"Survey of maintenance management for photovoltaic power systems"

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Survey of maintenance management for photovoltaic power systems

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Abstract:

The sustainability of the global energy production systems involves new renewable energies and the improvement of the existing ones. Photovoltaic industry is growing thanks to the development of new technologies that increase the performance of photovoltaic systems. These systems are commonly subject to harsh environmental conditions that decrease their energy production and efficiency. In addition, current photovoltaic technologies are more sophisticated, and the size of photovoltaics solar plants is growing. Under this framework, research on failures and degradation mechanisms, together with the improvement of maintenance management, becomes essential to increase the performance, efficiency, reliability, availability, safety, and profitability of these systems. To assess maintenance needs, this paper presents a double contribution: an exhaustive literature review and updated survey on maintenance of photovoltaic plants, and a novel analysis of the current state and a discussion of the future trends and challenges in this field. An analysis of the main faults and degradation mechanisms is done, including the causes, effects, and the main techniques to detect, prevent and mitigate them.

Keywords: Photovoltaics; renewable energy; maintenance; fault detection; fault prevention; solar power energy.

1. INTRODUCTION

The use of renewable energies has been rising in the last decade due to national and supranational government policies [1, 2], together with the location optimization of renewable power plants [3], where solar energy is one of the main renewable energies. The main solar power types are concentrated solar power (CSP) and photovoltaic (PV). CSP concentrates the solar energy to heat a transfer fluid to generate energy like a thermal plant [4, 5]. This technology presents four main configurations: Parabolic trough collector (PTC), solar power tower (SPT), linear Fresnel reflector (LFR) and parabolic dish systems (PDS). Other technologies, such as concentrated solar thermoelectric, are in development stage and are not economically feasible yet [6]. PV solar energy is based on the PV effect on semiconductor materials. Electricity is generated when sunlight incises on solar cells. This electricity can be directly used, stored or sent to the grid [7, 8]. Solar cells are mainly separated depending on their crystalline structure and materials, whereas PV systems are separated into stand-alone and grid-connected. The combination of solar cells, modules and arrays allows this technology to be used in small scale devices, such as calculators, or in large power plants, making PV one of the most flexible energy generation technologies.

PV solar energy generated 385 GWp in 2017, compared to 2008, when it was only 14 GWp [9]. Figure 1 shows the solar PV generation capacity over the last 10 years [10]. There is an exponential growth on the last years, being China, US and Germany the main investors. CSP has also increased its capacity to more than 3000 MW [11], but it still is less than 1% of the energy generated by PV [12].

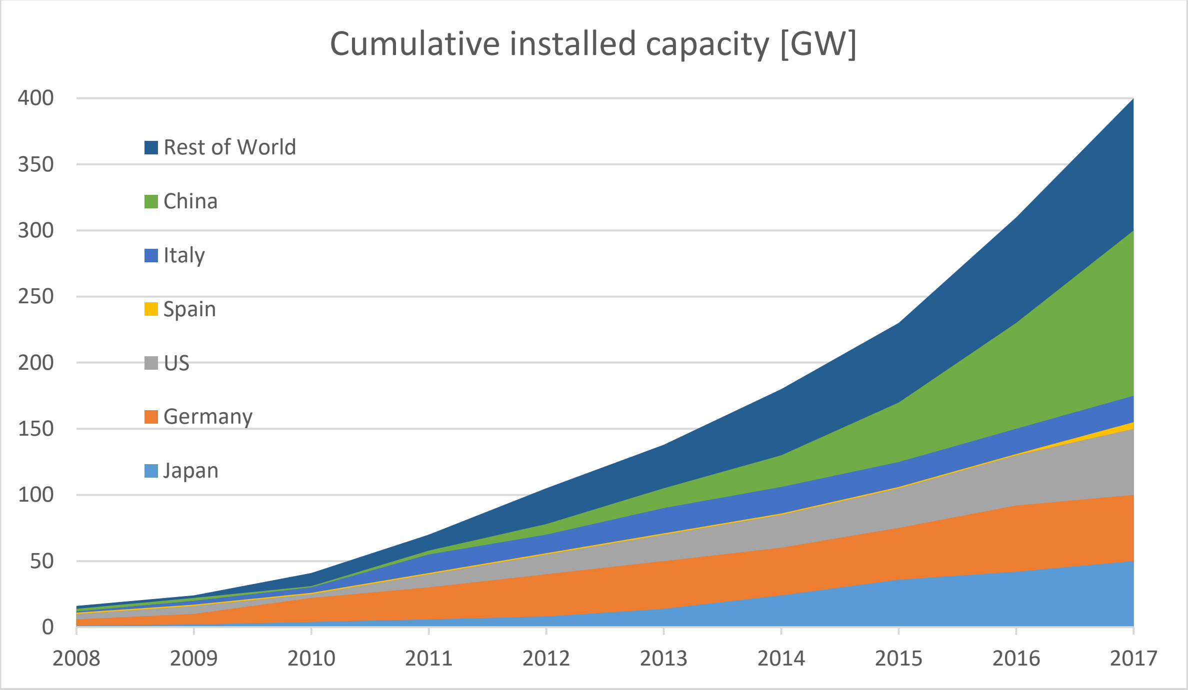

Figure 1. Evolution of PV energy generation in the last years. Figure adapted from [10].

The PV industry needs of novel and advanced technologies, together with robust approaches for advanced analytics to support the decision makers [13, 14]. New technologies will lead to reach the competitiveness in this sector, together with better efficiency, sustainability and maintenance policies [13, 15, 16]. Valuable research has been conducted to review aspects of PV technology, but it is limited to aspects such as the operation and maintenance issues, the effects of degradation mechanisms, or the development in different countries. Most of these reviews only discuss the advantages and disadvantages of the approaches without enough detailing of the procedures and structures of the methods. To expand the research, this paper first focuses on the main degradation mechanisms affecting PV technology, considering their causes and consequences; and then complements it with the most recent research dedicated to their detection, prevention, and mitigation. The topics and field of study covered by each publication are summarized in the corresponding tables. The main contributions of this paper to the current research are:

- This paper explains the principal faults in PV technology, and the main causes and consequences on the affected parts of PV modules. Similar publications on this field are [17], on the challenges faced for the operation and maintenance of PV systems, considering their inspection and different failure modes; or [18, 19] on the development of PV energy in India and England, respectively. Other reviews focus on one type of defects, such as Costa et al. [20] on soiling research and development; Reese et al. [21], on protocols to measure corrosion and degradation caused by outdoor exposure; Pawluk et al. [22], on the influence factors of snow power losses; Hamdi et al. [23], on the effects of humidity; or Kumar and Kumar [24], who made general review of PV technology and its failure modes. This paper analyses the most important defects affecting PV energy and their influence on the affected components.
- The most important issues related to failure prevention and mitigation techniques on PV are presented. Other reviews are focused on monitoring and fault detection systems [25]; the application of thermography for solar fields monitoring [26]; or the use of self-cleaning coatings on PV panels to prevent dust deposition [27]. Most literature in this field is focused on a specific technique, but this paper covers the most relevant literature about failure prevention and mitigation from a general perspective.
- This paper summarizes the most relevant publications analysed through two informative tables (Tables II and IV), where all the references can be consulted at a glance. These tables are organised attending to the main topic, degradation mechanism, type of study, experimental location, and the corresponding reference. These tables can be a useful index for readers to look for specific information.
- Each section contains not only a collection of relevant papers but also a brief discussion of the current state of the art. Moreover, after presenting the state of the art, quantitative and qualitative analyses of the main requirements and improvement in this field are done. The main trends and future challenges are gathered from these analyses.

This paper is the product of several European research projects (NIMO (FP7-ENERGY-2008-TREN1:239462) [28], OPTIMUS (FP7-ENERGY-2012-2-322430) [29] and INTERSOLAR (Fp7-sme-2013-605028) [30]) in the context of maintenance of renewable energy systems. In this framework, companies of the photovoltaic sector have manifested the benefits derived from a correct maintenance management and the necessity for the identification of the best practises within the photovoltaic maintenance field. The methodology followed in this work is aligned with the procedures followed during the mentioned projects, which is based on three fundamental stages:

- First, *seeking information*. This paper is the result of an exhaustive and deep searching of literature, mainly scientific papers. This literature has been found through the most important scientific databases (SCOPUS, Web of Science, IEEE Xplore, ScienceDirect, etc.). The research works are carefully summarized. The relevance of these works is also analyzed by considering some indicators such as the number of cites of the paper or the prestige of the journal according to the rankings.
- Second, *the classification of literature*. The selected papers are ordered and classified following a coherent structure. A contribution of this study is that it does not focus only on maintenance activities, but also describes the possible faults (causes and effects) that may occur. Therefore, this paper presents an operative perspective when describing the main maintenance techniques,

but also a purely experimental perspective when describing the faults and degradation mechanisms.

- Third, *the analysis and discussion of the state of the art*. This stage is one of the most important contributions of this paper since new knowledge is generated. By using metadata (such as topic, date of publication, cites, etc.) of the research works, a quantitative analysis is done to obtain statistical information of the current state of maintenance in PV solar plants. Moreover, due to the numerous papers studied in the previous stages, a qualitative analysis of the state of the art is carried out. Both qualitative and quantitative analysis allow to extract important conclusions, to discover trends and to identify weaknesses in this topic. This new information is essential for the identification of challenges and future research lines.

As the result of the described methodology, the paper is structured as follows: Section 2 explains the fundaments of the PV technology, systems and materials; Section 3 shows the main degradation mechanisms affecting PV technology, the publications about them and the main conclusions extracted from them. Section 4 summarizes the main research studies about prevention and mitigation of failures in PV technology. Section 5 presents the discussion of the state of the art analysis and summarizes the main references. Finally, Section 6 shows the conclusions and future challenges.

2. PHOTOVOLTAIC TECHNOLOGY

The basic unit in a PV solar power plant is the solar or PV cell. It is a device that generates electricity from the PV effect (movement of electrons in certain materials when irradiated by electromagnetic radiation), produced in a PN junction [31]. In this component, see Figure 2, electrons are able to move to the p-type part of the junction when the n-type part of the junction is irradiated with more energy than the band-gap energy of the material, creating a voltage and an electric current [31, 32].

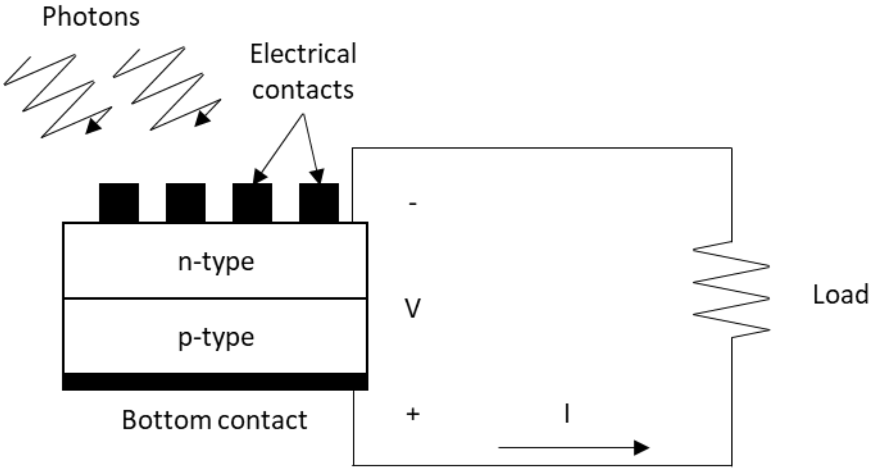

Figure 2. Schematics of a PN junction and its energy generation. Figure adapted from [31].

Solar cells are usually connected in series, parallel or combined forming a PV module to produce enough voltage and power. The PV array is a structure consisting of PV modules. Its power generation ranges from hundreds of watts to megawatts. The possibilities for connection are the same as for PV cells: series, parallel or combined. The following level are the PV power systems, qualitatively classified into stand-alone and grid connected (Figure 3). They can be also quantitatively classified according to their power generation capacity [31].

Stand-alone systems are the ones in which energy generation corresponds to the demand. They have been historically useful in installations where it is not common to connect demand with the main grid, e.g. rural houses. It can be used in small electronic devices, like calculators or watches. These systems can also be divided into with or without storage, and hybrid systems. The last ones combine generation of the PV solar panels with other system(s) when the power coming from the modules is not enough. These systems are usually supported, for example, by a wind turbine, a diesel generator or a cogeneration engine.

Grid-connected are large systems which provide energy and may be connected to the network via public grid or house grid. They are divided depending on their power range (Figure 3). There is some discussion on the boundaries of this classification, such as the consideration of hybrid as a type of PV systems on their own.

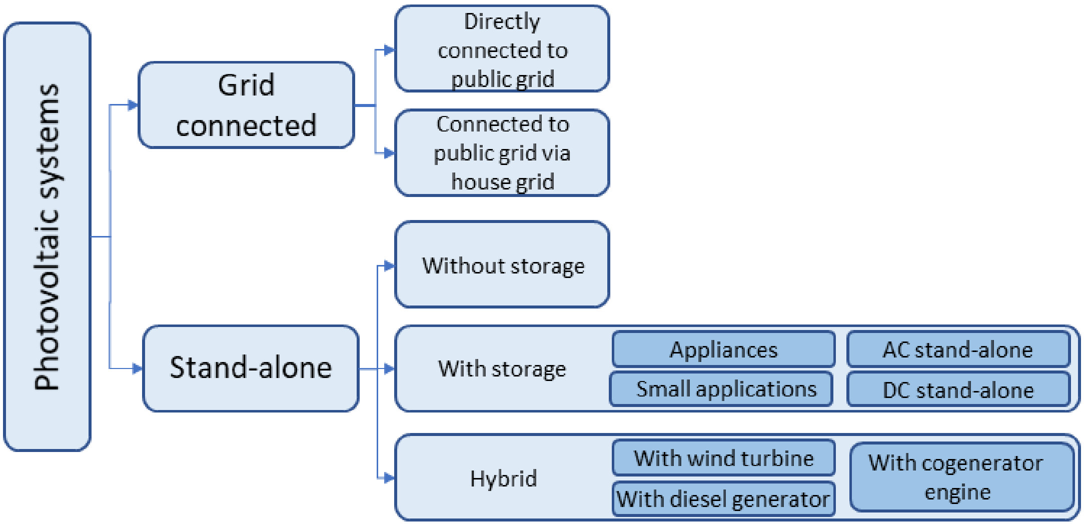

Figure 3. Classification of PV systems. Figure adapted from [31].

The PV materials must present several characteristics for its suitability, based on semiconductor properties [33], such as: band gap between 1.1 and 1.7 eV, readily available, non-toxic components, good PV conversion efficiency, manufacturing technique suitable for large productions and long-term stability. There is not complete agreement on the type of PV materials, but the two most common are crystalline and thin film, among other categories as organic or quantum dot materials [34, 35]. Some of the most relevant materials are:

- *Single-crystal silicon*: It has good stability and properties. The previous existence of silicon in electronics contributed to reduce its price. Its efficiency is the higher among silicon-based materials, 24.2%.
- *Poly-crystalline silicon*: Being cheaper than single-crystal, it is the most popular material for PV energy although its efficiency, 19.2%, is lower. This is compensated by its ease of assembly.
- *Amorphous silicon*: Its absorptivity is about 40 times greater than crystalline silicon. Its production process requires less energy, reducing its cost. However, it degrades under sun exposure and is highly defective, having the lowest efficiency of all silicon-based materials, 13.4%.
- *Gallium arsenide*: It has a high level of absorptivity and higher efficiency than silicon (28.8%), but it is considerably more expensive. It is used in concentrator systems and space applications.
- *Cadmium telluride*: It is one of the most promising thin film materials due to its lowest production cost among them. It has a high absorption coefficient and good efficiency (21.5%).

- *Copper indium diselenide*: It can achieve high energy conversion efficiency (21.5%) without suffering degradation. Some drawbacks are its difficult manufacturing and toxic gases created in the process.
- *Organic PV materials*: There is a high variety of materials where flexibility and colour are important, separated into sublimed small-molecule and solution processed polymer/fullerene solar cells. However, their efficiency is relatively low (11.5%), and are highly prone to degradation and corrosion.
- *Quantum dot*: These cells are made with synthesized, low-temperature solution processing, and their band gap is adjustable by composition and size. They have large voltage and current losses, and a distribution of quantum dot sizes resulting in distribution of band gap energies. Their efficiency is the lowest of all materials (9.9%).

To summarize, PVs is a well understood and largely studied technology, based on the PV effect that appears on a wide variety of materials. It has a large range of applications as a consequence of its scalability, from calculators to power plants. However, it is subjected to harsh environmental conditions in industrial applications that are likely to cause failures on the modules.

3. FAULTS AND DEGRADATION MECHANISMS IN PHOTOVOLTAICS

The performance of PV modules is conditioned mainly by two factors: the light received by the modules and the condition of cells and connections. Regarding the light received, the most important faults are soiling, shading and snow deposition. The condition of cells and connections are due principally by degradation, delamination hot spots, or cracks.

3.1. Soiling

Soiling is the deposition of dust, dirt, pollen and/or other elements on the surface of the PV modules. It is one of the most relevant aspects to be considered in solar energy, especially in desertic areas close to the equator. In consequence, research works focus more on dust than other depositions. Its effects are generally short term and temporary, since soiling is usually a reversible fault. Ilse et al. [36] explain the basis of soiling and condition the key parameters of dust: concentration, composition, size distribution, accumulation and removal, and environmental parameters. The causes of dust accumulation are divided into three groups [37]: environment factors (wind, temperature, humidity or pollution); dust nature (sand, clay, bacteria or carbon), and installation characteristics (material, orientation, location, type of area…).

Dust characterization and its effects depend on the location of the installation. John et al. [38] developed artificial soiling tests in laboratory to compare the composition and the effects of dust from locations in Mumbai and Jodhpur (India). Samples from those sites showed strong variations both in size and composition. For instance, the authors observed greater losses in samples from Mumbai (18% of losses with 5 g/m^2 of dust) than from Jodhpur (10% of losses with 5 g/m^2). Rao et al. [39] compared a clean panel with a dusty panel for laboratory and outdoor locations. They observed that, under similar conditions, the dusty panel had not remarkable losses in open circuit voltage compared to the clean one, but they found power losses ranging between 45-55% in the indoor tests and 6-8% in the outdoor tests. Javed et al. [40] made a comparison between dusts from different desertic places from all over the world. Other works about dust characterization have been developed by Javed et al. [41], Zitouni et al. [42] and Burton et al. [43].

Power losses due to soiling have been measured in laboratory (controlled irradiation and soiling rate conditions) and outdoor conditions, whose results depend on the materials and dust deposition. For indoor conditions, Burton and King [44] observed linear changes on losses up to 20% with 2 g/m^2 of dust on glass covers. For outdoor conditions, Saidan et al [45] obtained power losses greater than 18% for one month in Iraq; García et al [46] observed yearly losses averaging 11.9% on horizontal surfaces; Mejia et al. [47] determined losses up to 7.2% in dry periods in California; Caron and Litmann [48] measured peaks of more than 11% of losses in California. Finally, Kimber et al [49] observed a decreasing trend in the daily efficiency of 0.2% in dry climates, meaning between 1.5-6.2% yearly, depending on plant location; Gostein et al. [50] observed soiling rates ranging between 0.5% to 5% per month; and Pedersen et al. [51] defined a transmittance loss rate of 0.1% per 10 mg/m^2 approximately.

In summary, soiling is a phenomenon that affects mostly PV installations mainly in desert locations. Most of the publications focus on dust characterization than on power losses. Different studies have determined large variations between indoor and outdoor tests. Its effects are usually short term and easily mitigated by proper cleaning of the surface. This fault affects the installation intensity, but not the voltage.

3.2. Snow and ice deposition

Snow and ice are relevant in cold countries because the climate favours their apparition. Some of the main problems generated are total or partial obstruction of radiation, reduction of efficiency, cracking and delamination or mechanical loads. One advantage is the decrease of temperature of the modules [52], but there are drawbacks, e.g. light obstruction and moisture ingress on the modules. There is a large amount of research works related to its effects, or to prevent and mitigate this phenomenon. Usually, snow deposition is quantified through the power losses, image processing or temperature indicators [53].

Regarding power losses, Pawluk et al. [22] made a literature review on different climates and the influence factors, such as climate, adhesion and angle. They also review the most remarkable prediction and modelling techniques for short and long term; and mitigation methods, such as coatings and heating. Power losses are clearly seasonal, appearing only on cold months, as remarked by Heidari et al. [54]. They showed that snow deposition is only remarkable from October to April in USA, producing yearly energy losses of 30-35% on obstructed panels compared to 5-15% on unobstructed panels. Andrews et al. [55] designed a structure of solar panels with different tilt angles, and measured yearly the energy losses due to snow by using image processing. They observed a low influence of angle on losses, and few more losses in crystalline than in amorphous materials, ranging from 3% with an angle of 10° to 0.5% with 60°.

The effects of snow deposition have been modelled according to different parameters, e.g. air temperature, tilt angle, irradiance or material to improve operation and maintenance aspects. Marion et al. [56] used different sensors to measure snow losses and modelled a system to assess surveillance and maintenance of the modules. Powers et al. [57] considered temperatures, humidity and snowfall, among other parameters, to model losses and compare them on cleaned and covered modules, developing a model to predict snow deposition and losses for several years.

Image processing, heat transmission and fluid dynamics are used for modelling the snow sliding and melting, see for example the research works of Bogenrieder et al. [58] and Rahmatand et al. [59].

Finally, ice is produced in the same conditions as snow, but it has not been studied enough [60, 61]. Carriveau et al. [62] explain its effects on renewable energies in general, and commented the decrease of energy production because of high ice adhesion on PV panels. Pawluk et al. [63] explained the effects of ice adhesion and sliding on solar modules related to snow deposition and light irradiation.

In conclusion, snow deposition is a seasonal phenomenon happening on places with cold climates, that causes severe light obstruction, ice deposition and possible moisture ingress. It is modelled according to environmental and panel parameters and causes remarkable power losses on affected modules. Sliding and melting are modelled considering the influence of fluid dynamics and heat transmission, but they have not been studied enough. Studies related to ice are few and usually focus on sliding and melting rather than the losses produced.

3.3. Outdoor exposure: corrosion, delamination and degradation

Outdoor conditions and exposure to sunlight generate short and long-term consequences on PV modules, deeply related within themselves. Therefore, research usually explains their correlation and effects together. The main faults related to long term exposure are corrosion and delamination, due to moisture ingress and general degradation of the modules.

Corrosion affects more in organic PVs, but also modifies the crystalline and thin film modules characteristics. There are protocols to measure the influence of stability, influence of weather, temperature, etc. on this fault. Reese et al. [21] explained some of the main protocols, tests and requirements to measure corrosion and degradation on PV modules under different light, temperature and irradiation conditions. Regarding to the outdoor variables, Gevorgyan et al. [64] studied the stability of different modules after 10000 hours of testing in several countries. The modules were prepared and encapsulated to ensure their long-term stability.

Many studies on corrosion focus on the moisture effects. Park et al. [65] developed a method to calculate the accumulated degradation and performed accelerated tests to obtain the results. Osterwald et al. [66] studied electrochemical corrosion in thin-film modules using accelerated tests, varying the moisture of the testing chamber. Karl et al. [67] investigated lifetime of organic PV cells through comparison with calcium corrosion tests.

Delamination occurs due to the loss of adhesion between the encapsulant and the photosensible parts of the cells, see Figure 4. It facilitates the moisture and corrosion, leading to a performance reduction. It usually appears on metalized regions, as gridlines or bus bars. These defects are irreversible and contribute to the long-term degradation of the modules. There is a variety of methods to measure delamination and interface adhesion. Tracy et al. [68] developed a method consisting in the preparation of a standardized PV module and the subsequent measurement of the adhesion energy and chemical analysis. Jansen and Delahoy [69] evaluated the delamination in glass substrates applying an electrical current for up to 15 min and measuring the effects after the cooling of the sample. Tracy et al. [70] quantified the energy per surface required to separate two adhesive sheets, and proposed two different tests, for PV modules and for adhesive materials.

Terwilliger et al. [71] developed an extensive study of PV module packaging materials and their response to adhesion tests under different conditions. They measured the evolution of adhesion and moisture transport. The tests were made on a wide variety of samples ranked according to their performance on several aspects, such as adhesion, glass cleaning or shear strength. They concluded that: the approach provided better results than commercial products; combined packaging may allow moisture ingress but also egress of harmful substances; and the conditions of 85ºC and 85% moisture are too aggressive for testing, but 60ºC and 70% moisture are too mild. They also set that the ideal conditions for testing must be still determined.

The long term effects of delamination and discoloration are studied by Park et al. [72] on 25 year old modules in coastal environment, see Figure 4. The initial observations showed a decreasing of almost 18% of power generation, but no dielectric breakdowns on the modules. A visual test to detect the main defects was developed, discovering a clear deterioration in the modules, together with a decreasing of electrical properties in the defective cells and corrosion in the zones with metal contact of the cells. Discoloration is also studied by Sinha et al. [73], who classified its causes and used several non-destructive tests to identify its effects on long term exposed modules.

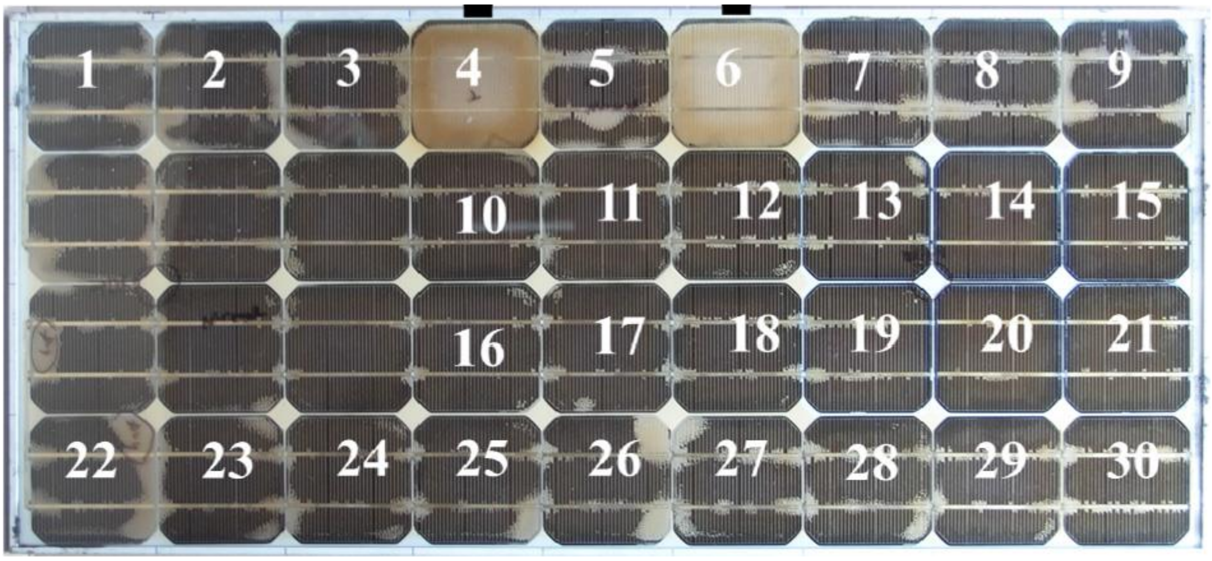

Figure 4. Degradation of a 25 year old PV module [72].

Van Dyk et al. [74] analysed the effects of the delamination and the moisture ingress in a PV module in South Africa. It is observed that physical degradation is clearly visible and varies with the distance to the frame, and this delamination allows moisture to penetrate. There was a decreasing of performance (more than 16%) and temperature variations within the different cells. The paper concludes that moisture regresses in hot and dry months, improving the performance.

Related to moisture ingress is the phenomenon named ‘snail trails’. It occurs when local areas of a PV cell react with moisture causing a chemical reaction with the silver, sulphur and phosphorus contained, study done by Meyer et al. [75]. This defect causes losses of electroluminescence, making it easy to be detected. According to Yang et al. [76], this phenomenon also causes performance losses, around 9%, but temperature does not increase in the affected cells.

Regarding general module degradation, research works are divided into cause definition and long term effects. Respect to the cause definition: Kounouhéwa et al. [77] summarized the different degradation causes, components affected and their effects; van Dyk et al. [78] investigated the electrical and physical degradation of the module under outdoor exposure,; and Bouraiou et al. [79], tested degradation, soiling, delamination or corrosion of exposed PV modules in Saharan environment. Regarding long term exposure, the most remarkable effects are permanent damage and power losses. For instance, the long term exposure was studied by Silvestre et al. [80] after 5 years in Madrid, Limmanee et al. [81], 4 years in Thailand and Chandel et al. [82], after 28 years in western India.

To conclude, the effects of outdoor exposure are irreversible and usually affect the long-term behaviour of the PV modules. Faults explained in this section are closely related, as corrosion and delamination are produced by moisture ingress and cause long-term degradation of the modules. Their effects are appreciable through the power profile and output of the modules.

3.4. Cracks

Cracks are considered breakages in the structure of PV modules. They are unpredictable, and the quantification of losses is complicated since their effects are unknown. Usually, the cracks are microscopic and, along the time, they grow and cause the apparition of larger ones [83]. The main crack types in a PV module are shown in Figure 5.

According to Köntges et al. [84], cracks appear both in the transport of the PV modules and in mechanical tests, due to vibrations and resonance modes of the modules. They compared the statistical distribution of cracks and observed a predominance of parallel and 45º oriented cracks, responsible of an approximated 70% of them. The results show a common distribution among modules from different manufacturers, concluding that mechanical loads during transport are the main cause of crack appearance and growth.

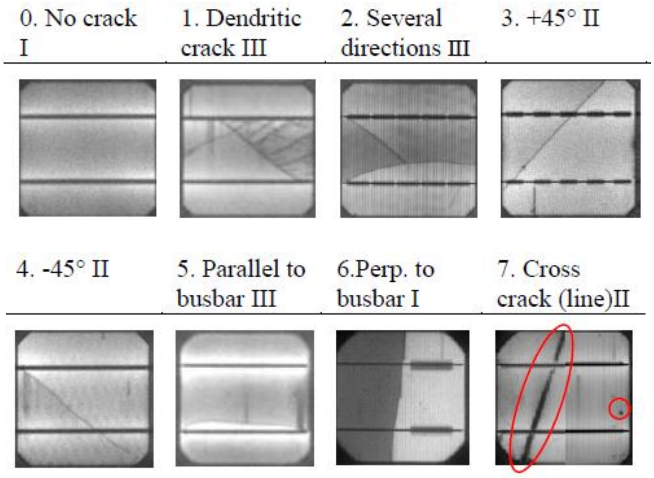

Figure 5. Crack classification for crack sorting [84].

Kajari-Schröder [85] studied crack distribution after mechanical load tests. They focused on the crack formation under homogeneous static mechanical loads, e.g. snow or wind. The electroluminescence was measured after the tests to determine crack distribution and orientation of the modules. Authors observed that 50% of cracks are parallel to the busbar, whereas diagonal, dendritic and several direction cracks are responsible of around 15% of the cracks. Kilikevičius et al. [86] studied the effects of dynamic loads, such as vibrations or wind, on the performance and crack apparition of PV modules. They achieved that the maximum fracture occurred at 16 Hz, with a maximum amplitude of 7mm at 20 Hz.

Käsewieter [87] studied a PV cell to measure the variation of electrical resistance under cyclic bending loads. On the first bending cycle, the creation of the crack was visible and audible, with a force drop and increase of the system resistance. The posterior cycles show an increment of the resistance, with less value at each time. Sander et al. [88] evaluated the electroluminescence of the modules with different loads to observe its evolution. They observe cracks before testing due to soldering or lamination in the manufacturing process. Both tests identified an exponential increment of the size and number of cracks during the experiments.

Image processing is also applied for crack detection by using different methods considering the electroluminescence of the PV cells. Dhimish et al. [89] developed a 3D model to examine micro cracks enhanced with logical gates. Song et al. [90] used an algorithm based on the named Gaussian pyramid and wavelet modulus. Other related studies were done by Dhimish et al. [91], analysing related size and direction of cracks to performance, and by van Mölken et al. [92], using electric modelling and electroluminescence measurements to study micro cracks and their effects.

In conclusion, cracks appear due mainly to mechanical loads, and their principal effects are changes in electroluminescence and power decreases. Most of literature focuses on crack distribution and properties evolution, usually taking advantage of the changes in the electroluminescence.

3.5. Hot spots

This fault consists in the increasing of temperature of PV solar cells due to, for example, partial shading of the solar module or deficient connections between cells, causing the energy dissipation in the form of heat instead of electricity [93, 94].

Moretón et al. [95] applied several methods to identify possible hot spots in two solar plants in the centre of Spain. They discovered cracks and bubbles in some cells by visual inspection, whilst thermography shown the actual location of hot spots (Figure 6). This study sets that the power losses of the whole module are a reliable source of information, but not the relation between temperature difference and PV cell power loss. Unmanned aerial vehicles (UAV) equipped with a thermal camera have been demonstrated to be a well-functioning technique [83], see, for example, the researchers done by de Oliveira et al. [96] on a solar farm, and Bharadwaj et al. [97] in a test site.

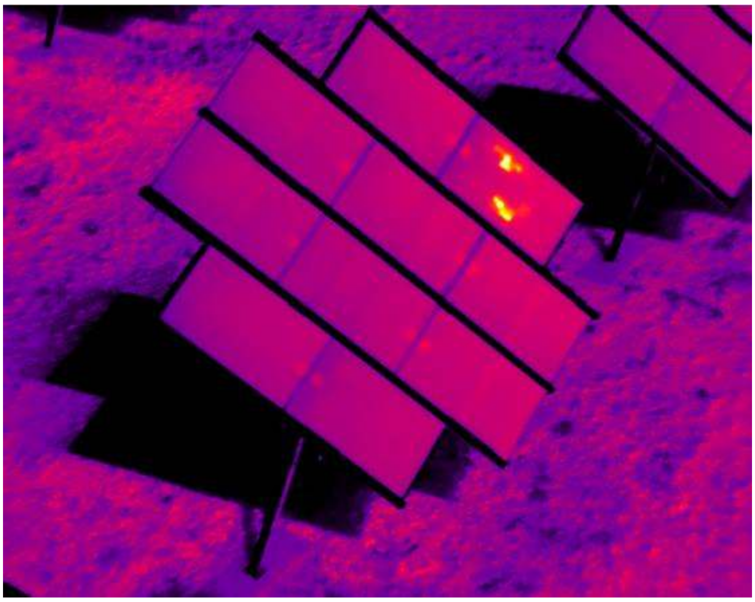

Figure 6. Hot spots in a PV module [95].

Simon and Meyer [98] made tests in darkness to identify the effect of impurities on the apparition of hot spots. Once the hot spots were identified, three areas were defined: hot spot centre, outside hot spot and non-hot spot. They were analysed by thermography and microscopy. The observations shown a direct correlation between areas of high impurity concentration and hot spot heating, as well as the components of these impurities: oxygen, carbon, iron and platinum. According to that, Ramspeck et al. [99] developed a setup oriented to process control of PV cells. The method consists in applying voltage to the cell and force it to work on reverse conditions, and then create a thermography of the cell, all in less than half a second. The process control compares reverse power and temperature, and it accepts or rejects the cells depending on their relation. This process allows the quality of the final product to be improved with a relative low investment.

There are many publications related to simulation and modelling of hot spots using different software. For instance, Deng et al. [100] designed a model to define heat dissipation under different shading conditions. Solheim et al. [101] modelled the thermal properties of a solar cell considering its several layers to calculate more precisely the thermal distribution. The simulation confirmed that the size of the hot spot is inversely proportional to the temperature on it. Rajput et al. [102] modelled hot spot behaviour and validated the results in outdoor conditions using a high speed thermocamera, PV modules with verified hot spots, and a meteorological station to measure environmental conditions. They discovered that wind speed reduces significantly the temperature of hot spots, similar behaviour of opaque and semi-transparent modules, and a negative correlation between the hot spot temperature and its quantity.

Other publications focus on electrical simulation and testing to analyse hot spots. Kim and Krein [103] developed an electrical model dependent on temperature, and Kim et al. [104] detect hot spots using several measurements based on electrical properties. Hot spots under shading conditions have been studied by Geisemeyer et al. [105] and Rossi et al. [106].

To summarize, hot spots are defects with different causes that produce a temperature increase and power losses on the affected cells and modules. The technique most used to detect them is thermography. This fault has been modelled electrically and by computer simulations.

It has been stated that the most relevant degradation mechanisms in PV energy depend on the light received and on the condition of cells and connectors. Regarding light received, short-term and reversible effects are caused by soiling and snow deposition, both producing light obstruction and power losses but with different causes. Long term effects appear under outdoor exposure and are mainly corrosion, delamination and degradation, which are irreversible and interrelated. Cracks and hot spots are the main fault mechanisms according to cells and connections. Preventive/Predictive maintenance tasks should be done to avoid and reduce the appearance and consequences of these faults.

4. FAILURE DETECTION, PREVENTION AND MITIGATION TECHNIQUES IN PHOTOVOLTAICS

The correct PV module condition may be compromised by the faults or failures, where preventive/predictive maintenance should be done correctly to avoid and minimize them. Nowadays, these maintenance tasks are mainly based on condition monitoring systems (CMS) [107, 108]. This section analysed CMS into three groups: failure detection, the act of identifying anomalies, defects or failures in systems; prevention, application of measurements and design changes of components and systems to avoid failures; and mitigation, application of measurements and design changes to minimize the effects.

4.1. Failure Detection techniques

This section is focused on the CMS and failure detection in PV installations, both individual PV panels and complete farms. New technologies and techniques are discussed, as well as the relevance of the I-V curves.

Triki-Lahiani et al. [25] made a review on monitoring and fault detection systems. They explained the different failure modes of PV modules and their effects and causes, showing some of the main parameters used to monitor and detect failures (irradiance, temperature, voltage and current, power, etc.). They also explained some of the different data analysis and processing techniques used, as circuit simulations, statistical analysis, artificial neural networks or predictive models. Another review is done by Packard et al. [109], who analysed the inspection of PV components and installations, and developed a standardized form to write down all the necessary information.

CMS can also be done remotely using online configurations [110]. Tina and Grasso [111] studied the effectivity of a stand-alone PV appliance and a remote CMS software capable of storing and plotting data from sensors (power, temperature, voltage, etc.), showing real time data and sending e-mail alerts about the appliance condition. Spataru et al. [112] used temperature and irradiance to show power output and made short-term predictions under different conditions, obtaining good sensitivity to deviations and capability to detect power losses above 5%.

Watson et al. [113] presented two techniques to continuous condition monitoring. These are a spectrophotometric analysis to record light absorption of the cell and corrosion progression for 24 h, and digital image acquisition during 100 h. The results differentiated between iron, zinc and aluminium, and molybdenum, tungsten and stainless steel, used for the coating. These results showed the accuracy of the methods to measure corrosion, and the different resistance to corrosion of the used metals. Pavan et al. [114] utilised two functioning PV plants to correlate soiling and power losses with a CMS consisting of: an acquisition board; a radiation sensor; two sensors per module for ambient temperature acquisition, and; a data logger and the server for the acquired dataset. The system analyses the predicted and measured power produced before and after cleaning the PV modules, showing an almost perfect correlation for their model.

Application of different approaches have been proven also effective. Touati et al. [115] used LabVIEW and sensors measuring ambient conditions and power output, sending them to an online platform and showing the evolution of power output and pattern recognitions before and after cleaning the modules. Other publications regarding PV monitoring using LabVIEW are done by Chouder et al. [116] and Rezk et al. [117], Fuentes et al. [118] using the open platform Arduino, and Shariff et al. [119], who made a brief literature review and used a Zigbee processing board for wireless online data acquisition.

Infrared testing and image processing are common inspection techniques in PV, there, many studies use these two techniques. Tsanakas et al. [26] reviewed the main aspects of online thermography of PV modules and the defects identified through this technology, together with the characterization of the intensity-voltage (I-V) curve of the modules. They explained publications of image processing to automatically identify and classify failures such as degradation, cracks, defective connections or shadowing. Other works related to the use of thermography and image processing have been presented by Gupta et al. [120], who compared the performance of high speed thermographic cameras to detect temperature variations on solar cells, Jaffery et al. [121], that use Fuzzy Logic systems to monitor and predict possible failures, and Buerhop et al. [122], studying the reliability of IR in an operating PV plant to identify different defects.

There are other techniques to detect failures: the six-layer detection algorithm, explained by Dhimish et al. [123], capable of detecting failures through the power output of the PV module; the parallel algorithm by Dhimis et al. [124], detecting different failures and shading effects using the power output of grid-connected modules; statistical approaches, such as the ones by Harrou et al. [125] and Garoudja et al. [126].

UAVs are also used for embedding CMS for PV panels, enabling to inspect large surfaces in short amounts of time [127, 128]. Herraiz et al. [129] presented a review on CMS for PV solar plants based on thermography. Quarter et al. [130] embedded digital and thermographic cameras to a UAV. They inspect panels and detect faults as cracks, hot spots or snail trails remotely. Grimmacia et al. [131] used a UAV to inspect both a rooftop installation and a PV plant in the north of Italy using also an embedded camera and a thermographic camera. Márquez and Ramirez [132] embedded a CMS for solar power plants inspections with radiometric and thermographic sensors.

The intensity-voltage (I-V) and power-voltage (P-V) curves are used to PV module condition analysis. I-V and P-V show the correlation between intensity or power output, respectively, and voltage output of a PV module, and are significantly affected by soiling, hot spots, partial shading or shunts. These curves are modelled by González-Longatt [133] considering parameters as temperature, power, voltage or current intensity. Some fault effects are explained by Schill et al. [134] taking into account different levels of soiling on the I-V curve. Moretón et al. [95], previously mentioned on section 3.5, employed them on hot spots detection, and Meyer and Van Dyk [135] used them to shunt resistance analysis.

To summarize, CMS is necessary to ensure proper functioning of PV modules and solar farms. Many tools and dedicated software are used with this purpose, aiming at a continuous inspection of the installations. Therefore, when faults are detected, actions can be done quickly. New technologies and automation, as the UAVs used for inspection, largely reduce the time needed and increase the efficiency of inspection tasks. I-V and P-V curves are powerful tools that can help to identify different faults and act in consequence. Nowadays, research works are required to efficiently inspect the massive surfaces of PV solar farms with the aim to increase their efficiency and life cycle.

4.2. Prevention Techniques

This section collects the main techniques used to prevent failures, such as coatings and surface modifications for dust and snow deposition, or fatigue analysis to study the statistical apparition of faults. The research is more focused on prevention than mitigation because most of the faults are irreversible.

Bahattab et al. [136] compared the performance of anti-soiling surfaces in laboratory and outdoor conditions for surface modifications, considered as the changes in the geometry of the module surface. They concluded that their laboratory tests can be reproduced in outdoor conditions, but the different dust natures make unlikely a direct transfer of results. Walwil et al. [137] modified several PV modules using glass texturing and coatings to compare their effects through their power output and temperature. They concluded that any modification supposes an increase of power output between 1-8% for texturing and 5-12% for coating. Other articles focused on surface modification are: Bhushan et al. [138], studying the cleaning efficiency of hydrophobic surfaces based on the lotus surface leaf; Nayshevsky and Lyons [139], analysing the behaviour of hydrophobic-hydrophilic surfaces under different moisture and configuration conditions; and Tucci et al. [140], focused on modelling electrostatic treatments on surfaces.

Regarding coatings and products applied to a surface not previously modified, Fathi et al. [141] compared the effectivity of a hydrophobic coating on solar panels with and without surface treatment. In the test, dust is added to a glass surface to compare how water is distributed over it. They measured lower temperatures and power losses on the treated modules, proving the beneficial effects of this treatment. Glaubitt and Löbmann [142] cover a sample surface using a coating with nanopores, and later subject to a dust exposure test. The results show a clear difference between coated and uncoated surface under different moisture and temperature experiments, where the transmittance losses in coated surface are less than 2%, while in uncoated glass surpass 7%. Figure 7 shows the differences between coated and uncoated surfaces after testing.

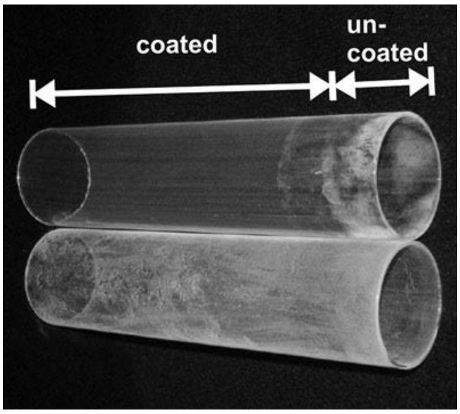

Figure 7. Coated and uncoated glass tubes after soiling testing [142].

The research regarding prevention of snow and ice deposition is focused on surface modifications and there are many reviews and classifications. Andersson et al. [143] classified four types of hydrophobic surfaces: structured, liquid infused, smooth and hybrid, and comment the research opportunities of them, as the effect of albedo or minimum angle for snow sliding. Jelle et al. [144] divided them into four groups: repellent, micro and nanostructured, superhydrophobic and icephobic. Fillion et al. [145] focus on icing prevention, reviewing the most relevant aspects to be considered when designing an icephobic coating, as ice nucleation, adhesion, condensation and durability. Other studies are: Jelle [146], explaining research opportunities for the future on snow and ice prevention; and Andrews et al. [147], studying the effectiveness of hydrodynamic surface coatings considering their optical and snow shedding effects.

Fatigue is also studied in order to prevent mechanical failure, e.g. how many mechanical cycles a module or connector can withstand before cracking or degrading. Paggi et al. [148] tested the effects of cyclic loads on crack apparition and electrical recovery, making measurements in the modules after a certain number of cycles. They observed that recovery decreases with the cycles and when measuring cracks. For ribbons, connector between cells, fatigue leading to misconnections may cause hot spots and temperature increases on the modules. Pander et al. [149] used a finite element model (FEM) simulation, a small PV module and copper ribbon to estimate its fatigue life. They studied the effects of displacement on connections between cells with a mechanical testing, and analysed them regarding the simulation results. Their results shown a good estimation for the simulation and the effectivity of fatigue testing for lifetime estimation. Other studies related to fatigue in ribbon connectors can be found in: Bosco et al. [150], comparing simulations and real tests on cell connectors; Wiese et al. [151], on microscopical effects of copper ribbons; and Meier et al. [152], considering the combined effects of temperature and mechanical loading.

In conclusion, prevention in PV energy is not as studied as CMS and fault detection. It focuses mainly on dust and snow prevention. Since most of the defects on PV solar modules are irreversible, like degradation, corrosion or cracks, research efforts focus on avoiding the apparition of these defects and modifying module surface before installing them to minimize power losses and faults on them. However, research is required on degradation prevention, finding new materials and improving isolation on modules to avoid moisture ingress and the apparition of cracks on the cells.

4.3. Mitigation Techniques

As most of faults are irreversible, research is more focused on prevention and detection than mitigation. The only reversible defects whose effects can be mitigated are dust and snow deposition. This section explains the approaches to minimize their effects, mostly cleaning the soiled modules or removing the snow and ice on them.

Regarding soiling, most of studies on mitigation are focused on cleaning methods or their classification. Alshehri et al. [153] distinguished and analysed manual and mechanized tools by hydraulic systems, robotic systems and deployable robotics. Jamil et al. [154] divided cleaning systems into labour, natural, water, mechanical and surface modifications.

The methods employed to mitigate soiling are also divided into water and dry based. Regarding water based, Moharram et al. [155] studied the influence of water and detergents on the performance of PV panels for a programmed routine, obtaining that the use of surfactants in a programmed schedule optimizes cleaning with a minimum use of water. Mazumder et al. [156] focused on high relative humidity locations and introduce techniques as coating modifications or active and automated water-cleaning methods. Dry cleaning was studied by Aly et al. [157], who propose a four-staged cleaning process: air spraying to remove coarse dust and particles; a polyurethane foam roller passing over the surface to clean dust and sand stuck; other spraying to eliminate possible dust rubbed, and; a electrostatically charged duster passes to remove very fine dust particles.

Other works on soiling cleaning and mitigation have been done by Li et al. [158], using the Kinect software to model the topology of the system to be cleaned, and Jones et al. [159], optimizing cleaning routines for PV plants in Saudi Arabia.

Regarding snow and ice mitigation, research is focused on heating panels to melt snow and ice. Weiss and Weiss [160] proposed a heating system on the bottom of the panels that causes avalanches and removes snow successfully after 15 minutes. Rahmatmand et al. developed two approaches on this topic: one focused on electrical heating [161], considering different inclinations with reverse current and a heater, this last one the more efficient, cleaning almost completely a panel after 20 min, and; other approach on the effects of circulating hot water under the panels [162], removing the snow after 16 min heating.

To summarize, research done on mitigation is not as extended as on prevention, since most of the defects are irreversible. The studies are focused on soiling and snow removal. Investigation on soiling is mainly done on cleaning under different methods, while research on snow and ice removal is based on heating the panels to melt and remove them. However, this supposes a challenge and opportunity for future research on this topic, both in the faults explained and the ones not mentioned.

5. DISCUSSION

On one hand, this paper analyses the main causes and effects of the main degradation mechanisms and, on the other hand, the principal detection, prevention and mitigation techniques applied. Table I summarises the main causes, effects and detection, together with the improvements, prevention or mitigation approaches.

Table I. Causes, effects and detection of main degradation mechanisms.

DEGRADATION MECHANISM	CAUSES	EFFECTS	DETECTION	IMPROVEMENTS, PREVENTION OR MITIGATION
Soiling	Dust and particle deposition	Light obstruction, power losses	Visual inspection, thermography, power output	Surface modifications, coatings
Snow and ice	Snow and ice deposition, low temperatures	Light obstruction, power losses, moisture ingress	Visual inspection, thermography, power output	Coatings, surface modifications
Outdoor exposure: corrosion, delamination and degradation	Outdoor exposure	Power losses, cell degradation,	Power output, visual inspection	Material engineering, module insulation
Cracks	Mechanical stress, bad handling	Power losses, hot spots, breakages	Electroluminescence, thermography, visual inspection	Material engineering, handling.
Hot spots	Mismatches, defective connections	Temperature increase, power losses	Power output, electroluminescence	Connection handling,
Fatigue	Use, outdoor exposure, mechanical stress	Cell degradation, power losses	Power output.	Connection handling,

Table II summarises the main degradation mechanisms, the type of study, the location and the main issue covered.

Table II. Degradation mechanisms in PV technology and studies related to them.

DEGRADATION MECHANISM	TYPE OF STUDY	STUDIES RELATED	LOCATION	TOPICS/KEYWORDS
Soiling	Causes and effects	[20]	Global	Literature review.
		[36]	Germany	Literature review, dust characterization.
		[37]	Global	Cause analysis, literature review.
		[38]	India	Dust characterization, gravimetric analysis, light absorption.
		[39]	India	Laboratory and outdoor, I-V curve.
		[40]	Qatar	Dust characterization, seasonal variations.
		[41]	Qatar	Dust characterization, cleanliness index
		[42]	Morocco	Dust characterization, monocrystalline silicon,
		[43]	USA	Artificial modelling, VT.
		[44]	USA	Artificial soiling, dust characterization, light absorption
		[45]	Jordan	Artificial soiling, I-V curve, dust characterization
		[46]	Spain	Optical losses, modelling
		[47]	USA	Conversion efficiency, effects of cleaning
		[48]	USA	Optical losses, different ambients.
		[49]	USA	Several ambients, outdoor exposure.
		[50]	USA, Arabia, Australia	Several stations, performance analysis.
		[51]	Norway, South Africa	VT, electrical measurements.
	Detection	[114]	Southern Italy	Economic impact of soiling, several stations, regression methods.
		[134]	Germany	I-V curve, partial shading.
	Prevention	[136]	Saudi Arabia	Different materials, dust characterization,
		[137]	Saudi Arabia	Texturing, coating, desert conditions.

		[138]	USA, Germany	Cleaning, hydrophobic surfaces
		[139]	USA	Hydrophobic surfaces, different configurations
		[140]	Italy	Modelling, Surface treatment, electrostatic treatment
		[141]	Germany	Hydrophobic coating, experimental testing.
		[142]	Germany	Sol-gel processing, porous coating, several materials.
	Mitigation	[140]	Italy	Dry cleaning, system modelling, influence of temperature.
		[153]	Saudi Arabia	Review, system description.
		[154]	Malaysia	Literature review, mitigation methods.
		[155]	Egypt	Desert ambient, several products, behaviour modelling.
		[156]	USA	Literature review, mitigation methods, high humidity.
		[157]	Saudi Arabia, Qatar	Dry cleaning, prototype, automated system.
		[158]	China, Italy	Kinect, 3D mapping.
		[159]	Saudi Arabia	Schedule optimization, several materials, cost analysis.
Snow and ice deposition	Causes and effects	[52]	Norway	Snow characterization, light obstruction.
		[53]	USA	Instrumentation, image processing, temperature
		[22]	Canada	Literature review, influence factors, mitigation.
		[54]	USA	Power losses, effect of angle.
		[55]	Canada, USA	Image recognition, power losses, different materials.
		[56]	USA	Image processing, modelling,
		[57]	Canada, USA	Power performance, snow characterization, image processing.
		[58]	Germany	Different materials, image processing.
		[59]	Canada	Snow sliding, modelling.
		[62]	International	Ice, renewable energy, mitigation, literature review.
		[63]	Canada	Ice adhesion, different materials.
	Prevention	[143]	Norway, Canada, USA	Snow repulsion, coating comparison.
		[144]	Norway	Surface modificaion, classification.
		[145]	Canada	Literature review, surface modification.
		[146]	Norway	Snow and ice, research opportunities, urban solar cells.
		[147]	Canada, USA	Surface coatings, snow.
		[163]	Norway, Canada, USA	Snow repulsion, coating comparison.
	Mitigation	[160]	Austria	Heating system, electrical modelling, thermography
		[161]	Canada	Heating system, different scenarios,
		[162]	Canada	Hot wáter heating system
Outdoor exposure: corrosion, delamination and degradation	Causes and effects	[21]	International	Protocol and tool establishment, organic, corrosion.
		[64]	International	Organic PV, laboratory, corrosion.
		[65]	South Korea	Accelerated tests, corrosion evolution.
		[66]	USA	Thin film modules, temperature dependence, water vapour, corrosion.
		[67]	Germany	Organic, EL, corrosion.
		[68]	USA	Adhesion, modelling, metrology.
		[69]	USA	Laboratory technique, procedure proposal.
		[70]	USA	Adhesion, delamination, modelling.
		[71]	USA	Packaging materials, water ingress.
		[72]	South Korea	Electrical characterization, outdoor conditions.
		[73]	India	Different NDT, cause identification, different modules.
		[74]	South Africa	Outdoor conditions, moisture ingress.
		[75]	Germany	Cause analysis, EL, laboratory testing, snail trails.
		[76]	China	Urban ambient, EL, thermography, snail trails
		[77]	Benin	Organic PV, literature review.
		[78]	South Africa	Thin-film module, outdoor exposure.
		[79]	Algeria	Degradation, soiling, delamination.
		[80]	Spain	Long term exposure, thin film, modelling.
		[81]	Thailand	Long term exposure, tropical ambient, comparison with other ambients.
		[82]	India	Long term exposure, tropical ambient, IR, VI.
	Detection	[113]	United Kingdom	Metal substrates, light measurement.
		[133]	Venezuela	I-V curve, Matlab modelling.
Cracks	Causes and effects	[84]	Germany	Classification, EL electrical characterization,
		[85]	Germany	Mechanical testing, FEM, EL.
		[86]	Lithuania	Dynamical loads, FEM.

		[87]	Germany, Spain	Electrical resistance measurement, mechanical testing.
		[88]	Germany	FEM, mechanical testing, several materials.
		[89]	United Kingdom, Algeria	3D modelling, microcracks.
		[90]	China	Wavelet, Gaussian pyramid.
		[91]	United Kingdom	EL, outdoor conditions, power output.
		[92]	Germany	Electrical modelling, thermography, EL.
	Detection	[26]	France, Germany	Literature review, image processing, classification.
Hot spots	Causes and effects	[95]	Spain	I-V curve, thermography, EL.
		[96]	Brazil	UAV, I-V curve, thermography.
		[97]	Sweden	I-V curve, polycrystalline silicon.
		[98]	South Africa	Inspection in darkness, laboratory, induced current.
		[99]	Germany	Process control, thermography.
		[100]	China	Simulation, impact of defects.
		[101]	Norway	FEM, different types.
		[102]	India	Modelling and validation, different materials.
		[103]	USA	Induced current, electrical and thermal modelling.
		[104]	USA	Detection, electrical modelling.
		[105]	Germany	Partial shading, induced current, simulation.
		[106]	Italy	Shading, thermal modelling,
	Detection	[130]	Italy	IR, UAV, remote monitoring.
		[131]	Italy	IR, UAV, remote monitoring.
Fatigue	Prevention	[148]	Italy	Mechanical and recovery testing, FEM analysis.
		[149]	Germany	Fatigue, numerical testing, connectors.
		[150]	USA, Japan	Mechanical testing, FEM simulations, several conditions.
		[151]	Germany	Different temperatures, microscopic analysis.
		[152]	Germany	Thermo-mechanical testing, system modelling.

Table III collects data about the ten countries with the largest PV energy production. The amount of publications has been approximated according to ScienceDirect. The variables that may be related to the PV energy production have been considered, such as population, the size of the country, the GDP or the average solar irradiation. The correlation between the PV energy production and each variable has been estimated through the Pearson´s correlation coefficient.

Table III. Degradation mechanisms in PV technology and studies related to them.

	PV energy production [GWh]	Publications	Population [164]	Area [Km^2][164]	GDP [billions of USD] [165]	Normal direct irradiation per year [kWh/m2] [166]	R&D expenditure [billions of USD][164]
China	176,1	32353	1,40E+09	9,60E+06	14216,503	1491	553,4
USA	62,6	29421	3,29E+08	9,16E+06	21344,667	1892	511,1
Japan	56	23366	1,26E+08	378000	5176,205	1112	165,7
Germany	45,4	26819	8,31E+07	357000	3963,88	900	118,8
India	32,9	17481	1,38E+09	3,29E+06	2971,996	1573	66,5
Italy	20,1	13177	6,05E+07	3,01E+05	2025,866	1582	27,4
UK	13	14987	6,66E+07	2,44E+05	2829,163	710	44,8
Australia	11,3	12024	2,52E+07	7,69E+06	1417,003	2759	23,3
France	9	16762	6,52E+07	6,44E+05	2761,633	1157	60
S. Korea	7,9	9484	5,18E+07	1,21E+05	1656,674	1301	91,6
Pearson´s correlation coefficient with PV energy production		0,82	0,68	0,69	0,66	0,00	0,85

Some conclusions can be extracted from this analysis. First, the correlation between the R&D expenditure and the PV energy is the highest correlation, even higher that the correlation with GPD or the size of the country. It leads to conclude that although the PV is a well-known technology, the investment in R&D is still necessary to improve the efficiency and the profitability of these systems. The amount of publications is also highly correlated with the PV production, being a direct consequence of the R&D expenditure.

A null correlation has been found between the average solar irradiation and the PV production. It could mislead the reader since the solar irradiation is a crucial factor for the PV production. This result reveals that the differences between the production of these countries is not due to their differences in the solar resource. In other words, regarding the ten most important PV producers, there are other influential factors, such as economic or political issues.

5.1. Discussion on degradation mechanisms

There are many different degradation mechanisms affecting PV technology, both cells and modules, in different aspects. Even though different materials and manufacturing processes are required to create PV cells and modules, all of them create a similar energy production system.

Soiling and snow deposition are important issues to be considered and, therefore, they are widely studied because PV modules require a large surface to harness energy. Moreover, snow deposition causes mechanical loads on PV panels that can generate cracks and moisture ingress, leading to corrosion and degradation, making it one of the most aggressive degradation mechanisms affecting PV energy, especially in cold countries. On the other hand, cracks, caused by mechanical loads, generate connection issues in the PV cells that may lead to hot spots and important power losses on the modules.

Corrosion seems to have a higher impact over organic PV materials. However, there are not many publications over this subject, therefore, it cannot be considered definite. The effect of the PV material type on potential failures is currently a gap in the literature. Moreover, the behaviour of degradation mechanisms concerning the type of PV material is also a field with little information.

Short-term appearing degradation mechanisms, as instantaneous cracks or monthly soiling and snow deposition, usually lead to long term ones, e.g. degradation and corrosion. This implies that research and prevention on the former ones is likely to reduce the effects and appearance of the latter ones. Therefore, research on environmental issues affecting PV modules, i.e. production and operation, methods that prevent mechanical loads on the PV panels must be addressed to increase their life service and profitability.

5.2. Discussion on detection, prevention and mitigation techniques

There are a large number of different technologies applied to detect, prevent and mitigate degradation mechanisms on PV energy. Most of them can be detected through CMS and non-destructive testing [127, 167]. The main references about CMS systems is collected in Table IV, considering also the techniques, the localisation and the content of the study.

Table IV. Failure detection, prevention and mitigation studies in PV technology.

Technique	Studies related	Location	Content
Condition Monitoring and failure detection	[25]	Tunisia	Literature review, modelling, several defects.
	[109]	USA	Inspection form, several locations.
	[111]	Italy	Online monitoring, data processing and acquisition.
	[112]	Denmark	Online monitoring, failure prediction.
	[115]	Qatar	LabVIEW, online monitoring, literature review.
	[116]	Spain	LabVIEW, data comparison and simulation.
	[117]	Saudi Arabia, Egypt	LabVIEW, data processing.
	[118]	Spain	Arduino, autonomous system, live monitoring.
	[119]	Malaysia	Literature review, Zigbee, online monitoring.
	[120]	Germany	High speed camera, image processing, IR.
	[121]	India	Fuzzy logic, machine learning, image processing.
	[122]	Germany	Image processing, I-V curve, thermography.
	[123, 124]	UK	Fault detection, P-V curve modelling.
	[125, 126]	Algeria, Saudi Arabia, Spain	Statistical detection, P-V curve modelling, different models.
	[135]	South Africa	I-V curve, shading, shunt resistance.

Thermography is one of the most relevant techniques, as many defects cause heat variations on the affected component. Its combination with UAVs and image processing made it a good approach for quick and automatic inspection of solar farms. I-V and P-V curves also provide information on the type and location of faults, and the application of data processing techniques allow to minimize maintenance time and costs.

Given the irreversible nature of most of failure mechanisms in PV, the research is more focused on prevention than mitigation, mainly on soiling and snow deposition. Most of the techniques are based on surface modifications and coatings, forcing a compromise between efficiency and failure avoidance. Fatigue, both thermal and mechanical, is one of the main factors leading to disconnections and electrical failures over time, that can be minimized but not avoided.

Regarding mitigation, research aims to solve problems associated with soiling and snow deposition, as these are the only reversible degradation mechanisms. Generally, automated or dry-cleaned routines are applied on the modules to minimize their effects.

In summary, detection, prevention and mitigation techniques are employed to ensure a proper work of PV modules. The references on prevention and mitigation have been usually focused on soiling and snow avoidance, but rarely considers other defects, leading to a knowledge gap on this field. The development of artificial intelligence and big data techniques can generate useful tools to maintain solar farms due the amount and variety of data. Therefore, research on this field is increasing.

5.3. Future challenges and trends

A quantitative analysis of the state of the art is presented in this section. This analysis shows the approximate amount of publications regarding degradation mechanisms in PV technology in Figure 8, and the proportion of publications on each defect in Figure 9. Data has been obtained by searching specific keywords in the main scientific databases (SCOPUS, Web of Science, IEEE Xplore, ScienceDirect), for instance "photovoltaic" plus the corresponding defect for each year. These data should be considered as an approximation of the values providing statistical information. A positive trend is observed for references focused on every defect, where references on the publications on corrosion and snow deposition are double. Corrosion is being, therefore, the most studied fault. Finally, publications on soiling have multiplied by 7 in the last ten years.

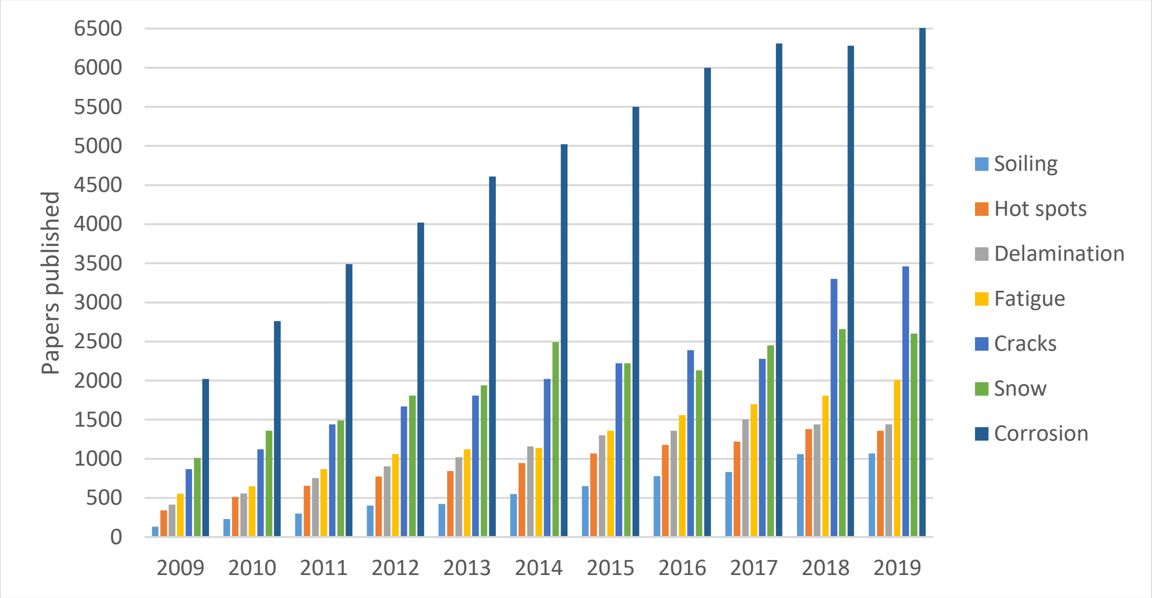

Figure 8. Publications related to defects in PV technology.

There have not been significant variations in the latest years according to the proportions of publications related to defects in PV technology. Corrosion by itself focuses almost 40% every year and, together with cracks and snow deposition, sum up to 70% of publications. Fatigue, delamination and hot spots are evenly distributed around 8%, and soiling has duplicated the proportion of publications since 2009 from 2.5% to 5.8%.

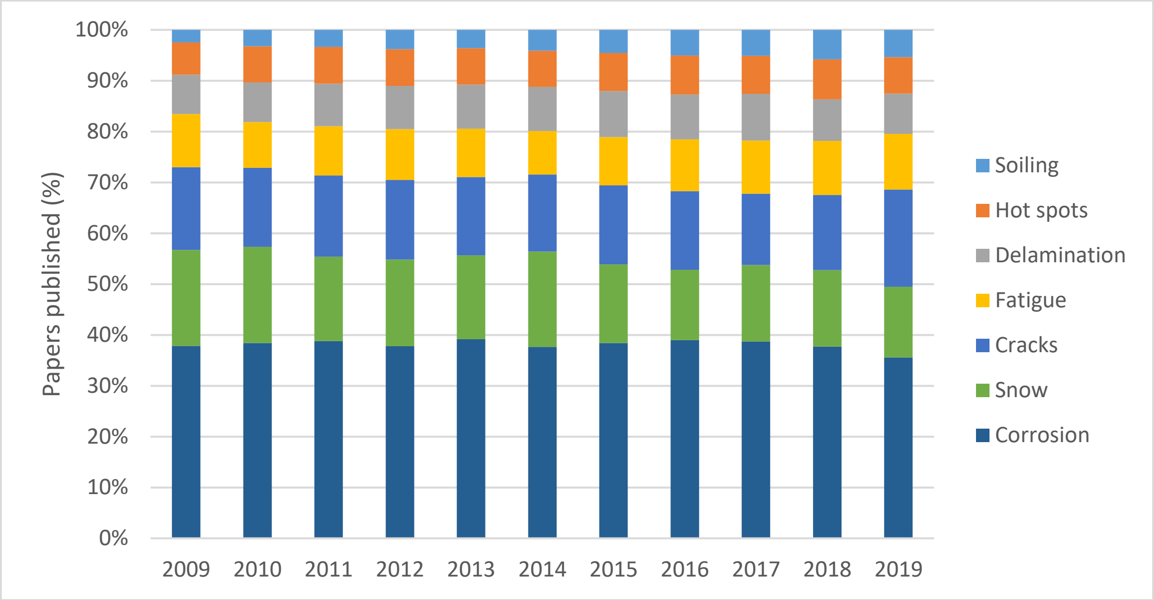

Figure 9. Proportion of publications related to defects in PV technology.

The following limitations and future challenges are extracted considering the quantitative analysis done:

- Most of research on PV degradation mechanisms focuses on corrosion, snow deposition and crack apparition. Other faults should be considered in the researches because there are not many publications focused on them. There is also a lack of information on how degradation mechanisms affect the different PV materials and technologies, considering both the likeliness and magnitude in which they may be affected.
- Though publications in soiling have increased considerably, their number is still much lower in respect to the other degradation mechanisms, and usually focused on dust characterization or prevention and mitigation. Research on short and long-term effects could be carried out to increase comprehension on this defect.
- Few publications have been found to study the consequences of the appearance of different degradation mechanisms on the same modules. A proper combination of these defects could be addressed to study the effects of this combination.
- Since development of PV technology has occurred in a relatively small period of time, there are few studies on the effects of long-term degradation of the modules or their treatment after service. Research on this topic is likely to increase as more solar modules reach the end of their life cycle, offering research opportunities on this field.

6. CONCLUSIONS

The paper has presented an overview of the main faults and degradation mechanisms associated to photovoltaic (PV) installations. Moreover, the principal techniques procedures employed to mitigate them have been analysed.

Although PV Technology can be employed in a wide range of systems due to its scalability, this paper focuses on the industrial field where the solar modules must enface environmental factors that cause degradations and defects. Soiling, snow deposition, corrosion or delamination, are the main phenomena caused by the weather conditions exposure of the PV modules. In addition, cracks or hot spots can also appear causing losses in the efficiency of the PV installation.

The references considered state that soiling usually affects to desert locations, and that it has a short-term effect that can be mitigated through proper maintenance actions. It has been detected that the number of studies published about soiling has doubled in the last ten years. Regarding the snow or ice deposition, a lack of studies has been detected in this field, being most of them oriented to prevent the ice, and very few to evaluate the losses produced by this phenomenon. Among the damaging agents due to weathering, corrosion is the most studied one (around 40% of all the publications about faults of photovoltaics). This fault type causes irreversible damages that affect severely to the power output of the PV modules.

Cracks are mentioned in more than 15% of the publications about PV defects. They can be caused by multiple agents, and most of the literature focuses on their detection, usually through electroluminescence variations. Other fault that can be generated by multiple causes are hotspots, which produce temperature gradients and important power losses. Thermography is a usually employed technique for its detection.

In order to ensure a correct state of the PV modules and solar farms, condition monitoring and detection techniques are employed. Novel technologies and approaches, such as unmanned aerial vehicles or artificial intelligence, lead to more efficient maintenance tasks and, subsequently, to a better performance of the installations.

Through the literature analysis, it has been detected that preventive maintenance in photovoltaic energy is less studied than condition monitoring or fault detection. The prevention activities are usually oriented to avoid the apparition of irreversible faults, e.g. corrosion or cracks.

Research on mitigation is not enough covered, since most of the faults of PV modules are irreversible, and their effects often cannot be attenuated. Methods and techniques for cleaning and dry the modules are usually the most studied topic. Therefore, the analysis of mitigation techniques on different faults can suppose a research opportunity.

This paper also presents a discussion of the actual context and trends of the research on PV energy. Regarding the main PV energy producers, a strong correlation between the amount of publications and the PV energy production has been detected, which is closely linked to the research and development expenditure. Moreover, it has been detected that the solar irradiation is not the factor that produces the main production inequalities between these countries.

Finally, some limitations and future challenges are identified, for example: a further explanation of the effects of degradation mechanisms over the different technologies and PV materials, such as the apparition of the named snail trails on organic materials; A survey on the economic and energy production losses associated to the apparition of the degradation mechanisms, and; The economic and energy production benefits of the detection, prevention and mitigation techniques applied to PV power production.

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