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Review Article

Detection of Cell Damage and Types in Solar Panels: A Comprehensive Review

Ferdi DOĞAN[1*], Miktat AKTAŞ[2], Nevzat OLGUN[3], Mücahit ÇALIŞAN[4], İbrahim TÜRKOĞLU[5]
[1] Adıyaman University, Computer Engineering Department, fdogan@adiyaman.edu.tr, Orcid No: 0000-0002-9203-697X
[2] Fırat University, Software Engineering Department, mkttkts@gmail.com, Orcid No: 0000-0002-0731-5668
[3] Afyon Kocatepe University, Software Engineering Department, nevzat.olgun@gmail.com, Orcid No: 0000-0003-2461-4923
[4] Bingöl University, Computer Engineering Department, mcalisan@bingol.edu.tr, Orcid No: 0000-0003-2651-5937
[5] Fırat University, Software Engineering Department, iturkoglu@firat.edu.tr, Orcid No: 0000-0003-4938-4167

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* Corresponding author

ABSTRACT

The proper operation of photovoltaic panels is important for the efficiency of the energy produced. This study examines in detail the types of damage that affect energy production from solar panels, their impact on energy production, and methods for detecting these damages. Cell damage in photovoltaic panels is examined under four main headings: mechanical damage (microcracks, delamination), thermal damage (hotspot formation, overheating), electrical damage (short circuits, disconnections), and environmental damage (dusting, UV exposure). Early detection of these damages is crucial for preventing energy losses and extending panel life. Therefore, damage detection methods have been compiled and examined under three main groups: traditional methods, advanced technological methods, and other complementary methods.

Traditional methods have been found to be limited in damage detection. In recent years, they have become increasingly prominent in terms of performance, particularly with the advantages offered by artificial intelligence methods. Furthermore, AI-assisted detection processes have been shown to be advantageous for automation. Solutions have been proposed for damage detection processes. The implementation of regular maintenance and repair processes and the dissemination of artificial intelligence-based approaches to ensure better panel operation were evaluated. The study addressed the current challenges of damage detection methods in solar panels. The negative impacts on energy production from panels and the advantages and disadvantages of damage detection were revealed. This study provides important guidance for the development and implementation of damage detection methods.

Introduction

a. General Background and Motivation

HE SUN is one of the most basic sources of life for the world. It is an important source of energy for plants, animals and humans. It maintains the temperature balance in the world with the energy it emits. It is also a renewable and sustainable energy source that reduces the use of fossil fuels [1]. Solar energy panels are used to generate electrical energy by taking advantage of the sun. Thanks to these panels, the light from solar energy is converted into electrical energy and made usable in daily life [2]. Energy production from solar energy panels is the fastest spreading technology among renewable energy sources. Especially in recent years, it has an important place in meeting the energy needs of countries. Solar energy production plants are being established in many parts of the world in terms of environmental sustainability and economic benefits [3]. The rays coming from the sun hit the photovoltaic (PV) cells in the panel and are absorbed by the photons. These absorbed rays energize the electrons in the silicon in the cell and enable them to be free. Free electrons move thanks to the electric field in the cell. Direct current (DC) is produced thanks to this movement. The metal parts in the cells collect the electricity and direct it to the circuit. An inverter is used to convert the generated direct current into alternating current (AC). The generated electricity is transferred to the grid [4]. Figure 1 shows the working principle.

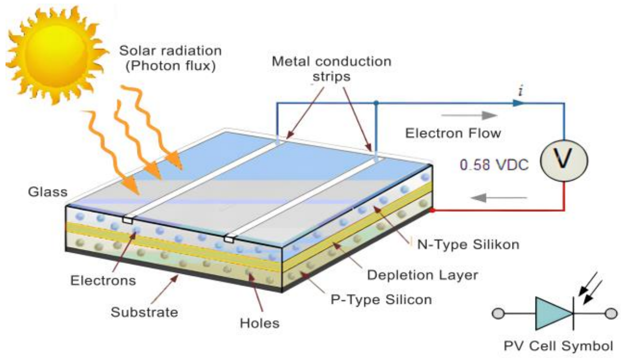

Figure 1. Principle of electricity production from photovoltaic panels [5]

The efficiency of electrical energy production with solar energy panels is an important issue. In order to produce more energy, there are many points that need to be considered from production to maintenance of solar energy panels. Therefore, regular maintenance and monitoring applications of solar energy panels have an important place in production [6]. In addition, innovative solutions for solar energy panels should be followed and integration should be ensured in this process. These solutions include energy management systems, correct material usage and autonomous panel systems that follow the sun [7]. With innovative solutions, the use of such energy systems is increasing and spreading to wider audiences.

The layers and panel structure in a standard panel are shown in Figure 2. The outermost metal support frame is followed by the protective glass layer, polymer encapsulant layer-EVA, PV cells, secondary encapsulant layer, insulating backsheet material and DC connection module.

Figure 2. Layer structure that makes up photovoltaic panels

The solar panel production stages vary depending on the machinery and equipment used, the properties of the intermediate materials used in the panel, and the type of panel, but generally occur in the following order. The production process begins with the "windshield" being taken from the pallet and placed on the carrier (conveyor) and ends with the production panel being taken from the carrier and packaged.

• Placing the front glass on the production line, laying transparent encapsulant EVA of the same dimensions on it.
• Arranging the PV solar cells in series with the help of machines called stringers or tabbers and connecting them in series with conductive strips.
• Making the connections between the cell series with flat conductive busbars with the help of manual soldering or autonomous soldering machine.
• Laying the back EVA (Different colored transparent, white or black intermediate material can be used in this layer.).
• EL-1 (1st Quality Control and Classification Machine): In this station, the measurement results are recorded as xml, image (jpg) and word files. From the data here, the test date, the time spent, whether there is a short circuit in the panel, whether there are micro fractures, active fractures, metallization errors and deteriorations in the cells, their sizes and numbers, if any, can be clearly determined. With the EL test, short-circuited, broken or damaged cells, if any, are detected and separated for replacement or repair.
• Baking is done under a certain pressure at 150-200 degrees with the Baking-Lamination machine. After this process, it is no longer possible to repair or replace the panel at the solar cell level.
• Visual Inspection to detect any malfunctions such as bubbles (EVA not fully adhering), stripe slippage, color changes, if any, on the panel.
• EL-2 (2nd Quality Control and Classification Machine): In this station, the measurement results give the same outputs as in the 1st Classification machine. EL test is used to detect any short circuits, broken or damaged cells during baking or visual inspection. Only panel classification is performed at this station, and repair or replacement is no longer possible.
• Installation, soldering of electrical boxes (j-box) in accordance with the positive and negative poles of the solar panel and silicone is applied to the box content after the soldering process to prevent it from being affected by external factors.
• Frame assembly in appropriate dimensions for the solar panel is performed with the help of silicone.
• Solar Simulator: Electrical values such as Nominal Power (Pmax) (W), Nominal Power Voltage (Vmp), Nominal Power Current (Imp), Open Circuit Voltage (Voc), Short Circuit Current (Isc), voltage, measurement temperature are taken for the produced panel. This data is used in packaging and field installations.
• Panels with similar current and power are packaged in the same boxes, and again during installation, these data are taken into account and panels with similar current and power are used in the same array.

Panels are divided into different types according to the materials and technologies used. These are Crystalline Silicon Panels, Thin-Film Panels, Flexible Panels, Bifacial Panels, Organic Photovoltaic (OPV) Panels and Concentrated Photovoltaic (CPV) panels [8-13].

The most commonly used panel type among these types of panels is crystalline silicon panels. These panels are of two types: monocrystalline and polycrystalline. Monocrystalline panels, which have a single crystal structure, offer high efficiency. These panels have an efficiency between 18% and 22%, and with TOPCon (Tunnel Oxide Passivated Contact) technology, 25-26% efficiency can be achieved. In these panels, 27-28% efficiency rates can be achieved by using SHJ (Silicon Heterojunction) technology. In laboratory environments, 35% efficiency rates have been achieved with perovskite-silicon tandem solar cells [14]. Since polycrystalline panels are produced using more than one crystal, their production costs are low and their efficiency is 15%-18% lower than monocrystals. Thin film panels are produced using materials such as amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS). The feature of these types of panels is that they are light and flexible. Since they are easily portable, they are highly preferred in large surface areas and building-integrated systems. Their efficiency varies between 8%-18% [15, 16].

Flexible solar energy panels have also emerged with developing panel technologies. These types of panels using thin film technology can achieve very good results even on uneven surfaces. Their light structure and flexibility make these panels suitable for personal use. Being portable can provide convenience in caravans and places where electricity is not accessible. However, they are not suitable for large-scale energy production. They have low durability and have a lower efficiency structure compared to other panels [17]. The new generation bifacial solar energy panels, which have both front and back surfaces, produce more energy by absorbing light. They also provide more energy production by absorbing the light reflected from the ground in open areas. These panels, which have a glass-glass structure, are quite suitable for durable, large-scale and commercial projects [18].

Double-faced panels provide 5% to 15% additional production depending on the location, ground color and type. With the development of technology, OPV panels, which are one of the latest technologies, are made of organic materials containing carbon. They are environmentally friendly panels with low production costs. They are used in architectural applications and smart wearable technologies with their transparent and colored options. Due to their low efficiency, they are not preferred in large-scale and commercial enterprises [19]. Another type of solar energy panel is CPV panels, which obtain solar energy by concentrating it with the help of lenses and mirrors. These types of panels are systems that try to obtain maximum energy by following the sun's movement. Since they need solar radiation, such panel systems are used in regions with high radiation such as deserts. They have high costs and complex structures. For this reason, they are preferred in large-scale energy production projects instead of individual use [20]. In land-based solar power plants, tracker applications can provide approximately 20% additional production. Solar energy panel types are shown in Figure 3.

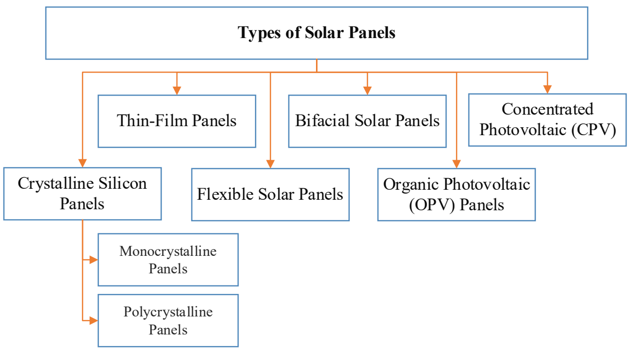

Figure 3. Types and classes of solar energy panels

Electricity generation from solar energy has significant potential both in terms of creating direct employment in local economies and reducing energy production costs. It is seen as an indispensable energy source for the economic and sustainable future. It also provides significant economic contributions to various sectors. This sector, which also has a high potential for economic growth and job creation, provides permanent jobs for approximately 10 million people every year [21]. In some studies, it has been seen as an income-generating activity in rural areas and it has been stated that it provides economic contributions to people living in economic regions [22]. When cost-return analysis is taken into account, it appears as a system that provides significant returns and reduces costs. It has been stated in a study that it can provide approximately 19 million dollars in reducing carbon emissions and 30-year fuel costs [23].

The use of solar energy in some sectors in Tatarstan has provided approximately 5% reduction in electricity costs. It has reduced production costs in sectors by increasing institutional efficiency [24]. It is used as an alternative energy source instead of diesel generators, which are widely used in off-grid areas in Bangladesh, and reduces greenhouse gas emissions [25]. With technological developments, energy use and gain are being tried to be optimized with artificial intelligence-supported estimation processes. This can also provide serious economic gains [21]. While the cost per watt was $4731 in 2010, it was seen that it decreased to $883 per watt in 2020. This is another data showing that the economic contribution of solar energy panels in energy production is increasing [21]. It is seen that the contribution of solar energy panels in energy production has a very high potential economically.

The sectors where solar energy panels are used are diverse. Solar panels, which are used even in spacecraft, have been designed to meet the need for electricity in many areas and sectors, to reduce investment costs, and to be used as an investment tool. They are used in many areas such as meeting individual electricity needs in residences, meeting the energy needs of businesses in commercial buildings, operating irrigation systems in the agricultural sector, greenhouse lighting, charging electric vehicles in the transportation sector, reducing energy costs in industrial facilities, storing energy, meeting lighting and energy needs in the public, heating and cooling [26-30].

Storing energy is important to increase the efficiency of solar energy panels and to provide uninterrupted energy needs. Storing the energy in such systems balances the fluctuations in energy demands. It both creates a sustainable energy infrastructure and provides long-term healthy energy efficiency. Storing the energy obtained with solar energy is an important factor for widespread use. Storage with lithium batteries in Scandinavian climates offers affordable cost options in systems where housing is located [31]. Such steps to be taken in the world in terms of sustainability are an important initiative for more efficient use of energy.

b. Research Gap and Need

It is very important for both investors and those who use this energy that solar energy panels and cells in the panel produce energy in a healthy way. The healthy operation of the cells is an issue that increases the stability and predictability of energy production. Energy production in solar energy panels is affected by environmental factors, mechanical damage, thermal damage, moisture ingress, dust and pollution. Damage can occur in the cells in the panels according to these factors. The performance of damaged cells decreases and they produce less energy.

These cells cannot receive enough sunlight. This reduces the amount of energy that can be obtained [32]. This situation also negatively affects the panels that are connected to each other and reduces the amount of energy produced. Predicting damage in advance or performing preventive maintenance processes is a significant issue in terms of electricity production. In addition, the damages that occur are among the factors that directly affect the life of the panel.

PV panels can easily be affected by damages caused by different factors. Damages caused by different reasons directly affect the operation of the system and energy production. Failure to detect damages at an early stage can lead to small-scale damages growing and therefore major negativities in energy production. If small-scale cracks on the cell are not detected at an early stage, the cracks grow and the panel becomes almost incapable of producing energy. This situation can also create different effects. For example, disconnections can completely stop energy production. Another type of damage, hot spot damage, can damage other cells if not detected and can cause the panel to lose its function completely. For this reason, systems formed by solar energy panels must be regularly monitored and potential damages must be detected. Early detection will ensure that energy efficiency is maintained and long-term operating costs are reduced [33, 34].

Damage to the cells in the panel may cause more cells to fail in the system and cause a wider failure with a chain effect. Especially if a single cell in the panel is damaged, the entire system in a series-connected array will be affected and energy production will decrease. The electrical resistance created by the damaged cell may prevent the flow of current from other cells. This leads to an unbalanced power distribution and causes inefficiency [35]. If mechanical and environmental damages cannot be detected, moisture and dirt accumulation increases and the panels deteriorate more quickly over time. Such problems negatively affect the entire system performance of both individual panels and large-scale power plants [36]. Being able to detect damages is important for maintaining efficiency and creating a long-lasting system. Image processing-based analyses, electroluminescence imaging methods, imaging with thermal cameras and artificial intelligence-based damage detection methods are widely used for damage detection [37]. Early detection of damages positively affects energy efficiency and extends the life of the panel. For this reason, faults must be detected quickly using smart systems.

c. Purpose, Contribution, and Organization of the Study

The aim of this study is to present the electrical energy produced from solar energy panels as a sustainable and clean energy source. The long life and efficient operation of such PV panels are affected by damages caused by various factors. Cell damages in the panels, thermal reasons, electrical and environmental factors and mechanical damages reduce the system efficiency and cause losses. For this reason, the types of damage in solar energy panels and the methods used to detect these damages are also compared in this study. Then, a solution proposal is made for the difficulties experienced in the detection process. The study examines the traditional and advanced technological methods used to classify cell damages and detect damages.

In this study, PV damage detection methods are systematically classified, their advantages and disadvantages are compared, and a gap in the literature is filled by emphasizing their applicability under different conditions.

In the first part of this study, the reasons for using solar energy panels, their economic contribution, damages affecting efficiency, losses caused by damages and the importance of detecting damages are emphasized. The second part of the study examines the types of damages in solar energy panels. The types and causes of damages are emphasized. The third part addresses the methods used to detect damages and types in solar energy panels. These methods are examined under 3 main headings: traditional damage detection methods, advanced technology damage detection methods and other methods. The fourth section includes studies conducted in the literature for damage detection studies. These studies are examined in detail under the headings of mechanical damage detection methods, visual inspection detection methods, photoluminescence (PL) analysis methods, electroluminescence imaging methods, drone-based inspection methods, methods for thermal damage and methods for electrical damage. The fifth section describes the findings obtained as a result of the evaluations and the difficulties encountered.

Types of damage to solar panels

Various damages can occur in solar energy panels when exposed to production or outdoor conditions for a long time. The damages that occur will lead to a decrease in panel efficiency, a shortening of the panel life and a decrease in the amount of energy that can be obtained. Damages in solar energy panels should be examined in a wide range from structural defects that occur during the production phase to deformations resulting from long-term use. Damages in solar energy panels are divided into 4 main headings. The classification of damage types in panels is given in Figure 4.

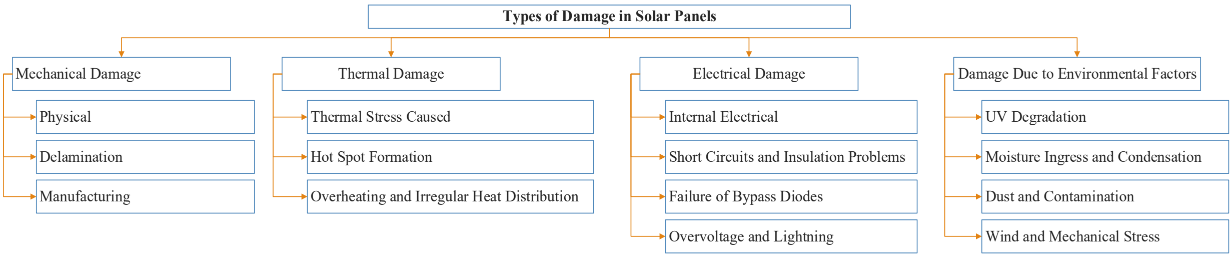

Figure 4. Types and classes of damage to solar panels

d. Mechanical damages

These types of damages occurring on panels are structural deteriorations caused by physical reactions. These types of damages are damages caused by manufacturing errors, impacts during transportation and assembly, environmental conditions and long-term mechanical stresses. Mechanical damages are damages that directly affect the electrical conductivity and optical properties of the panel and reduce the energy production capacity. This type of damage also includes cracks, fractures, surface deformations and delamination.

Physical Damage: One of the most common damages in solar energy panels is microcracks in the cells. Although microcracks are quite difficult to see with the naked eye, they grow over time and reduce the energy production capacity of the panel [38, 39]. This type of damage is usually caused by material stress during production. Improper applications during panel transportation or assembly can cause this damage. Physical damage can occur in the form of breaks or cracks in the cells due to weather conditions such as hail, strong winds and external impacts [40]. This damage interrupts the flow of electricity and causes significant losses in the power output of the panel.

Delamination (Layer Separation): Solar energy panels consist of more than one layer of material. The separation of these layers from each other over time is called delamination. Delamination occurs due to the poor quality of the adhesive material used in production or due to factors such as heat, UV radiation, and humidity in external conditions. Layer separation disrupts the integrity of the cell and can cause the cell to come into direct contact with the external environment [41, 42]. This reduces panel durability, can cause water to enter the panel, and can cause the panel to lose its function completely over time [43].

Production-Related Damages: A large portion of mechanical damage is damage caused by production. In this process, the use of poor quality materials, faulty lamination processes, improper assembly techniques, and faulty cell placement can negatively affect the long-term durability of the panels [44]. The pressures applied between the layers during the production phase can cause micro cracks in the cells, and over time, these cracks can lead to large fractures [45].

In order to prevent mechanical damage, quality control processes must be implemented with great care in the stages from production to assembly. It is necessary to be careful during panel transportation and installation, and to take appropriate protective measures to increase durability against possible adverse environmental conditions. Early detection and repair of damage will be a measure that increases efficiency by extending the life of the panels.

e. Thermal damages

Panels are exposed to temperature fluctuations due to changing environmental conditions. This can cause thermal damage in solar panels. Such thermal damage can negatively affect the structural integrity and electricity production of the panels, causing losses in energy production capacity. The main reason for thermal errors is usually temperature changes, and these errors can cause fatigue of the material. This causes overheating in certain areas and then irregular heat distribution [46]. This shortens the life of the panels and causes irreparable damage [47].

Thermal Stress-Related Damages: Energy-producing panels are exposed to changes in air temperature and weather conditions throughout the day. While the temperature increases on the panels during the day, the temperature can drop rapidly at night. In such cases, different types of materials in the internal structure of the panel are exposed to different expansions and contractions. This creates heat-induced stress. Cracking or microcracks may occur in the panel due to stress. [48]. Sometimes, deformations may occur in solder joints and intracellular conduction. This causes an increase in series resistance in the panel and, as a result, low power generation [49].

Hot Spot Formation: When solar energy panels are exposed to partial shade or irregular lighting, hot spots (hot spots) may form on the panel. This type of shading causes certain cells to operate under reverse polarization. This can cause damage by causing local heating [50]. Irregular radiation and electrical incompatibility between modules can cause thermal stresses and cause this hot spot damage. This damage reduces efficiency and negatively affects energy production. Hot spots can also disrupt the connections within the module and cause fire [51].

Overheating and Irregular Heat Distribution: In cases where the temperature in solar panels is not distributed homogeneously within the panel, some areas may experience more heating. This may be due to errors made during assembly, insufficient air flow in the panel, or internal resistance differences. Material deterioration accelerates in panel areas where the temperature is high, and the panel quickly begins to expire [41].

Thermal damage can be prevented or the level of damage can be minimized when appropriate assembly techniques are applied, adequate ventilation of the panels is provided, and dust, dirt and other obstructive factors are eliminated by regular cleaning operations. Advanced control systems can detect temperature abnormalities and take preventive measures. Controlling thermal damage has a positive effect on production efficiency and extends the life of the panel.

f. Electrical damages

One of the types of damage that causes serious losses in system efficiency is electrical damage. It can occur due to reasons such as cell breaks, short circuits, disconnections, and voltage increases. Electrical failures can pose serious risks in terms of safety and can cause dangerous situations such as fire [52]. For this reason, regular maintenance and follow-up processes can prevent serious problems by detecting such damages early.

Internal Electrical Damages: PV cells in solar panels produce electrical energy by being connected in series or parallel within the panel. Due to disconnections or resistance increases between the cells, conductivity decreases and losses occur in electricity production. Breakages in the cells and solder deterioration in the connections block the current and reduce the power of the panel. In the long term, poor quality soldering and faulty assembly can cause the connection points to deteriorate. [53-55].

Short Circuits and Insulation Problems: Electrical circuits in solar panels can deform over time or be damaged by environmental factors. Short circuits can occur as a result of contact of internal conductors or disruption of circuit integrity due to environmental factors. Short circuits can cause the entire panel to fail and cause fire. In addition, leakage currents can occur as a result of the erosion of the insulation material over time and the ingress of moisture through the erosion [56]. The leakage current that occurs reduces system performance and endangers electrical safety.

Failure of Bypass Diodes: Bypass diodes used in solar panels are elements that protect the panels from damage caused by shading and other abnormalities. These diodes can fail over time due to heating and electrical wear. High temperature and leakage current formation, corrosion and arc faults can cause these diodes to fail [57]. The resulting failure can create hot spots and pave the way for different failures. It also increases the risk of fire and negatively affects the energy production of the panels [58].

Overvoltage and Lightning Damage: Lightning strikes damage the internal circuit elements of panels exposed to overvoltage, and this negatively affects the operation of the panel [59, 60]. Permanent damage can occur in the panel. Such situations necessitate the use of voltage protection elements and grounding systems [61].

In order to prevent this type of electrical damage, regular maintenance and monitoring systems should be used and the connection points and cable insulation should be checked periodically. Voltage differences and abnormalities should be detected early with smart monitoring systems and preventive maintenance processes should be implemented. Minimizing this damage will contribute to more efficient operation of the panels and extend their life.

g. Environmental damages

Solar panels are exposed to external damages due to environmental factors as long as they produce energy. The climate conditions of the geography where the panels are located, weather conditions, pollution, humidity, UV rays, wind and natural factors can cause deformations in the panel's external and internal structure over time. This type of damage reduces the panels' capacity to absorb light and convert it into energy and reduces efficiency. Environmental damages usually develop slowly and can take a long time to be noticed. Therefore, regular maintenance and monitoring systems are important for healthier panels.

UV Degradation: The materials inside solar panels exposed to ultraviolet rays undergo structural deterioration over time. Chemical changes can occur especially on the polymer layers and coatings on the outer surface of the panel [62, 63]. This causes yellowing, cracking and matting on the surface of the panel and, as a result, a decrease in light transmittance. The decrease in light transmittance prevents sunlight from reaching the panel cells, leading to a decrease in energy production. This type of degradation causes significant losses in energy production. To prevent this type of deterioration, UV-resistant coatings should be used and periodic maintenance processes should be followed [64].

Moisture Ingress and Condensation: Water vapor ingress into solar panels that are constantly exposed to rain, snow and humidity in the outdoor environment can have a negative effect on the operation of the panels. Generally, wear may occur in the coatings of the panels due to production or material reasons and small leaks may occur [65]. These leaks cause internal evaporation and cause oxidation and corrosion in circuit elements. Oxidation occurring at connection points and circuit boards reduces conductivity and leads to energy losses. At low temperatures, water droplets may form on cell surfaces due to condensation. These droplets deteriorate electrical properties and reduce efficiency [66]. In order to prevent moisture ingress, the sealing structure must be strengthened and the panels must be protected with water drainage channels [67].

Dust and Pollution: Solar panels located outdoors are constantly exposed to some negativities brought by the open air process. Polluting elements such as dust, dirt, bird droppings, and pollen accumulate on the panel surface over time. They reduce the light absorption of the panel [68]. Panels get dirty more quickly in industrial areas and regions close to desert climates. Since dust accumulation prevents the passage of sunlight into the cells, energy production decreases. While dirt and dust accumulation in some areas of the panel reduces energy production in that area, it can cause the clean area to work more and heat up, causing hot spots to form. Cleaning the surface of the panels at certain intervals is an important method to prevent such situations [69, 70].

Wind and Mechanical Stress: Solar panels are exposed to different weather conditions. Wind is a natural factor that has indirect and direct negative effects on solar panels. Unusual weather conditions such as storms, strong winds, and hurricanes strain the mechanical parts of the panels. The pressure created by the wind puts a load on the connection points and surface of the panel [71]. Over time, cracks, loosening of screws at connection points, and deterioration of the angles of the panels can occur. Dust, sand, stone and other particles carried by the wind can contaminate the panel surface and even cause micro cracks. Such damage can disrupt the integrity of the panel and negatively affect the performance of the panel in the long term. In order to reduce the effect of wind, more robust and aerodynamically suitable frames should be used during the assembly process of the panels and the connection points should be regularly maintained [72, 73].

Damage caused by environmental conditions in solar panels is one of the important factors that negatively affect the performance of the panels. External factors such as UV degradation, moisture ingress and condensation, dust and dirt, wind and mechanical stress cause deterioration on the outer surface and internal structure of the panel over time, reducing the panel efficiency. This can make the panels unusable. To protect against such situations, smart monitoring systems, protective coatings, regular maintenance processes and appropriate assembly techniques should be used. These measures ensure that the panels have a longer life. I-V curves are analyzed to show damage, aging or performance data in solar energy panels [74]. Figure 5 shows the I-V graph of an average panel and the graph showing the performance loss according to damage types.

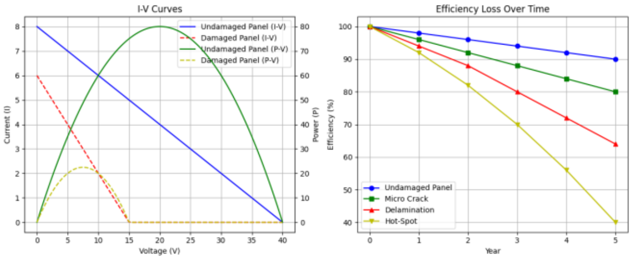

Figure 5. I-V curve and representation of performance losses according to damages

The most common types of damage in solar energy panels, the factors that cause these damages and the possible consequences are given in Table 1.

Damage assessment methods

Damage to solar panels is an important factor affecting the healthy operation, efficiency and life of the system. Detecting these damages and taking the necessary precautions affects the life of the panel. It contributes to the amount of energy produced. It is directly related to the efficiency of the system. Damage detection methods can be examined in 3 main sections. These are traditional methods, artificial intelligence-based technologies and detection methods that include electrical measurements. Damage detection methods are classified as in Figure 6.

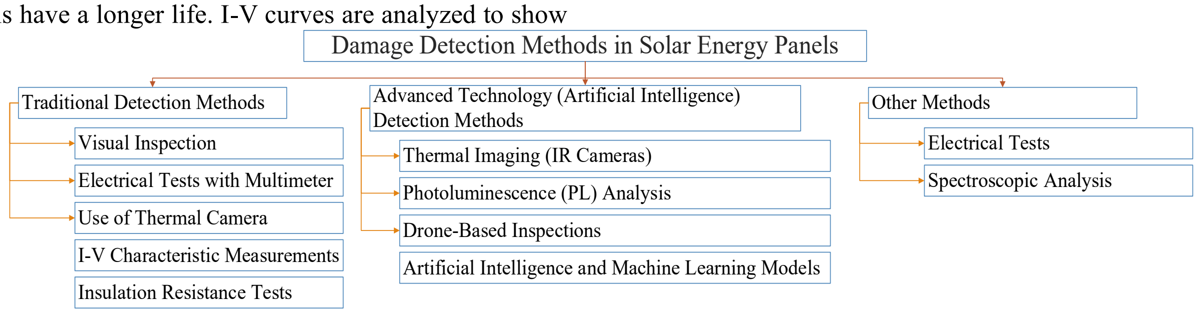

Figure 6. Solar Panels damage detection methods

Table 1. Types and causes of damage in solar energy panels

Damage Type	Causes	Results	Examples
Mechanical Damages	Hail, wind, impacts during transportation, incorrect assembly	Cell cracks, panel breaks, decrease in energy production	Cracks seen on panels after hail or breakage due to panels falling during transportation
Thermal Damages	Overheating, temperature fluctuations, inadequate ventilation	Hot spot formation, loss of efficiency, cell burns	Formation of hot spots in certain areas of panels due to excessive heat in summer
Electrical Damages	Bad connections, short circuits, overload, use of low-quality materials	Cell burns, decrease in energy production, system failures	Panels not working or short circuits due to poorly soldered connections
Environmental Damages	Dust, humidity, UV rays, chemical pollution, bird droppings	Panel surface deterioration, decrease in cell performance, energy loss	Permanent stains on the panel surface due to bird droppings not being cleaned for a long time

a. Traditional detection methods

Although traditional methods have been used to detect damage for many years, they have some limitations. These methods are based on processes that require manual control based on operator experience. Visual inspections, manual measurements and basic test equipment are generally used in the operations performed. Such applications can be applied in field conditions that do not require advanced technology and can contribute to maintenance processes [75]. However, they are insufficient in detecting some damages (micro cracks, electrical faults in the internal structure, material degradation under the surface, etc.).

Traditional damage detection methods can be listed as visual inspection, electrical tests with multimeters, use of thermal cameras (limited application), I-V characteristic measurements and insulation resistance tests. In visual inspection, existing physical damages are examined with the naked eye or with the help of magnifying glasses. In tests performed with multimeters, electrical connection tests of the cells are performed and evaluations are made. Temperature differences are analyzed with thermal cameras and damage points in the cells are found. I-V characteristic measurements provide the evaluation of panel performance by generating the current-voltage curve of the panels. Insulation resistance tests check the safety of the system against ground leakage. Although each method controls different damage structures, the fact that the processes are operator dependent and not automatic is seen as a disadvantage.

1. Visual inspection

This method uses the human eye or simple optical instruments (e.g., magnifying glasses, flashlights) to detect visible cracks, discoloration, or surface contamination. It's inexpensive and easy to use. However, it cannot detect microcracks or internal defects below the surface. It is the most basic damage detection method. This inspection performed by an operator is the most basic damage detection method used. In some cases, auxiliary tools such as a magnifying glass or flashlight can be used to carefully examine the panel surface [76].

Physical damages on the panel surface are seen as cracks, scratches, breaks or color changes. Mechanical damages can occur due to damages caused by hail, strong winds, transportation or assembly. Thermal damages show themselves as burn marks or overheated areas on the panel surface. Since abrasion and corrosion at the connection points can cause losses in the long term, attention should be paid during visual inspection. Small cracks and thin cracks under the surface can be easily noticed with the help of a flashlight and a magnifying glass. It is possible to make detailed analyses with the support of a light source, especially in inspections performed at night or when the light is low [77]. The application of this type of inspection method in large-scale solar power plants is quite time-consuming. In a large system, it is possible for the operator to miss the damages. Figure 7 shows some panel images that can be detected by visual inspection.

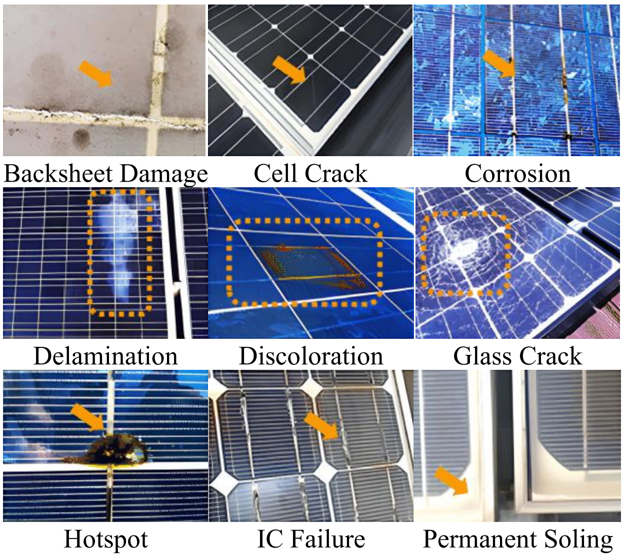

Figure 7. Example images that can be detected by visual inspection[78]

2. Electrical tests with multimeter

Multimeter is a widely used measuring device for manually testing the electrical performance and faults of panels. Open-circuit voltage (Voc) and short-circuit current (Isc) can be measured to detect connection faults or disconnections. Any deviation from normal values indicates the presence of potential faults. This is effective for basic faults, but it cannot provide detailed information about internal deterioration. The obtained results are compared with the nominal values of the panel [79].

Open circuit voltage is the highest voltage that the panel can produce without being connected to any load. If the measured value is lower than expected, this indicates a cell fault or disconnection or cable wear problems. Abnormal fluctuations in the output voltage of the panel can be detected and continuity at the connection points can be checked. Short circuit current measurement shows the highest current that the panel can give when short circuited. If the short circuit current is below normal values, it can be considered that there is a connection problem in the cells. Measurements made with a multimeter are an effective method for determining basic level electrical faults [80]. However, it is not possible to perform detailed performance analyses or detect complex faults.

3. Thermal camera use

Thermal cameras, which display surface temperature differences on solar panels, help determine cell damage. This method, which is one of the traditional damage detection methods, can detect hot spots and prevent larger problems that may occur in the future. Thermal cameras detect infrared radiation emitted from the panel surface, creating a temperature map that indicates abnormal heating (hot spots). Hot spots typically indicate faulty cells, poor connections, or shadowing effects. However, this method only reveals surface temperature differences and cannot detect subsurface defects. Hot spots are usually caused by short circuits, manufacturing errors and connection problems. They reduce the life and performance of panels. Abnormal temperature differences on the panel surface can occur due to cell damage, dirty areas and overloaded circuits. Thermal cameras help operators determine whether there is damage by showing temperature maps on the panels [81].

Detecting stress-related damage at an early stage provides important information to prevent panel wear over time. Constant exposure of certain areas on the panel to a temperature may cause permanent damage in the future. Thermal cameras can be considered an important and effective tool when used together with visual inspection. Although thermal cameras have some limitations, it has been observed that they can produce accurate results under appropriate conditions. Environmental factors are important for imaging to produce accurate results. If measurements are not made in an environment where solar radiation is not sufficient, temperature differences may not be observed clearly. In addition, since thermal cameras detect surface temperatures, they cannot detect damage to the layers inside the panel[82]. Temperature differences can occur not only in the event of a fault, but also due to contamination, connection problems or incorrect installation. This shows that it would not be correct to use thermal cameras as a sole diagnostic method[50, 83].

4. Current-voltage (I-V) characteristic measurements

The most commonly used method for analyzing the performance of solar panels is the I-V characteristic measurement method. This is the examination of the current-voltage (I-V) characteristic curves [84]. These measurements help detect possible faults in the system by measuring the power of the panel, the maximum power point (MPP), the open Voc and the short circuit current. This method plots the panel's I-V curve under illumination. Key parameters such as MPP, Voc, and Isc are analyzed. Deviations from the expected curve shape indicate performance losses, aging, or internal malfunctions. [85, 86]. This test is a method that allows us to obtain information about the general health status of the panel.

5. *Insulation Resistance Tests*

Insulation resistance tests are important to ensure the safety and efficiency of the system. This method measures the resistance between the panel circuits and ground. A drop in insulation resistance typically indicates moisture ingress or material deterioration. This can lead to leakage currents and safety risks. Determination of electrical leakage within the panel is used to reduce risks that may occur due to oxidation and physical wear. Measurement of insulation losses due to moisture and oxidation is evaluated to ensure safe and efficient operation in the long term. Detection of grounding problems is one of the tests that should be applied regularly to ensure electrical safety, especially in large-scale solar power plants [87, 88].

Traditional detection systems are still widely used to determine physical, electrical and thermal problems in panels. The greatest advantage of this method is that they are easy to apply. Since microcracks are insufficient to detect inner layer damage, their use in combination with advanced technology-supported damage detection methods will yield more positive results.

b. Advanced technology (artificial intelligence) detection methods

The limits of detecting damage to solar panels with traditional methods can be overcome with advanced technological detection methods [89]. Advanced technology methods should be used to increase the accuracy of the results obtained with traditional methods, to make them automatic, to be independent of the operator or expert, and to accelerate the damage detection process. Artificial intelligence methods are at the forefront of these methods. Artificial intelligence methods can detect errors, make future predictions and carry out preventive maintenance processes using data received from different electrical and electronic devices. This enables the system to be used for a long time. It will help to get energy from the system at the highest limit. Infrared imaging, PL analysis [90], drone-based inspections [91], artificial intelligence and machine learning models are shown among the advanced technology detection methods.

1. Thermal imaging (infrared cameras)

Infrared imaging can detect infrared light reflected, transmitted or emitted by panels. Infrared wavelengths can operate according to near (NIR: 0.75-1.4 microns), short (SWIR: 1.4-3 microns) and medium (MWIR: 3-8 microns) wavelengths. Infrared cameras are an important tool used to detect abnormalities caused by temperature in solar panels. Hot spot formations, connection breaks, surface temperature differences caused by thermal stress can be easily viewed with infrared cameras [92]. Although thermal imaging and infrared imaging used in traditional methods are similar to each other, infrared imaging can also operate at different wavelengths. Infrared imaging can detect material damage, fine surface cracks and manufacturing defects. Negativities in the panel can be automatically learned through different software added to infrared imaging devices [93].

2. *Photoluminescence Analysis*

PL analysis is a sensitive high-tech method used to detect microcracks, manufacturing defects and damages such as material degradation in solar panels. Excited solar cells emit photons when illuminated by a specific light source. By analyzing these emissions, defects such as microcracks, potential-induced deterioration, and material inhomogeneity can be detected with high resolution. While a healthy solar panel emits photons of a certain wavelength, there are deviations in the emissions in defective or damaged cells. It offers high resolution compared to traditional thermal imaging and infrared imaging. This makes it easier to detect damages that cannot be seen with the naked eye [91].

The differences in the emission of photons emitted back from the cells vary according to the type and size of the defects. It is an effective high-tech method for early detection of damages in solar cells [94]. Portable PL devices developed in recent years also make field-based inspections possible [95]. This contributes to the maintenance and monitoring processes of large-scale power plants.

3. Drone-based inspections

One of the advanced technology methods frequently used in the detection of damage in solar panels in recent years is drone-based systems [96]. It allows the time-consuming inspection period to be completed in a shorter time, especially in large-scale solar energy production systems. Drones equipped with RGB or thermal cameras capture aerial images of large solar power plants. These images are then analyzed using computer vision or machine learning to identify cracks, hot spots, and shading anomalies. This significantly reduces inspection time compared to manual methods. The biggest advantage of drone-based damage detection processes is that they are performed automatically, minimizing human intervention. This increases safety and efficiency in field work. In recent years, analyses have been performed on images obtained by drones using artificial intelligence techniques, and damage detections are made accurately and quickly [97].

4. Artificial intelligence and machine learning models

One of the most important methods for damage detection in solar panels is artificial intelligence and machine learning methods. It is quite successful in both damage detection and classification of damages. It provides results by analyzing large amounts of data. The rapid acquisition of results allows the detection process in large power plants to be done quickly and automatically. Artificial intelligence methods, which save both time and cost, provide solutions to image processing, estimation and classification problems [97, 98].

Deep learning models like CNNs or YOLO analyze large panel image datasets to automatically identify the type, location, and severity of defects [99]. Classic machine learning methods (SVM, Random Forest) can also classify electrical or thermal data. These approaches minimize human intervention and enable real-time automated detection. It analyzes large-scale data by minimizing human intervention. It detects damage, quickly determines the type, location and size of the damage. It provides information about maintenance processes in large-scale power plants, especially by using image processing techniques. It can detect cell cracks, temperature abnormalities, pollution and structural defects in panels sensitively and accurately compared to manual methods.

By analyzing large amounts of panel cell images or sensor data using deep learning models, various types of damage such as cell delamination, cell fractures, and disconnections can be classified. Using deep convolutional neural networks (AlexNet, VggNet, GoogleNet, Resnet, etc.) together with object detection algorithms (YOLO, Faster R-CNN, SSD, etc.), the location, position, and type of damage can be found in panel images [100]. It can automatically analyze high-resolution images and perform damage detection [37, 91, 95, 97]. Edge detection and color-texture analysis can detect microcracks, stains, and material deterioration using image processing and deep learning models. This rapid detection process ensures that preventive maintenance measures are taken and panel systems have a longer life. In addition, classical machine learning methods such as support vector machines (SVM), random forest can be used to analyze data from panel sensors and perform damage detection [101]. Such methods can process multidimensional data such as temperature differences, electrical measurements, panel efficiency changes, and determine possible future damage probabilities. Artificial intelligence and advanced technology-based damage detection systems contribute significantly to the maintenance and repair processes of panels. These systems have the ability to produce faster, more automatic and more accurate results than traditional systems. Artificial intelligence-based systems can create early warning systems and minimize maintenance costs in power plants. These systems are expected to continue to increase.

c. Other Methods

In the damage detection processes in solar panels, there are other methods besides traditional methods and advanced technological methods based on artificial intelligence. These methods include scientific methods that analyze the physical and chemical properties of the panel. These methods are aimed at determining the source and type of damage. These can be listed as electrical tests and spectroscopic analyzes.

1. Electrical tests

Various damages can occur in PV systems. One of the methods to be used in the detection of the damages that occur is electrical tests. The most frequently used of these tests is time domain reflectometry (TDR). It sends a high-frequency signal to solar panels connected in series. The sent signal is reflected in the series. The reflected signal is analyzed. In this way, open circuit, short circuit and series resistance increases are detected. The signal sent with the time domain reflectometer analyzes voltage increases and time shifts. With this analysis, connection breaks and failures can be detected [102, 103]. An advanced version of the time domain reflectometer is the spread spectrum time domain reflectometer (SSTDR). It uses spread spectrum signals. It can detect damaged cells and modules in the array. Physical effects and busbar damage can be detected with this method [104, 105].

One of the electrical detection methods is the monitoring of voltage and current parameters. These parameters are monitored to detect faults such as open circuit, short circuit, partial shading. Open circuit voltage and short circuit current characteristics are used and detections are made according to the determined threshold value [106]. Artificial intelligence and machine learning based approaches are also used to detect these types of faults. The analysis of amplitudes and frequencies of currents and voltages is done using machine learning methods [107, 108]. One of the electrical tests is the Thevenin equivalent resistance calculation. It calculates the equivalent resistance of the panel array and distinguishes open and short circuits [109]. One of the electrical test methods is the analysis of Dynamic Current-Voltage characteristics. When there is damage, the normal operating range of reverse saturation current and connection capacitance values deviate. This method can be used to estimate parameters and provides remote fault detection [110, 111]. Eddy current measurements are used to detect cracks in solar panels. This method reveals visually unnoticeable cracks. It performs this process by measuring induced electromagnetic fields [112]. Another test method is differential power processing converters (DPP). This method measures ac impedance and finds partial shading. In this way, it detects panel deterioration. It offers a versatile solution for solar panels [113]. Electrical test methods are given in Table 2.

Table 2. Comparison of electrical testing methods

Method	Working Principle	Benefits
Time Domain Reflectometry	It sends high frequency signals. Thus, impedance change is detected.	Detects open circuits, short circuits and series resistance increases.
Spread Spectrum TDR	It uses spread spectrum signals for noise immunity.	Detects and locates damaged cells and modules.
Voltage and Current Observation	Current and Voltage parameters are monitored.	Identifies open circuits, short circuits and partial shading.
Machine Learning Integration	Machine learning algorithms are used to classify electrical properties.	High accuracy in fault identification.
Thevenin Equivalent Resistance	It calculates equivalent resistance to classify faults.	Distinguishes open and short circuits.
Dynamic I-V Properties	It estimates internal parameters from dynamic I-V data.	Fast parameter estimation and remote diagnosis.
Eddy Current Measurements	It detects cracks through electromagnetic induction.	Effective for thin and large cells.
DPP Transducers	It uses ac impedance for diagnosis and increases power efficiency.	Versatile solution for partial shading and distortion.

2. Spectroscopic analyses

Spectroscopic analyses are among the advanced test methods. They are used to examine material composition, coating defects and surface deteriorations. It can also be done to examine the quality of semiconductor materials in solar cells and to determine the chemical origins of the damages.

One of the advanced test methods used to examine material composition, coating defects and surface deteriorations in solar panels is spectroscopic analysis. This analysis method is an important evaluation criterion especially for evaluating the quality of semiconductor materials used in solar cells and determining the chemical origins of the damages [114, 115].

Raman spectroscopy, one of the spectroscopies, is an optical method that analyzes the chemical bonds on the material surface and changes in the crystal structure [116]. It is frequently used to detect defects, surface tensions and oxidations in silicon crystals. FTIR (Fourier Transform Infrared Spectroscopy) is a technique used to determine polymeric coating deterioration on the panel surface, oxidation caused by humidity and aging effects [117]. It is also used to analyze chemical changes in the material due to weather conditions [118]. In addition, XRF (X-Ray Fluorescence) analysis is a method used to determine the elemental components in solar panels and to detect damage caused by production [90]. It provides the emission of x-rays sent to the panel. The energy and density of the rays determine the type and amount of elements in the panel. This technique analyzes the metals and contaminants in the module and contributes to the increase in production capacity [119]. These methods support preventive maintenance processes to prevent greater damage that may occur by examining intracellular and surface deterioration with precision.

In this study conducted to detect damage in solar energy panels, the strengths and weaknesses of the methods in Table 3 are presented. This table contains information about the methods used, the advantages and disadvantages of these methods, their areas of use and examples of applications.

Table 3. Damage detection methods in solar energy panels: advantages, disadvantages and areas of use

Method	Advantages	Disadvantages	Areas of Use	Sample Applications
Visual Inspection	Low cost,	Prone to human error,	Surface damage detection	Detection of cracks, fractures or contamination on the panel surface
Use of Thermal Cameras	Easy applicability, Fast results	No detailed analysis,	Detection of thermal damage and hot spots	Detection of hot spots in cells, determination of connection problems
PL Analysis	Fast and effective,	Micro damages cannot be detected	Analysis of micro cracks and intracellular deterioration	Detection of micro cracks in cells, quality control during production
Artificial Intelligence and Machine Learning	Can detect hot spots	High cost,	Automatic detection of all types of damage	Analysis of drone images, classification of thermal images
Drone-Based Inspection	Provides non-contact measurement	Can be affected by environmental factors (e.g. wind, temperature)	Inspection of large-scale solar fields	Rapid scanning of panels in large areas, detection of environmental damage
Current-Voltage (I-V) Measurements	High sensitivity	Requires special equipment,	Detection of electrical connection problems	Measurement of energy production performance of cells, determination of short circuits
Spectroscopic Analysis	Can detect micro cracks and intracellular damage	Costly and time consuming	Cell material analysis	Detection of chemical deterioration on the cell surface, analysis of the effects of UV rays

While carrying out the damage detection processes in solar panels, as seen in Figure 8, starting from the visual inspection processes, the thermal camera detection process, electroluminescence, PL detection process, electrical detection processes and artificial intelligence detection processes are carried out respectively. As a result of the examinations, a report is created and preventive maintenance processes are carried out.

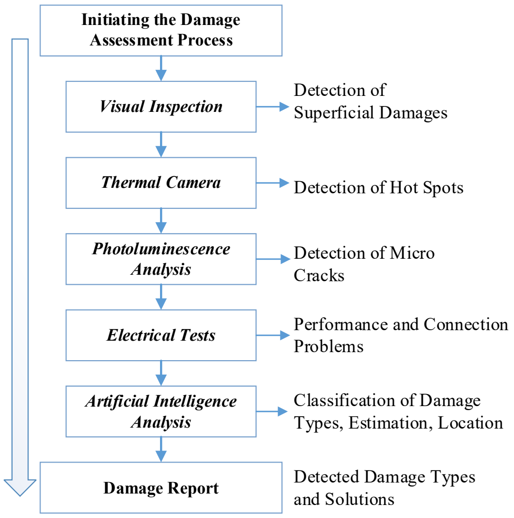

Figure 8. Damage detection process steps

In addition to technical performance, the cost aspect of each method is also crucial for practical applications. Table 4 provides a comparative cost analysis of the detection methods discussed.

Table 4. Cost analysis of photovoltaic damage detection methods.

Detection Method	Cost Level	Cost-Related Explanation
Visual Inspection	Low	Requires only human labor and simple optical tools (e.g., magnifier, flashlight). Suitable for small-scale systems but labor-intensive in large farms.
Multimeter Electrical Tests	Low	Inexpensive devices; effective for basic faults but cannot detect complex or internal defects.
Thermal Camera Imaging	Medium	Requires infrared camera equipment; moderate cost, widely available. Accuracy depends on environmental conditions.
I–V Characteristic Measurements	Medium	Needs specialized measurement equipment; suitable for performance analysis but less practical for large-scale continuous monitoring.
Insulation Resistance Tests	Low–Medium	Requires insulation resistance meters; moderate cost, mainly for safety and leakage checks.
Electroluminescence (EL) Imaging	High	Requires darkroom setup, current source, and CCD camera. High accuracy but costly equipment and not practical for field-scale use without infrastructure.
Photoluminescence (PL) Imaging	High	Needs controlled light sources and sensitive cameras. High resolution but expensive and more common in research or advanced QC.

Drone-Based Inspections	Medium–High	Requires UAV platform, high-resolution/thermal cameras, and software. Initial investment is high, but long-term cost savings due to reduced labor and inspection time.
AI and Machine Learning Approaches	High	Require high-performance computing resources, labeled datasets, and integration with imaging hardware. High initial cost but scalable for large solar farms.
Electrical Tests (TDR, SSTDR, etc.)	Medium	Specialized equipment needed; higher accuracy than simple multimeter tests, but costlier and requires technical expertise.
Spectroscopic Analyses (Raman, FTIR, XRF, etc.)	High	Laboratory-grade equipment required. Very accurate but costly and time-consuming, limiting applicability for field inspections.

Literature review and current situation studies

Damages are an important problem that negatively affects energy production and the operating performance of the system. Correctly detecting damages is valuable in terms of optimizing maintenance and repair processes and minimizing losses. There are many methods developed in the literature regarding damage detection methods. These methods vary depending on the type of damage. However, there are also special studies developed according to the problems encountered. In the literature review, subheadings were also examined depending on the damage types. These were categorized as mechanical damages, thermal damages, electrical damages and environmental damages. In the literature review, the advantages, limitations and application areas of the methods used were tried to be revealed. The frequency of use of the studies, literature gaps and difficulties encountered were also mentioned. The review was carried out systematically, and the aim was to establish a basis that would shed light on future studies by determining literature gaps.

a. Mechanical damage detection methods

There are different methods in the literature for the detection of mechanical damage. Methods such as visual inspection, PL analysis and drone-based inspection are widely used in the determination of such damages. While visual inspection stands out as a low-cost and fast method, PL analysis provides high sensitivity in the detection of microcracks and internal defects at the cell level. In addition, drone-based inspections provide fast and effective damage detection in large areas. These methods used in the detection of mechanical damages will be discussed in detail and the advantages, limitations and applications of each method in the literature will be examined.

Mechanical damages usually occur due to hail, wind, impacts during transportation or improper assembly. Damages can manifest themselves as cell cracks, panel breaks or surface deformations.

b. Visual inspection methods

Visual inspection has some advantages and limitations. Many studies have been conducted from traditional visual inspections to advanced imaging and artificial intelligence-supported approaches. The detection of each defect is carried out with different imaging techniques.

The Qatar Environment and Energy Research Institute focused on visual and infrared inspection of the solar energy system that was put into operation in 2014. In the study, visual cracks in the rear glass, yellowing in the encapsulating material, cracks and pits in the back layer were observed. Cracks and color changes in the back layer were detected in 19% of the modules, yellowing in 8%, and pits in the back layer in 4%. Infrared inspections were performed for hot spot detection. Hot spots were detected in the junction boxes in 39%, hot spots were detected in the box in 6%, and hot spots were detected in an area far from the junction boxes in 1%. It was observed that dust and wind seen in the desert climate had negative effects on the panels [120].

One of the visual inspection methods is the processing of images obtained from the panels in a computer environment with the support of artificial intelligence. Mechanical damages in the image are tried to be detected using image processing techniques and artificial intelligence techniques. One of these studies was the development of a deep learning-based system to automate damages in solar panels. The damage was tried to be detected with the DenseNet121 deep learning model. Deep learning model was used to detect cracks, connection point damages and hot spot damages. It produced more successful results than inspection with traditional methods [121, 122].

In a study conducted for the detection of deteriorations, visual, I-V curve analysis, infrared, electroluminescence imaging, digital image processing with UV light and microscopic techniques were used to detect deteriorations. The study emphasized that 78% of panel deteriorations were reported at a rate of less than 1% per year. Studies emphasized that deterioration occurred in panels between 20-25 years of age [123]. A study conducted in Kenya focused on the physical deterioration of panels under different climatic conditions. It focused on the detection of visible damages in panels using imaging methods. It emphasized that the damages caused deterioration and decreased performance. It was also stated that visible damages could be due to production, transportation and assembly. Table 5 includes a few literature reviews for the techniques used for visual inspection and the findings in the studies conducted with these techniques.

Table 5. Techniques used for visual inspection.

Technical	Key Findings	Quotes
Visual Inspection	It works well in detecting dirt, dust, and shading. Qualified personnel are required to detect defects such as microcracks.	Cardinale-Villalobos [124], Cardinale-Villalobos [125], Packard [126], Chicca & TamizhMani [127], Roy & Gupta [128]
Infrared Thermography	It is used to detect hotspot defects. It should be used with other methods to detect microscopic damage.	Cardinale-Villalobos [124], Nakagawa & Fujita [76]
Electroluminescence Imaging	It is suitable for microcrack detection. It is used with other methods for detailed detections.	Nakagawa & Fujita [76], Cardinale-Villalobos [124], Chicca & TamizhMani [127]
Deep Learning Based Models	Yolo models can be preferred from object detection algorithms. It shows successful results in semi-automatic detections in large-scale power plants.	Probhakaran [129], Haeruman [130], Barrett[131]
UV-Fluorescence Imaging	It is suitable for detecting polymer degradation and cell cracks, which provide high-performance results.	Buerhop-Lutz [132]

c. Photoluminescence analysis methods

PL analysis methods are used to analyze cell cracks in panels, interconnection failures, electrical potential difference, humidity, temperature, and degradation in insulation materials. The occurrence of such damages causes a significant decrease in panel performance [133, 134]. In a study conducted for this purpose, a PL imaging method, which is a highly efficient and low-cost technique, was proposed. This method includes an imaging system taken from a drone. An image is attempted to be captured with a light source placed on the drone. The study showed that 300 panel images can be processed per minute. Cracks are attempted to be detected from these images. In addition, this study aims to create a detection method and try to verify cracks [135]. Again, a similar study suggests using the PL imaging technique. It has been stated that it would be appropriate to combine high-resolution images with infrared as a panel imaging method in outdoor areas [136]. Another study indicated that PL imaging is a suitable approach for quality control processes in panels. It was stated that it would be more appropriate to analyze damages in panels with red and green light sources [137]. Table 6 shows studies on PL method.

Table 6. Techniques used for PL analysis

Technical	Description	Quotes
Airborne PL Imaging	This type of imaging system is obtained by drones. It is used in large-scale power plants.	Doll [135]
Solar Light Excited PL Imaging	It obtains PL images using sunlight as an excitation source.	Bhoopathy[134], Plaza [138]
Time Resolved PL Imaging	It measures carrier lifetimes for panel cell quality assessment and defect detection.	True [139]
Modulated Light PL Imaging	It uses modulated light to determine and restore defect patterns.	Dong [140]
Partial PL Imaging	It obtains images by illuminating to detect cell defects in the non-imaged section.	Plaza [138]

d. Electroluminescence imaging

Using EL imaging, it is possible to detect cell cracks, especially in PV panels. In EL testing, electric current is applied to the PV module in a dark environment. The emitted photons are captured by a CCD camera, producing images in which cracks and crystal defects appear as dark lines.

Especially in polycrystalline solar cells, crystallographic defects are typically also seen as dark lines. Therefore, the detection of cell cracks with EL imaging has not yet been successfully automated. Therefore, cell cracks are detected by a person who has been trained on how to recognize cell cracks in PV cells and panels. A well-trained person can detect cracks by looking at the EL image of a solar panel [141].

As can be seen in Figure 8, the test is performed in a dark environment, by applying reverse current to the PV solar panel, and the reflected photons are captured by the CCD camera, and images similar to radiology results are obtained, as in Figure 9.

And the images can be interpreted by experts, as in radiology results.

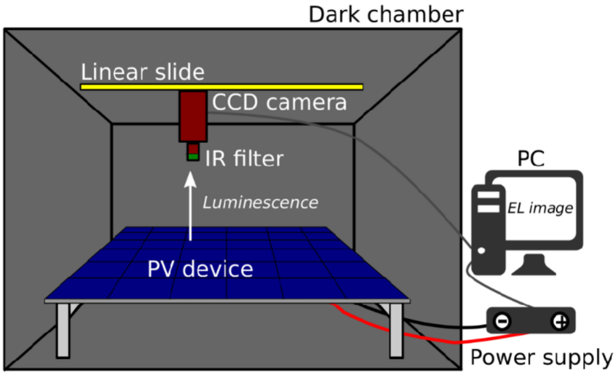

Figure.9. Illustration of the EL imaging technique[142]

e. Drone-based inspection methods

Drones integrated with high-resolution cameras are an important method used in damage detection, especially in large-scale panel systems. This method enables hot spot detection, crack detection and shading anomalies [143-145].

Thermal imaging, deep learning and computer vision, multispectral imaging and 3D remote sensing techniques are used in drone-based damage detection. Thermal imaging, which is used to detect temperature-based damage, provides important findings for the detection of hot spots, faulty diodes and low-performing panels. The thermal images obtained allow damage detection and classification [144, 146, 147].

Detection of damage in images obtained by drones can be achieved with convolutional neural networks, object detection algorithms and different deep learning models. High accuracy results are obtained with such approaches [131, 148, 149].

Multispectral cameras mounted on drones can capture both visible and infrared images. These images allow for the detection of damage to panels by creating geographical regions [96]. In addition, panel models can be created with 3D high-resolution images obtained by remote sensing. This can facilitate the monitoring of panels [145]. Table 7 provides data on the advantages of drone-based approaches and what they can do, as well as studies supporting this data.

There are some limitations in drone-based systems. Technical problems [150], environmental factors [96] and legal regulation [151] problems cause limited use. Table 8 provides a comparison of drone-based methods.

Table 7. Advantages of drone-based approaches

Advantage Category	Details	Quotes
Cost Effectiveness	Reduction of labor costs, shortening of inspection time, less equipment requirement, less human intervention	Rocha [148], Høiaas [144]
High Efficiency	Rapid inspection in large-scale power plants, obtaining high-resolution images and detecting defects, shortening of maintenance and repair process	Polymeropoulos [143], Cardoso [145].
Improved Accuracy	Higher accuracy with artificial intelligence approaches using thermal imaging system, module detection with object detection algorithms.	Kuznetsov [152], Zhang [146]
Non-Destructive and Non-Contact	Reduction of risk of damage to panels due to aerial images taken by drones	Moorthy [153]

Table 8. Comparison of drone-based inspection methods

Technology	Description	Accuracy/Performance	Quotes
Thermal Imaging	Detection of temperature anomalies	High accuracy	Høiaas [144], Zhang [146]
Deep Learning (YOLO)	High accuracy in detecting defects with object detection methods and deep learning.	87% mAP	Barrett [131], Terzoglou [149]
Multispectral Imaging	Captures infrared images for hotspot detection.	High accuracy	Duan [96]
3D Remote Sensing	Used for detailed monitoring and 3D modeling.	99.12% detection rate	Cardoso [145]
CNN Based Models	Performs segmentation and classification in defect detection.	76% mAP	Barrett [131]

f. Methods for Thermal Damage

Thermal damage caused by the heating of solar panels occurs for different reasons. Temperature fluctuations, panel shading and overheating can be given as examples. Such reasons lead to hot-spot formation and loss of efficiency in energy production in panels.

Different methods are used to detect various damages in the studies. Baltacı and his colleagues tried to detect the damages caused by hot-spot and bypass circuit overheating by using thermal imaging method. It is aimed to detect the damages at an early stage and to start preventive maintenance processes accordingly with image processing techniques and machine learning methods [154]. In another study, Gallardo-Saavedra and his colleagues examined 17,142 images to detect hot spot formations in panels. Hot spot, overheated bypass circuits, connection defects were emphasized. The aim of the study was to develop a software to detect the damages. They tried to analyze the defect models with the statistical data obtained [155]. In another study, 6 different defect types were tried to be detected using infrared thermography. Ahmed and his colleagues classified these images using deep learning models. The study, which achieved a success rate of 95%, achieved successful results with a new method based on artificial intelligence [156].

In one study, a camera was placed on an unmanned aerial vehicle to obtain thermal camera images. It was aimed to quickly detect defects in small distributed energy production facilities. Statistics on panels were obtained using image processing techniques. Machine learning algorithms are used to determine defects. Hot spot, bypass circuit heating defects were detected [157].

In another study, panel images were obtained with a thermal camera mounted on an unmanned aerial vehicle. In the study, work was done on the classification and examination of the images obtained. The YOLO5 algorithm, one of the object detection algorithms, was used for damage detection from the images obtained. This algorithm detects hot spot, stain, diode damage, open circuit and short circuit damage [146].

In a study focusing on surface temperatures on panels, the focus is on images taken from a thermal camera with an unmanned aerial vehicle. A perception is evaluated according to statistical data such as the average density and standard deviation of the surface temperature on the panel. The processes tested with this proposed method achieved 97% success. The importance of evaluating statistical analysis data is emphasized in the study [158]. In another study, three-dimensional simulation of double-faced panels was performed using pulsed thermography images for damage detection. This method was used for delamination, cracked cell detection and hot spot detection [159]. In another study, damages in panels were tried to be detected by infrared thermography cameras. The study was built on the performance information measured by image processing techniques of the obtained images [93]. Some studies have been conducted that process thermographic images to determine defects in solar panels. The importance of seeing small defects by manually examining thermographic images was emphasized. 870 thermographic camera images were used in the study. Temperature-related damages in the image were analyzed using a software [155].

In another study, thermographic images were processed and interpreted to see panel health. In the study, it was stated that it works effectively in the temperature range of -20 to +55 degrees using 320x240 resolution images [160]. Thermal cameras have focused on testing low-cost cameras for the detection of heat-related damage. The different camera images obtained have yielded success rates close to those obtained with low-cost cameras. Supportive results have been obtained for such approaches to reduce maintenance costs in businesses [161].

In one study, three-dimensional images were extracted from images taken with a ground-based thermal camera. It is emphasized that the information that may arise from radiation in this three-dimensional image contains important data in determining the type of damage [162]. Studies on thermal cameras are given in Table 9.

Table 9. Studies conducted with thermal images

Detection Method/Technique	Thermal Damage/Defect Type Identified	Application/Context
Thermal Imaging	Hot Spots, Bypass Circuit Overheating	Detects thermal anomalies and faults in PV modules using infrared thermography[154, 155]
Deep Feature Machine Learning	Hot Spots, Broken Cells, Delamination	Uses deep convolutional networks and shallow classifiers for fast and accurate fault detection[156, 159]
UAV Based Thermal Imaging	Hot Spots, Blemishes, Bypass Diode Damage	Combines UAVs with thermal cameras for large-scale, efficient inspection of PV modules[146, 157]
Statistical Analysis of Thermography	Defective Panels, Temperature Anomalies	Analyzes thermal intensity and standard deviation to detect faults with high accuracy[93, 158]
Pulsed Thermography	Delamination, Cracked Cells, Hot Spots	Uses pulsed infrared thermography to detect defects in bifacial PV modules[159]
Single Cell Thermographic Analysis	Overheating, Shadowing Effects	Analyzes temperature gradients to distinguish defects and external effects[163]
Computer Vision Tools	Hot Spots, Open Circuit, Short Circuit	Uses ResNet-50 to classify anomalies in aerial IR videos with over 90% accuracy[164]
Infrared Computer Vision	Hot Spots, Ground Leakage, Circuit Problems	Combines thermography with image processing for utility-scale PV array inspection[93]
Thermal Image Processing	Hot Spots, Junction Box Problems	Processes thermographic images to identify and classify defects in PV modules[155, 160]
Low Cost Thermal Cameras	Hot Spots, Faulty Cells	Evaluates the performance of low-cost cameras to detect hot spots with minimum error rates[161]
Machine Vision Techniques	Hot Spots, Reflections, External Radiation	Detects and classifies hot spots while minimizing artifacts from reflections and external sources[162]

g. Methods for electrical damages

One of the various damage headings in solar panels is electrical damage. This type of damage reduces the panel efficiency and can cause the panels to become completely dysfunctional in the future, or even cause fire. Studies on electrical damage have been compiled in the literature. These studies are grouped and given in a table.

Nakagawa et al. compared thermal infrared imaging and electroluminescence imaging techniques and analyzed the effectiveness of these methods in detecting electrical damage. The study showed that detecting temperature anomalies with thermal imaging is effective in determining the location of electrical faults, while electroluminescence imaging provides a more sensitive analysis. Comparing these two methods provides an important reference to understand which method is more suitable in different conditions[165].

Olšan et al. presented a comprehensive analysis combining optical, thermal and electroluminescence methods for the assessment of electrical damage in PV panels. The study showed that the combination of these three methods allows for more accurate detection of electrical damage. This approach provides an effective solution for the detection of electrical faults, especially microcracks and connection problems in panels[166].

Smith and Colvin developed a low-current diagnostic metric for the detection of electrical damages in PV modules. This innovative method allows the detection of electrical faults even at low current levels, which is a significant advantage especially in early diagnosis and preventive maintenance processes. The study proposes a more sensitive and energy-efficient approach for the detection of electrical damages [80].

Eskandari et al. developed a multi-layered integrative approach for the diagnosis, classification and severity determination of electrical faults in PV arrays. This method allows not only the detection of electrical damages but also the determination of the severity of the damage. The study provides an important solution for the management of electrical faults, especially in large-scale solar power plants[167].

Machine learning-based approaches are also increasingly used for the detection of electrical damages. Saeed et al. compared different machine learning techniques for detecting electrical faults in solar panel systems and determined the most effective methods. The study shows that machine learning algorithms have significant potential in detecting electrical damages quickly and accurately. Similarly, Muttashar and Shakir developed a machine learning-based approach on a simulated PV system and achieved higher accuracy rates in detecting electrical faults [168, 169].

Deep learning methods also provide remarkable results in detecting electrical damages. Hadrawi et al. developed a deep autoencoder-based method to detect mismatch faults in PV modules. This method provides an effective solution especially in detecting complex electrical faults. Chen et al. conducted a study on diagnosing electrical faults in PV panels using deep learning-based image recognition technology. The study reveals the potential of image processing techniques in detecting electrical damages [170, 171].

In conclusion, these studies on the detection and analysis of electrical damages in solar panels show the effectiveness of different methods and technologies. These studies, which are conducted in a wide range from optical and thermal imaging techniques to machine learning and deep learning based approaches, are given in Table 10.

Table 10. Classification according to electrical damage detection methods

Method Category	Quotes	Year	Highlights
Multiple Method Combinations	Olšan ve diğerleri[166]	2017	Combination of optical, thermal and electroluminescent methods
Imaging Techniques	Nakagawa ve diğerleri[165]	2023	Comparison of thermal infrared and electroluminescent imaging
Diagnostic Metrics	Smith ve Colvin[80]	2024	Low-current diagnostic metric
Integrated Approaches	Eskandari ve diğerleri[167]	2024	Multi-layered integrative approach

Conclusion and evaluation

The efficiency of solar energy panels varies depending on the healthy operation of the panels. The most important factor that ensures energy efficiency is that the panels operate without damage.

The focus of this study is to detect existing or potential damage to the panel at an early stage in order to obtain maximum benefit from solar energy panels. The types of damage in solar energy panels and damage detection methods are comprehensively discussed in this study. In addition, the negativities caused by the damages are examined in detail in the study. The methods used to detect these damages and the positive and negative aspects of these methods are also given. The findings obtained as a result of the study are generally as follows.

- The types of damage in solar energy panels are divided into 4 main categories. These damages are mechanical damages, thermal damages, electrical damages and damages caused by environmental conditions.
- The types of damages that occur are contamination and dust damage, connection problem damage, corrosion, delamination, electrical breakdown, broken cells, hotspots and micro cracks.
- The studies conducted for damage detection are basically examined in 3 main categories. These are divided into detection methods with traditional methods, advanced technology (artificial intelligence) detection methods and other methods.
- Among the damage detection methods, detections can be made with different applications in traditional methods. These are visual inspection, electrical tests

with multimeter, use of thermal cameras, current-voltage (I-V) measurement and insulation resistance tests.

• The cost of traditional methods is low. However, their applicability in large-scale systems is quite difficult. Traditional detection methods are insufficient in detecting some damages. Traditional methods are suitable for small-scale systems.

• Advanced technology (artificial intelligence) detection methods are divided into 4 main headings. These are the use of thermal imaging and infrared cameras, PL analysis, drone-based inspections, and damage detection methods using artificial intelligence and machine learning models.

• Especially in large-scale systems, advanced technology systems are highly efficient for damage detection. It is preferred in terms of automating the process by minimizing human intervention. It is much more successful than traditional methods. Equipment with good hardware is needed to use artificial intelligence-based models. In recent years, methods based on damage detection have increased considerably with the use of artificial intelligence models. This shows that artificial intelligence-based methods are preferred more than traditional methods.

• Other damage detection methods are electrical tests and spectroscopic analyses. The data obtained with these methods are usually analyzed using machine learning models. In the studies conducted, it is seen that the data obtained with these methods produce successful results after the integration with artificial intelligence.

Considering the results obtained from the examinations conducted in this study, statistical information regarding the studies conducted according to the damage types is given in Figure 10. This figure was created with the information obtained from field studies, academic research and sectoral reports.

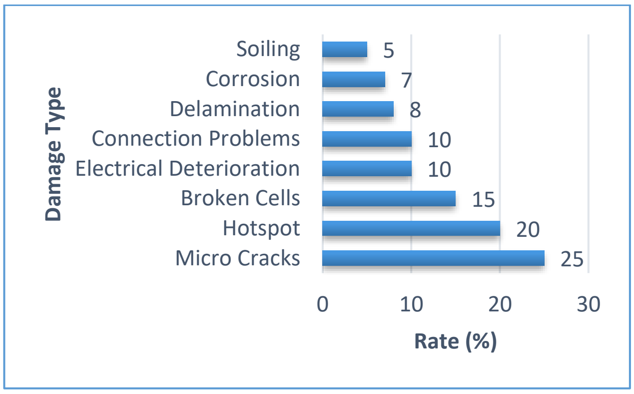

Figure 10. Proportional distribution of damage types encountered in solar energy panels

The most studied damage type is micro cracks. It has been observed that this damage type is followed by hotspot damage types. The least studied damage types are contamination and corrosion. The reasons for the formation of micro cracks are production-related damages. It has been observed that these cracks cause greater damages during transportation and installation processes. The most studied damage type is hotspot. It has been emphasized that this damage type negatively affects the operation of the panels.

The reason for the lack of studies on the corrosion damage type is the low moisture content in the mechanical parts. It is thought that with the increase in the presence of floating solar power plants, this damage type will occur more and the studies will increase. The lack of studies on the pollution-related damage type shows that this type of damage is encountered less. It is thought that this type of damage formation is seen in small numbers due to the sufficient cleaning work done in the maintenance and repair processes in solar power plants. Many different methods have been applied to detect the damages that occur. The results obtained with this study have allowed us to make a statistical analysis on the amount of damage detection methods. Statistical information regarding the damage detection methods used in solar energy panels in the reviewed studies is shown in Figure 11.

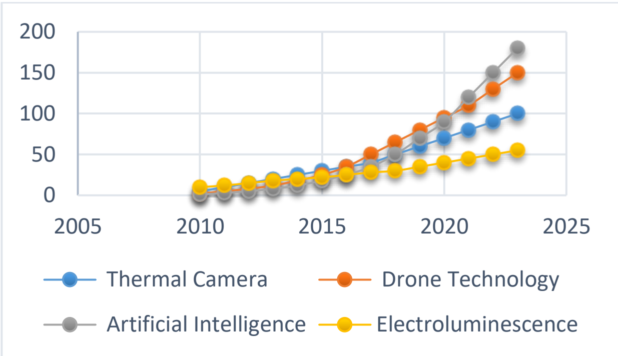

Figure 11. Usage trends of damage detection methods in solar energy panels by year

As can be understood from the graph, studies on damage detection conducted between 2010-2023 were examined. When the study was examined, artificial intelligence methods showed a significant increase and ranked first. Today, artificial intelligence aims to reach results by analyzing data obtained with different methods. It is thought that the high success rate and the automatic execution of the processes are important factors at this point. In addition, the fact that no expert is needed to perform the analysis brings this method to the forefront. One of the most frequently used methods in the examination is drone-based damage detection methods. In large-scale power plants, scans made with drones are carried out quickly. Artificial intelligence detection methods, especially in recent years, have been increasing and play a role in the detection of almost all types of damage.

The main difficulties encountered in the damage detection process in solar energy panels are as follows:

Traditional methods are insufficient in detecting micro cracks and damages in the panel internal structure. Traditional methods require experts trained in this field. Employing such an expert, especially in small-scale power plants, is a costly process. Since advanced technology methods require high-cost equipment, they increase initial costs. Preparation of the artificial intelligence system requires expertise. Drone and PL damage detection methods are also high-cost equipment. Data is needed to develop artificial intelligence-based methods. Since the establishment of such systems and obtaining data is a time-consuming process, obtaining data is quite difficult and time-consuming.

Despite the difficulties encountered, the suggested solutions are as follows:

- Detection of damages that are difficult to detect with traditional methods using artificial intelligence and machine learning methods.
- Use of advanced imaging techniques that produce high-resolution images instead of low-resolution images. Production of low-cost systems.
- Carrying out regular maintenance processes to reduce damage. Ensuring the integration of software supported by low-cost mobile applications.
- Giving importance to cleaning to eliminate the permanent effect of environmental factors.
- It is necessary to ensure that faster and more accurate results are obtained with advanced deep learning models.

The study analyzes the types of damage and examines the detection methods applicable to photovoltaic panels. Methods are categorized as traditional, advanced, and alternative approaches. It fills a significant gap in the literature by evaluating the advantages and limitations of the methods. Environmental and weather conditions also affect the application of methods. For example, thermal imaging is highly sensitive to radiation and wind, negatively impacting its reliability in the field. Inspection processes performed with EL and PL systems are reliable in indoor environments. However, their applicability to outdoor environments is quite limited. UAV(Unmanned Aerial Vehicle)-based inspections are affected by wind and visibility, while visual inspection can be hindered by dust, rain, or surface contamination. AI-based approaches also depend on the characteristics of the training dataset, and their performance may degrade if environmental conditions differ from those represented in the training data. These considerations highlight the importance of considering environmental robustness when evaluating and selecting PV damage detection techniques for real-world applications. It highlights how each method can be used across different system sizes and environmental conditions, making it a useful resource for researchers and businesses.

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References

[1] G. Kopp and J. L. Lean, "A new, lower value of total solar irradiance: Evidence and climate significance," *Geophysical Research Letters,* vol. 38, no. 1, 2011.

[2] I. Dincer, "Renewable energy and sustainable development: a crucial review," *Renewable and sustainable energy reviews,* vol. 4, no. 2, pp. 157-175, 2000.

[3] N. S. M. N. Izam, Z. Itam, W. L. Sing, and A. Syamsir, "Sustainable development perspectives of solar energy technologies with focus on solar Photovoltaic—A review," *Energies,* vol. 15, no. 8, p. 2790, 2022.

[4] F. H. Hasan, S. Algburi, and S. B. Ezzat, "Investigating the Impact of Internal and External Factors on Solar Cell Performance to Enhance Energy Conversion Efficiency," *NTU Journal of Renewable Energy,* vol. 8, no. 1, pp. 14-23, 2025.

[5] H. H. Öztürk, "Güneş Enerjisinden Fotovoltaik Yöntemle Elektrik Üretiminde Güç Dönüşüm Verimi Ve Etkili Etmenler," 2008.

[6] M. D. Patabo, J. G. Daud, S. I. Ponnokaraeng, G. Tongkotou, I. T. Kapoh, and Y. L. Sariowan, "Maintenance Of Solar Power Plants For Household Electricity Use," *Jurnal Syntax Admiration,* vol. 5, no. 12, pp. 5897-5903, 2024.

[7] M. S. K. Mithil, M. A. Talha, and S. Ahmad, "Enhancing Solar System Efficiency Based on Precise Real-Time Energy Data Analysis and Sun Position Tracking," in *2024 6th International Conference on Electrical Engineering and Information & Communication Technology (ICEEICT)*, 2024: IEEE, pp. 290-295.

[8] L. El Chaar and N. El Zein, "Review of photovoltaic technologies," *Renewable and sustainable energy reviews,* vol. 15, no. 5, pp. 2165-2175, 2011.

[9] R. B. Domurcuk, M. Asker, P. Demircioğlu, and İ. Böğrekci, "THE ANALYSIS OF PHOTOVOLTAIC PANEL SYSTEMS," *International Journal of 3D Printing Technologies and Digital Industry,* vol. 5, no. 1, pp. 13-22, 2021.

[10] Y. Qian *et al.*, "Thin-film organic semiconductor devices: from flexibility to ultraflexibility," *Sci. China Mater,* vol. 59, no. 7, pp. 589-608, 2016.

[11] X. Li, P. Li, Z. Wu, D. Luo, H.-Y. Yu, and Z.-H. Lu, "Review and perspective of materials for flexible solar cells," *Materials Reports: Energy,* vol. 1, no. 1, p. 100001, 2021.

[12] M. P. Maniscalco, S. Longo, G. Miccichè, M. Cellura, and M. Ferraro, "A critical review of the environmental performance of bifacial photovoltaic panels," *Energies,* vol. 17, no. 1, p. 226, 2023.

[13] S. Sivaraj *et al.*, "A comprehensive review on current performance, challenges and progress in thin-film solar cells," *Energies,* vol. 15, no. 22, p. 8688, 2022.

[14] L. Wang *et al.*, "Highly Efficient Monolithic Perovskite/TOPCon Silicon Tandem Solar Cells

Enabled by "Halide Locking"," *Advanced Materials,* p. 2416150, 2025.

[15] T. D. Lee and A. U. Ebong, "A review of thin film solar cell technologies and challenges," *Renewable and Sustainable Energy Reviews,* vol. 70, pp. 1286-1297, 2017.

[16] M. Alves, A. Pérez-Rodríguez, P. J. Dale, C. Domínguez, and S. Sadewasser, "Thin-film micro-concentrator solar cells," *Journal of Physics: Energy,* vol. 2, no. 1, p. 012001, 2019.

[17] R. A. Rahimi, S. H. Yahaya, D. F. M. H. Seria, and M. N. Sani, "A comprehensive review on architectural design and development of flexible photovoltaic solar panel," *Multidisciplinary Reviews,* vol. 7, no. 12, pp. 2024299-2024299, 2024.

[18] R. O. Yakubu, L. D. Mensah, D. A. Quansah, and M. S. Adaramola, "A systematic literature review of the bifacial photovoltaic module and its applications," *The Journal of Engineering,* vol. 2024, no. 8, p. e12421, 2024.

[19] X. Kong, T. He, H. Qiu, L. Zhan, and S. Yin, "Progress in organic photovoltaics based on green solvents: from solubility enhancement to morphology optimization," *Chemical Communications,* vol. 59, no. 81, pp. 12051-12064, 2023.

[20] N. Jost, T. Gu, J. Hu, C. Domínguez, and I. Antón, "Integrated micro-scale concentrating photovoltaics: a scalable path toward high-efficiency, low-cost solar power," *Solar RRL,* vol. 7, no. 16, p. 2300363, 2023.

[21] O. O. Apeh, E. L. Meyer, and O. K. Overen, "Contributions of solar photovoltaic systems to environmental and socioeconomic aspects of national development—A review," *Energies,* vol. 15, no. 16, p. 5963, 2022.

[22] H. Huq, "Solarenergy Fuels for Sustainable Livelihoods: Case Study of Southwest Coastal Region of Bangladesh," *Geography, Environment, Sustainability,* vol. 11, no. 4, pp. 132-143, 2019.

[23] M. Amani, A. Smaili, and A. Ghenaiet, "Thermo-economic assessment of the first integrated solar combined cycle system of hassi r'mel," *Mechanics,* vol. 26, no. 3, pp. 242-251, 2020.

[24] L. Kulikova, A. Goshunova, and D. Nutfullina, "Economic Analysis of Solar Energy Using in Oil Sector Economy in Republic of Tatarstan," in *IOP Conference Series: Materials Science and Engineering*, 2017, vol. 262, no. 1: IOP Publishing, p. 012066.

[25] M. M. Rahman, A. Islam, S. Salehin, and M. A. Al-Matin, "Development of a model for techno-economic assessment of a stand-alone off-grid solar photovoltaic system in Bangladesh," *Int. J. Renew. Energy Res,* vol. 6, no. 1, pp. 140-149, 2016.

[26] T. Rus, R.-P. Moldovan, and M. Á. Pardo Picazo, "LCA analysis of a roof mounted PV system: a Romanian case study," *Frontiers in Environmental Science,* vol. 12, p. 1413629, 2024.

[27] N. A. Mostafa and A. Aboelezz, "Feasibility-sustainability study of power generation using solar energy at an industrial site: a case study from Egypt," *Energy, Sustainability and Society,* vol. 14, no. 1, p. 36, 2024.

[28] P. Ponce, C. Pérez, A. R. Fayek, and A. Molina, "Solar energy implementation in manufacturing industry using multi-criteria decision-making fuzzy TOPSIS and S4 framework," *Energies,* vol. 15, no. 23, p. 8838, 2022.

[29] Y. Gebreyohannes, M. Bayray, and J. Lauwaert, "A review on solar thermal utilization for industrial heating and cooling processes: global and Ethiopian perspective," *Momona Ethiopian Journal of Science,* vol. 12, no. 2, pp. 232-256, 2020.

[30] V. Brezoczki and G. Filip, "Aspects of the use solar energy valorification for industrial and public lighten area," in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 749, no. 1: IOP Publishing, p. 012028.

[31] J. Hyvönen, A. Santasalo-Aarnio, S. Syri, and M. Lehtonen, "Feasibility study of energy storage options for photovoltaic electricity generation in detached houses in Nordic climates," *Journal of Energy Storage,* vol. 54, p. 105330, 2022.

[32] A. Vasić-Milovanović, "Increased temperature and radiation damage influence on solar cells characteristics," *FME transactions,* vol. 41, no. 1, pp. 77-81, 2013.

[33] S. Duman and M. Alçı, "Yarım ve tam fotovoltaik hücreleri ile tasarlanan güneş enerjisi panellerinin toplam verimliliğini etkileyen parametrelerinin incelenmesi," *Niğde Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi,* vol. 11, no. 3, pp. 592-600, 2022.

[34] D. Dwivedi, P. K. Yemula, and M. Pal, "Detection of malfunctioning modules in photovoltaic power plants using unsupervised feature clustering segmentation algorithm," *arXiv preprint arXiv:2212.14653,* 2022.

[35] M. Dhimish, V. d'Alessandro, and S. Daliento, "Investigating the impact of cracks on solar cells performance: Analysis based on nonuniform and uniform crack distributions," *IEEE Transactions on Industrial Informatics,* vol. 18, no. 3, pp. 1684-1693, 2021.

[36] I. Bodnár, D. Matusz-Kalász, and R. R. Boros, "Exploration of Solar Panel Damage and Service Life Reduction Using Condition Assessment, Dust Accumulation, and Material Testing," *Sustainability,* vol. 15, no. 12, p. 9615, 2023.

[37] F. Doğan, S. Oyucu, E. Bicer, and A. Aksoz, "Deep learning models for damage type detection in wind turbines," *PeerJ Computer Science,* vol. 11, p. e3163, 2025.

[38] M. Bdour, Z. Dalala, M. Al-Addous, A. Radaideh, and A. Al-Sadi, "A comprehensive evaluation on types of microcracks and possible effects on power degradation in photovoltaic solar panels," *Sustainability,* vol. 12, no. 16, p. 6416, 2020.

[39] M. Aktaş, F. Doğan, and İ. Türkoğlu, "Classification of Solar Cells EL Images with Different Busbars Via Deep Learning Models," *Sakarya University Journal of Computer and Information Sciences,* vol. 7, no. 2, pp. 217-226, 2024.

[40] M. Dhimish, V. Holmes, M. Dales, and B. Mehrdadi, "Effect of micro cracks on photovoltaic output power: case study based on real time long term data measurements," *Micro & Nano Letters,* vol. 12, no. 10, pp. 803-807, 2017.

[41] T. Rahman *et al.*, "Investigation of degradation of solar photovoltaics: A review of aging factors, impacts, and future directions toward sustainable energy management," *Energies,* vol. 16, no. 9, p. 3706, 2023.

[42] A. A. Hasan, A. Ahmed Alkahtani, S. A. Shahahmadi, M. Nur E. Alam, M. A. Islam, and N. Amin, "Delamination-and electromigration-related failures in solar panels—A review," *Sustainability,* vol. 13, no. 12, p. 6882, 2021.

[43] G. Oreski and G. Pinter, "Peeling of Flexible Laminates—Determination of Interlayer Adhesion of Backsheet Laminates Used for Photovoltaic Modules," *Materials,* vol. 15, no. 9, p. 3294, 2022.

[44] R. Herrero *et al.*, "Experimental analysis and simulation of a production line for CPV modules: impact of defects, misalignments, and binning of receivers," *Energy Science & Engineering,* vol. 5, no. 5, pp. 257-269, 2017.

[45] F. Spertino and J. S. Akilimali, "Are manufacturing $ I $–$ V $ mismatch and reverse currents key factors in large photovoltaic arrays?," *IEEE Transactions on Industrial Electronics,* vol. 56, no. 11, pp. 4520-4531, 2009.

[46] M. Dhimish and G. Badran, "Investigating defects and annual degradation in UK solar PV installations through thermographic and electroluminescent surveys," *npj Materials Degradation,* vol. 7, no. 1, p. 14, 2023.

[47] X. Chen, T. Karin, and A. Jain, "Analyzing the impact of design factors on solar module thermomechanical durability using interpretable machine learning techniques," *Applied Energy,* vol. 377, p. 124462, 2025.

[48] Y. Aoki, M. Okamoto, A. Masuda, and T. Doi, "Module performance degradation with rapid thermal-cycling," *Proceedings of Renewable Energy,* 2010.

[49] C. Han, "Simulation of series resistance increase through solder layer cracking in Si solar cells under thermal cycling," *Energies,* vol. 16, no. 6, p. 2524, 2023.

[50] O. E. Ikejiofor, Y. E. Asuamah, H. O. Njoku, and S. O. Enibe, "Detection of hotspots and performance deteriotations in pv modules under partial shading conditions using infrared thermography," *Engineering Proceedings,* vol. 2, no. 1, p. 71, 2020.

[51] J. Zaraket, N. Kokanyan, M. Aillerie, and C. Salame, "Evolution of PV solar modules parameters operating in extreme environments," in *AIP Conference Proceedings*, 2020, vol. 2307, no. 1: AIP Publishing.

[52] D. Razia, A. Raj, S. P. Singh, A. Amudha, P. Karthigaikumar, and N. Wasatkar, "Electrical Deterioration Caused by Lightning: Implications for Solar Power Plants," in *2023 International Conference on Power Energy, Environment & Intelligent Control (PEEIC)*, 2023: IEEE, pp. 612-615.

[53] A. Arjhangmehr and S. A. H. Feghhi, "Displacement damage analysis and modified electrical equivalent circuit for electron and photon-irradiated silicon solar cells," *Radiation Effects and Defects in Solids,* vol. 169, no. 10, pp. 874-884, 2014.

[54] C. M. Whitaker, B. G. Pierce, A. M. Karimi, R. H. French, and J. L. Braid, "PV cell cracks and impacts on electrical performance," in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, 2020: IEEE, pp. 1417-1422.

[55] N. G. Irias, H. de Paula, P. Pereira, E. N. Cardoso, and B. M. Lopes, "Degradation of photovoltaic panels induced by electric potential: Theoretical survey and computational study on the inverter operation influence," in *2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC)*, 2015: IEEE, pp. 1-6.

[56] Y. Zhang, Z. Lv, M. Yu, J. Tang, and W. Wei, "Fault tolerance enhancement of the PV module system by improving the topology and control strategy," *IET Generation, Transmission & Distribution,* vol. 14, no. 6, pp. 975-985, 2020.

[57] 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, p. 2416, 2018.

[58] J. Johnson, "Electrical and Thermal Finite Element Modeling of Arc Faults in Photovoltaic Bypass Diodes," Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA …, 2012.

[59] R. Pomponi and R. Tommasini, "Risk assessment and lightning protection for PV systems and solar power plants," *RE&PQJ,* vol. 10, no. 9, 2012.

[60] N. H. Zaini *et al.*, "Lightning surge analysis on a large scale grid-connected solar photovoltaic system," *Energies,* vol. 10, no. 12, p. 2149, 2017.

[61] A. Formisano, C. Petrarca, J. C. Hernández, and F. J. Muñoz-Rodríguez, "Assessment of induced voltages in common and differential-mode for a PV module due to nearby lightning strikes," *IET Renewable Power Generation,* vol. 13, no. 8, pp. 1369-1378, 2019.

[62] N. Pinochet, R. Couderc, and S. Therias, "Solar cell UV-induced degradation or module discolouration: Between the devil and the deep yellow sea," *Progress in Photovoltaics: Research and Applications,* vol. 31, no. 11, pp. 1091-1100, 2023.

[63] J. Ciempka, A. Thomson, and I. Haedrich, "Impact of Damp Heat and Ultraviolet Radiation on Common Solar Module Encapsulant Materials," 2015.

[64] A. Sinha *et al.*, "UV-induced degradation of high-efficiency silicon PV modules with different cell architectures," *Progress in Photovoltaics: Research and Applications,* vol. 31, no. 1, pp. 36-51, 2023.

[65] B. Mohamed, S. Zambou, and S. S. Zekeng, "Influence of moisture on the operation of a mono-crystalline based silicon photovoltaic cell: A numerical study using SCAPS 1 D," *arXiv preprint arXiv:1712.08117,* 2017.

[66] H. H. Al-Kayiem and M. N. Reda, "Analysis of solar photovoltaic panel integrated with ground heat exchanger for thermal management," *International Journal of Energy Production and Management,* vol. 6, no. 1, pp. 17-31, 2021.

[67] A. Pagodaripour, A. Ghasemkhani, H. Ghazizade-Ahsaee, and A. Namjo, "The assessment and experimental study of photovoltaics panel by spraying water (case study: Kerman, Iran)," *Energy Equipment and Systems,* vol. 8, no. 4, pp. 389-399, 2020.

[68] S. S. Jaafar, H. A. Maarof, R. T. Salh, H. Sahib, and Y. H. Azeez, "Non-Uniform Dust Distribution Effect On Photovoltaic Panel Performance," *Renewable Energy & Sustainable Development,* vol. 9, no. 1, 2023.

[69] M. Katoch, V. Dahiya, and S. K. Yadav, "The performance analysis of dusty photovoltaic panel," *Archives of Thermodynamics,* vol. 44, no. 2, 2023.

[70] R. Pimpalkar, A. Sahu, and R. B. Patil, "An Artificial Intelligence and Machine Learning Model to Estimate the Cleaning Periodicity for Dusty Solar Photovoltaic (PV) Modules in A Composite Environment," *Journal of Mines, Metals and Fuels,* pp. 2794-2804, 2023.

[71] A. M. Aly, G. Bksuamlak, and V. Crepel, "Wind loads on ground-mounted solar panels: a multi-scale computational and experimental study," 2013.

[72] H. Alrawashdeh and T. Stathopoulos, "Experimental investigation of the wind loading on solar panels: effects of clearance off flat roofs," *Journal of Structural Engineering,* vol. 148, no. 12, p. 04022202, 2022.

[73] T. Yambe, Y. Uematsu, and K. Sato, "Wind loads on roofing system and photovoltaic system installed parallel to flat roof," *Proceedings International Structure Engineering Constraction,* vol. 7, no. 1, 2020.

[74] M. Aghaei *et al.*, "Review of degradation and failure phenomena in photovoltaic modules," *Renewable and Sustainable Energy Reviews,* vol. 159, p. 112160, 2022.

[75] S. Jin, Y. Liu, and C. He, "Detection method of solar cell surface defects based on C4. 5-G algorithm," in *International Conference on Cloud Computing, Performance Computing, and Deep Learning (CCPCDL 2023)*, 2023, vol. 12712: SPIE, pp. 184-191.

[76] K. Nakagawa and G. Fujita, "Comparative analysis of methods for determining degradation of PV modules and image analysis: Evaluation of Efficient Inspection Techniques Using Thermal Infrared Imaging Electroluminescence Imaging Techniques," in *2024 6th International Conference on Power Engineering and Renewable Energy (ICPERE)*, 2024: IEEE, pp. 1-4.

[77] Z. Xi, Z. Lou, Y. Sun, X. Li, Q. Yang, and W. Yan, "A vision-based inspection strategy for large-scale photovoltaic farms using an autonomous UAV," in *2018 17th International Symposium on Distributed Computing and Applications for Business Engineering and Science (DCABES)*, 2018: IEEE, pp. 200-203.

[78] A. Shihavuddin *et al.*, "Image based surface damage detection of renewable energy installations using a unified deep learning approach," *Energy Reports,* vol. 7, pp. 4566-4576, 2021.

[79] A. M. Gabor *et al.*, "The impact of cracked solar cells on solar panel energy delivery," in *2020 47th IEEE photovoltaic specialists conference (PVSC)*, 2020: IEEE, pp. 0810-0813.

[80] R. Smith and D. Colvin, "Low-Current Diagnostic Metric for Photovoltaic Module Damage," in *2024 IEEE 52nd Photovoltaic Specialist Conference (PVSC)*, 2024: IEEE, pp. 0189-0189.

[81] I. Khan and S. Khan, "Thermal imaging based maximum power point tracking for solar modules in variable ambient temperature," *SN Applied Sciences,* vol. 3, no. 5, p. 536, 2021.

[82] F. J. Suárez-Domínguez, M. B. Prendes-Gero, Á. Martín-Rodríguez, and A. Higuera-Garrido, "IR thermography applies to the detection of solar panel," *Revista de la Construcción,* vol. 14, no. 3, pp. 9-14, 2015.

[83] R. Vaillon, O. Dupré, R. B. Cal, and M. Calaf, "Pathways for mitigating thermal losses in solar photovoltaics," *Scientific reports,* vol. 8, no. 1, p. 13163, 2018.

[84] M. Zegrar, M. T. Benmessaoud, and F. Z. Zerhouni, "Design and implementation of an IV curvetracer dedicated to characterize PV panels," *International Journal of Electrical and Computer Engineering,* vol. 11, no. 3, p. 2011, 2021.

[85] M. García *et al.*, "Outdoor IV characterization of tilted and vertical bifacial PV modules," in *Journal of Physics: Conference Series*, 2023, vol. 2538, no. 1: IOP Publishing, p. 012002.

[86] A. Augusto, A. Killam, S. G. Bowden, and H. Wilterdink, "Measuring outdoor I–V characteristics of PV modules and systems," *Progress in Energy,* vol. 4, no. 4, p. 042006, 2022.

[87] R. Araneo and M. Mitolo, "Insulation resistance and failures of a high-power grid-connected photovoltaic installation: A case study," *IEEE Industry Applications Magazine,* vol. 27, no. 3, pp. 16-22, 2021.

[88] N. Ketjoy, P. Mensin, and W. Chamsa-Ard, "Impacts on insulation resistance of thin film modules: A case study of a flooding of a photovoltaic power plant in Thailand," *PLoS One,* vol. 17, no. 9, p. e0274839, 2022.

[89] A. Thakfan and Y. Bin Salamah, "Artificial-intelligence-based detection of defects and faults in photovoltaic systems: A survey," *Energies,* vol. 17, no. 19, p. 4807, 2024.

[90] Z. B. Duranay, "Fault detection in solar energy systems: A deep learning approach," *Electronics,* vol. 12, no. 21, p. 4397, 2023.

[91] S. Jaybhaye, V. Sirvi, S. Srivastava, V. Loya, V. Gujarathi, and M. Jaybhaye, "Classification and Early Detection of Solar Panel Faults with Deep Neural Network Using Aerial and Electroluminescence Images," *Journal of Failure Analysis and Prevention,* vol. 24, no. 4, pp. 1746-1758, 2024.

[92] G. Tanda and M. Migliazzi, "Infrared thermography monitoring of solar photovoltaic systems: A comparison between UAV and aircraft remote sensing platforms," *Thermal Science and Engineering Progress,* vol. 48, p. 102379, 2024.

[93] D. F. Ramirez, D. Pujara, C. Tepedelenlioglu, D. Srinivasan, and A. Spanias, "Infrared Computer Vision for Utility-Scale Photovoltaic Array Inspection," in *2024 15th International Conference on Information, Intelligence, Systems & Applications (IISA)*, 2024: IEEE, pp. 1-4.

[94] Y. Hong, R. Pan, J. Su, and M. Li, "Infrared image detection of defects in lightweight solar panels based on improved MSRCR and YOLOv8n," *Infrared Physics & Technology,* vol. 141, p. 105473, 2024.

[95] C. Ruan, W. Tang, X. Hu, and W. Yan, "Deep learning-based method for PV panels segmentation and defects detection with infrared images," in *2021 China Automation Congress (CAC)*, 2021: IEEE, pp. 7166-7171.

[96] R. Duan and Z. Ma, "A method for detecting photovoltaic panel faults using a drone equipped with a multispectral camera," *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* vol. 10, pp. 59-65, 2024.

[97] Z. Wang, P. Zheng, B. Bahadir Kocer, and M. Kovac, "Drone-Based Solar Cell Inspection With Autonomous Deep Learning," *Infrastructure Robotics: Methodologies, Robotic Systems and Applications,* pp. 337-365, 2024.

[98] F. Doğan and İ. Türkoğlu, "Derin öğrenme algoritmalarının yaprak sınıflandırma başarımlarının karşılaştırılması," *Sakarya University Journal of Computer and Information Sciences,* vol. 1, no. 1, pp. 10-21, 2018.

[99] F. Doğan and İ. Türkoğlu, "Derin öğrenme modelleri ve uygulama alanlarına ilişkin bir derleme," *Dicle Üniversitesi Mühendislik Fakültesi Mühendislik Dergisi,* vol. 10, no. 2, pp. 409-445, 2019.

[100] M. Aktas, F. Doğan, and İ. Türkoğlu, "Analysis Of Cracks In Photovoltaic Module Cells From Electroluminescence Images By Deep Learning," in *1st International Conference on Computing and Machine Intelligence*, 2021, pp. 103-103.

[101] S. Jaybhaye, O. Thakur, R. Yardi, V. Raut, and A. Raut, "Solar panel damage detection and localization of thermal images," *Journal of Failure Analysis and Prevention,* vol. 23, no. 5, pp. 1980-1990, 2023.

[102] T. Takashima, J. Yamaguchi, K. Otani, K. Kato, and M. Ishida, "Experimental studies of failure detection methods in PV module strings," in *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, 2006, vol. 2: IEEE, pp. 2227-2230.

[103] T. Takashima, J. Yamaguchi, and M. Ishida, "Fault detection by signal response in PV module strings," in *2008 33rd IEEE Photovoltaic Specialists Conference*, 2008: IEEE, pp. 1-5.

[104] Z. Li, K. Wu, Z. Yang, C. Wu, and F. Wang, "Fault Diagnosis of Photovoltaic Array Based on BP Neural Network and SSTDR," in *2023 IEEE PELS Students and Young Professionals Symposium (SYPS)*, 2023: IEEE, pp. 1-6.

[105] M. U. Saleh *et al.*, "Detection and localization of damaged photovoltaic cells and modules using spread spectrum time domain reflectometry," *IEEE Journal of Photovoltaics,* vol. 11, no. 1, pp. 195-201, 2020.

[106] T. Pei and X. Hao, "A fault detection method for photovoltaic systems based on voltage and current observation and evaluation," *Energies,* vol. 12, no. 9, p. 1712, 2019.

[107] Y. Tao, T. Yu, and J. Yang, "Photovoltaic Array Fault Diagnosis and Localization Method Based on Modulated Photocurrent and Machine Learning," *Sensors,* vol. 25, no. 1, p. 136, 2024.

[108] M. A. Raslan and Ç. Ertuğrul, "Fault Detection and Diagnosis Technic Using Electrical Characteristics of a PV Module and Machine Learning Classifier," *Uluslararası Mühendislik Araştırma ve Geliştirme Dergisi,* vol. 12, no. 3, pp. 73-88, 2020.

[109] B. K. Karmakar and A. K. Pradhan, "Detection and classification of faults in solar PV array using Thevenin equivalent resistance," *IEEE Journal of Photovoltaics,* vol. 10, no. 2, pp. 644-654, 2020.

[110] W. Wang, A. C.-F. Liu, H. S.-H. Chung, R. W.-H. Lau, J. Zhang, and A. W.-L. Lo, "Fault diagnosis of photovoltaic panels using dynamic current–voltage characteristics," *IEEE Transactions on Power Electronics,* vol. 31, no. 2, pp. 1588-1599, 2015.

[111] W. Wang, A. C.-f. Liu, H. S.-h. Chung, R. W.-h. Lau, J. Zhang, and A. W.-l. Lo, "Fault diagnostic device for photovoltaic panels," in *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2015: IEEE, pp. 2609-2616.

[112] J. C. Treece and B. F. Shamee, "Detecting Cracks in Semiconductor Solarcells from Eddy-Current Measurements," in *Review of Progress in*

Quantitative Nondestructive Evaluation: Volume 8, Part A and B: Springer, 1989, pp. 1281-1288.

[113] K. Honda, K. Aikawa, and M. Uno, "Electrical Diagnosis Technique Using Differential Power Processing Converters for Photovoltaic Panels," in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 2020: IEEE, pp. 1791-1796.

[114] J. Nyakuchena, X. Zhang, and J. Huang, "Synchrotron based transient x-ray absorption spectroscopy for emerging solid-state energy materials," *Chemical Physics Reviews,* vol. 4, no. 2, 2023.

[115] J. Aulich *et al.*, "Spectrometric Characterization for Triple-Junction Solar Cells," *Solar RRL,* vol. 8, no. 3, p. 2300783, 2024.

[116] M. De Biasio, J. Zikulnig, W. Muehleisen, M. Simor, and P. J. Bolt, "Raman spectroscopy and photoluminescence imaging for predictive quality monitoring of CIGS solar cells," in *Dimensional Optical Metrology and Inspection for Practical Applications XI*, 2022, vol. 12098: SPIE, pp. 137-143.

[117] L. Gedvilas *et al.*, "FTIR Laboratory in Support of the PV Program," National Renewable Energy Lab.(NREL), Golden, CO (United States), 2003.

[118] J. P. Ganesan *et al.*, "Raman microspectroscopy of a silicon solar cell," in *2021 IEEE 48th Photovoltaic Specialists Conference (PVSC)*, 2021: IEEE, pp. 1014-1017.

[119] G. C. Eder, Y. Lin, Y. Voronko, and L. Spoljaric-Lukacic, "On-site identification of the material composition of PV modules with mobile spectroscopic devices," *Energies,* vol. 13, no. 8, p. 1903, 2020.

[120] K. Ali, A. A. Abdallah, M. Kivambe, J. H. Zaini, and M. M. Nauman, "Visual and IR Inspection Analysis of PV Modules Installed at the Desert Climate of Qatar," in *Defect and Diffusion Forum*, 2023, vol. 428: Trans Tech Publ, pp. 149-154.

[121] S. R. Joshua, S. Park, and K. Kwon, "Visual Diagnostics: Deep Learning with DenseNet121 for Identifying Faults in Solar Panels," in *2024 15th International Conference on Information and Communication Technology Convergence (ICTC)*, 2024: IEEE, pp. 1514-1519.

[122] F. Doğan, İ. Türkoğlu, "Comparison of deep learning models in terms of multiple object detection on satellite images," *Journal of Engineering Research,* vol. 10, no. 3, pp. 89-108, 2021.

[123] E. Kaplani, "PV cell and module degradation, detection and diagnostics," in *Renewable Energy in the Service of Mankind Vol II: Selected Topics from the World Renewable Energy Congress WREC 2014*, 2016: Springer, pp. 393-402.

[124] L. Cardinale-Villalobos, C. Meza, A. Méndez-Porras, and L. D. Murillo-Soto, "Quantitative comparison of infrared thermography, visual inspection, and electrical analysis techniques on photovoltaic modules: a case study," *Energies,* vol. 15, no. 5, p. 1841, 2022.

[125] L. Cardinale-Villalobos, R. Rimolo-Donadio, and C. Meza, "Solar panel failure detection by infrared UAS digital photogrammetry: a case study," *Int. J. Renew. Energy Res.(IJRER),* vol. 10, no. 3, pp. 1154-1164, 2020.

[126] C. E. Packard, J. H. Wohlgemuth, and S. R. Kurtz, "Development of a visual inspection data collection tool for evaluation of fielded PV module condition," National Renewable Energy Lab.(NREL), Golden, CO (United States), 2012.

[127] M. Chicca and G. TamizhMani, "Nondestructive techniques to determine degradation modes: Experimentation with 18 years old photovoltaic modules," in *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 2015: IEEE, pp. 1-5.

[128] S. Roy, S. K. Gupta, J. Prakash, G. Habib, K. Baudh, and M. Nasr, "Ecological and human health risk assessment of heavy metal contamination in road dust in the National Capital Territory (NCT) of Delhi, India," *Environmental Science and Pollution Research,* vol. 26, pp. 30413-30425, 2019.

[129] S. Prabhakaran, R. A. Uthra, and J. Preetharoselyn, "Deep Learning-Based Model for Defect Detection and Localization on Photovoltaic Panels," *Computer Systems Science & Engineering,* vol. 44, no. 3, 2023.

[130] A. Haeruman, S. U. Haq, M. Mohandes, S. Rehman, and S. S. I. Mitu, "AI-Based PV Panels Inspection using an Advanced YOLO Algorithm," *Materials Research Proceedings,* vol. 43.

[131] A. Barrett, D. Bratanov, N. Amarasingam, D. Sera, and F. Gonzalez, "Machine Learning Based Damage Detection in Photovoltaic Arrays Using UAV-Acquired Infrared and Visual Imagery," in *2024 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2024: IEEE, pp. 264-271.

[132] C. Buerhop-Lutz, O. Stroyuk, O. Mashkov, J. A. Hauch, and I. M. Peters, "Unveiling the Potential of Ultraviolet Fluorescence Imaging as a Versatile Inspection Tool: Insights from Extensive Photovoltaic Module Inspections in Multi-MWp Photovoltaic Power Stations," *Solar RRL,* vol. 8, no. 24, p. 2400566, 2024.

[133] R. Ebner, B. Kubicek, and G. Ujvari, "Non-destructive techniques for quality control of PV modules: Infrared thermography, electro-and photoluminescence imaging," in *IECON 2013-39th Annual Conference of the IEEE Industrial Electronics Society*, 2013: IEEE, pp. 8104-8109.

[134] R. Bhoopathy, O. Kunz, M. Juhl, T. Trupke, and Z. Hameiri, "Outdoor photoluminescence imaging of photovoltaic modules with sunlight excitation," *Progress in Photovoltaics: Research and Applications,* vol. 26, no. 1, pp. 69-73, 2018.

[135] B. Doll *et al.*, "Aerial photoluminescence imaging of photovoltaic modules," *physica status solidi*

(RRL)–Rapid Research Letters, vol. 17, no. 12, p. 2300059, 2023.

[136] B. Doll *et al.*, "Photoluminescence for defect detection on full-sized photovoltaic modules," *IEEE Journal of Photovoltaics,* vol. 11, no. 6, pp. 1419-1429, 2021.

[137] J. Zikulnig, W. Mühleisen, P. J. Bolt, M. Simor, and M. De Biasio, "Photoluminescence imaging for the in-line quality control of thin-film solar cells," in *Solar*, 2022, vol. 2, no. 1: MDPI, pp. 1-11.

[138] A. Redondo Plaza *et al.*, "Partial photoluminescence imaging for inspection of photovoltaic cells: Artificial LED excitation and sunlight excitation," *Energies,* vol. 16, no. 11, p. 4531, 2023.

[139] B. True, "Time resolved photoluminescence imaging systems and methods for photovoltaic cell inspection," ed: Google Patents, 2011.

[140] M. Dong, Y. Qian, H. Wang, and Y. Lang, "Photoluminescence detection method for silicon photovoltaic modules at high light level," *Optical Engineering,* vol. 62, no. 3, pp. 033102-033102, 2023.

[141] M. Abdelhamid, R. Singh, and M. Omar, "Review of microcrack detection techniques for silicon solar cells," *IEEE Journal of Photovoltaics,* vol. 4, no. 1, pp. 514-524, 2013.

[142] K. G. Bedrich, "Quantitative electroluminescence measurements of PV devices," Loughborough University, 2017.

[143] I. Polymeropoulos, S. Bezyrgiannidis, E. Vrochidou, and G. A. Papakostas, "Enhancing solar plant efficiency: A review of vision-based monitoring and fault detection techniques," *Technologies,* vol. 12, no. 10, p. 175, 2024.

[144] I. Høiaas, K. Grujic, A. G. Imenes, I. Burud, E. Olsen, and N. Belbachir, "Inspection and condition monitoring of large-scale photovoltaic power plants: A review of imaging technologies," *Renewable and Sustainable Energy Reviews,* vol. 161, p. 112353, 2022.

[145] A. Cardoso, D. Jurado-Rodríguez, A. López, M. I. Ramos, and J. M. Jurado, "Automated detection and tracking of photovoltaic modules from 3D remote sensing data," *Applied Energy,* vol. 367, p. 123242, 2024.

[146] X. Zhang *et al.*, "Inspection and classification system of photovoltaic module defects based on UAV and thermal imaging," in *2022 7th International Conference on Power and Renewable Energy (ICPRE)*, 2022: IEEE, pp. 905-909.

[147] N. Le, H. Vu, N. Porntipworawech, S. Waisayarat, and M. Doan, "Integration of Aerial Thermal Imaging and Deep Learning for Fault Detection in Photovoltaic Panels: A Study at Thinh Long Solar Power Plant," in *2024 International Conference on Smart Energy Systems and Technologies (SEST)*, 2024: IEEE, pp. 1-6.

[148] D. Rocha *et al.*, "Multidefect detection tool for large-scale PV plants: Segmentation and classification," *IEEE Journal of Photovoltaics,* vol. 13, no. 2, pp. 291-295, 2023.

[149] G. Terzoglou, M. Loufakis, P. Symeonidis, D. Ioannidis, and D. Tzovaras, "Employing deep learning framework for improving solar panel defects using drone imagery," in *2023 24th International Conference on Digital Signal Processing (DSP)*, 2023: IEEE, pp. 1-5.

[150] B. Urtasun *et al.*, "Pulsed thermography digital motion stabilization for the unmanned vehicle inspection of solar farms and gfrp wind blades through uavs and ugvs," in *Thermosense: Thermal Infrared Applications XLIII*, 2021, vol. 11743: SPIE, pp. 42-57.

[151] O. I. Olayiwola and F. Camara, "Challenges and opportunities for autonomous UAV inspection in solar photovoltaics," in *International Conference on Renewable Energy and Environment Engineering*, 2024: EDP Sciences, p. 01003.

[152] P. Kuznetsov *et al.*, "Method for the automated inspection of the surfaces of photovoltaic modules," *Sustainability,* vol. 14, no. 19, p. 11930, 2022.

[153] P. Moorthy *et al.*, "Aerial Intelligence for Precision Monitoring and Fault Identification in Large-Scale Solar Farms Using Advanced Drone Technology and Deep Learning Technique," in *2024 15th International Conference on Computing Communication and Networking Technologies (ICCCNT)*, 2024: IEEE, pp. 1-7.

[154] Ö. Baltacı, Z. Kıral, K. Dalkılınç, and O. Karaman, "Thermal image and inverter data analysis for fault detection and diagnosis of PV systems," *Applied Sciences,* vol. 14, no. 9, p. 3671, 2024.

[155] S. Gallardo-Saavedra, L. Hernádez-Callejo, and Ó. Duque-Pérez, "Analysis and characterization of PV module defects by thermographic inspection," *Revista Facultad de Ingeniería Universidad de Antioquia,* no. 93, pp. 92-104, 2019.

[156] W. Ahmed, M. U. Ali, M. P. Mahmud, K. A. K. Niazi, A. Zafar, and T. Kerekes, "A comparison and introduction of novel solar panel's fault diagnosis technique using deep-features shallow-classifier through infrared thermography," *Energies,* vol. 16, no. 3, p. 1043, 2023.

[157] F. H. K. Al-Zaabi, A. M. S. Al Washahi, R. K. M. Al-Maaini, and M. K. Boddu, "Advancing Solar PV Component Inspection: Early Defect Detection with UAV Based Thermal Imaging and Machine Learning," in *2023 Middle East and North Africa Solar Conference (MENA-SC)*, 2023: IEEE, pp. 1-3.

[158] D. Kim, J. Youn, and C. Kim, "Automatic fault recognition of photovoltaic modules based on statistical analysis of UAV thermography," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* vol. 42, pp. 179-182, 2017.

[159] A. El-Amiri, A. Saifi, A. Obbadi, Y. Errami, S. Sahnoun, and A. Elhassnaoui, "Defects detection in bi-facial photovoltaic modules PV using pulsed

thermography," in *2018 Renewable Energies, Power Systems & Green Inclusive Economy (REPS-GIE)*, 2018: IEEE, pp. 1-6.

[160] G. Acciani, G. Simione, and S. Vergura, "Thermographic analysis of photovoltaic panels," in *International Conference on Renewable Energies and Power Quality (ICREPQ'10)*, 2010, pp. 23-25.

[161] M. Dávila-Sacoto, L. Hernández-Callejo, V. Alonso-Gómez, S. Gallardo-Saavedra, and L. G. González, "Detecting hot spots in photovoltaic panels using low-cost thermal cameras," in *Ibero-American Congress of Smart Cities*, 2019: Springer, pp. 38-53.

[162] O. Menéndez, R. Guamán, M. Pérez, and F. Auat Cheein, "Photovoltaic modules diagnosis using artificial vision techniques for artifact minimization," *Energies,* vol. 11, no. 7, p. 1688, 2018.

[163] P. Guerriero, G. Cuozzo, and S. Daliento, "Health diagnostics of PV panels by means of single cell analysis of thermographic images," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, 2016: IEEE, pp. 1-6.

[164] L. Bommes, T. Pickel, C. Buerhop-Lutz, J. Hauch, C. Brabec, and I. M. Peters, "Computer vision tool for detection, mapping, and fault classification of photovoltaics modules in aerial IR videos," *Progress in Photovoltaics: Research and Applications,* vol. 29, no. 12, pp. 1236-1251, 2021.

[165] K. Nakagawa, A. Kaligambe, and G. Fujita, "Comparative Analysis of Defective Solar PV Module Inspection Using Thermal Infrared and Electroluminescence Imaging Techniques," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*, 2023: IEEE, pp. 98-102.

[166] T. Olšan, M. Libra, V. Poulek, B. Chalupa, and J. Sedláček, "Combination of three methods of photovoltaic panels damage evaluation," *Sci Agric Bohem,* vol. 48, no. 2, pp. 98-101, 2017.

[167] A. Eskandari, A. Nedaei, J. Milimonfared, and M. Aghaei, "A multilayer integrative approach for diagnosis, classification and severity detection of electrical faults in photovoltaic arrays," *Expert Systems with Applications,* vol. 252, p. 124111, 2024.

[168] M. Abdelsattar Mohamed Saeed, A. A. A. Rasslan, and A. Emad-Eldeen, "Comparative Analysis of Machine Learning Techniques for Fault Detection in Solar Panel Systems," *SVU-International Journal of Engineering Sciences and Applications,* vol. 5, no. 2, pp. 140-152, 2024.

[169] H. S. Muttashar and A. M. Shakir, "Enhancing PV Fault Detection Using Machine Learning: Insights from a Simulated PV System," 2024.

[170] A. Hadrawi, Y. S. Akil, and D. Utamidewi, "A Deep Autoencoder-Based Method for Detecting Mismatch Faults in Photovoltaic Modules," in *2024 International Conference on Electrical Engineering and Computer Science (ICECOS)*, 2024: IEEE, pp. 1-6.

[171] C. Li'na, B. Hui, R. Mengmeng, M. Fanlin, Z. Tian, and L. Jing, "Research on fault diagnosis of photovoltaic panels based on deep learning image recognition technology," in *International Conference on Computer Graphics, Artificial Intelligence, and Data Processing (ICCAID 2023)*, 2024, vol. 13105: SPIE, pp. 91-97.