and production phases. The failure of diodes can lead to a reduction in the overall production efficiency of the module (**fig. 27.c** illustrates the degradation of the diodes) [99]. Additionally, the failure of diodes can result in the degradation of other components within the photovoltaic system. For instance, the color of the cell may darken when the diode temperature rises [100], which can cause deterioration of the junction box or the appearance of hot spots in the photovoltaic cells. . Furthermore, failure of diodes may not be easily detected, which could require noticing the mismatch in the I-V curves or by visual inspection.

(a) (b) (c)

Fig. 27. Bypass and blocking diodes: (a) schematic, (b) junction boxes, (c) brunt diodes, X-rays inspection [97].

The identification of diode degradation symptoms was performed using imaging techniques. **Fig.28** show infrared images of a solar panel with a failed bypass diode. The surface temperature difference between the photovoltaic cells is evident.

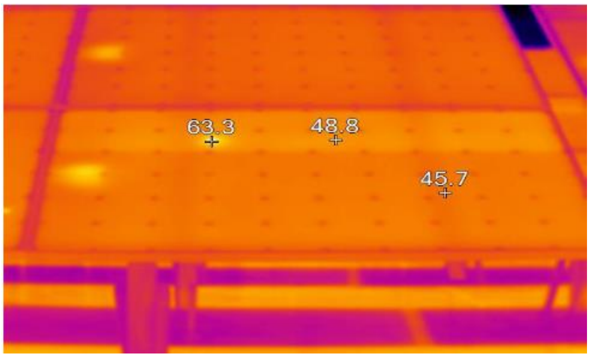


Fig. 28. Infrared image clearly shows a defective bypass diode (Ti27, FLUKE Co., Ltd) [100].

The defective bypass diode forms a closed circuit with the solar cells, thereby generating current from the photovoltaic cells and inducing heat in the photovoltaic cell. **Fig.29** illustrates working and internally degraded bypass diodes using X-ray images. A normal diode shows a clean junction between the metal and the semiconductor, whereas a defective bypass diode shows a bias of the metal towards the silicon layer [101].

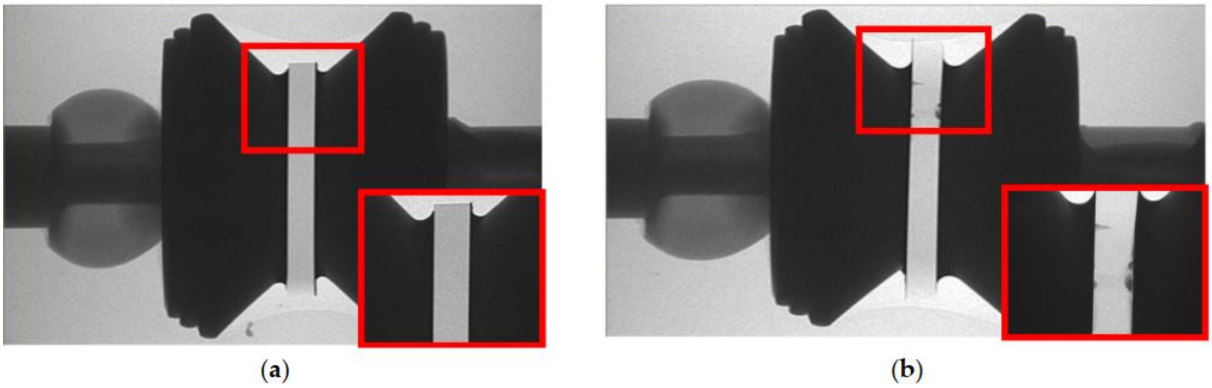


Fig. 29. The X-ray images clearly show that the bypass diode in (a) is healthy, while the one in (b) is defective [101].

4.2.5. Potential induced degradation (PID)

A number of tests and studies have recently been conducted on what is known as Potential -induced degradation. This occurs as a result of leakage of electrical currents generated when there is a high voltage between the solar cells and the frame and the modules packaging. The sodium property causes cations to be pushed from the glass towards the coated material or the photovoltaic cell, Leakage currents flow from the protective frame towards the photovoltaic cells, through several paths in p-type PV modules made of c-silicon (**Fig.30**) [102]. They take paths on the casing with the front glass surface in several directions and on the casing with the back layer in several directions. The direction of the leakage currents reversed, as shown in **Fig.31** [103],[104]. Among the leakage current paths, path 1 is the most harmful because its conductivity increases under humid, rainy weather. which leads to the degradation of the photovoltaic cell and a decrease in its efficiency. In such instances, the ground fault protection system, sodium-free glass, or anti-reflective coating materials serve and other methods [105], as effective mitigating solutions for this phenomenon [106]. It is of paramount importance to adhere to a set of fundamental principles, namely periodic inspection, continuous monitoring, and maintenance, in order to guarantee the reliability and durability of the photovoltaic system and to prevent a multitude of potential failure modes, including PID [104]. This ultimately contributes to the production of sustainable, clean energy.

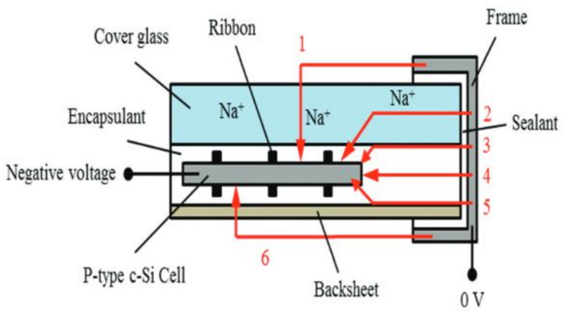


Fig. 30. The illustration depicts a cross-section of a solar module comprising a glass encapsulation cell and a backsheet. It demonstrates the various potential leakage current paths and has been adapted from ref [102],[104].

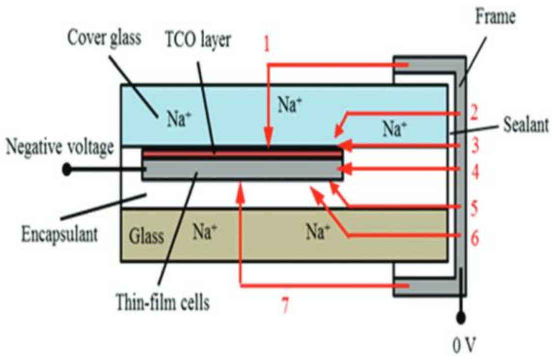


Fig. 31. The second illustration presents a cross-section of a thin-film solar module with a glass sheet serving as a backsheet. It models the potential leakage current paths and has been adapted from ref [103],[104].

4.2.6. Snail tracks defect in photovoltaic modules

One of the most prevalent defects affecting photovoltaic modules is the appearance of snail tracks on the surface of these modules during the initial operational period. This phenomenon is influenced by environmental factors, particularly in the first few months following installation. This degradation has been attributed to several factors [107], the primary of which appears to be the hot climate, high temperatures, and ultraviolet rays, which accelerate their appearance and enhance their formation. This manifests as a change in the color of the silver metal coating, which becomes dark gray or black. The snail tracks on the glass of solar modules are visible to the naked eye. They typically emerge between three months and a year after the commencement of operation or installation of solar panels. **Fig.32** depicts illustrative images of snail tracks in PV modules [108].

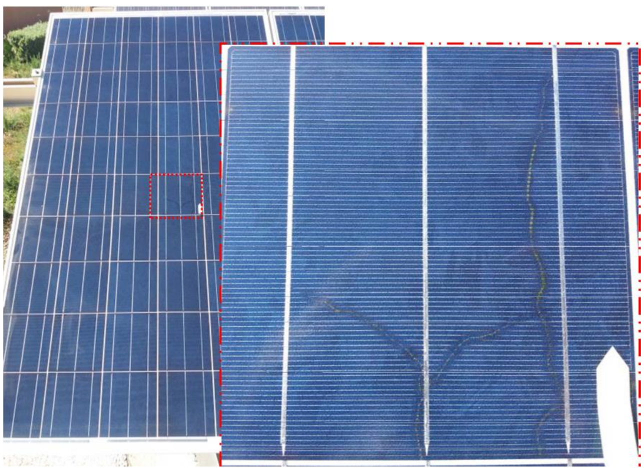


Fig. 32. Defective snail trails on a solar panel [108].

The color change and appearance of snail traces may occur along micro-cracks that are not visible or detectable, or at the edges of photovoltaic cells. Snail traces serve as a reliable indicator of the presence of micro-cracks in modules.

The selection of an appropriate EVA material [109], and the design of the back support cover may influence the reduction of the formation of these tracks. During the manufacturing process, ultraviolet radiation, mechanical stress [110], and freeze testing techniques are used to stimulate the formation of tracks in modules. The snail tracks have been demonstrated to affect the energy production of photovoltaic modules, with a reduction in output of up to 3% /year [111].

4.2.7. Backsheet (BS) Defects

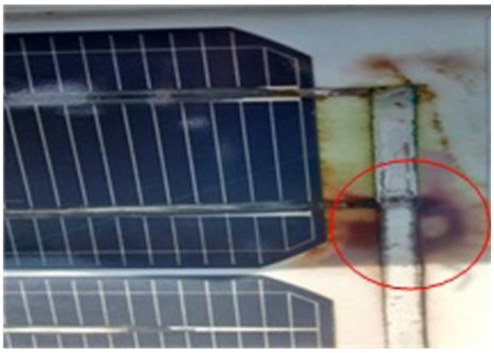
One of the key challenges currently facing the smooth operation of solar installations is the prevalence of backsheet (BS) defects [112]. The backsheet is the final and most fundamental layer of the modules. It typically begins with thermal and mechanical instability, followed by a decline in electrical insulation and, subsequently, the penetration of moisture and air. In response to these challenges, the overall composition of the backsheet has increased in layers, with each layer performing a specific protective function. The degradation of photovoltaic modules is often accompanied by the deterioration of the backsheet (**fig.33**) [113], which may manifest as cracking, layer separation, peeling, corrosion, and degradation of the ethylene vinyl acetate (EVA) layer. The prompt treatment of backsheet failure conditions necessitates an understanding of the underlying failure mechanisms, enabling the accurate and effective detection and diagnosis of such conditions. A number of proposals have been put forth with the aim of identifying backsheet failure conditions in a non-destructive manner. These involve the use of detection and diagnosis techniques based on imaging techniques [114], such as the identification of backsheet failure modes using SAM to visualize changes in the depth of its layers and the identification of cracks between layers [115]. The performance of solar modules and the safety of their components under external environmental stresses and pressures serves as an indicator of the reliability, durability, and safety of photovoltaic systems.

(a) (b)

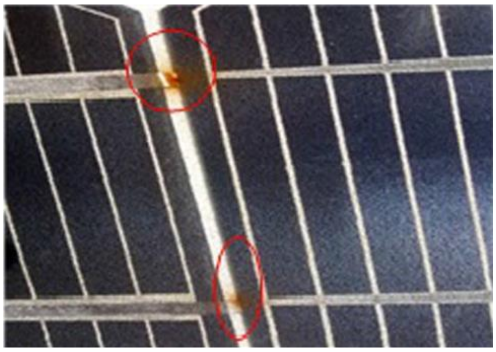
Fig. 33. (a) Delamination of the PV module's backsheet; (b) The presence of bubbles in the backsheet of the PV module [113].

4.2.8. Corrosion Defects

Corrosion represents one of the most prevalent failure and degradation modes observed in solar modules. This degradation process is often gradual in nature [116]. The formation and accumulation of oxides on metals and connections, as well as their subsequent destruction through electrochemical and chemical reactions, is the primary cause of this degradation. The process is further accelerated by heat and high humidity, which can enter between the photovoltaic cells and the encapsulated material, thereby weakening the adhesion coefficient [117]. This ultimately leads to water leakage into the modules. Additionally, peeling defects contribute to accelerated corrosion due to their moisture content. This enhances electrical conductivity, leading to increased leakage currents and subsequent performance degradation in the modules. Corrosion degradation affects various components of photovoltaic panels (**fig.34**) [118], including the edges of modules, which may result in cracking defects, and corrosion in junction boxes, which may cause wiring failures.



(a)



(b)

Fig. 34. (a) A corrosion defect is visible in the conductive band between the strings. (b) A corrosion defect is visible in the conductive band between the PV cells *)* [118].

5. The use of AI models in the detection of defects in photovoltaic modules

Machine learning is a field of artificial intelligence that focuses on the analysis and understanding of data. The objective is to identify and extract the most pertinent features and details, enabling the performance of a multitude of functions, including diagnosis, prediction, classification, and regression problems, among others. Its applications span a range of industries, including manufacturing [119], medicine [120], social media [121], and services [122]. Furthermore, it has become a crucial component of image recognition [123]. Artificial intelligence technology is employed in the solar energy sector for a variety of purposes. For instance, weather data is leveraged to forecast energy production [124], [125], while aerial images of solar modules are utilized to identify visual defects. The existing literature on diagnosing the degradation of solar modules and cells based on artificial intelligence models has primarily focused on developing methods that facilitate accurate and rapid detection of anomalies in solar panels. These methods can be broadly classified into three categories. The first category uses ML algorithms to analyze data imported from sensors in order to detect and classify defects in the photovoltaic system. The second category relies on deep learning algorithms to analyze and detect defects and classify degradation conditions in solar modules based on historical data or by using unmanned aerial vehicles with imaging techniques to detect visual defects [126]. The last category relies on pre-trained models and often uses imaging technology as a means of detecting defects. Table 2 presents a comprehensive overview of the existing literature on the detection and classification of diverse solar visual degradation modes through the application of artificial intelligence (AI) models.

Table.1. The table illustrates the application of machine learning techniques in the diagnosis of photovoltaic module degradation conditions.

Ref	Inspection Technology	Degradation Pattern	AI Model	Category	Dataset Size	Performance standards
[127]	EL imaging	Cracks, micro-cracks, finger failures, no defects	SVM, RF, k-NN	Classification/ ML	46,000 image	F1 score, Accuracy, Recall, Precision.
[128]	EL imaging	micro-crack	VGG-16, VGG-19, Inception-v3, ResNet50-v2	Detection / pre-trained	2,624 images	Accuracy, Precision, Recall, F-1, AUC ROC
[129]	EL imaging	cracks, micro-cracks, PID, and shaded areas	CNN	Detection/ DL	/	Accuracy, Precision.
[130]	MCOM and ELPV datasets	micro-cracks	VGG-16	Detection/ pre-trained	/	Precision, Recall, F-1
[131]	EL imaging	Cracks	Alex-net	Detection/ DL	876 solar panels	Precision, Recall, F-Score
[132]	IR imaging	Hotspot	CNN, Naive Bayes	Classification/ DL, ML	274 images	Accuracy
[133]	Hot Spot Images	Hotspot	Google-Net, ResNet-50, Alex-Net, MobileNet-v2	Classification/ pre-trained	10,495 images	confusion matrices, Accuracy, Precision, Sensitivity, Specificity, F1-score
[134]	Thermal images	Single Cell Hotspot, Multi Cell Hotspot, Dust and Shadow, Diode Fault, PID	ResNet-50, Faster R-CNN	Classification, Detection / pre-trained	837 images	Accuracy, mAP
[135]	Thermal imaging	Hotspot	YOLOv5	Detection/ pre-trained	1000 images	frame rate, precision, recall, mAP@.5, mAP@0.95
[136]	IR imaging	Hotspot	S-YOLOv5	Detection/ pre-trained	5600 panel images	Precision, Recall, mAP, FPS
[137]	PPL, V_{OC} , I_{SC} , I_{RR}	micro crack, hot-spotting	SVM, NN	Detection, Classification/ ML	/	Accuracy, AP
[138]	EL imaging	black-core, crack, edge	CNN	Detection/ DL	1720 images	Confusion matrix, Accuracy, Precision, Recall, and F1 Score
[139]	Thermal images	Degradation	FPN, U-Net, DeepLabV3+	Detection, segmentation/ DL	1153 images	IoU Score, Dice Score, F-score, Precision, Recall, Accuracy
[140]	RGB images	Hotspots, Micro cracks, Erosion, Dust deposition	RMVDM, HOLT	Detection, classification/ DL	2088 images	Accuracy
[141]	SEM, IR imaging	material defect	multi-task learning (MTL)	Segmentation, classification, regression/ DL	212 images	MSE, AE, IoU

Conclusion

The article provides a general, comprehensive, and accessible overview of the subject matter, intended for novice researchers in the field of solar energy. The article begins by providing an overview of the various types of photovoltaic installations currently available. It then proceeds to examine the various visual inspection techniques that can be employed to identify potential faults in photovoltaic modules. These techniques include thermal imaging, photoelectric imaging, ultraviolet fluorescence imaging, and other. Subsequently, the article identifies the common deterioration cases and defects that photovoltaic system units are exposed to. Despite the diversity of manufacturing materials, these units share a common set of components, including bypass diodes, frames, junction boxes, packaging materials, connectors, wires, and electrical circuits. These components are subjected to quality and reliability testing in both laboratory and field settings. However, it is challenging to accurately assess the reliability of certain components under uncertain environmental conditions. Indeed, any deterioration affecting any of these elements results in a reduction in system performance, thereby leading to a decline in energy production. In some instances, these defects may even pose a potential risk of disaster. This review employs a simplified sequence for general comprehension and presentation of the degradation mechanisms, attempting to establish a correlation between them and the underlying causes, whether as a consequence of another degradation process or as a result of environmental stress. The appearance of hot spots, discoloration of the packaging material, and peeling are attributed to the presence of infrared radiation, ultraviolet radiation, and misinformation. A review of the methodologies and techniques used for the detection and identification of degradation conditions reveals that artificial intelligence models have made significant contributions to this field and have demonstrated excellent performance in the detection and classification of visual defects using aerial photography techniques. In conclusion, this review can provide a contribution to the field of solar energy, thereby facilitating its use on a large scale.

References

[1] T. Voïta, "European Solar PV Manufacturing : Terminal Decline or Hope for a Rebirth ," 2024.

[2] J. Assadeg, K. Sopian, and A. Fudholi, "Performance of grid-connected solar photovoltaic power plants in the Middle East and North Africa," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 5, pp. 3375–3383, 2019, doi: 10.11591/ijece.v9i5.pp3375-3383.

[3] K. Osmani, A. Haddad, T. Lemenand, B. Castanier, M. Alkhedher, and M. Ramadan, "A critical review of PV systems' faults with the relevant detection methods," *Energy Nexus*, vol. 12, no. September, p. 100257, 2023, doi: 10.1016/j.nexus.2023.100257.

[4] K. Abdulmawjood, S. S. Refaat, and W. G. Morsi, "Detection and prediction of faults in photovoltaic arrays: A review," *Proc. - 2018 IEEE 12th Int. Conf. Compat. Power Electron. Power Eng. CPE-POWERENG 2018*, no. March, pp. 1–8, 2018, doi: 10.1109/CPE.2018.8372609.

[5] N. Afifah, Indrabayu, A. Suyuti, and Syafaruddin, "A review on image processing techniques for damage detection on photovoltaic panels," *ICIC Express Lett.*, vol. 15, no. 7, pp. 779–790, 2021, doi: 10.24507/icicel.15.07.779.

[6] Y. Zhang *et al.*, "The PV System Doctor - Comprehensive diagnosis of PV system installations," *Energy Procedia*, vol. 130, pp. 108–113, 2017, doi: 10.1016/j.egypro.2017.09.404.

[7] B. Aboagye, S. Gyamfi, E. A. Ofosu, and S. Djordjevic, "Characterisation of visual defects on installed solar photovoltaic (PV) modules in different climatic zones in Ghana," *Sci. African*, vol. 20, 2023, doi: 10.1016/j.sciaf.2023.e01682.

[8] S. Gallardo-Saavedra, L. Hernández-Callejo, and Ó. Duque-Pérez, "Analysis and characterization of PV module defects by thermographic inspection," *Rev. Fac. Ing.*, no. 93, pp. 92–104, 2019, doi: 10.17533/udea.redin.20190517.

[9] D. Rahmouni , M.D. Mouss, M. Benbouzid , L.H. Mouss, "Enhancing Photovoltaic Module Reliability : A Comparative study of Deep Learning Models for Failure Diagnosis Using Electroluminescence Images," no. *The first International Conference on Electrical Engineering and Advanced Technologies, ICEEAT23*.

[10] I. E. Commission, "International Standard IEC 61215-2005," *Iec*, p. 51, 2005.

[11] ISO 8573:2010, *International Standard International Standard*, vol. 2003. 2003.

[12] B. Taghezouit, F. Harrou, Y. Sun, and W. Merrouche, "Model-based fault detection in photovoltaic systems: A comprehensive review and avenues for enhancement," *Results Eng.*, vol. 21, no. January, p. 101835, 2024, doi: 10.1016/j.rineng.2024.101835.

[13] C. C. License and D. Version, *Advanced Signal Processing Techniques Applied to Power Systems Control and Analysis*. 2020. doi: 10.3390/books978-3-03936-187-8.

[14] S. Buddha *et al.*, "Signal processing for photovoltaic applications," *2012 IEEE Int. Conf. Emerg. Signal Process.*

Appl. ESPA 2012 - Proc., no. February, pp. 115–118, 2012, doi: 10.1109/ESPA.2012.6152459.

[15] B. Meyers, M. Deceglie, C. Deline, and D. Jordan, “Signal Processing on PV Time-Series Data: Robust Degradation Analysis without Physical Models,” *IEEE J. Photovoltaics*, vol. 10, no. 2, pp. 546–553, 2020, doi: 10.1109/JPHOTOV.2019.2957646.

[16] A. Woyte *et al.*, *Analytical Monitoring of Grid-connected Photovoltaic Systems, Report IEA-PVPS T13-03*. 2014.

[17] ISO 8573:2010, “International Standard International Standard,” *61010-1 © Iec2001*, vol. 2003, p. 13, 2003.

[18] T. Reports, S. Articles, T. Implementations, and T. Reports, *Te c h n i c a l*, vol. 23, no. 2. 2021.

[19] A. Asnil, K. Krismadinata, I. Husnaini, H. Hazman, and E. Astrid, “Real-Time Monitoring System Using IoT for Photovoltaic Parameters,” *TEM J.*, vol. 12, no. 3, pp. 1316–1322, 2023, doi: 10.18421/TEM123-11.

[20] N. M. Kumar, K. Atluri, and S. Palaparthi, “Internet of Things (IoT) in Photovoltaic Systems,” *2018 Natl. Power Eng. Conf. NPEC 2018*, no. March, pp. 1–4, 2018, doi: 10.1109/NPEC.2018.8476807.

[21] N. Xie, Y. Chen, and P. He, “Application of Wireless Sensor Network Technology Using Intelligent Algorithm in Mismatch Detection of Photovoltaic Power Generation,” *Wirel. Commun. Mob. Comput.*, vol. 2022, 2022, doi: 10.1155/2022/7688109.

[22] M. M. Rahman, I. Khan, and K. Alameh, “Potential measurement techniques for photovoltaic module failure diagnosis: A review,” *Renew. Sustain. Energy Rev.*, vol. 151, no. October 2020, p. 111532, 2021, doi: 10.1016/j.rser.2021.111532.

[23] M. Köntges *et al.*, *Review of Failures of Photovoltaic Modules*, no. April 2015. 2014.

[24] A. E. Nieto, F. Ruiz, and D. Patiño, “Characterization of electric faults in photovoltaic array systems,” *DYNA*, vol. 86, no. 211, pp. 54–63, 2019, doi: 10.15446/dyna.v86n211.79085.

[25] F. Li, W. Dong, and W. Wu, “A general model for comprehensive electrical characterization of photovoltaics under partial shaded conditions,” *Adv. Appl. Energy*, vol. 9, no. December, p. 100118, 2023, doi: 10.1016/j.adapen.2022.100118.

[26] M. Vuković, M. S. Wiig, G. A. dos Reis Benatto, E. Olsen, and I. Burud, “A review of imaging methods for detection of photoluminescence in field-installed photovoltaic modules,” *Prog. Energy*, vol. 6, no. 3, 2024, doi: 10.1088/2516-1083/ad4250.

[27] M. Maziuk, L. Jasińska, J. Domaradzki, and P. Chodasewicz, “Imaging Methods of Detecting Defects in Photovoltaic Solar Cells and Modules: a Survey,” *Metrol. Meas. Syst.*, vol. 30, no. 3, pp. 381–401, 2023, doi: 10.24425/mms.2023.146426.

[28] C. Buerhop, L. Bommes, J. Schlipf, T. Pickel, A. Fladung, and I. M. Peters, “Infrared imaging of photovoltaic modules: a review of the state of the art and future challenges facing gigawatt photovoltaic power stations,” *Prog. Energy*, vol. 4, no. 4, 2022, doi: 10.1088/2516-1083/ac890b.

[29] G. Tessier *et al.*, “Quantitative thermoreflectance imaging: Calibration method and validation on a dedicated integrated circuit,” *IEEE Trans. Components Packag. Technol.*, vol. 30, no. 4, pp. 604–608, 2007, doi: 10.1109/TCAPT.2007.898384.

[30] J. A. Tsanakas, L. Ha, and C. Buerhop, “Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges,” *Renew. Sustain. Energy Rev.*, vol. 62, pp. 695–709, 2016, doi: 10.1016/j.rser.2016.04.079.

[31] A. W. Kandeal *et al.*, “Infrared thermography-based condition monitoring of solar photovoltaic systems: A mini review of recent advances,” *Sol. Energy*, vol. 223, no. May, pp. 33–43, 2021, doi: 10.1016/j.solener.2021.05.032.

[32] G. C. Eder, Y. Voronko, C. Hirschl, R. Ebner, G. Újvári, and W. Mühleisen, “Non-destructive failure detection and visualization of artificially and naturally aged PV modules,” *Energies*, vol. 11, no. 5, pp. 1–14, 2018, doi: 10.3390/en11051053.

[33] M. Elrawemi, L. Blunt, L. Fleming, F. Sweeney, and D. Robbins, “Defect detection in thin-film photovoltaics;

Towards improved efficiency and longevity," *IREC 2014 - 5th Int. Renew. Energy Congr.*, pp. 1–5, 2014, doi: 10.1109/IREC.2014.6827021.

[34] S. Deitsch *et al.*, "Automatic classification of defective photovoltaic module cells in electroluminescence images," *Sol. Energy*, vol. 185, pp. 455–468, 2019, doi: 10.1016/j.solener.2019.02.067.

[35] W. Mühleisen *et al.*, "Scientific and economic comparison of outdoor characterisation methods for photovoltaic power plants," *Renew. Energy*, vol. 134, pp. 321–329, 2019, doi: 10.1016/j.renene.2018.11.044.

[36] A. Morlier, M. Siebert, I. Kunze, G. Mathiak, and M. Kontges, "Detecting Photovoltaic Module Failures in the Field during Daytime with Ultraviolet Fluorescence Module Inspection," *IEEE J. Photovoltaics*, vol. 7, no. 6, pp. 1710–1716, 2017, doi: 10.1109/JPHOTOV.2017.2756452.

[37] F. Vorster and E. Van Dyk, "UV fluorescence imaging of photovoltaic modules," *6th South. African Sol. Energy Conf.*, pp. 1–5, 2019, [Online]. Available: https://www.sasec.org.za/papers2019/39.pdf

[38] K Eder (Speaker), . K.Yuliya Voronko, Paul Grillberger, Bernhard Kubicek, "UV-Fluorescence measurements as tool for the detection of degradation effects in PV-Modules," *Energy Convers. Hydrog.*, 2017, [Online]. Available: https://publications.ait.ac.at/en/publications/uv-fluorescence-measurements-as-tool-for-the-detection-of-degrada

[39] "Ocean Optics.," *SPIE Demin Proc*, vol. 64, 1975.

[40] S. B. Bae *et al.*, "380-nm ultraviolet light-emitting diodes with InGaN/AlGaN MQW structure," *ETRI J.*, vol. 35, no. 4, pp. 566–570, 2013, doi: 10.4218/etrij.13.1912.0029.

[41] Ocean Optics, *Maya2000Pro Series Spectrometers Installation and Operation Manual*. 2009.

[42] M. Kontges, A. Morlier, G. Eder, E. Fleis, B. Kubicek, and J. Lin, "Review: Ultraviolet Fluorescence as Assessment Tool for Photovoltaic Modules," *IEEE J. Photovoltaics*, vol. 10, no. 2, pp. 616–633, 2020, doi: 10.1109/JPHOTOV.2019.2961781.

[43] B. Doll *et al.*, "Aerial Photoluminescence Imaging of Photovoltaic Modules," *Phys. Status Solidi - Rapid Res. Lett.*, vol. 17, no. 12, 2023, doi: 10.1002/pssr.202300059.

[44] A. Redondo Plaza *et al.*, "Partial Photoluminescence Imaging for Inspection of Photovoltaic Cells: Artificial LED Excitation and Sunlight Excitation," *Energies*, vol. 16, no. 11, 2023, doi: 10.3390/en16114531.

[45] M. Agrawal, V. V. S. H. Prasad, G. Nijhawan, S. S. Jalal, B. Rajalakshmi, and S. P. Dwivedi, "A Comprehensive Review of Electron Microscopy in Materials Science: Technological Advances and Applications," *E3S Web Conf.*, vol. 505, pp. 1–11, 2024, doi: 10.1051/e3sconf/202450501029.

[46] M. Elrawemi, L. Blunt, L. Fleming, F. Sweeney, and D. Robbins, "Defect detection in thin-film photovoltaics; Towards improved efficiency and longevity," *IREC 2014 - 5th Int. Renew. Energy Congr.*, 2014, doi: 10.1109/IREC.2014.6827021.

[47] H. S. Min, "Scanning Electron Microscopy Analysis of Thin Films: A Review," *Res. Asp. Chem. Mater. Sci. Vol. 5*, no. December, pp. 16–28, 2022, doi: 10.9734/bpi/racms/v5/4419e.

[48] W. Gunawan, S. Stepanus, L. Lisapaly, F. Mustari, and H. S. Sutomo, "Micro crack imaging of silicon solar cells with SEM (Scanning Electron Microscopy)," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 878, no. 1, 2021, doi: 10.1088/1755-1315/878/1/012062.

[49] M. Joshi, A. Bhattacharyya, and S. W. Ali, "Characterization techniques for nanotechnology applications in textiles," *Indian J. Fibre Text. Res.*, vol. 33, no. 3, pp. 304–317, 2008.

[50] J. T. Wätjen, *Microscopic Characterisation of Solar Cells: An Electron Microscopy Study of Cu(In,Ga)Se 2 and Cu 2 ZnSn(S,Se) 4 Solar Cells*. 2013.

[51] G. O. Osayemwenre, E. L. Meyer, and S. Mamphweli, "Sem analysis as a diagnostic tool for photovoltaic cell degradation," *Dig. J. Nanomater. Biostructures*, vol. 10, no. 2, pp. 479–487, 2015.

[52] V. Kirubakaran *et al.*, "Infrared Thermal Images of Solar PV Panels for Fault Identification Using Image Processing Technique," *Int. J. Photoenergy*, vol. 2022, 2022, doi: 10.1155/2022/6427076.

[53] S. Umar, M. S. Qureshi, and M. U. Nawaz, "Thermal Imaging and AI in Solar Panel Defect Identification," *Int. J. Adv. Eng. Technol. Innov.*, vol. 1, no. 3, pp. 73–95, 2024, [Online]. Available: https://ijaeti.com/index.php/Journal/article/view/230

[54] F. A. Khan, B. K. Gautam, S. Singh, S. Cse, and U. Pradesh, "Detection of Defects in Solar Panels Using Thermal Imaging By Pca and Ica Method," *Int. Res. J. Eng. Technol.*, vol. 4, no. 6, pp. 1700–1703, 2017, [Online]. Available: https://irjet.net/archives/V4/i6/IRJET-V4I6555.pdf

[55] A. Gurras, L. Gergidis, C. Mytafides, L. Tzounis, and A. S. Paipetis, "Automated detection-classification of defects on photo-voltaic modules assisted by thermal drone inspection," *MATEC Web Conf.*, vol. 349, p. 03015, 2021, doi: 10.1051/matecconf/202134903015.

[56] S. Gallardo-Saavedra, L. Hernández-Callejo, M. D. C. Alonso-García, J. Muñoz-Cruzado-alba, and J. Ballestín-Fuertes, "Infrared thermography for the detection and characterization of photovoltaic defects: Comparison between illumination and dark conditions," *Sensors (Switzerland)*, vol. 20, no. 16, pp. 1–16, 2020, doi: 10.3390/s20164395.

[57] B. L. Aarseth and E. S. Marstein, "Defect recognition and power loss estimation of pv systems using infrared thermography," *36th Eur. Photovolt. Sol. Energy Conf. (36th EU PVSEC)*, pp. 1567–1572, 2019, doi: 10.4229/EUPVSEC20192019-5CV.4.5.

[58] M. Rivki, A. M. Bachtiar, T. Informatika, F. Teknik, and U. K. Indonesia, "No Title," no. 112, pp. 1171–1175.

[59] L. Bommes *et al.*, "Anomaly Detection in IR Images of PV Modules using Supervised Contrastive Learning," 2020.

[60] L. Pratt, D. Govender, and R. Klein, "Defect detection and quanti fi cation in electroluminescence images of solar PV modules using U-net semantic segmentation," *Renew. Energy*, vol. 178, pp. 1211–1222, 2021, doi: 10.1016/j.renene.2021.06.086.

[61] J. Zhang, X. Chen, H. Wei, and K. Zhang, "A lightweight network for photovoltaic cell defect detection in electroluminescence images based on neural architecture search and knowledge distillation," 2023.

[62] S. Deitsch, V. Christlein, C. Buerhop-lutz, and A. Maier, "Automatic Classification of Defective Photovoltaic Module Cells in Electroluminescence Images Automatic Classification of Defective Photovoltaic Module Cells in Electroluminescence Images," no. July, 2018, doi: 10.48550/arXiv.1807.02894.

[63] R. Benatto *et al.*, "Enhancement of electroluminescence images for fault detection in photovoltaic panels," 2018.

[64] A. Mansouri *et al.*, "Defect detection in photovoltaic modules using electroluminescence imaging," pp. 1–5.

[65] H. Chen, Y. Pang, Q. Hu, and K. Liu, "Solar Cell Surface Defect Inspection Based on Multispectral Convolutional Neural Network," pp. 1–14.

[66] B. Dana *et al.*, "Methods for In Situ Electroluminescence Imaging of Conditions," 2020, doi: 10.1109/JPHOTOV.2020.3001723.

[67] A. M. Gabor and P. Knodle, "UV Fluorescence for Defect Detection in Residential Solar Panel Systems," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 2575–2579, 2021, doi: 10.1109/PVSC43889.2021.9518884.

[68] Andrew M. GaborPhilip Knodle, "UV Fluorescence for Defect Detection in Residential Solar Panel Systems," in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021. doi: DOI: 10.1109/PVSC43889.2021.9518884.

[69] H. A. S. K. G. M. V. Alberts, "Enhanced Defect Detection in Desert-Exposed PV Modules Through Three Imaging Techniques," 2023. doi: DOI: 10.1109/MENA-SC54044.2023.10374513.

[70] S. Kaplanis, E. Kaplani, and P. N. Borza, "PV Defects Identification through a Synergistic Set of Non-Destructive Testing (NDT) Techniques," *Sensors*, vol. 23, no. 6, 2023, doi: 10.3390/s23063016.

[71] B. D. D. et Al, "Photoluminescence for Defect Detection on Full-Sized Photovoltaic Modules," *August*

2021IEEE J. Photovoltaics PP(99)1-11, 2021, doi: 10.1109/JPHOTOV.2021.3099739.

[72] Z. H. Raghavi Bhoopathy, Oliver Kunz, Mattias Juhl, Thorsten Trupke, "Outdoor photoluminescence imaging of solar panels by contactless switching: Technical considerations and applications," *Prog. PHOTOVOLYAICS*, doi: https://doi.org/10.1002/pip.3216.

[73] X. Peng, J. Tian, and H. Huang, "Research on Solar Cell Defect Detection Method Based on Photoluminescence," vol. 7, no. 8, pp. 202–209, 2021, doi: 10.6911/WSRJ.202108.

[74] M. R. Ahan, A. Nambi, T. Ganu, D. Nahata, and S. Kalyanaraman, "AI-assisted Cell-Level Fault Detection and Localization in Solar PV Electroluminescence Images," *SenSys 2021 - Proc. 2021 19th ACM Conf. Embed. Networked Sens. Syst.*, pp. 485–491, 2021, doi: 10.1145/3485730.3493455.

[75] A. Binomairah *et al.*, "Detection of microcracks and dark spots in monocrystalline PERC cells using photoluminescene imaging and YOLO-based CNN with spatial pyramid pooling," *EPJ Photovoltaics*, vol. 13, 2022, doi: 10.1051/epjpv/2022025.

[76] F. Yan, S. Johnston, K. Zaunbrecher, M. Al-Jassim, O. Sidelkheir, and A. Blosse, "Defect-band emission photoluminescence imaging on multi-crystalline Si solar cells," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, no. July, pp. 002231–002235, 2011, doi: 10.1109/PVSC.2011.6186400.

[77] O. Nos *et al.*, "Quality control method based on photoluminescence imaging for the performance prediction of c-Si/a-Si:H heterojunction solar cells in industrial production lines," *Sol. Energy Mater. Sol. Cells*, vol. 144, pp. 210–220, 2016, doi: 10.1016/j.solmat.2015.09.009.

[78] C. Sun, E. Müller, M. Meffert, and D. Gerthsen, "Analysis of crystal defects by scanning transmission electron microscopy (STEM) in a modern scanning electron microscope," *Adv. Struct. Chem. Imaging*, vol. 5, no. 1, pp. 1–9, 2019, doi: 10.1186/s40679-019-0065-1.

[79] M. Dhimish and A. M. Tyrrell, "Power loss and hotspot analysis for photovoltaic modules affected by potential induced degradation," *npj Mater. Degrad.*, vol. 6, no. 1, 2022, doi: 10.1038/s41529-022-00221-9.

[80] A. A. Q. Hasan, A. A. Alkahtani, S. A. Shahahmadi, M. N. E. Alam, M. A. Islam, and N. Amin, "Delamination-and electromigration-related failures in solar panels—a review," *Sustain.*, vol. 13, no. 12, 2021, doi: 10.3390/su13126882.

[81] G. B. Balachandran, M. Devisridhivyadharshini, M. E. Ramachandran, and R. Santhiya, "Comparative investigation of imaging techniques, pre-processing and visual fault diagnosis using artificial intelligence models for solar photovoltaic system – A comprehensive review," *Meas. J. Int. Meas. Confed.*, vol. 232, no. January, p. 114683, 2024, doi: 10.1016/j.measurement.2024.114683.

[82] J. Ramanujam *et al.*, "Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review," *Prog. Mater. Sci.*, vol. 110, p. 100619, 2020, doi: 10.1016/j.pmatsci.2019.100619.

[83] M. A. G. Mary D Archer, *Clean Electricity From Photovoltaics (2nd Edition)*. World Scientific, 2014. [Online]. Available: https://www.worldscientific.com/

[84] M. Aghaei *et al.*, "Review of degradation and failure phenomena in photovoltaic modules," *Renew. Sustain. Energy Rev.*, vol. 159, no. 2022, p. 112160, 2022, doi: 10.1016/j.rser.2022.112160.

[85] C. Hajjaj *et al.*, "Degradation and performance analysis of a monocrystalline PV system without EVA encapsulating in semi-arid climate," *Heliyon*, vol. 6, no. 6, p. e04079, 2020, doi: 10.1016/j.heliyon.2020.e04079.

[86] J. Kim, M. Rabelo, S. P. Padi, H. Yousuf, E. C. Cho, and J. Yi, "A review of the degradation of photovoltaic modules for life expectancy," *Energies*, vol. 14, no. 14, pp. 1–21, 2021, doi: 10.3390/en14144278.

[87] M. Dhimish, V. Holmes, P. Mather, and M. Sibley, "Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance," *Sol. Energy Mater. Sol. Cells*, vol. 179, pp. 72–79, 2018, doi: 10.1016/j.solmat.2018.02.019.

[88] M. Dhimish, M. Theristis, and V. d'Alessandro, "Photovoltaic hotspots: A mitigation technique and its thermal cycle," *Optik (Stuttg).*, vol. 300, no. January, p. 171627, 2024, doi: 10.1016/j.ijleo.2024.171627.

[89] M. Köntges *et al.*, *IEA PVPS Subtask 3.2: Review of Failures of Photovoltaic Modules*. 2014.

[90] Z. Kherici, H. Cheghib, N. Kahoul, M. Youness, B. C. Affari, and T. Hazem, "Failure modes of standard photovoltaic modules in Sahara Desert," *11th Int. Renew. Energy Congr. IREC 2020*, no. January, 2020, doi: 10.1109/IREC48820.2020.9310409.

[91] V. Poulek *et al.*, "PV Panel and PV Inverter Damages Caused by Combination of Edge Delamination, Water Penetration, and High String Voltage in Moderate Climate," *IEEE J. Photovoltaics*, vol. 11, no. 2, pp. 561–565, 2021, doi: 10.1109/JPHOTOV.2021.3050984.

[92] P. Manganiello, M. Balato, and M. Vitelli, "A Survey on Mismatching and Aging of PV Modules: The Closed Loop," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7276–7286, 2015, doi: 10.1109/TIE.2015.2418731.

[93] J. Wohlgemuth, T. Silverman, D. C. Miller, P. McNutt, M. Kempe, and M. Deceglie, "Evaluation of PV module field performance," *2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015*, no. July 2016, 2015, doi: 10.1109/PVSC.2015.7356132.

[94] J. H. Wohlgemuth, M. D. Kempe, and D. C. Miller, "Discoloration of PV encapsulants," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, no. June 2013, pp. 3260–3265, 2013, doi: 10.1109/PVSC.2013.6745147.

[95] J. A. Tanesab, A. Amheka, R. Sinaga, J. J. Mauta, and E. Hattu, "A preliminary study of common defects of photovoltaic modules in West Timor, Indonesia," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 542, no. 1, 2020, doi: 10.1088/1755-1315/542/1/012041.

[96] M. Dhakshinamoorthy, K. Sundaram, P. Murugesan, and P. W. David, "Bypass diode and photovoltaic module failure analysis of 1.5kW solar PV array," *Energy Sources, Part A Recover. Util. Environ. Eff.*, vol. 44, no. 2, pp. 4000–4015, 2022, doi: 10.1080/15567036.2022.2072023.

[97] S. Silvestre, A. Boronat, and A. Chouder, "Study of bypass diodes configuration on PV modules," *Appl. Energy*, vol. 86, no. 9, pp. 1632–1640, 2009, doi: 10.1016/j.apenergy.2009.01.020.

[98] T. Hamada, T. Azuma, I. Nanno, N. Ishikura, M. Fujii, and S. Oke, "Impact of Bypass Diode Fault Resistance Values on Burnout in Bypass Diode Failures in Simulated Photovoltaic Modules with Various Output Parameters," *Energies*, vol. 16, no. 16, 2023, doi: 10.3390/en16165879.

[99] A. Mellit, G. M. Tina, and S. A. Kalogirou, "Fault detection and diagnosis methods for photovoltaic systems: A review," *Renew. Sustain. Energy Rev.*, vol. 91, no. March, pp. 1–17, 2018, doi: 10.1016/j.rser.2018.03.062.

[100] D. Gfeller, R. Neukomm, and U. Muntwyler, "The Bypass-Diode A Weakness in today ' s PV Systems," *37th Eur. Photovolt. Sol. Energy Conf.*, vol. 4, no. September, p. 3400, 2020.

[101] W. G. Shin, S. W. Ko, H. J. Song, Y. C. Ju, H. M. Hwang, and G. H. Kang, "Origin of bypass diode fault in c-Si photovoltaic modules: Leakage current under high surrounding temperature," *Energies*, vol. 11, no. 9, 2018, doi: 10.3390/en11092416.

[102] N. G. D. N. S. S. E. Schneller, "Evolution of Leakage Current Paths in MC-Si PV Modules From Leading Manufacturers Undergoing High-Voltage Bias Testing," *IEEE J. Photovoltaics*, vol. Volume: 4, no. 2156–3381, pp. 654–658, 2014, doi: 10.1109/JPHOTOV.2013.2294764.

[103] J. A. del C. C.R. Osterwald, T.J. McMahon, "Electrochemical corrosion of SnO2:F transparent conducting layers in thin-film photovoltaic modules," *Sol. Energy Mater. Sol. Cells*, vol. Volume 79, no. Issue 1, 2003, doi: https://doi.org/10.1016/S0927-0248(02)00363-.

[104] W. Luo *et al.*, "Potential-induced degradation in photovoltaic modules: A critical review," *Energy Environ. Sci.*, vol. 10, no. 1, pp. 43–68, 2017, doi: 10.1039/c6ee02271e.

[105] W. Zhang, Y. Wang, P. Xu, D. Li, and B. Liu, "A potential induced degradation suppression method for photovoltaic systems," *Energy Reports*, vol. 10, no. October, pp. 3955–3969, 2023, doi: 10.1016/j.egyr.2023.10.064.

[106] G. Badran and M. Dhimish, "Potential Induced Degradation in Photovoltaic Modules: A Review of the Latest Research and Developments," *Solar*, vol. 3, no. 2, pp. 322–346, 2023, doi: 10.3390/solar3020019.

[107] R. G. Arti Pareek, “Analysis and insights into snail trail degradation in photovoltaic modules,” *Sol. Energy*, vol. Volume 275, p. Page 112613.

[108] B. Abdellatif *et al.*, “Experimental evaluation of performance drop for crystalline photovoltaic modules affected by snail trails defect,” *PVCon 2018 - Int. Conf. Photovolt. Sci. Technol.*, no. July 2021, pp. 1–5, 2018, doi: 10.1109/PVCon.2018.8523959.

[109] H.-C. Liu, C.-T. Huang, W.-K. Lee, S.-S. Yan, and F.-M. Lin, “A Defect Formation as Snail Trails in Photovoltaic Modules,” *Energy Power Eng.*, vol. 07, no. 08, pp. 348–353, 2015, doi: 10.4236/epe.2015.78032.

[110] S. Meyer *et al.*, “Snail trails: Root cause analysis and test procedures,” *Energy Procedia*, vol. 38, pp. 498–505, 2013, doi: 10.1016/j.egypro.2013.07.309.

[111] T. Orta Doğu Teknik Üniversitesi (Ankara and Institute of Electrical and Electronics Engineers, “PVCON 2018 Photovoltaic Conference : International Conference on Photovoltaic Science and Technologies : 2-4 July 2018, Middle East Technical University - Culture and Convention Center, Ankara, Turkey.,” *2018 Int. Conf. Photovolt. Sci. Technol.*, pp. 1–5, 2018.

[112] C. Buerhop-Lutz, O. Stroyuk, T. Pickel, T. Winkler, J. Hauch, and I. M. Peters, “PV modules and their backsheets - A case study of a Multi-MW PV power station,” *Sol. Energy Mater. Sol. Cells*, vol. 231, no. June, p. 111295, 2021, doi: 10.1016/j.solmat.2021.111295.

[113] P. Rajput, M. Malvoni, N. M. Kumar, O. S. Sastry, and G. N. Tiwari, “Risk priority number for understanding the severity of photovoltaic failure modes and their impacts on performance degradation,” *Case Stud. Therm. Eng.*, vol. 16, no. November, p. 100563, 2019, doi: 10.1016/j.csite.2019.100563.

[114] J. Markert, S. Kotterer, D. E. Mansour, D. Philipp, and P. Gebhardt, “Advanced analysis of backsheet failures from 26 power plants,” *EPJ Photovoltaics*, vol. 12, no. December, 2021, doi: 10.1051/epjpv/2021006.

[115] D. E. Mansour, S. Kotterer, D. Philipp, and P. Gebhardt, “PV Backsheet Failure Analysis by Scanning Acoustic Microscopy,” *37th EUPVSEC*, no. September, pp. 1014–1018, 2020, [Online]. Available: https://www.ise.fraunhofer.de

[116] A. Fairbrother, L. Gnocchi, C. Ballif, and A. Virtuani, “Corrosion testing of solar cells: Wear-out degradation behavior,” *Sol. Energy Mater. Sol. Cells*, vol. 248, no. March, p. 111974, 2022, doi: 10.1016/j.solmat.2022.111974.

[117] A. Ndiaye, A. Charki, A. Kobi, C. M. F. Kébé, P. A. Ndiaye, and V. Sambou, “Degradations of silicon photovoltaic modules: A literature review,” *Sol. Energy*, vol. 96, no. October, pp. 140–151, 2013, doi: 10.1016/j.solener.2013.07.005.

[118] P. Rajput, G. N. Tiwari, O. S. Sastry, B. Bora, and V. Sharma, “Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India,” *Sol. Energy*, vol. 135, pp. 786–795, 2016, doi: 10.1016/j.solener.2016.06.047.

[119] S. J. Plathottam, A. Rzonca, R. Lakhnori, and C. O. Iloeje, “A review of artificial intelligence applications in manufacturing operations,” *J. Adv. Manuf. Process.*, vol. 5, no. 3, pp. 1–19, 2023, doi: 10.1002/amp2.10159.

[120] R. Liu, Y. Rong, and Z. Peng, “A review of medical artificial intelligence,” *Glob. Heal. J.*, vol. 4, no. 2, pp. 42–45, 2020, doi: 10.1016/j.glohj.2020.04.002.

[121] L. I. A. Choisit, L. E. S. Con, and T. Présentés, “RÉSEAUX SOCIAUX ET IA,” pp. 18–23, 2018.

[122] A. Simard, “L’adoption de l’intelligence artificielle (IA) pour le développement de services publics intelligents.,” *Commun. Technol. développement*, vol. 11, no. March, 2022, doi: 10.4000/ctd.6904.

[123] L. P. Valérie Bousson, Nicolas Benoist, Pierre Guetat, Grégoire Attané, Cécile Salvat, “Application of artificial intelligence to imaging interpretations in the musculoskeletal area: Where are we? Where are we going?,” *Rev. Rhum.*, vol. 90, no. 5, pp. 575–584, doi: https://doi.org/10.1016/j.rhum.2023.07.018.

[124] M. I. Munawar, I. Alam, and M. S. Ali, “An efficient energy prediction model for solar energy power system using Artificial Intelligence technique,” *Int. Conf. Recent Acad. Stud.*, vol. 1, pp. 139–145, 2023, doi: 10.59287/icras.686.

[125] K. J. Iheanetu, “Solar Photovoltaic Power Forecasting: A Review,” *Sustain.*, vol. 14, no. 24, 2022, doi: 10.3390/su142417005.

[126] D. Rahmouni, “Diagnosis of External Faults in Photovoltaic Systems based on a Deep Learning approach,” pp. 47–57, 2024. Journal of Renewable Energies ICREPS’24 Naama (2024) 47 – 57 DOI: https://doi.org/10.54966/jreen.v1i1.1293

[127] H. R. Parikh et al., “Solar cell cracks and finger failure detection using statistical parameters of electroluminescence images and machine learning,” Appl. Sci., vol. 10, no. 24, pp. 1–15, 2020, doi: 10.3390/app10248834.

[127] M. R. Rahman, S. Tabassum, E. Haque, M. M. Nishat, F. Faisal, and E. Hossain, “CNN-based Deep Learning Approach for Micro-crack Detection of Solar Panels,” 2021 3rd Int. Conf. Sustain. Technol. Ind. 4.0, STI 2021, no. December, 2021, doi: 10.1109/STI53101.2021.9732592.

[128] S. Hassan and M. Dhimish, “Dual spin max pooling convolutional neural network for solar cell crack detection,” Sci. Rep., vol. 13, no. 1, pp. 1–16, 2023, doi: 10.1038/s41598-023-38177-8.

[129] X. Qian, J. Li, J. Cao, Y. Wu, and W. Wang, “Micro-cracks detection of solar cells surface via combining short-term and long-term deep features,” Neural Networks, vol. 127, pp. 132–140, 2020, doi: 10.1016/j.neunet.2020.04.012.

[130] M. Aktas, F. Doğan, and İ. Türkoğlu, “Analysis Of Cracks In Photovoltaic Module Cells From Electroluminescence Images By Deep Learning.,” 1st Int. Conf. Comput. Mach. Intell., no. February, pp. 103–103, 2021.

[131] F. Fan, Z. X. Na, C. Z. Zhang, H. R. Li, and C. L. Tong, “Hot Spot Detection of Photovoltaic Module Infrared Near-field Image based on Convolutional Neural Network,” J. Phys. Conf. Ser., vol. 2310, no. 1, 2022, doi: 10.1088/1742- 6596/2310/1/012076.

[132] H. AÇIKGÖZ, D. KORKMAZ, and Ç. DANDIL, “Classification of Hotspots in Photovoltaic Modules with Deep Learning ,” Turkish J. Sci. Technol., vol. 17, no. 2, pp. 211–221, 2022, doi: 10.55525/tjst.1158854.

[133] S. P. Pathak, D. S. Patil, and S. Patel, “Solar panel hotspot localization and fault classification using deep learning approach,” Procedia Comput. Sci., vol. 204, pp. 698–705, 2022, doi: 10.1016/j.procs.2022.08.084.

[134] T. Sun, H. Xing, S. Cao, Y. Zhang, S. Fan, and P. Liu, “A novel detection method for hot spots of photovoltaic (PV) panels using improved anchors and prediction heads of YOLOv5 network,” Energy Reports, vol. 8, pp. 1219–1229, 2022, doi: 10.1016/j.egyr.2022.08.130.

[135] Q. Zheng, J. Ma, M. Liu, Y. Liu, Y. Li, and G. Shi, “Lightweight Hot-Spot Fault Detection Model of Photovoltaic,” Sensors (Switzerland), vol. 22, 2022.

[136] D. P. Winston et al., “Solar PV’s Micro Crack and Hotspots Detection Technique Using NN and SVM,” IEEE Access, vol. 9, pp. 127259–127269, 2021, doi: 10.1109/ACCESS.2021.3111904.

[137] E. Ozturk, E. Ogliari, M. Sakwa, A. Dolara, N. Blasuttigh, and A. M. Pavan, “Photovoltaic modules fault detection, power output, and parameter estimation: A deep learning approach based on electroluminescence images,” Energy Convers. Manag., vol. 319, no. April, p. 118866, 2024, doi: 10.1016/j.enconman.2024.118866.

[138] J. Sherozbek, J. Dadajon, and L. Malrey, “Photovoltaics Plant Fault Detection Using Deep Learning Techniques,” Remote Sens., pp. 149–160, 2022.

[139] S. Prabhakaran, R. A. Uthra, and J. Preetharoselyn, “Deep Learning-Based Model for Defect Detection and Localization on Photovoltaic Panels,” Comput. Syst. Sci. Eng., vol. 44, no. 3, pp. 2683–2700, 2023, doi: 10.32604/csse.2023.028898.

[140] S. Scott, W. Y. Chen, and A. Heifetz, “Multi-Task Learning of Scanning Electron Microscopy and Synthetic Thermal Tomography Images for Detection of Defects in Additively Manufactured Metals,” Sensors, vol. 23, no. 20, 2023, doi: 10.3390/s23208462.