International Journal of Applied Power Engineering (IJAPE)
Vol. 13, No. 2, June 2024, pp. 483~498
ISSN: 2252-8792, DOI: 10.11591/ijape.v13.i2.pp483-498

Recent research and developments of degradation assessment and its diagnosis methods for solar PV plant: a review

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Article Info

Article history:

Received Jul 3, 2023
Revised Sep 6, 2023
Accepted Sep 16, 2023

Keywords:

Climatic regions
Degradation analysis
Performance of solar PV
Solar cell technologies
Solar photovoltaic
Solar PV power plants

ABSTRACT

The world is moving forward to a transition in the form of increasing the contribution of renewable energy sources in the energy sector, and among these, solar photovoltaic-based power generation is catching pace. Several factors are responsible for the lowering of outputs due to different degradation causes such as hotspots, corrosion, humidity, ultraviolet (UV) irradiation, temperature effects, dust, aging, weathering, yellowing, snail trails, discoloration, junction box failure, delamination, cracks, and faults from the solar photovoltaic (PV) plants. This paper presents a comprehensive review of the various form of degradation and their implications on solar PV power plant performance. The review has been carried out considering the different degradation causes and their identification methods in solar PV plant. Further, the analysis has been done on the basis of the earlier studies to understand the rates of degradation for various solar PV power plants in various climatic conditions. The PV technologies used in solar power plants are also responsible for the change in the performance of power plants over time; therefore, degradation based on different solar PV cell technologies is also analyzed. The visual inspection tools like thermal imaging with IR cameras help identify areas with abnormal heat patterns, indicating potential issues like cell or interconnect failures, loose electrical connections, or bypass diode malfunctions while EL cameras are used to identify low-level electrical excitation and defects such as cracks, hotspots, and cell-level degradation.

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1. INTRODUCTION

The energy is the basic need for people worldwide to ease the work and improving the living comfort. In India, approximately 65% of electrical energy is produced by the thermal power plants which used the fossil fuel and similar figure is observed globally [1]. The whole of world is going to increase the harnessing of renewable energy sources like solar, wind, biomass, ocean thermal, and ocean waves. The solar is most prominent source at present because of the matured PV system technology [2].

India has approximately 748 GW potential of solar energy. The target of solar power generation during 2022 has been achieved by 50 GW PV power generations, and it is possible due to the national solar mission program launched by the government of India [3]. With more solar photovoltaic (PV) systems being installed, it's more important to maintain the installed system's performance in order to achieve the maximum efficiency. Various failures and degradation have been found in installed solar PV systems such as hotspots, cracking cells, encapsulation degradation like yellowing, browning, delaminating, and discoloration [4].

Karthikeyan *et al*. [5] presented the main causes of degradation in which one of important is the moisture. It was observed that the moisture in glass entered due to low-quality polymer-based ethylene-vinyl acetate (EVA) and loss of adhesion of the encapsulation module. It was suggested to use high-quality EVA material that must be undergone through rigorous testing to meet industry standards. Additionally, manufacturers can use moisture-resistant back sheet materials and apply effective sealing techniques to prevent moisture penetration.

Various degradation has been found in the solar PV plant, and such defects mostly depend on the PV module's technology and climate conditions [6], [7]. It's worth noting that many of these causes are interrelated, and a combination of factors can contribute to the degradation of solar panels over time. Regular maintenance and inspection can help to identify and address any issues before they become serious problems These defects include hotspots, snail trails, corrosion frame adhesive degradation, potential induced degradation, EVA discolouration, encapsulation delamination, soiling loss, micro-cracks in cells, and light-induced degradation are commonly found and contribute to decreasing the performance of solar PV plants. The visual inspection method is widely used to find these defects in solar PV plants.The cities located in the northern region produce less electricity than those in the southern region, in particular [8]-[10]

Encapsulation delamination can occur when the materials used to encapsulate the solar cells in a module break down or separate over time. This can lead to reduced performance and even failure of the module. Encapsulant darkening and an anti-reflective layer both contribute to a lower short circuit current in a PV module. Hotspots can't be determined by an infrared camera [11]. Solar panels are exposed to temperature variations throughout the day, and this can cause the materials in the panels to expand and contract, leading to microcracks in the cells and modules. Cracks and hotspots can be found by the EL camera [12]. The implementation of Boltzmann annealing and a logarithmic temperature progression method determines the maximum cell temperature. Furthermore, quick annealing and logarithmic temperature updates show the maximum band gap. The quick annealing and linear temperature upgrade technique, on the other hand, improves the material band gap by about 96.7% [13]. Solar panels are designed to withstand exposure to UV radiation, but over time, this can cause the protective coatings on the panels to degrade, leading to reduced efficiency and power output. Humidity can lead to the corrosion of the metal parts in a solar panel, particularly if the panel has been installed in a humid climate. Climate variables such as temperature, UV radiation, and humidity increased the variation in degradation rate in the PV module [14]. Due to high temperature, the hot climate region has higher defects such as encapsulant discolouration and metallization corrosion [15].

EVA is a polymer used to encapsulate solar cells in some modules. Over time, exposure to sunlight and other environmental factors can cause the EVA to discolor and degrade, reducing the module's performance. Dust on the PV module in a hot and humid climate causes optical degradation such as encapsulation discolouration and delamination, which reduces the short circuit current [16], [17]. In a desert climate, temperature, ultraviolet radiation, and humidity lead to snail trails, burn marks, cracking, and bubbles in the PV module [18], [19]. Corrosion is the most damaging agent due to weathering factors such as moisture ingression, humidity, high temperatures in a hot climate, and a hot and humid climate. It contributes to the PV module's series resistance being at the forefront [20], [21]. Accelerated stress tests, such as thermal cycling, damp heat, and UV light exposure, can detect potential induced degradation. The potential-induced degradation (PID) effect in the PV module is caused by a high impedance, humidity, and UV radiation [22]. The simulation of solar PV systems using PV SYST software resulted in a 2.5% light-induced degradation (LID) per year due to optical degradation and high UV exposure [23]. The suggested study [24] uses an artificial neural network (ANN) approach to determine the outcome of PV under partial shadowing environmental conditions, as well as the maximum PV output system, and analyzes the PV system performance when based on different irradiance levels.

The current research study provides a complete overview of various types of degradation and their consequence on solar PV plant performance. It is also presented the previous studies to better understand the degradation rate for various solar PV systems with climate conditions. The study is required for the case of India because the climate conditions are not similar in all regions of India. The article is also showing the various PV technologies and the degradation rate of their performance according the time, seasonal variation, high heating effect and other related parameters. The study can be used by the manufacturers, LCA analyst, and other bigger consumers of PV power plants.

2. PHOTOVOLTAIC MODULE TECHNOLOGIES

The photovoltaic technologies have been developed time to time and the dependence of it only the advancement of materials and the efficiency of the cell. The Figure 1 shows the various solar photovoltaic (PV) technologies globally available. The mono-crystalline, polycrystalline, and gallium arsenide solar cells made of crystalline silicon, whereas amorphous, cadmium indium selenium, copper indium gallium selenium is made of non-crystalline silicon PV technologies that have lower efficiency than crystalline silicon solar cells. Another PV technology is polymer-based solar cells consisting of organic and dye-sensitized solar cells. These are subcategorized in to four major groups such as: crystalline solar cell, thin film solar cell, organic and dye sensitized solar cells and future cell technologies (like bifacial solar cells, floating solar cells, building integrated solar cells).

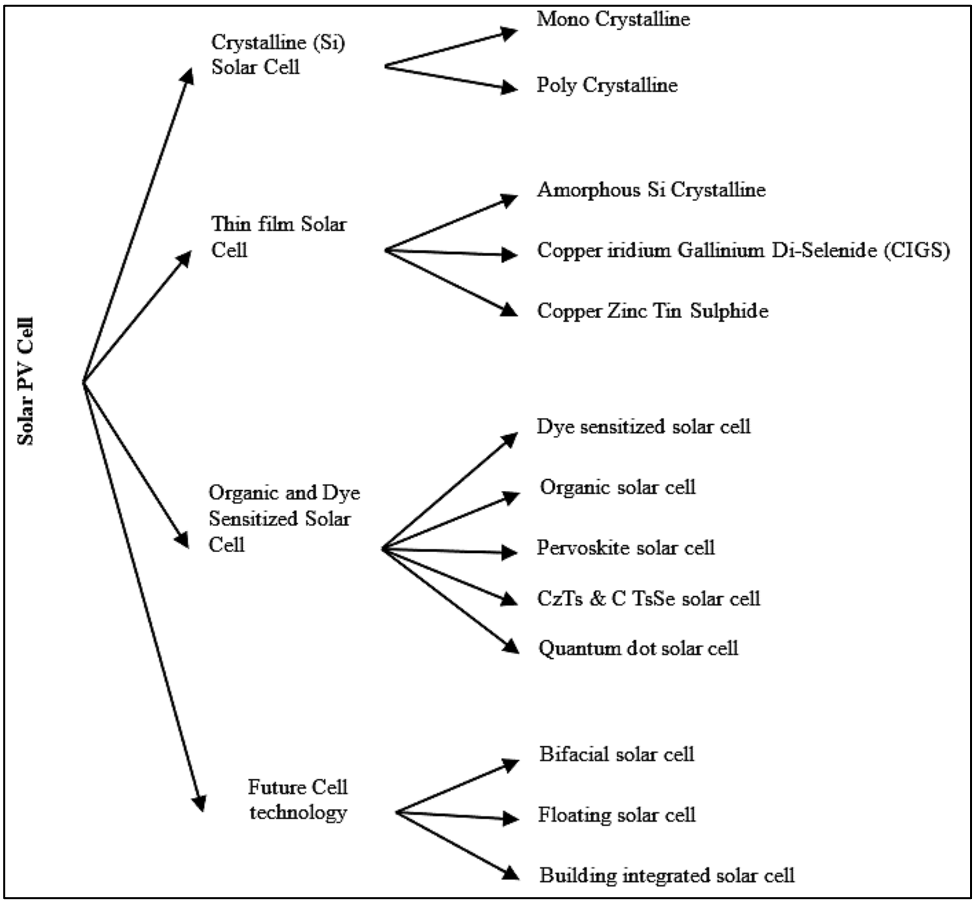

Figure 1. Types of solar PV technologies

3. DEFECT IN PV CELL AND CAUSES OF DEGRADATION

3.1. Various types of degradation defects in PV cell module

A number of methodologies have been used to detect and assess the various degradation effects in solar PV cells. The review considers multiple causes of degradation, such as hotspots, corrosion, humidity, UV irradiation, temperature effects, dust, aging, weathering, yellowing, snail trails, discolouration, junction box failure, delamination, cracks, and faults which are shown in Figure 2. The degradation types is based on previous studies that have looked at degradation rates for solar PV power plants in different climate and other causes. The review also takes into account the impact of different PV technologies on the performance of solar power plants over time.

The causes of the various degradations mentioned are varied and complex, and often involve multiple factors. Here are some brief explanations of some of the most common causes of each type of degradation.

- Hotspots: hotspots can be caused by shading, cell defects, or poor electrical connections. When a solar cell is shaded or has a defect, it can become a "hotspot" where the current flowing through the cell is much higher than in the surrounding cells. This can lead to overheating and damage to the cell or module.
- Snail trails: snail trails are caused by a combination of moisture and electrically conductive contaminants on the surface of solar cells. These contaminants can come from the manufacturing process or from the environment, and can cause corrosion and other types of damage to the cells.
- Corrosion: corrosion can occur when moisture or other environmental factors cause the metal contacts in a solar cell or module to oxidize. This can lead to reduced performance and even failure of the module

- Frame adhesive degradation: Frame adhesive degradation can occur when the adhesive used to bond the glass, cells, and frame of a solar module breaks down over time. This can lead to delamination and other types of damage.
- EVA discoloration: EVA is a polymer used to encapsulate solar cells in some modules. Over time, exposure to sunlight and other environmental factors can cause the EVA to discolor and degrade, reducing the module's performance.
- Encapsulation delamination: encapsulation delamination can occur when the materials used to encapsulate the solar cells in a module break down or separate over time. This can lead to reduced performance and even failure of the module.
- Soiling loss: soiling loss occurs when dirt, dust, or other contaminants accumulate on the surface of a solar module, reducing its performance.
- Cell microcracks: microcracks can occur in solar cells due to stress or other factors during the manufacturing process or during installation. These cracks can lead to reduced performance and even failure of the module.
- Potential induced degradation (PID): PID is caused by the buildup of a negative voltage between the solar cells and the frame of the module. This can cause a loss of power output and other types of damage.
- Light-induced degradation (LID): LID occurs when the performance of a solar cell decreases rapidly a“Performance and degradation assessment of large-scale grid-connected solar photovoltaic power plant in tropical semi-arid environment of India fter it is first exposed to sunlight. It occurs because the silicon used in solar cells contains trace amounts of impurities such as boron and oxygen, which can interact with the light to create defects in the crystal lattice of the silicon. These defects act as recombination centers for the charge carriers in the cell, reducing the efficiency of the cell.

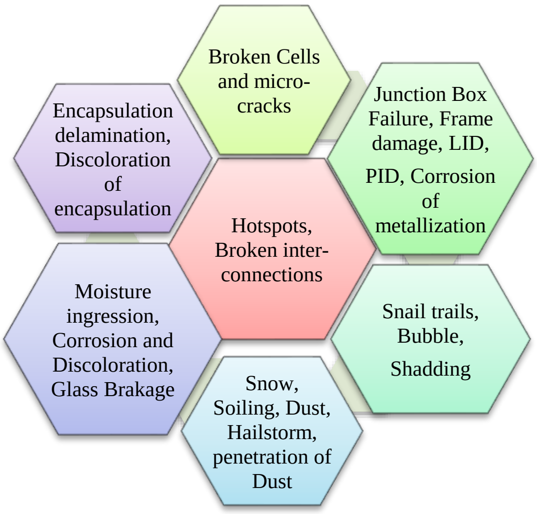

Figure 2. Types of degradation defects in PV module

3.2. Causes of degradation defects in solar PV module

There are several factors that can contribute to degradation defects in solar PV modules over time. To addressing these potential causes of degradation defects, solar PV module manufacturers can improve the lifespan and efficiency of their products. Exposure to the elements over time can cause damage to the module's components, such as the protective layer, which can lead to a decrease in performance.

The optical degradation of PV module will be increasing due to hot and humid climate therefore encapsulation discolouration and delamination occurs, which reduces the short circuit current [17]. In a desert climate, temperature, ultraviolet radiation, and humidity lead to snail trails, burn marks, cracking, and bubbles in the PV module [18], [19]. Corrosion is the most damaging agent of weather parameters like moisture ingression, humidity, and high temperatures in a hot climate as well as in hot and humid climate. It contributes the PV module's series resistance [20], [21]. These induced degradations can be detected by accelerated stress tests, such as thermal cycling, damp heat, and UV light exposure. The causes of PID effect in the PV module is high impedance, humidity, and UV radiation [22]. Malvoni *et al*. [23] observed 2.5% LID per year due to optical degradation and high UV exposure. It was found through simulated results in PVSYST software. Finding degradation defects in solar PV modules provides numerous advantages, including improved performance, cost savings, system longevity, safety compliance, warranty utilization, effective maintenance planning, and data-driven decision-making.

3.3. Defects come due to climate change

According to a recent article, the distinct climates worldwide have different forms of degradation in solar PV systems. It was found that the temperature, humidity, wind, and UV exposure are the most important factors which affect the rate of degradation. In hot and dry climates, such as deserts, PV modules may experience higher levels of degradation due to the extreme heat. The high temperatures can accelerate the chemical reactions that lead to degradation, as well as increase the thermal stress on the materials. This can result in a decrease in the efficiency of the PV module over time [24]-[26].

In humid regions with high levels of wind and dust, such as coastal areas, the accumulation of dust and debris on the surface of the PV module can also lead to degradation. The dust can reduce the amount of sunlight that reaches the cells, reducing the overall efficiency of the module. The Pollution rates vary from day to day and month to month; hence pollution cannot be considered constant throughout the year. The findings suggested that cleaning once every fifteen days is required to reduce losses associated with frequent cleaning due to water and manpower usage [27]. Under harsh environments, eight maximum power points were generated for eight sun intensities regardless of the location of the shadows. and it determines the root cause of PV string failures such as shadow effects or module flaws [28]. Overall, it is important to consider the specific climate conditions of a given region when designing and installing PV modules to ensure optimal performance and longevity. The Figure 3 shows the numerous types of climates seen in different locations.

A prospective observational study on different climates in the world found that hot and dry climates have observed the PV panel degradation in the form of delamination, yellowing, and hotspots [26]. This study [29] found that the output energy of PV systems is affected by ambient temperature in tropical wet and dry climates. Encapsulant discolouration and delamination are the primary defects in hot and humid climates [30]. This subject has been extensively explored in the literature [31] that hot and dry climate zones have discolouration, whereas hot and humid climates have corrosion type of primary degradation effects. Authors have found a yellowing, browning, interconnect corrosion, and broad spread type of delamination degradation in tropical climates, whereas breakage and cracks in cells are found in semi-arid climate regions [4], [32].

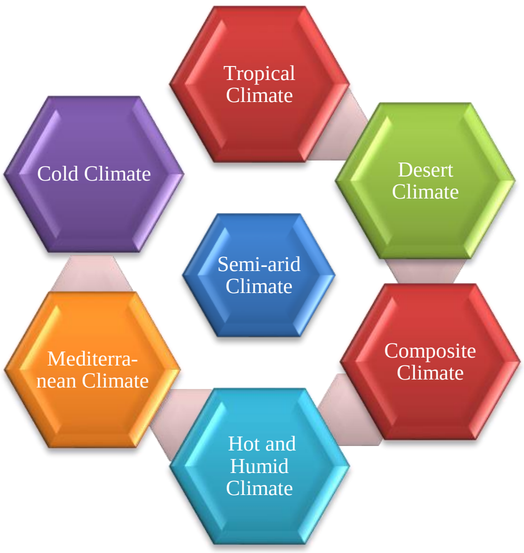

Figure 3. Different types of climates

3.4. Defect found in PV technologies modules in various climatic regions

Table 1 summarizes the types of degradations and their effect on solar PV modules and used methodology. A systematic approach of study expressed the degradation rate depends on both methodology and the technology of solar PV systems [33]. The results reveal that as the exposure period of dust over the panel increases, so do the short circuit current, open circuit voltage, maximum current, average power, cell temperature, and efficiency [34]. The degradation effect on PV technologies presents that m-Si PV technology has a 0.27–0.50% degradation rate per year in semi-arid climate zone. A 20-year observation-based study was investigated that desert climate due to dust penetration, burn marks, cracking, bubbles, snail trails, and delamination have 1.75% degradation per year. The result of previous study [35] shows that thin-film PV technology has main issues such as glass breakage and absorber corrosion. In tropical climate locations, this technology degrades at the fastest rate of 6.1%. The study found that in tropical climate locations, the degradation rate of thin-film PV technology is the fastest and degradation rate is higher than in other climatic conditions, such as temperate or arid climates, which suggests that the use of thin-film PV technology in tropical areas may require more maintenance and monitoring [36]. Hot climate zone has primary degradation defects such as frame grounding corrosion, back sheet problems, and hotspots, and these defects show a 5% degradation rate per year [37].

Table 1. Comparison of degradation rate based on analysis period

S. No	Year	Analysis period (Year)	Degradation Rate per annum (%)	Effect due to PV Module technology/climate	References
1	2016	20	1.5	Desert Climate	[19]
2	2017	3.5	1.48	m-Si/Mediterranean climate	[38]
3	2017	4	6.10	Thin Film/tropical climate	[36]
4	2018	1	2.72	Multi-Crystalline Silicon	[39]
5	2018	2.6	1.5	Amorphous and Microcrystalline technology	[40]
6	2018	1.9	2.9	CdTe module	[32]
7	2019	1	0.6–5	crystalline photovoltaic	[33]
8	2020	4	0.27–0.50	mono-crystalline module/semi-arid climate	[19]
9	2020	15	0.7	crystalline silicon	[8]
10	2020	30	0.04–0.05	Mono-Si, Poly-Si, CdTe, and CIS/arid climatic	[26]
11	2022	12	0.95	Glass/polymer frameless modules/Hot-Dry Desert Climate.	[34]
12	2021	7	0.27	Crystalline silicon/Hot and dry climate	[20]
13	2021	10	0.5	Crystalline silicon module	[35]
14	2021	1.4	1.18	Polycrystalline/Floating solar PV	[36]
15	2020	-	3 2 5	Composite climate Moderate climate Hot and humid climate	[28]

4. PROPOSED METHODS TO DETECT THE DEGRADATIONS IN PV MODULE

There is a vast literature on methods available in studies to find the degradation in PV modules. The Visual inspection method is widely used to detect degradation. Visual inspection is a method of evaluating a component or system using the naked eye or with the help of magnifying glasses, bore-scopes, or other visual aids. It is a simple and cost-effective method of assessing the condition of a system or component. The average degradation rate of various PV technologies is presented in Figure 4. It is observed that the highest degradation was found for thin film PV cell by 6.10% and lowest degradation found in polycrystalline by 1.18% [21], [29], [41]-[43].

Many studies have been carried out regarding this subject as PV cell degradation and it is reviewed and evaluated that the highest number of studies presented the average or lower degradation rates but some 5-6 studies were presented the highest degradation rate. It is clearly expressed in Figure 5 [44], [45]. Figure 6 shows the tools to identify the degradation defects in PV system. The current-voltage (I-V) curve tracer, thermal image camera, electro-luminance camera, and PV analyzer kit are all required for this procedure [4], [26], [43], [46]-[48]. The equipment is required for these methods are described as:

4.1. I-V curve testing

I-V curve testing is a method of determining the current-voltage characteristics of a component or system. It is typically used to evaluate the performance of photovoltaic (PV) cells or modules. The equipment required for this method is an I-V curve tracer and a DC power supply.

4.2. Thermography

Thermography is a method of measuring the temperature of a component or system using infrared radiation. It is used to identify thermal anomalies, such as hot spots or cold spots, which can indicate potential problems. The equipment required for this method is an IR camera and a DC power supply.

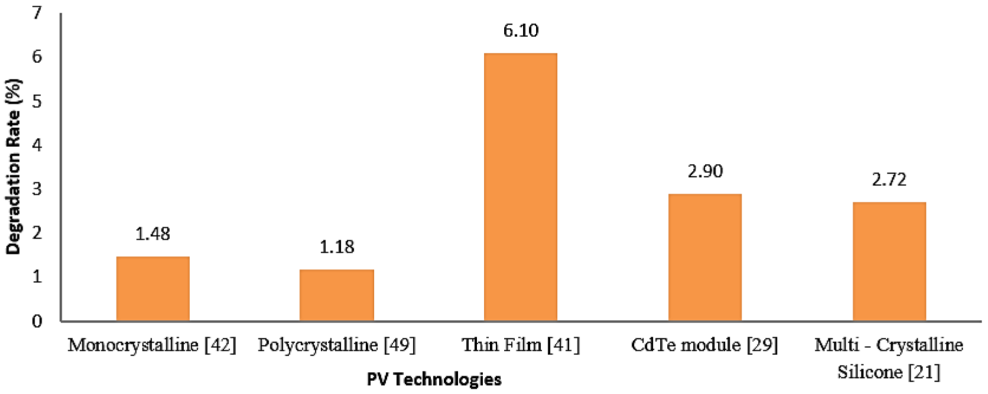

Figure 4. Comparison of average degradation rate of PV technology

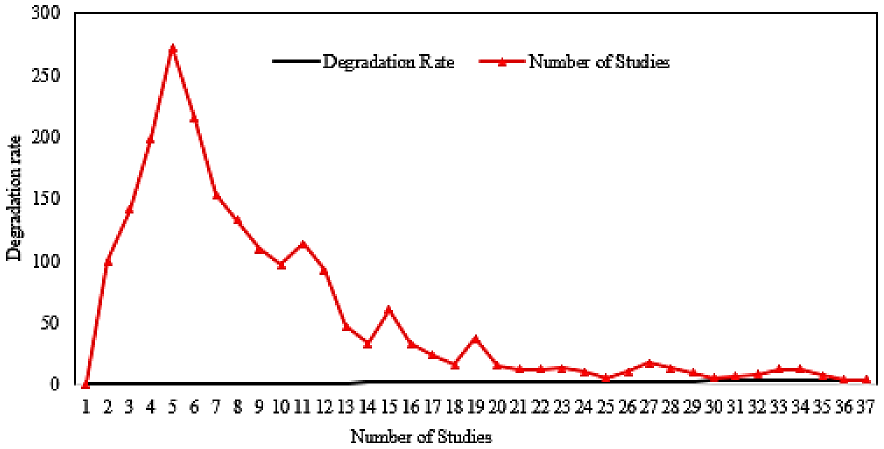

Figure 5. Comparison between degradation rate and number of studies

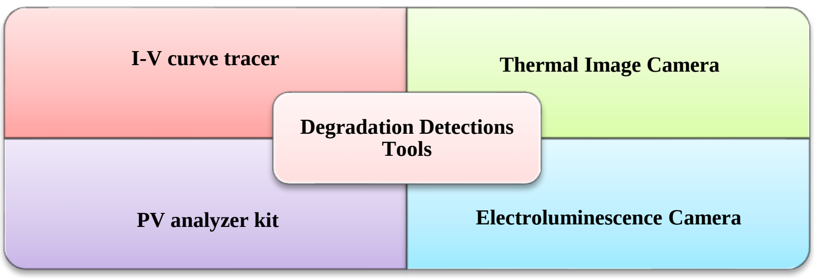

Figure 6. Tools to identify degradation in PV system

4.3. Electroluminescence

Electroluminescence (EL) is a method of evaluating the condition of PV cells or modules by measuring the amount of light emitted when a voltage is applied to the cell. It is used to identify defects or damage to the cells or modules. The equipment required for this method is an EL camera and a DC power supply.

4.4. Insulation testing

Insulation testing is a method of evaluating the condition of insulation materials used in electrical systems or components. It is used to identify defects or damage to the insulation, which can cause electrical faults or safety hazards. The equipment required for this method is an insulation resistance tester.

4.5. Inspection of disconnection in interconnection of cells

Inspection of disconnection in interconnection of cells is a method of evaluating the condition of the interconnection between PV cells or modules. It is used to identify defects or damage to the interconnection, which can cause a decrease in the efficiency of the PV system. The equipment required for this method is an interconnect breakage tester.

4.6. Continuous checking of current and voltage generation

Current, voltage, and continuity checking is a method of evaluating the electrical parameters of a system or component. It is used to identify faults or defects in the system or component. The equipment required for this method is an ammeter, voltmeter, or multi-meter [49]. A review of the literature conducted shows that PR values are higher in the winter than in the summer and found the 15.9% and 14.1% PV array losses for fixed and tracking PV system respectively [39].

In Figure 7, a-Si and μc-Si technology uses a combination of amorphous and microcrystalline silicon layers to achieve high efficiency while also reducing the cost of production. The amorphous layer is used to absorb light while the microcrystalline layer provides better electrical conductivity. these two technologies have demonstrated superior performance due to their unique designs and are a promising option for the future of solar energy production.

Ambient temperature and soiling effect decrease the PR by 0.7% and 0.03%, respectively, with an increase of 1 °C temperature [51]. The maximum power point of a solar cell varies during the day due to variations in sun energy and temperature [52]. The cold climate region has higher PR values due to lower temperatures than the hot climate region [42], [53]. Using PVSYST software to compare projected values, the influence of temperature on PV modules was discovered [21], [26], [29], [35], [38], [54]. The loads on the bus bars are chosen based on the house's electricity needs. Because the real power system has certain issues with power quality and overloading. The phase short circuit current is approximately 1.72 kA, and the peak short circuit current is approximately 3.28 kA [55]. The degradation rate is derived by examining the Nameplate value by electrical characteristics such as open-circuit voltage Voc, short-circuit current Isc, fill factor (FF), series resistance Rs, and shunt resistance Rsh, as proved experimentally [43]. The electrical properties such as Voc and Isc of CdTe-based PV technology decreased by 2.29% and 2.86% after 23 months of environmental exposure [41]. The Siemens PSSE software simulation result demonstrated that when large PV plants generate power for the grid, the system is susceptible to the stability issue. It was discovered that a larger PV generator causes the system to become unstable at its maximum capacity [56]. The series resistance of a PV module is frequently increased due to corrosion-type degradation [21]. The various software tools available and popularly used for solar PV system design and simulation are listed in Figure 8.

The various energy prediction models have been developed and used to find the level/levels of degradation and losses using PVSYST, SolarGIS, PVWATT, and MATLAB software. The highest energy loss, 14.4%, has been predicted due to temperature using PVSYST software by comparing the measured value of PR [57]. Light-induced degradation of 2.5% was investigated using PVSYST software. Environmental factors like ambient temperature, solar irradiance, and ohmic losses were predicted to analyze the output energy through PVSYST, PVWATT, and PVGIS simulation software [42]. By examining the P-V and I-V properties of outdated PV modules with MATLAB software, almost 90% of the power may be recycled [58]. The effect of ambient temperature on the PV system's power output is evaluated using MATLAB software. It’s decreased with an increase in the ambient temperature [59]. Artificial rabbit optimization exceeds all other algorithms in conventional testing applications but in partially shaded situations, the most valuable player (MVP) algorithm surpasses all others in terms of efficiency and tracking speed [60], [61].

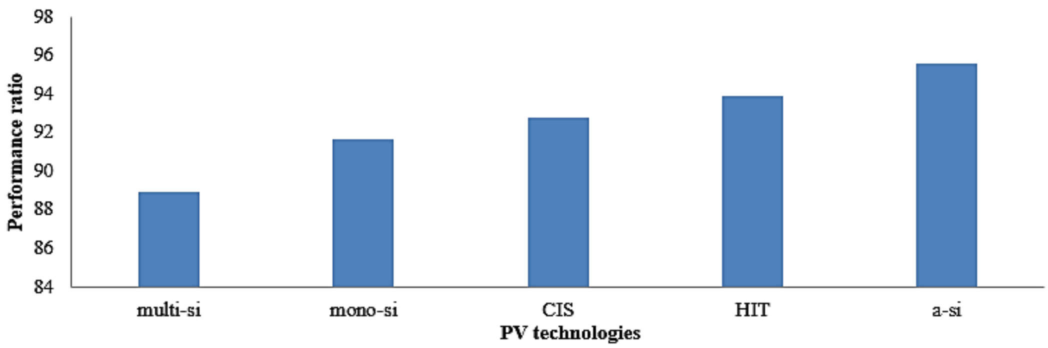

Figure 7. Performance ratio comparison of different technologies in literature [50]

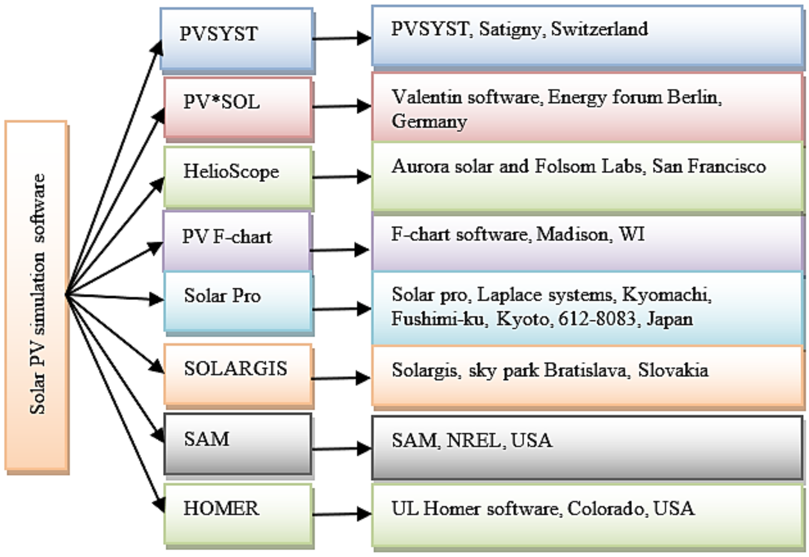

Figure 8. Various solar PV design and simulation software

Sophisticated laboratory tools, electron microscopy, solar simulator, and accelerated stress tests have been used to find the degradation defects such as grounding wire corrosion, mechanical stress, back sheet peeling, Microcracks, hotspot, and moisture-induced degradation [37], [62]. The result of these studies shows that micro-cracks lead to a power loss of 0.9 to 42.8% and also increase the cell temperature up to 7.6 °C [63]. In laboratories, accelerated stress tests such as moist heat, thermal cycling, UV light exposure, and hail testing were performed to determine the effect of environmental elements like temperature, UV radiation, and humidity [22].

Degradation rate can be found by various statistical methods such as linear least squares regression (LLS), classical seasonal decomposition (CSD), the holt-winters seasonal model (HW), and the seasonal and trend decomposition using loess (STL) [23]. The study, which was based on numerous elements such as voltage, current, and output power under various weather conditions, was carried out using the MATLAB Simulink tool [64]. The linear square fitting method is widely used to find the degradation rate. The most common machine learning algorithm, such as linear regression, sequential minimal optimization regression, and random forest estimates, has been used to forecast the degradation rate in amorphous silicon (a-Si) PV technology [18], [42], [57], [65], [66].

In Figure 9 is described the different method to find the degradation rate and its effect in PV systems. It is expressed that a preferred approach for the developed diagnostic methods is machine learning algorithms, which suggests that there is a growing trend towards utilizing artificial intelligence for failure diagnosis. Another commonly used approach for failure diagnosis is power loss analysis. Figure 10 expressed the various methods to find degradations rate and effect.

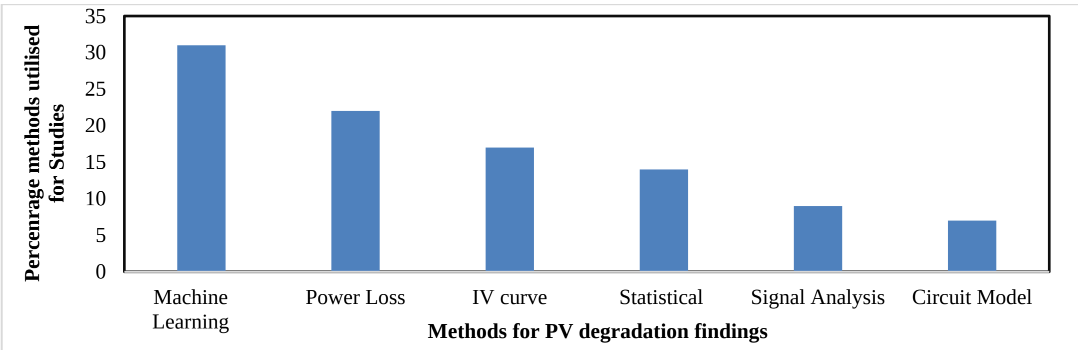

Figure 9. Comparison of various methods of degradation finding [49]

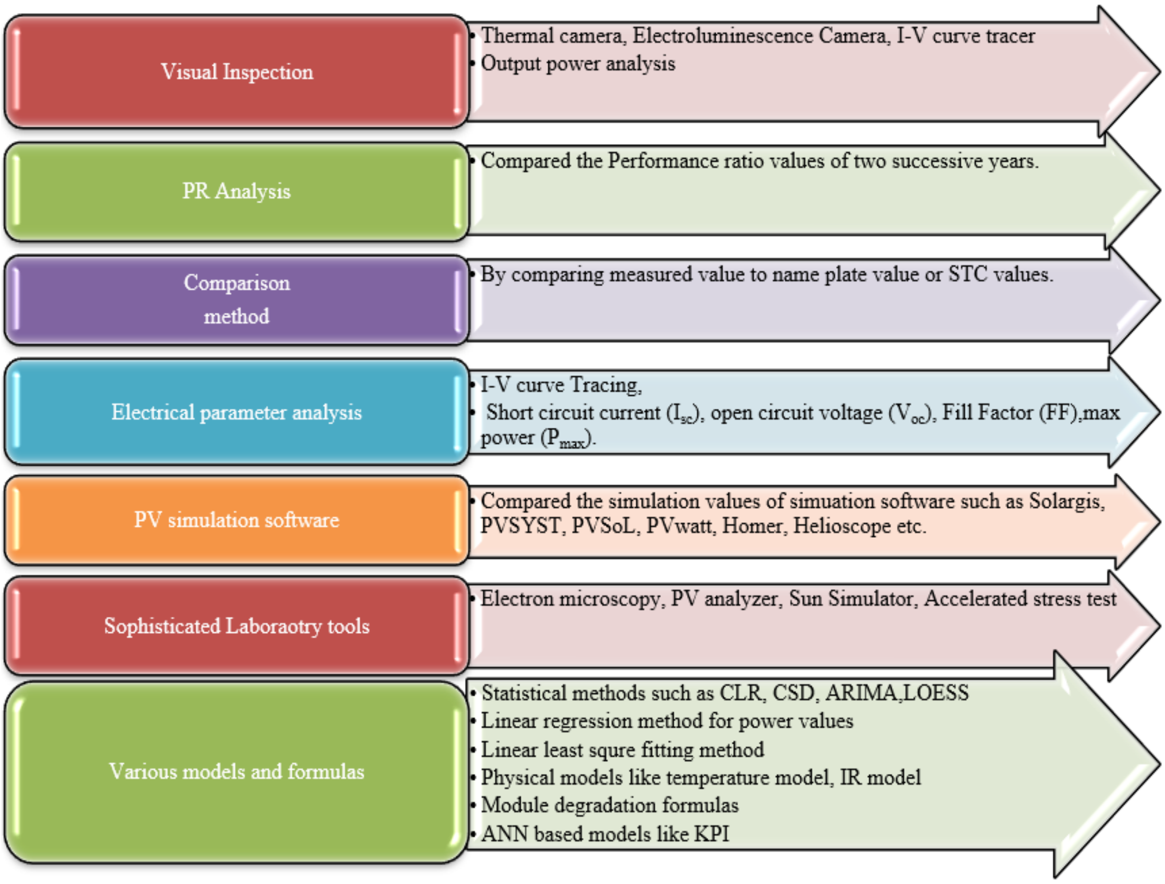

Figure 10. Various methods to find degradations rate and effect

The Table 2 [67]-[100] (see Appendix) presented the rigorous review of the PV module degradation according to various finding. Analyzing the PV module's electrical characteristics can be used to calculate the degradation rate. After 4 years of analysis, the degradation rate of 2% was observed by studying PV modules' series and shunt resistance using a single solar cell model developed by MATLAB software [101]. Another study conducted in northern India presents that light-induced degradation has 2.5% losses per year [102]. According to this study [26], heterojunction technology (HIT) PV technology has the lowest degradation rate, whereas polycrystalline (pc-Si), Cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si) have the highest degradation rate in a hot climate.

Degradation refers to a reduction in the performance or quality of a material or system over time due to various factors such as wear and tear, aging, corrosion, or other environmental factors. The effect of degradation can vary depending on the type and severity of the degradation, but it can ultimately lead to a loss of functionality or even failure of the material or system. To analyze the degradation and its effect, different methodologies can be used depending on the type of degradation and the material or system being analyzed.

5. RESULTS AND DISCUSSION

The aim of this study was to focus on the effect of degradation on various climate regions, degradation detection and analysis methods, various simulation software used, comparison of degradation rate based on analysis period, different methods to find the degradation rate, and cause of various degradation defects in solar plants. Various methods have been used to find the degradation rate, such as visual inspection, electrical parameter analysis and comparison, performance analysis, and various statistical methods like linear least square method fitting method, CLR, CSD, and ARIMA LOESS. But visual inspection method was widely used in most studies. In this method, IR camera, Electroluminescence camera, PV analyzer, and I-V curve tracer have been used to detect the degradation in PV modules. Various sophisticated laboratory tools such as electron microscopy, PV analyzer, sun simulator, and accelerated stress test has been used to find the various degradation defects in installed solar PV module. Performance ratio analysis is one of the most important methods to find solar PV plant efficiency and degradation effect during their lifetime.

Based on a thorough analysis of the literature, it is clear that there has been a significant increase in the installation of PV plants in various geographical regions. Variations in degradation rate depend on the PV technologies and climate regions. We need to be more aware in hot climate zone installed plants due to the higher degradation rate observed by various studies. Dust, burn marks, cracking, bubbles, snail trails delamination, and hotspots degradation defects were mostly found due to higher temperatures and high ultraviolet exposure regions such as dessert and hot climates. Cause of various degradation such as hotspots, snail trails, corrosion, frame adhesive degradation, Potential induced degradation, EVA discolouration, encapsulation delamination, soiling loss, cell microcracks, light-induced degradation has been discovered.

EL imaging can accurately detect numerous failures and aging effects in solar modules in a very short time. For example, it can detect cracks, broken cells, and shunts in crystalline silicon solar cells, as well as delamination and corrosion in thin-film solar cells. It can also detect hot spots, which are areas of localized heating that can reduce the performance and lifespan of a solar module.

EL imaging is a valuable tool for ensuring the quality and reliability of solar modules, and it is becoming increasingly important as the demand for solar energy continues to grow. IR thermography is a non-destructive method used to detect temperature anomalies in PV modules, which can be an indication of potential issues. I-V characterization measures the electrical output of the PV modules under different conditions, such as different levels of irradiance and temperature. Insulation resistance testing is used to identify any potential issues with the wiring and connections.

6. CONCLUSION AND FUTURE RESEARCH SCOPE

Understanding the plant layout, operation, and maintenance information is important to identify potential issues that may affect the plant's performance. This includes information on the cleaning method and frequency, corrective maintenance, and replacement of components. Visual inspections of the plant can identify any physical damage, such as cracks or hotspots, that may affect performance.

The study may involve analyzing data on solar energy production, weather patterns, and environmental conditions to determine how these factors contribute to degradation. Additionally, the study may explore various techniques for detecting and diagnosing degradation issues, such as visual inspections, performance monitoring, and machine learning algorithms. The goal of the study is likely to improve our understanding of how degradation affects solar energy systems and inform the development of strategies to mitigate degradation and improve the performance and reliability of solar power plants.

Studies have shown that different PV technologies have varying degradation rates in hot climates, with some technologies performing better than others. For example, thin-film PV modules have been observed to have a lower degradation rate in hot climates compared to crystalline silicon modules. This is because thin-film modules have a higher temperature coefficient, which means that their performance is less affected by high temperatures. the degradation rate of PV plants in India can vary depending on the climate region where they are located. Arid regions tend to have a higher degradation rate compared to tropical and coastal regions. However, it is important to note that the degradation rate can also depend on other factors such as the type of PV technology used and the maintenance practices followed.

To be precise, defect detection approaches and algorithms that have the following capabilities must be developed: i) Capability of detecting many defects without disrupting electricity production; ii) The ability to identify and locate faults; and iii) Cost-effective and adaptable, allowing for compatibility with current PV systems. In addition to the impact of climate on PV technologies, it is also important to consider the maintenance and cleaning of PV plants in hot climates. Dust accumulation on PV modules can significantly reduce their efficiency, and regular cleaning is necessary to ensure optimal performance.

APPENDIX

Table 2. Types of degradation and their effect and analyzing methodology

Authors	Year	Types of degradation and effects	The method used for degradation analysis
Carigiet *et al.* [67]	2021	For the Multi crystalline technology module, a 0.6% degradation difference was found in outdoor and indoor measurements in 8 years.	Applied the linear regression in power values to find the degradation.
Aboagye *et al.* [68]	2021	Power degradation rate 0.8% per year found.	I-V curve tracing and degradation rate were found by comparing the measured value to the nameplate value.
Clavijo-Blanco *et al.* [69]	2021	Browning, yellowing, back sheet scratches, an anti-reflective layer, hotspots.	Visual inspection, EL and electrical insulation.
Tariq *et al.* [70]	2021	Dust deposition such as Fly ash, cement and rice husk.	Examined the various type of dust concentration and spectral transmission.

Table 2. Types of degradation and their effect and analyzing methodology (continued)

Authors	Year	Types of degradation and effects	The method used for degradation analysis
Kherici *et al*. [71]	2021	Main degradation mechanisms such as output power drop, encapsulation discoloration and corrosion.	Visual inspection, IR camera, I-V curve measurement.
Bolinger *et al*. [72]	2020	Found 1.3% degradation rate.	A fixed-effect statistical regression model was used to find the degradation.
Chanchangi *et al*. [73]	2020	Dust formation cause degradation.	Various mitigation of cleaning methods is described like: - Manual cleaning. - Natural cleaning like wind, rainfall. - Automated cleaning like water, mechanized. - Self-cleaning like Superhydrophobic plane, super hydrophilic plane, Electrodynamic screen.
Quansah *et al*. [74]	2020	Delamination, bubbles, glass breaking, snail tracks, burn marks in the junction box, yellowing of encapsulation.	- I-V curve tracer. - Visual inspection.
Kumar and Subathra [75]	2019	Effect of solar Irradiance on the module.	- The linear square fitting method. - Used three machine learning algorithms (linear regression, sequential minimal optimization regression and random forest estimates).
Kumar *et al.* [76]	2019	Weather effect.	Linear least square fitting method Weather effect on PR.
Gupta *et al.* [77]	2019	As a result of the hailstorm, there are cracks parallel to the busbars, diagonal cracks perpendicular to the busbars, and cracks in multiple directions.	Study of the effect of hailstorm.
Shah *et al.* [78]	2019	Inter raw spacing and tilt angle.	Experimental study.
Khan *et al.* [79]	2019	Temperature and humidity.	DH stress testing and electroluminescence scanning technique.
Luo *et al*. [80]	2018	Optical transmittance of encapsulation, soiling effect, loss of short circuit current.	Analysed electric parameter of the system.
Thotakura *et al.* [81]	2018	Output Energy affected by ambient temperature, solar incidence, manufacturing mismatch and ohmic wiring.	By analyzing the output power.
Tanesab *et al.* [82]	2018	The de-rating factor is dust and its climate-dependent.	Power degradation analysis.
Dhoke *et al*. [83]	2018	Degradation cause of line-line fault and value of string current (I_{sc}) decreased.	Proposed module degradation factor formula to find the degradation.
Zhang *et al.* [84]	2018	It can be used to find the microcracks and hotspots and detect suspicious defects.	Proposed the unmanned aerial vehicle (UAV) based on thermal imaging & luminescence imaging system.
Subramaniyan *et al.* [85]	2018	Module temperature, ultraviolet radiation, and relative humidity. Cause of degradation in m-Si module technology	Physics-based and data-driven modelling such as the Arrhenius model, activation energy (E_a), statistical modelling.
Quansah and Adaramola [86]	2018	Early degradation ranged from 21.8% to 13.8% of initial performance.	Time-series regression of both temperature-corrected and uncorrected performance ratio measurements.
Haidar *et al*. [87]	2018	Temperature affects the performance of the PV module.	Experimental study.
Jamil *et al*. [88]	2017	Dust or soil effects degrade the life of the PV module	By analyzing the system output power.
Oprea and Bâra [89]	2017	To find the effect on the performance on the module	Proposed the ANN-based key performance indicator (KPI) analysis method to calculate the performance of PV power plants.
Kumar and Kumar [90]	2017	Temperature, UV light exposure, moisture, humidity, and thermal cycling, cause Degradation.	Degradation and failure modes such as visual inspection: - I-V characteristics - Ultrasonic inspection - Electroluminescence imaging - Infrared imaging Laser Beam Induced Current (LBIC)
Bedrich *et al.* [91]	2017	A method for the correction of electroluminescence (EL) images	A method for the correction of electroluminescence (EL) images.
Kim *et al.* [92]	2015	Hotspots occur due to an increase in the value of capacitance and DC impedance.	Proposed the string level hotspot detection concept.
Crozier *et al*. [93]	2015	Gray-white discoloration, White discoloration, Mechanical damage	Electroluminescence and I-V characteristics technique, I-V Curve tracer, PV SIM modelling program.

Table 2. Types of degradation and their effect and analyzing methodology (continued)

Authors	Year	Types of degradation and effects	The method used for degradation analysis
Micheli *et al*. [94]	2014	Irradiance and temperature effect on PV module.	Experimental study.
Ndiaye *et al.* [95]	2013	Encapsulant, temperature, humidity, corrosion, discoloration, delamination, and breakage.	Literature review.
TamizhMani and Kuitche [96]	2013	All degradation modes like broken cells, interconnection, and severe corrosion. Hotspot, ground faults, solder bond failure, broken cells, encapsulant delamination, structure failing soiling.	Detailed literature review on degradation.
Sharma and Chandel [97]	2013	The soil on the glass, oxidation of the anti-reflective coating, and wave pattern in the back sheet.	Using a sun simulator to measure the characteristics of module parameters before and after outdoor exposure. Visual inspection method, IR, I-V curve tracer.
Crozier *et al.* [98]	2013	Inactive cell area, Microcracks, broken contact finger	Experimental study, (difference of nominal max power and measured max power) classification of EL image.
Mansouri *et al*. [99]	2012	Microcracks and cell breakage transparent	By using EL images with properly adjusted and configured condition.
Munoz *et al*. [100]	2009	Yellowing, delamination, bubbles, crack in the cells, defects in the antireflective coating, burned cells.	Visual inspection, I-V curve measurement, thermal evaluation by IR imaging.

REFERENCES

[1] V. Pillai, "Power technology," 2023. https://www.tndindia.com/a-bright-future-for-solar-power-in-india/ (accessed Jun. 14, 2023).

[2] O. Heffernan, "Renewable energy sources and climate change mitigation: special report of the Intergovernmental Panel on Climate Change," *Choice Reviews Online*, vol. 49, no. 11, pp. 49-6309-49–6309, Jul. 2012, doi: 10.5860/CHOICE.49-6309.

[3] A. Agarwal, "A bright future for solar power in India," *Power Technology*, 2019. https://www.power-technology.com/features/feature-the-top-10-biggest-thermal-power-plants-in-india (accessed Jun. 14, 2023).

[4] M. C. C. de Oliveira *et al.*, "Comparison and analysis of performance and degradation differences of crystalline-Si photovoltaic modules after 15-years of field operation," *Solar Energy*, vol. 191, no. 11, pp. 235–250, Oct. 2019, doi: 10.1016/j.solener.2019.08.051.

[5] S. P. Karthikeyan, P. Sanjeevikumar, F. Blaabjerg, J. B. Holm-nielsen, and B. Supratik, "A review for assessment on solar panel degradation," *IEEE India Info*, vol. 14, no. August, pp. 93–98, 2019, [Online]. Available: file:///C:/Users/sumit/Desktop/phd folder/(32)2011(114)Analysis of degradation mechanisms.pdf.

[6] J. L. Braid and R. H. French, "Overview," in *Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules*, Elsevier, 2019, pp. 3–21.

[7] B. Bora *et al.*, "Failure mode analysis of PV modules in different climatic conditions," *IEEE Journal of Photovoltaics*, vol. 11, no. 2, pp. 453–460, Mar. 2021, doi: 10.1109/JPHOTOV.2020.3043847.

[8] T. E. Ali, M. A. Abdala, A. Al-Khaykan, D. A. Alwahab, and J. M. Counsell, "Energy generation by crystalline silicon photovoltaic network per meter square in Iraq," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 4, pp. 3606–3612, Aug. 2023, doi: 10.11591/ijece.v13i4.pp3606-3612.

[9] N. K. Kasim, N. M. Obaid, H. G. Abood, R. A. Mahdi, and A. M. Humada, "Experimental study for the effect of dust cleaning on the performance of grid-tied photovoltaic solar systems," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 1, pp. 74–83, Feb. 2021, doi: 10.11591/ijece.v11i1.pp74-83.

[10] M. A. M. Abdelsalam *et al.*, "Experimental study of the impact of dust on azimuth tracking solar PV in Sharjah," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 5, pp. 3671–3681, Oct. 2021, doi: 10.11591/ijece.v11i5.pp3671-3681.

[11] J. E. F. da Fonseca, F. S. de Oliveira, C. W. Massen Prieb, and A. Krenzinger, "Degradation analysis of a photovoltaic generator after operating for 15 years in southern Brazil," *Solar Energy*, vol. 196, pp. 196–206, Jan. 2020, doi: 10.1016/j.solener.2019.11.086.

[12] A. Peinado Gonzalo, A. Pliego Marugán, and F. P. García Márquez, "Survey of maintenance management for photovoltaic power systems," *Renewable and Sustainable Energy Reviews*, vol. 134, p. 110347, Dec. 2020, doi: 10.1016/j.rser.2020.110347.

[13] R. Mehta, "Optimal assessment of smart grid based photovoltaic cell operational parameters using simulated annealing," *International Journal of Applied Power Engineering (IJAPE)*, vol. 11, no. 4, pp. 333–344, Dec. 2022, doi: 10.11591/ijape.v11.i4.pp333-344.

[14] I. Kaaya, J. Ascencio-Vásquez, K. A. Weiss, and M. Topič, "Assessment of uncertainties and variations in PV modules degradation rates and lifetime predictions using physical models," *Solar Energy*, vol. 218, pp. 354–367, 2021, doi: 10.1016/j.solener.2021.01.071.

[15] N. Bansal, S. P. Jaiswal, and G. Singh, "Comparative investigation of performance evaluation, degradation causes, impact and corrective measures for ground mount and rooftop solar PV plants – A review," *Sustainable Energy Technologies and Assessments*, vol. 47, p. 101526, Oct. 2021, doi: 10.1016/j.seta.2021.101526.

[16] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation rates - An Analytical Review," *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12–29, Jan. 2013, doi: 10.1002/pip.1182.

[17] Á. Fernández-Solas, L. Micheli, F. Almonacid, and E. F. Fernández, "Optical degradation impact on the spectral performance of photovoltaic technology," *Renewable and Sustainable Energy Reviews*, vol. 141, p. 110782, May 2021, doi: 10.1016/j.rser.2021.110782.

[18] A. Fezzani *et al.*, "Degradation and performance evaluation of PV module in desert climate conditions with estimate uncertainty in measuring," *Serbian Journal of Electrical Engineering*, vol. 14, no. 2, pp. 277–299, 2017, doi: 10.2298/SJEE1702277F.

[19] S. Mohammed, B. Boumediene, and B. Miloud, "Assessment of PV modules degradation based on performances and visual inspection in Algerian Sahara," *International Journal of Renewable Energy Research*, vol. 6, no. 1, pp. 106–116, 2016, doi: 10.20508/ijrer.v6i1.3155.g6765.

[20] S. Kumar, R. Meena, and R. Gupta, "Imaging and micro-structural characterization of moisture induced degradation in crystalline silicon photovoltaic modules," *Solar Energy*, vol. 194, pp. 903–912, 2019, doi: 10.1016/j.solener.2019.11.037.

[21] T. Hayashi, T. Nagayama, T. Tanaka, and Y. Inui, "Influence of degradation in units of PV modules on electric power output of PV system," *Journal of International Council on Electrical Engineering*, vol. 8, no. 1, pp. 119–127, 2018, doi: 10.1080/22348972.2018.1477095.

[22] J. Kim, M. Rabelo, S. P. Padi, H. Yousuf, E. C. Cho, and J. Yi, "A review of the degradation of photovoltaic modules for life expectancy," *Energies*, vol. 14, no. 14, p. 4278, Jul. 2021, doi: 10.3390/en14144278.

[23] M. Malvoni, N. M. Kumar, S. S. Chopra, and N. Hatziargyriou, "Performance and degradation assessment of large-scale grid-connected solar photovoltaic power plant in tropical semi-arid environment of India," *Solar Energy*, vol. 203, pp. 101–113, Jun. 2020, doi: 10.1016/j.solener.2020.04.011.
[24] H. F. Hashim, M. M. Kareem, W. K. Al-Azzawi, and A. H. Ali, "Improving the performance of photovoltaic module during partial shading using ANN," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 4, pp. 2435–2442, 2021, doi: 10.11591/ijpeds.v12.i4.pp2435-2442.
[25] M. Aghaei *et al.*, "Review of degradation and failure phenomena in photovoltaic modules," *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112160, May 2022, doi: 10.1016/j.rser.2022.112160.
[26] N. Bansal, P. Pany, and G. Singh, "Visual degradation and performance evaluation of utility scale solar photovoltaic power plant in hot and dry climate in western India," *Case Studies in Thermal Engineering*, vol. 26, 2021, doi: 10.1016/j.csite.2021.101010.
[27] M. R. Said, A. A. El-Samahy, and H. M. El Zoghby, "Cleaning frequency of the solar PV power plant for maximum energy harvesting and financial profit," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 1, pp. 546–554, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp546-554.
[28] B. Yu and Y. Jung, "Performance analysis of a residential photovoltaic string under partial shading," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 1, pp. 85–93, Feb. 2023, doi: 10.11591/ijece.v13i1.pp85-93.
[29] I. Baghdadi, A. El Yaakoubi, K. Attari, Z. Leemrani, and A. Asselman, "Performance investigation of a PV system connected to the grid," *Procedia Manufacturing*, vol. 22, pp. 667–674, 2018, doi: 10.1016/j.promfg.2018.03.096.
[30] N. C. Park, J. S. Jeong, B. J. Kang, and D. H. Kim "The effect of encapsulant discoloration and delamination on the electrical characteristics of photovoltaic module," *Microelectronics Reliability*, vol 53 pp. 1818–1822, 2013, doi: 10.1016/j.microrel.2013.07.062.
[31] S. Chattopadhyay *et al.*, "Visual degradation in field-aged crystalline silicon PV modules in India and correlation with electrical degradation," *IEEE Journal of Photovoltaics*, vol. 4, no. 6, pp. 1470–1476, 2014, doi: 10.1109/JPHOTOV.2014.2356717.
[32] C. Hajjaj *et al.*, "Degradation and performance analysis of a monocrystalline PV system without EVA encapsulating in semi-arid climate," *Heliyon*, vol. 6, no. 6, p. e04079, Jun. 2020, doi: 10.1016/j.heliyon.2020.e04079.
[33] A. Phinikarides, N. Kindyni, G. Makrides, and G. E. Georghiou, "Review of photovoltaic degradation rate methodologi," *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 143–152, Dec. 2014, doi: 10.1016/j.rser.2014.07.155.
[34] A. Pradhan, B. Panda, L. Nanda, and C. Jena, "Analysis of dust on the parameters of PV module and design of an effective solar dust cleaner," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 2, pp. 900–907, Jun. 2022, doi: 10.11591/ijpeds.v13.i2.pp900-907.
[35] S. Chawla and V. A. Tikkiwal, "Performance evaluation and degradation analysis of different photovoltaic technologies under arid conditions," *International Journal of Energy Research*, vol. 45, no. 1, pp. 786–798, Jan. 2021, doi: 10.1002/er.5901.
[36] A. Limmanee *et al.*, "Degradation analysis of photovoltaic modules under tropical climatic conditions and its impacts on LCOE," *Renewable Energy*, vol. 102, pp. 199–204, Mar. 2017, doi: 10.1016/j.renene.2016.10.052.
[37] V. Sharma and S. S. Chandel, "Corrosion and moisture ingress identification," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 753–767, 2013, doi: 10.1016/j.rser.2013.07.046.
[38] M. Malvoni, A. Leggieri, G. Maggiotto, P. M. Congedo, and M. G. De Giorgi, "Long term performance, losses and efficiency analysis of a 960 kWP photovoltaic system in the Mediterranean climate," *Energy Conversion and Management*, vol. 145, pp. 169–181, 2017, doi: 10.1016/j.enconman.2017.04.075.
[39] R. K. Prakhya and C. Lokeshwar Reddy, "Estimating the performance ratio and degradation factor of rooftop solar PV plant," *CVR Journal of Science & Technology*, vol. 14, no. 01, pp. 32–37, 2018, doi: 10.32377/cvrjst1407.
[40] N. Aarich, M. Raoufi, A. Bennouna, and N. Erraissi, "Outdoor comparison of rooftop grid-connected photovoltaic technologies in Marrakech (Morocco)," *Energy and Buildings*, vol. 173, pp. 138–149, 2018, doi: 10.1016/j.enbuild.2018.05.030.
[41] R. Rawat, S. C. Kaushik, O. S. Sastry, B. Bora, and Y. K. Singh, "Long-term performance analysis of CdTe PV module in real operating conditions," *Materials Today: Proceedings*, vol. 5, no. 11, pp. 23210–23217, 2018, doi: 10.1016/j.matpr.2018.11.052.
[42] 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, Apr. 2023, doi: 10.3390/en16093706.
[43] J. Mallineni, B. Knisely, K. Yedidi, S. Tatapudi, J. Kuitche, and G. TamizhMani, "Evaluation of 12-year-old PV power plant in hot-dry desert climate: Potential use of field failure metrics for financial risk calculation," in *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, Jun. 2014, pp. 3366–3371, doi: 10.1109/PVSC.2014.6925656.
[44] J. Pascual, F. Martinez-Moreno, M. García, J. Marcos, L. Marroyo, and E. Lorenzo, "Long-term degradation rate of crystalline silicon PV modules at commercial PV plants: An 82-MWp assessment over 10 years," *Progress in Photovoltaics: Research and Applications*, vol. 29, no. 12, pp. 1294–1302, Dec. 2021, doi: 10.1002/pip.3456.
[45] A. Goswami and P. K. Sadhu, "Degradation analysis and the impacts on feasibility study of floating solar photovoltaic systems," *Sustainable Energy, Grids and Networks*, vol. 26, p. 100425, Jun. 2021, doi: 10.1016/j.segan.2020.100425.
[46] B. Bora, O. S. Sastry, S. Mondal, and B. Prasad, "Reliability testing of PV module in the outdoor condition," in *Progress in Solar Energy Technology and Applications*, Wiley, 2019, pp. 1–37.
[47] M. Santhakumari and N. Sagar, "A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques," *Renewable and Sustainable Energy Reviews*, vol. 110, pp. 83–100, Aug. 2019, doi: 10.1016/j.rser.2019.04.024.
[48] Y. Zefri, A. Elkettani, I. Sebari, and S. A. Lamallam, "Thermal infrared and visual inspection of photovoltaic installations by uav photogrammetry—application case: Morocco," *Drones*, vol. 2, no. 4, pp. 1–24, Nov. 2018, doi: 10.3390/drones2040041.
[49] S. R. Madeti and S. N. Singh, "Monitoring system for photovoltaic plants: A review," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 1180–1207, Jan. 2017, doi: 10.1016/j.rser.2016.09.088.
[50] A. Balaska, A. Tahri, F. Tahri, and A. B. Stambouli, "Performance assessment of five different photovoltaic module technologies under outdoor conditions in Algeria," *Renewable Energy*, vol. 107, pp. 53–60, Jul. 2017, doi: 10.1016/j.renene.2017.01.057.
[51] D. H. Daher, L. Gaillard, M. Amara, and C. Ménézo, "Impact of tropical desert maritime climate on the performance of a PV grid-connected power plant," *Renewable Energy*, vol. 125, pp. 729–737, Sep. 2018, doi: 10.1016/j.renene.2018.03.013.
[52] A. Balal, M. Abedi, and F. Shahabi, "Optimized generated power of a solar pv system using an intelligent tracking technique," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 4, pp. 2580–2592, Dec. 2021, doi: 10.11591/ijpeds.v12.i4.pp2580-2592.
[53] H. Yousuf *et al.*, "A review on degradation of silicon photovoltaic modules," *New & Renewable Energy*, vol. 17, no. 1, pp. 19–32, Mar. 2021, doi: 10.7849/ksnre.2021.2034.
[54] S. Verma, D. K. Yadav, and N. Sengar, "Performance evaluation of solar photovoltaic power plants of semi-arid region and suggestions for efficiency improvement," *International Journal of Renewable Energy Research*, vol. 11, no. 2, pp. 762–775, 2021, doi: 10.20508/ijrer.v11i2.11957.g8210.

[55] M. N. Hawas, I. J. Hasan, and M. J. Mnati, "Simulation and analysis of the distributed photovoltaic generation systems based on DIgSILENT power factory," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 28, no. 3, pp. 1227–1238, Dec. 2022, doi: 10.11591/ijeecs.v28.i3.pp1227-1238.
[56] M. N. F. Mohd Tajudin, M. N. Mohd Hussain, M. M. Hussain, and I. R. Ibrahim, "Stability model integration for large scale solar photovoltaic system using Western electricity coordinating council model," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 13, no. 4, pp. 3641–3650, 2023, doi: 10.11591/ijece.v13i4.pp3641-3650.
[57] S. Bordihn, A. Fladung, J. Schlipf, and M. Köntges, "Machine Learning based Identification and Classification of Field-Operation caused Solar Panel Failures observed in Electroluminescence Images," *IEEE Journal of Photovoltaic*, vol. 12, no. 3, pp. 827-832, 2022, doi: 10.1109/JPHOTOV.2022.3150725.
[58] H. Ashfaq, I. Hussain, and A. Giri, "Comparative analysis of old, recycled and new PV modules," *Journal of King Saud University - Engineering Sciences*, vol. 29, no. 1, pp. 22–28, Jan. 2017, doi: 10.1016/j.jksues.2014.08.004.
[59] F. Zaoui, A. Titaouine, M. Becherif, M. Emziane, and A. Aboubou, "A combined experimental and simulation study on the effects of irradiance and temperature on photovoltaic modules," *Energy Procedia*, vol. 75, pp. 373–380, Aug. 2015, doi: 10.1016/j.egypro.2015.07.393.
[60] S. Ravi, M. Premkumar, and L. Abualigah, "Comparative analysis of recent metaheuristic algorithms for maximum power point tracking of solar photovoltaic systems under partial shading conditions," *International Journal of Applied Power Engineering (IJAPE)*, vol. 12, no. 2, pp. 196–217, Jun. 2023, doi: 10.11591/ijape.v12.i2.pp196-217.
[61] B. M. Dawoud and S. C. Lim, "Performance comparison of fixed and single axis tracker photovoltaic system in large scale solar power plants in Malaysia," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 21, no. 1, pp. 10–17, Jan. 2021, doi: 10.11591/ijeecs.v21.i1.pp10-17.
[62] Y. N. Chanchangi, A. Ghosh, S. Sundaram, and T. K. Mallick, "An analytical indoor experimental study on the effect of soiling on PV, focusing on dust properties and PV surface material," *Solar Energy*, vol. 203, pp. 46–68, Jun. 2020, doi: 10.1016/j.solener.2020.03.089.
[63] M. Dhimish, "Micro cracks distribution and power degradation of polycrystalline solar cells wafer: Observations constructed from the analysis of 4000 samples," *Renewable Energy*, vol. 145, pp. 466–477, Jan. 2020, doi: 10.1016/j.renene.2019.06.057.
[64] A. Grover and R. Adlakha, "Inverter based implementation of maximum power point techniques," *International Journal of Applied Power Engineering*, vol. 11, no. 3, pp. 229–236, Sep. 2022, doi: 10.11591/ijape.v11.i3.pp229-236.
[65] N. M. Kumar and M. Malvoni, "A preliminary study of the degradation of large-scale c-Si photovoltaic system under four years of operation in semi-arid climates," *Results in Physics*, vol. 12, pp. 1395–1397, Mar. 2019, doi: 10.1016/j.rinp.2019.01.032.
[66] F. Aziz, A. Ul Haq, S. Ahmad, Y. Mahmoud, M. Jalal, and U. Ali, "A novel convolutional neural network-based approach for fault classification in photovoltaic arrays," *IEEE Access*, vol. 8, pp. 41889–41904, 2020, doi: 10.1109/ACCESS.2020.2977116.
[67] F. Carigiet, C. J. Brabec, and F. P. Baumgartner, "Long-term power degradation analysis of crystalline silicon PV modules using indoor and outdoor measurement techniques," *Renewable and Sustainable Energy Reviews*, vol. 144, p. 111005, Jul. 2021, doi: 10.1016/j.rser.2021.111005.
[68] B. Aboagye, S. Gyamfi, E. A. Ofosu, and S. Djordjevic, "Degradation analysis of installed solar photovoltaic (PV) modules under outdoor conditions in Ghana," *Energy Reports*, vol. 7, pp. 6921–6931, Nov. 2021, doi: 10.1016/j.egyr.2021.10.046.
[69] J. A. Clavijo-Blanco, G. Álvarez-Tey, N. Saborido-Barba, J. L. Barberá-González, C. García-López, and R. Jiménez-Castañeda, "Laboratory tests for the evaluation of the degradation of a photovoltaic plant of 2.85 MWp with different classes of PV modules," *Renewable Energy*, vol. 174, pp. 262–277, Aug. 2021, doi: 10.1016/j.renene.2021.04.024.
[70] M. Tariq, M. K. Ansari, F. Rahman, M. A. Rahman, and I. Ashraf, "Effect of soiling on the performance of solar PV modules: A case study of aligarh," *Smart Science*, vol. 9, no. 2, pp. 121–132, Apr. 2021, doi: 10.1080/23080477.2021.1901340.
[71] Z. Kherici, N. Kahoul, H. Cheghib, M. Younes, and B. Chekal Affari, "Main degradation mechanisms of silicon solar cells in Algerian desert climates," *Solar Energy*, vol. 224, pp. 279–284, Aug. 2021, doi: 10.1016/j.solener.2021.06.033.
[72] M. Bolinger, W. Gorman, D. Millstein, and D. Jordan, "System-level performance and degradation of 21 GWDCof utility-scale PV plants in the United States," *Journal of Renewable and Sustainable Energy*, vol. 12, no. 4, Jul. 2020, doi: 10.1063/5.0004710.
[73] Y. N. Chanchangi, A. Ghosh, S. Sundaram, and T. K. Mallick, "Dust and PV Performance in Nigeria: A review," *Renewable and Sustainable Energy Reviews*, vol. 121, p. 109704, Apr. 2020, doi: 10.1016/j.rser.2020.109704.
[74] D. A. Quansah, M. S. Adaramola, and G. Takyi, "Degradation and longevity of solar photovoltaic modules—An analysis of recent field studies in Ghana," *Energy Science and Engineering*, vol. 8, no. 6, pp. 2116–2128, Jun. 2020, doi: 10.1002/ese3.651.
[75] N. M. Kumar and M. S. P. Subathra, "Three years ahead solar irradiance forecasting to quantify degradation influenced energy potentials from thin film (a-Si) photovoltaic system," *Results in Physics*, vol. 12, pp. 701–703, Mar. 2019, doi: 10.1016/j.rinp.2018.12.027.
[76] N. M. Kumar, M. Malvoni, N. Hatziargyriou, and S. S. Chopra, "Data related to crystalline photovoltaic plant performance in the semi-arid climate of India," *Data in Brief*, vol. 31, p. 105696, Aug. 2020, doi: 10.1016/j.dib.2020.105696.
[77] V. Gupta, M. Sharma, R. K. Pachauri, and K. N. Dinesh Babu, "Comprehensive review on effect of dust on solar photovoltaic system and mitigation techniques," *Solar Energy*, vol. 191, pp. 596–622, Oct. 2019, doi: 10.1016/j.solener.2019.08.079.
[78] S. F. A. Shah, I. A. Khan, and A. H. A. Khan, "Performance evaluation of two similar 100MW solar PV plants located in environmentally homogeneous conditions," *IEEE Access*, vol. 7, pp. 161697–161707, 2019, doi: 10.1109/ACCESS.2019.2951688.
[79] F. Khan and J. H. Kim, "Performance degradation analysis of c-Si PV modules mounted on a concrete slab under hot-humid conditions using electroluminescence scanning technique for potential utilization in future solar roadways," *Materials*, vol. 12, no. 24, 2019, doi: 10.3390/ma1224047.
[80] W. Luo *et al.*, "Analysis of the long-term performance degradation of crystalline silicon photovoltaic modules in tropical climates," *IEEE Journal of Photovoltaics*, vol. 9, no. 1, pp. 266–271, Jan. 2019, doi: 10.1109/JPHOTOV.2018.2877007.
[81] S. Thotakura *et al.*, "Operational performance of megawatt-scale grid integrated rooftop solar PV system in tropical wet and dry climates of India," *Case Studies in Thermal Engineering*, vol. 18, p. 100602, Apr. 2020, doi: 10.1016/j.csite.2020.100602.
[82] J. Tanesab, D. Parlevliet, J. Whale, and T. Urmee, "Energy and economic losses caused by dust on residential photovoltaic (PV) systems deployed in different climate areas," *Renewable Energy*, vol. 120, pp. 401–412, May 2018, doi: 10.1016/j.renene.2017.12.076.
[83] A. Dhoke, R. Sharma, and T. K. Saha, "PV module degradation analysis and impact on settings of overcurrent protection devices," *Solar Energy*, vol. 160, pp. 360–367, 2018, doi: 10.1016/j.solener.2017.12.013.
[84] Y. Zhang *et al.*, "The PV system doctor – comprehensive diagnosis of PV system installations," *Energy Procedia*, vol. 130, pp. 108–113, Sep. 2017, doi: 10.1016/j.egypro.2017.09.404.
[85] A. B. Subramaniyan, R. Pan, J. Kuitche, and G. TamizhMani, "Quantification of environmental effects on PV module degradation: A physics-based data-driven modeling method," *IEEE Journal of Photovoltaics*, vol. 8, no. 5, pp. 1289–1296, 2018, doi: 10.1109/JPHOTOV.2018.2850527.
[86] D. A. Quansah and M. S. Adaramola, "Assessment of early degradation and performance loss in five co-located solar photovoltaic module technologies installed in Ghana using performance ratio time-series regression," *Renewable Energy*, vol. 131, pp. 900–910, Feb. 2019, doi: 10.1016/j.renene.2018.07.117.

[87] Z. A. Haidar, J. Orfi, and Z. Kaneesamkandi, "Experimental investigation of evaporative cooling for enhancing photovoltaic panels efficiency," *Results in Physics*, vol. 11, pp. 690–697, Dec. 2018, doi: 10.1016/j.rinp.2018.10.016.

[88] W. J. Jamil, H. Abdul Rahman, S. Shaari, and Z. Salam, "Performance degradation of photovoltaic power system: Review on mitigation methods," *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 876–891, Jan. 2017, doi: 10.1016/j.rser.2016.09.072.

[89] S. V. Oprea and A. Bâra, "Key technical performance indicators for power plants," in *Recent Improvements of Power Plants Management and Technology*, InTech, 2017.

[90] M. Kumar and A. Kumar, "Performance assessment and degradation analysis of solar photovoltaic technologies: A review," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 554–587, Oct. 2017, doi: 10.1016/j.rser.2017.04.083.

[91] K. G. Bedrich, M. Bliss, T. R. Betts, and R. Gottschalg, "Electroluminescence imaging of PV devices: Camera calibration and image correction," in *2017 IEEE 44th Photovoltaic Specialist Conference, PVSC 2017*, Jun. 2017, pp. 3254–3255, doi: 10.1109/PVSC.2017.8366325.

[92] K. A. Kim, G. S. Seo, B. H. Cho, and P. T. Krein, "Photovoltaic hot-spot detection for solar panel substrings using AC parameter characterization," *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1121–1130, Feb. 2016, doi: 10.1109/TPEL.2015.2417548.

[93] J. L. Crozier, E. E. van Dyk, and F. J. Vorster, "Identification and characterisation of performance limiting defects and cell mismatch in photovoltaic modules," *Journal of Energy in Southern Africa*, vol. 26, no. 3, pp. 19–26, Sep. 2015, doi: 10.17159/2413-3051/2015/v26i3a2126.

[94] D. Micheli, S. Alessandrini, R. Radu, and I. Casula, "Analysis of the outdoor performance and efficiency of two grid connected photovoltaic systems in northern Italy," *Energy Conversion and Management*, vol. 80, pp. 436–445, Apr. 2014, doi: 10.1016/j.enconman.2014.01.053.

[95] A. Ndiaye, A. Charki, A. Kobi, C. M. F. Kébé, P. A. Ndiaye, and V. Sambou, "Degradations of silicon photovoltaic modules: A literature review," *Solar Energy*, vol. 96, pp. 140–151, Oct. 2013, doi: 10.1016/j.solener.2013.07.005.

[96] G. TamizhMani and J. Kuitche, "Accelerated lifetime testing of photovoltaic modules solar America board for codes and standards," *A report of Solar America Board for Codes and Standards*, p. 106, 2013.

[97] V. Sharma and S. S. Chandel, "Performance and degradation analysis for long term reliability of solar photovoltaic systems: A review," *Renewable and Sustainable Energy Reviews*, vol. 27, pp. 753–767, Nov. 2013, doi: 10.1016/j.rser.2013.07.046.

[98] J. L. Crozier, E. E. Van Dyk, and F. J. Vorster, "Classification of electroluminescence imaging results for large- scale PV Quality Testing.

[99] A. Mansouri, M. Zettl, O. Mayer, M. Lynass, M. Bucher, and O. Stern, "Defect detection in photovoltaic modules using electroluminescence imaging," in *27th European Photovoltaic Solar Energy Conference and Exhibition*, 2012, vol. 64617926, pp. 3374–3378.

[100] M. A. Munoz, M. C. Alonso-García, N. Vela, and F. Chenlo, "Early degradation of silicon PV modules and guaranty conditions," *Solar Energy*, vol. 85, no. 9, pp. 2264–2274, Sep. 2011, doi: 10.1016/j.solener.2011.06.011.

[101] P. Malik, R. Chandel, and S. S. Chandel, "A power prediction model and its validation for a roof top photovoltaic power plant considering module degradation," *Solar Energy*, vol. 224, pp. 184–194, Aug. 2021, doi: 10.1016/j.solener.2021.06.015.

[102] N. M. Kumar, R. P. Gupta, M. Mathew, A. Jayakumar, and N. K. Singh, "Performance, energy loss, and degradation prediction of roofintegrated crystalline solar PV system installed in Northern India," *Case Studies in Thermal Engineering*, vol. 13, p. 100409, Mar. 2019, doi: 10.1016/j.csite.2019.100409.

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