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Review

Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management

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Abstract: The degradation of solar photovoltaic (PV) modules is caused by a number of factors that have an impact on their effectiveness, performance, and lifetime. One of the reasons contributing to the decline in solar PV performance is the aging issue. This study comprehensively examines the effects and difficulties associated with aging and degradation in solar PV applications. In light of this, this article examines and analyzes many aging factors, including temperature, humidity, dust, discoloration, cracks, and delamination. Additionally, the effects of aging factors on solar PV performance, including the lifetime, efficiency, material degradation, overheating, and mismatching, are critically investigated. Furthermore, the main drawbacks, issues, and challenges associated with solar PV aging are addressed to identify any unfulfilled research needs. Finally, this paper provides new directions for future research, best practices, and recommendations to overcome aging issues and achieve the sustainable management and operation of solar energy systems. For PV engineers, manufacturers, and industrialists, this review's critical analysis, evaluation, and future research directions will be useful in paving the way for conducting additional research and development on aging issues to increase the lifespan and efficiency of solar PV.

Keywords: solar PV; aging factors; degradation; lifespan; efficiency

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1. Introduction

Utilizing solar PV to generate energy is not a simple operation due to degradation, which can result in a reduction in solar PV performance and efficiency [1,2]. According to recent studies, the rate of degradation varies between 0.6% and 0.7% per year [3,4]. Photovoltaic (PV) degradation can be both linear and non-linear depending on the underlying mechanisms causing the degradation. Linear degradation occurs when the rate of degradation is constant over time, resulting in a gradual decrease in the performance of the PV module. Non-linear degradation occurs when the rate of degradation varies over time, resulting in an accelerated or decelerated decrease in performance. There are several factors that can contribute to the linear degradation of PV modules. One of the most significant factors is exposure to sunlight, which can cause the gradual breakdown of the materials used in the PV module. This breakdown can result in a 2.8% reduction in the performance ratio of the PV module, leading to a gradual decrease in performance over time [5–7]. In general, solar PV has a 25-year expected lifespan. Solar PV modules will not survive for this long in the majority of cases. Aging is the term that is used to describe the degradation of a PV module before its expected lifespan [8,9]. The factors that underlie the reduction in the lifetime of a PV module can be defined as aging factors. The roots of this degeneration are aging-related issues. Researchers and scientists from all around the world have discovered that one of the major causes of reduced life expectancy is aging. Aging factors are among those that significantly affect both performance and efficiency. Each aging factor has its own individual impact, but when combined, they significantly affect the lifespan of PV modules.

The PV sector has been growing at a quicker rate than ever during the past few decades. When the energy crisis is at its worst, solar PV has emerged as one of the most sustainable energy sources due to its amazing attributes, including reduced carbon emissions. Solar photovoltaic energy has been viewed as the primary source of energy in many industrialized nations. The International Energy Agency predicts that by 2025, solar energy will account for 60% of the overall renewable energy capacity, making it the most important source of energy [10]. China, the world's largest producer of solar panels, has pledged to boost its use of non-fossil fuels to 25% by 2030 and has set a target to meet 27.5% of the global energy demand with solar energy by 2050 [11]. African nations such as Ghana have begun to make the greatest use of renewable energy, as has the Asian tech giant China. The Ghanaian government has adopted a master plan to increase 42.5 MW in 2015 to 1363.63 MW by 2030, with solar PV sources alone making up over 50% of the total power [12,13]. Solar highways also have tremendous opportunities in Bangladesh [14]. Solar PV has enormous potential, but it also has significant limitations, such as intermittent power supply and reduced efficiency because of radiation intensity, dust, and temperature.

Since solar PV aging is a severe concern, numerous noteworthy studies have been conducted to solve PV aging and degradation issues. For instance, Santhakumari and Sagar reviewed the environmental elements that contribute to the PV performance deterioration of silicon-wafer-based solar PV modules [15]. Although a variety of PV failures caused by environmental conditions were discussed by the authors, it was not established how these factors affect the PV module's age. Therefore, a thorough examination of the relationship between aging and environmental factors is still necessary. The effects of electromigration and delamination on PV module failure were investigated by Hasan et al. [16]. Other aging variables, such as temperature, cracks, and dust, have not been studied. Consequently, more research on all aging-related aspects is necessary for greater comprehension. The effects of soiling on the deterioration of PV modules were examined by Conceiçao et al. [17]. Unquestionably, one of the most potent aging variables that cause PV modules to age quickly is soiling. Soiling is the process through which dirt or dust gathers and deposits itself on solar panels, and the accumulation of dirt, dust, and other contaminants on the surface of a photovoltaic (PV) module can have a significant impact on the performance and aging of the module. The primary reason for this is that soiling can reduce the amount of sunlight that reaches the surface of the PV module, which in turn can lead to a reduction in the power output and an increase in the operating temperature. When soiling accumulates on the surface of a PV module, it creates a layer of material that reduces the amount of sunlight that can penetrate the underlying layers of the module. This reduction in light intensity can lead to a decrease in the overall power output of the module of 60–70%, which can impact the performance of the entire PV system [18]. In addition, the accumulation of soiling can also increase the operating temperature of the module, which can accelerate the aging of the materials used in the module. Nonetheless, other aging factors have not been investigated. Zhang et al. explored the degradation mechanisms of perovskite solar cells, where the authors showed that the deterioration of solar cells occurs over time but that the contributions of various degradation pathways to PV aging are as yet unknown [19]. Kim et al. delivered a brief review of the lifespan of solar PV, with the authors focusing on how various types of accelerated stress reduce the longevity of PV modules [20]. Even though there was extensive consideration of many aging variables, this investigation failed to establish a connection between degradation factors and PV aging. Damo et al. evaluated the effects of light, heat, and humidity and showed how the PV panel was harmed by these environmental elements [21]. While it was obvious that environmental variables contributed to the aging of PV panels, technical failures of PV modules, including cracks and other installation failures, such as glass breakage, were not investigated. Meuret et al. assessed the long-term performance and degradation of various PV modules in hot climate circumstances, in which amorphous silicon PV modules decayed more quickly than other silicon modules in various temperate climate situations [22]. However, there was no consideration of how temperature affects the lifetime or long-term degeneration of PVs. An overview of the numerous studies on PV deterioration and aging is shown in Table 1.

Table 1. Recent studies, contributions, and research gaps for different factors that affect PV degradation and aging.

Refs.	Objective/Target	Contributions	Limitations
[12]	Analyze the impact of environmental conditions on the performance degradation of silicon-wafer-based PV modules.	This paper provides a comprehensive summation of several methods for preventing PV modules from degrading owing to environmental elements such as dust, ambient temperature, wind speed, snowfall, hailstorms, etc.	Although there are numerous additional ways that PV may degrade, such as cracks, discoloration, and delamination that cause the PV modules to age, the review primarily focused on environmental variables.
[13]	Delamination- and electromigration-related failures of PV module.	This review gives a comprehensive analysis of the causes and consequences of and associations between electromigration and delamination.	The study shows a relationship between the two most common aging variables—delamination and electromigration—but further research into the relationship with additional aging factors is required.
[14]	Examine the degradation of a PV module due to soiling.	This study provides an in-depth examination of the soiling impact on PV modules over time (1942 to 2019).	Although a comprehensive overview of the literature on the soiling impact on PV modules is provided in this work, it does not show how soiling accelerates PV aging.
[15]	Degradation pathways of perovskite solar cells.	Summary of the key degradation mechanism of Perovskite solar cells.	However, the authors did not look into other aspects influencing PV aging in actual operating situations. The research concluded that artificial aging conditions are not analogous to real operational environments.
[16]	The lifetime expectancy of PV module.	This study presents a discussion of various factors that affect the aging of PV modules.	Although this article provides a broad overview of aging variables, it does not address the additional effects of these factors on variables other than lifespan expectancy.
[18]	Long-term performance and degradation analysis of different PV modules under temperate climatic conditions.	With a ratio of 0.9 0.009%/year and 0.75 0.003%/year, a-Si degrades more quickly than its equivalents, followed by m-Si (0.53 0.01%/year and 0.41 0.003%/year) and p-Si (0.36 0.01%/year and 0.28 0.004%/year).	The temperature influence was studied for degradation rates. The deterioration rate does not take into account the impact of other aging processes, such as delamination and crack hotspot discoloration.

This review offers a brief description of the factors contributing to solar PV aging and degradation to fill in the gaps left by the available studies. Additionally, this study offers a thorough analysis of aging factors, emphasizing their effects and potential future paths. The following is a summary of this review's contributions:

- A critical analysis of various degradation rates of solar PV in various countries.
- A thorough examination of several aging factors, highlighting objectives, cases, techniques, contributions, and research gaps.
- A critical investigation of how aging influences the longevity, effectiveness, and materials of solar PV.
- Improvements, opportunities, and future directions for the advancement of PV lifetime and efficiency toward sustainable energy management.

The remainder of the article is split into six groups. Solar PV degradation analysis is presented in Section 2. Several aging variables that impact PV performance are discussed in Section 3. Section 4 provides an illustration of the effects of aging variables, including material deterioration, decreased lifetime, and efficiency degradation. Section 5 presents potential areas for future improvements toward sustainable energy management. A conclusion is provided in Section 6.

2. Degradation Analysis for Solar PV

The degradation of a PV (photovoltaic) module is the term used to describe the steady decline in efficiency and output power of a solar panel over time as a result of numerous environmental influences, manufacturing flaws, and material degradation. Several mathematical models have been introduced by researchers to evaluate the performance of PV modules and analyze PV degradation. A typical polycrystalline PV cell's V-I characteristic is expressed by the following equation using the usual double-diode model:

$$I = I_{ph} - I_{s1}[e^{\frac{V+IR_s}{V_t}} - 1] - I_{s2}[e^{\frac{V+IR_s}{A_{vt}}}] - \frac{V+IR_s}{R_s} \tag{1}$$

where

$$V_t = \frac{kT}{e} \tag{2}$$

where V and I are the terminal voltage and current of a cell, as shown in Equations (1) and (2), respectively, K is the Boltzmann constant, T is the absolute ambient temperature (°K), and e is the electronic charge. In order to approximate the Shockley–Read–Hall recombination in the space-charge layer of the photodiode, the diode parameter A is often set to 2. The following empirical correlations of Equations (3)–(8) acquired from experimental polycrystalline cell characterization, as described in other studies, are used to determine the model parameters I_{ph}, I_{s1}, I_{s2}, A, R_s, and R_p from the values of irradiance E (w/m^2) and ambient temperature T (°K).

$$I_{ph} = K_0 E(1 + K_1 T) \tag{3}$$

$$I_{S1} = K_2 T^3 e^{\frac{K_3}{T}} \tag{4}$$

$$I_{S2} = K_4 T^{1.5} e^{\frac{K_3}{T}} \tag{5}$$

$$A = K_6 E + K_7 T \tag{6}$$

$$R_s = K_8 + \frac{K_9}{E} + K_{10} T \tag{7}$$

$$R_p = K_6 E + K_7 T \tag{8}$$

Setting $I = 0$ and $V = V_{oc}$ in the double-diode model yields the open-circuit voltage V_{oc} for a single cell, as illustrated in Equation (9) below. The highest open-circuit voltage (V_{oc}) that a terminal voltage (V) can reach is zero.

$$V_{oc} = R_p \times [I_{ph} - I_{s1}[e^{\frac{V_{th}}{V_t}} - 1] - I_{s2}[e^{\frac{V_{th}}{A_{vt}}}]] \quad (9)$$

As a solar panel's performance declines over time, it is referred to as PV degradation. Solar panels are made to turn sunlight into energy, but with time, several things may cause them to deteriorate, lowering their effectiveness and power production [23]. PV deterioration can have both internal and external sources. Environmental elements such as temperature, humidity, wind, and UV radiation are examples of external influences [24]. These elements have the potential to harm solar cells or the layer that protects them, which might eventually lead to a decrease in efficiency [25]. The deterioration of the electrical connections between cells or faults in the solar cells, such as fractures or contaminants, are examples of internal issues. The solar panel's design, its operating circumstances, and the quality of the materials used in its construction all impact the rate of panel degradation [26]. Manufacturers frequently offer warranties that guarantee a specific level of performance for a set period of time, sometimes 25 or 30 years, and that might provide insight into the predicted pace of degradation [27].

High temperature is a major cause of PV degradation. When a solar panel is exposed to high temperatures, it can cause several forms of damage that reduce the panel's efficiency and overall performance [28]. Some of the ways in which high temperatures can cause PV degradation include:

- Thermal stress: High temperatures can result in thermal stress inside the solar panel, which may cause the solar cells or other components to break or delaminate [29].
- Electrical resistance: The electrical resistance of the solar cells and interconnections increases with temperature, which can lower the efficiency of the panel [30].

Moisture can also be a cause of PV degradation. Moisture can enter the solar panel through various pathways, such as through cracks or defects in the panel's protective layers or through electrical contacts between cells [31]. Once inside the panel, moisture can cause several forms of damage that reduce the panel's efficiency and overall performance. Moisture can lead to PV degradation through the following mechanisms:

- Corrosion: Moisture can lead to the corrosion of the metal solar panel parts, including the frame and electrical connections. This may result in higher resistance and lower efficiency [32].
- Delamination: The materials used in solar panels, such as the encapsulant or back sheet, can delaminate as a result of moisture. This may cause the layers to separate, exposing the solar cells to moisture or other external elements [31].
- Electrical leakage: Moisture can also result in electrical leakage between solar panel cells or other components. This may result in decreased efficiency and a higher chance of electrical fires or failures [33].

PV deterioration can also be brought on by wind speed. Strong wind speeds can put the solar panel under mechanical stress, which can result in different types of damage that lower the panel's performance and efficiency [34]. The following are some ways that wind speed might lead to PV deterioration:

- Mechanical stress and vibration: Strong winds can bend or cause the solar panel to shake, which can put mechanical strain on the solar cells or other parts. This may cause the solar cells or other components to develop micro-cracks or delaminate, reducing the panel's power output [35].
- Structural damage: Damage to the solar panel's structure, such as the bending or deformation of the frame or supports, can also result from high wind speeds. This may result in the solar cells or other components being out of alignment, which will lower the panel's efficiency [36].

While it is often not as important a factor as temperature, moisture, or wind velocity, solar irradiance can also result in PV deterioration. The quantity of sunshine that strikes the solar panel is known as solar irradiance, and it has the potential to harm the panel in a number of ways that lower its overall performance and efficiency [37]. Solar irradiation can degrade PV in the following ways:

- Hotspots: When a portion of a solar cell is exposed to more sunlight than the rest of the cell, hotspots can form on the surface of the solar cell as a result of solar irradiance. This may result in localized cell damage and heating, which lowers the panel's overall power output. Several technologies, such as drone imaging, have been demonstrated to locate hotspots [38–40].
- Light-induced deterioration: When solar cells are exposed to sunlight for a lengthy period of time, they lose efficiency. Solar irradiance may also cause this type of deterioration. This can be influenced by the type of silicon used in the solar cells or by the presence of contaminants [41].

PV deterioration can also be brought on by the cell temperature. When exposed to sunlight, a solar cell transforms part of the energy into heat and some of it into electricity [42]. The solar cell's temperature may rise as a result of this heat, which may result in a number of types of damage that lower the cell's efficiency and overall performance.

- Light-induced deterioration: Long-term exposure to sunlight causes solar cells to lose efficiency. This kind of degradation might also be brought on by solar radiation. The kind of silicon used in the solar cells or the presence of impurities may have an impact on this [42].
- Thermal stress: Sudden temperature variations can put the solar cell under thermal stress, which can cause the micro-cracking or delamination of the cell or other components. Light- and elevated-temperature-induced degradation (LETID) can cause a decrease in the efficiency of solar cells, which leads to a decrease in the power output of the PV module. This decrease in power output reduces the overall energy production of the PV system and can result in lower financial returns. Additionally, LETID can also cause physical damage to the solar cells, such as cracking, delamination, and corrosion, which can lead to a shorter lifetime of the PV module. This might decrease the cell's power output and increase existing damage [29,43].

Over the past few decades, the temperature of the Earth has notably increased. The data show that high temperature, humidity, moisture, and elevated air temperature are the main factors that cause degradation. The degradation rates vary between −0.8% and −4.9% per year. Research has also found that the average efficiency of multi-Si solar cells under various operating conditions ranges from 5.17% to 18%, with a mean annual efficiency of 8.7%. Proper installation and the use of certain technologies, such as passivated emitter and rear contact (PERC) modules, can help reduce degradation rates in hot climates. Wind velocity, solar irradiance, and cell temperature are also significant factors that affect degradation rates. Table 2 presents a summary of recent studies of PV degradation causes.

Table 2. Recent studies and findings of the main causes of PV degradation.

Reference	Country	Cell Type	Key Findings	Cause of Degradation	Degradation Rate
[44]	Australia	Multi-Si solar cell	Comparatively, a smaller number of hotspots were seen in hot weather conditions than in cold weather.	High temperature and humidity	−1.35% to −1.46%/year
[45]	Thailand	Multi-Si solar cell	One of the major degradation factors is moisture.	Moisture and humidity	−1.5% to −4.9%/year
[46]	India	Multi-Si solar cell	The main defects observed in PV modules after 28 years of exposure are encapsulant discoloration, delamination, oxidation of front grid fingers and anti-reflective coating, glass breakage, and bubbles in the back sheet.	Humidity and high cell temperature	−1.4%/year
[47]	Poland	Multi-Si solar cell	Up to 850 MW of rooftop PV can be installed in the city, which has the potential to reduce electrical-energy-related emissions by almost 30%.	Elevated air temperature	>−0.9%/year
[48]	Singapore	Multi-Si solar cell	Greenhouse gas emissions of 0.0811 kg CO_2-eq/kWh would decrease the annual emissions from campus electricity use by 27%,	Ambient temperature	−2.0%/year
[49]	Republic of Korea	Multi-Si solar cell	Low degradation in hot climates can be achieved for Al-BSF technology if properly installed to reduce heat transfer to thermally decouple the modules from the roof. They also found that monofacial and bifacial passivated emitter and rear contact (PERC) modules reduced degradation.	Discoloration and corrosion	−1.3%/year
[49]	Spain	Multi-Si solar cell	Regarding the total system efficiency of the power plants, the range for all years is between 10% and 12%.	Wind velocity	−0.8% to −1.1%/year
[50]	Greece	Multi-Si solar cell	The PV efficiency was found to be about 18% lower than that under standard laboratory test conditions and similar operating conditions. The mean annual PV efficiency was 8.7%.	Ambient temperature, solar irradiation, and wind speed	−0.9% to −1.13%/year
[51]	Cyprus	Multi-Si solar cell	The average efficiency was found to be 5.17% for a-Si, 15.40% for heterojunction with intrinsic thin-layer (HIT) cells, and 10.78% for multicrystalline silicon (mc-Si) modules.	Solar irradiance and cell temperature	−0.8% to −1.1%/year

3. Major Aging Factors of Solar PV

Scientists and academics have recently been more interested in the significance of producing electricity from solar PV for a variety of reasons, including reduced carbon emissions, long-term solutions for future energy sources, sustainable development, and industrial reliance. However, several elements influence the power generated by PV modules in such a manner that it entirely degrades with time. A visual representation of aging variables is shown in Figure 1. A solar panel generally has a 25-year lifespan. Throughout its lifespan, a solar panel's performance may be influenced both directly and indirectly by many factors. Dust, discoloration, delamination, crack humidity, and temperature are the main factors reducing efficiency.

Aging factors are technological and environmental elements that directly or indirectly contribute to the decline in PV performance. Although the rate of PV performance deterioration brought on by aging factors is extremely minimal over the short term, they can have a significant impact over the long term and can affect how long solar photovoltaic modules last. Over time, the efficiency loss rate for aged monocrystalline and polycrystalline panels is (0.7–1)% according to the Renewable Energy Laboratory (NREL) [20]. When solar panels are exposed to aging factors such as dust, delamination, discoloration, fractures, humidity, and temperature, they deteriorate much more quickly.

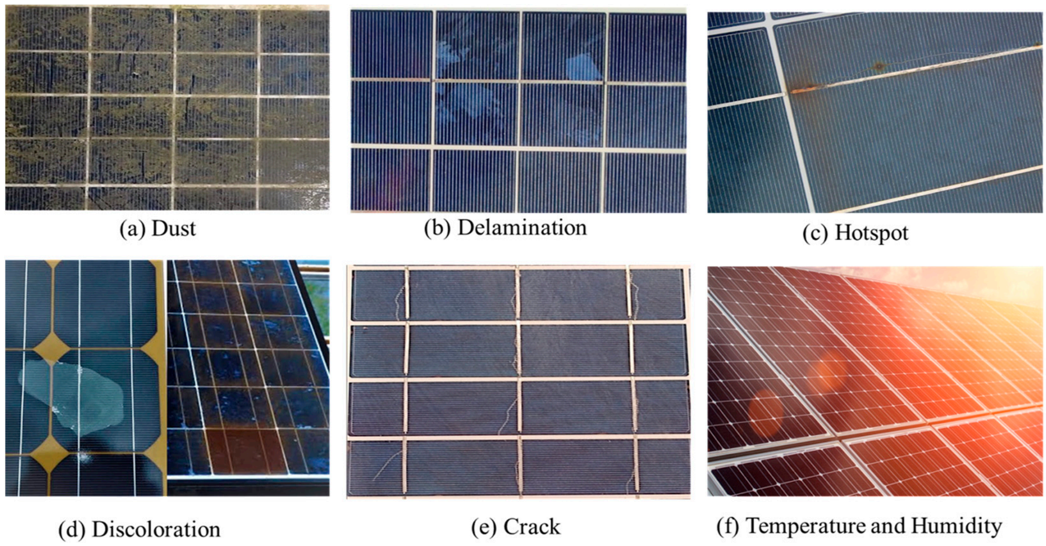
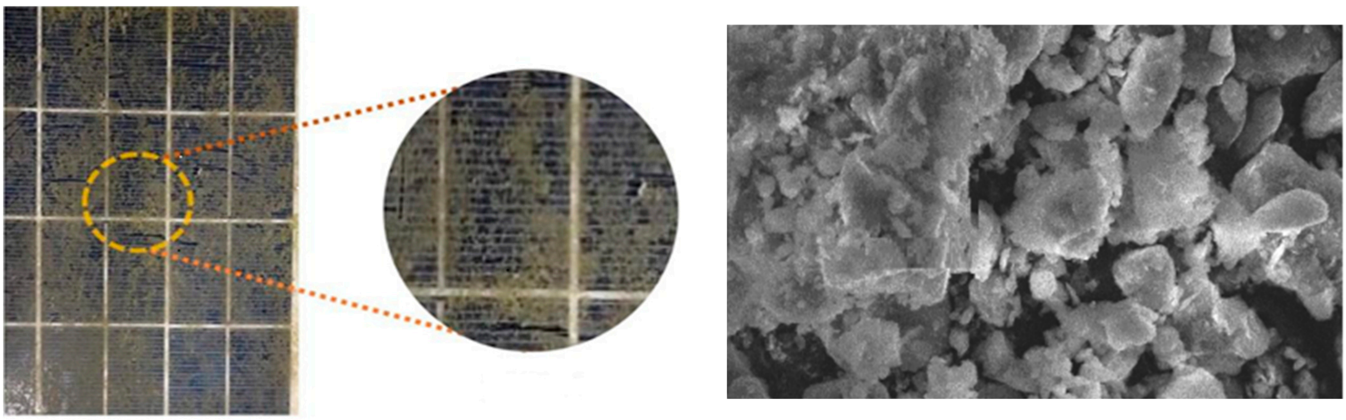


Figure 1. Key aging factors that affect the longevity of the PV module (this figure was developed from the original sample and experiments that were carried out in the laboratory).

3.1. Dust

Generally, dust is defined as small, solid particles with diameters of less than 500 µm. The particles are made up of dust in the air that originates from many environmental causes. The solar PV's output power decreases as a result of these airborne particles building up on its surface and causing shedding on the PV panel. However, the shape, size, and accumulation structure of dust may affect the shedding and its effect on both the lifetime and the efficiency of the PV module. The accumulation of dust particles on solar panels is shown in Figure 2, along with a microscopic image of these tiny particles. The significant influence that dust has on PV performance makes it one of the most critical issues confronting scientists and academics today.



(**a**) (**b**)

Figure 2. (**a**) Accumulation of dust on the PV surface and (**b**) microscopic view of the accumulated dust (this figure was developed from the original sample and experiments that were carried out in the laboratory).

Six photovoltaic modules were exposed to the elements for 6 months in a study by Adinoyi about the effect of dust accumulation on the solar photovoltaic module's output power [52]. The findings show that the output power of solar PV decreased by 50% with the accumulation of dust on a panel left uncleaned for 6 months. With time, this output decline became more pronounced, which caused the panel to permanently age. An experimental examination of the effects of dust deposition on solar PV was conducted by Aslan Gholami et al. [53]. The experiment was conducted for 70 days without any precipitation, and the rate of dust buildup was 6.0986 (g/m^2). The results indicate a 21.47% reduction in output power. Dust can form on the surface of photovoltaic (PV) panels through various mechanisms, which depend on the location and environment in which the panels are installed. Natural processes such as wind erosion, volcanic eruptions, and forest fires can generate dust particles that can travel long distances and settle on the surfaces of PV panels. Human activities such as construction, mining, and transportation can generate large amounts of dust that can be carried by the wind and deposited on PV panels. Agricultural activities such as plowing, harvesting, and livestock grazing can also generate dust that can settle on the surfaces of PV panels. A sawtooth wave shape of dust accumulation is typically seen [54,55]. Another investigation was performed by Ahmed Amine Hachicha et al. in the UAE climate, where it has been amply demonstrated that the tilt angle has a direct impact on the buildup of dust on the surface of the solar panel and that the dust density has a linear relationship with solar PV deterioration [56]. A solar panel's effectiveness decreases over time when it is dirty, and this process gradually and permanently ages the panel. Another investigation was performed by Juaidi et al. in Palestine, where a grid-connected PV plant was exposed for 7 months to determine the impact of dust on the efficiency of the entire PV plant, and the results indicate that the average rate of power reduction was 2.93% per month, which clearly shows that dust significantly influenced the power reduction in a large-scale PV system as well [57]. Kazem et al. evaluated the effect of aging on a grid-connected photovoltaic system by investigating a 1.4 KW PV plant exposed for 7 years; the results indicate that the efficiency of the PV modules decreased by 5.88%, and it is also notable that the degradation rate was severe during the summer months because of the dust density [58]. The rate of PV degradation has a linear relationship with dust density. Frost formation on solar panels can have a significant impact on the general performance of the panels. When frost forms on the surface of a solar panel, it creates a layer that reduces the amount of sunlight that can be absorbed by the panel. This, in turn, reduces the output power of the panel. The reduction in output power can be as high as 25% in a month, depending on the thickness of the frost layer [59].

Because of varying geographic conditions, the impact of dust differs from country to country. Saudi Arabia is one of the Asian desert countries where the rate of dust production is quite high and the weather is very dry. According to research, 6 months of PV panel neglect might result in a more than 50% reduction in output power [52]. Another Iranian study discovered that the tilt angle affects the amount of dust that accumulates on the PV module's surface. At tilt angles of 0°, 15°, 30°, and 45°, the dust accumulation was determined to be 33.4%, 15.8%, 12.1%, and 11.7%, respectively [60]. PV panels in a dry tropical climate, compared to mild regions such as China, are significantly impacted by dust as well. According to Chen et al., dust can lower power production by 7.4%, which is considerably less than in areas with deserts [61]. According to research conducted in Nepal, dust can reduce a PV module's effectiveness by 29.76% [62]. Scenarios demonstrating the impact of dust in Asian nations are shown in Table 3.

Table 3. Impact of dust in Asian countries on monocrystalline and polycrystalline solar PV modules.

Author	Country	Exp. Period	Panel Type	Dust Density	Experimental Conditions	Key Findings
Tafti and Yaghoubi [60]	Iran	8 months	Crystalline silicon	NA	Outdoors	The average daily energy output by PV modules was reduced by 8.6% when they were level and by 0.8% when they were tilted at angles of 15°, 30°, and 45°. Dust storms decreased the daily average energy produced by PV modules by 58.2%, 27.8%, 21.7%, and 20.7%, respectively, at tilt angles of 0°, 15°, 30°, and 45°. For PV modules with tilt angles of 0°, 15°, 30°, and 45°, the average decrease rates of daily energy output owing to dust collection were determined to be 33.4%, 15.8%, 12.1%, and 11.7%, respectively.
Adinoyi and Said [52]	Saudi Arabia	6 months	Both poly and mono	6.184 gm^2	Outdoors	Solar module output power dropped by more than 50%. A single dust storm has the potential to degrade a PV module's power output by up to 20%. When subjected to identical circumstances, polycrystalline modules' backside temperatures were marginally higher than those of monocrystalline modules. The majority of the particles were about 10 µm.
Javed et al. [63]	Qatar	2 months	Not mentioned	100 $mg\text{-}m^2/day$	Outdoors	The most abundant component in the collected dust was shown to be calcium. The collected dust's 90th percentile particle size (based on volume) was 32 µm.
Abbas et al. [64]	Pakistan	3 months	Polycrystalline	0.681 $mg\text{-}cm^2$	Outdoors	Due to dust accumulation on the PV modules' surfaces, the average output power decreased by up to 22% in June, 16% in July, and 18% in August, with an overall 3% reduction in efficiency.
Kazem and Chaichan [65]	Oman	-	Not mentioned	1 g/m^2	Laboratory	Output power decreased by 35–40%. Most particles ranged in size from 2 to 63 µm. Quartz silicates (SiO_2) and calcium oxide (CaO) made up the majority of the dust, accounting for 55.79% and 30%, respectively.
Chen et al. [61]	China	7 days	Monocrystalline	0.644 g/m^2	Outdoors	Reduced the PV output power by 7.4%. SiO_2 and $CaCO_3$ were the major components of dust.
Paudyal and Shakya [62]	Nepal	5 months	Polycrystalline	9.6711 g/m^2	Outdoors	Efficiency was reduced by 29.76%.

3.2. Discoloration

One of the key issues that contribute to the early aging of solar PV is discoloration. PV cells cause discoloration by altering the material's color. The encapsulant ethylene-vinyl acetate (EVA) corrodes as a result of this incident. EVA is a substance that transmits radiation well and degrades slowly under sunshine. This thermoplastic polymer is employed as an encasing agent in solar modules because, when heated, it creates a sealing and insulating coating around the solar cells. The aging of PET (polyethylene terephthalate) in addition to EVA (ethylene-vinyl acetate) can further cause delamination in photovoltaic (PV) modules. The aging of PET in the presence of EVA can cause delamination due to the formation of chemical bonds between the two materials, which weakens the adhesion between the layers. The aging process can be accelerated by exposure to heat, humidity, and ultraviolet (UV) radiation, which are common environmental stressors in PV applications. The delamination of PV modules can be a significant problem, as it can lead to the formation of air gaps and moisture ingress, which can reduce the efficiency of the module and ultimately result in its failure [66]. The presence of air pockets or voids between the solar cells and the EVA encapsulant layer can reduce the fill factor of a solar cell. When the EVA layer does not completely fill the gaps between the solar cells, air pockets can form, which can act as barriers to the flow of the electrical current. The fill factor (FF) is a measure of the efficiency of a solar cell, and it represents the maximum electrical power that can be obtained from the solar cell at the maximum power point, relative to the open-circuit voltage and short-circuit current. It is expressed as a percentage, and a higher fill factor indicates a more efficient solar cell. Light has multiple hues due to its different wavelengths, which are related to the fluctuating frequency and energy of the light source. Using a light source, solar cells generate electricity. As a result, the effect of light irradiance and other characteristics of sunlight, such as the frequency and photonic energy, have a significant impact on solar cells. The degeneration of solar cells is brought on by their discoloration, which can lead to irreversible cell degradation and accelerate aging [67–69]. This degradation is often seen after a prolonged period of exposure and worsens over time. Figure 3 illustrates the aging process due to discoloration.

An experimental test on how Moroccan deterioration affects PV performance was conducted by Bouaichi et al. The panel was exposed to the Mid-South Moroccan climate for two years, and the results indicate that the deterioration rate was an average of 7.56% each year [70]. This reduced the PV module's electricity output by 13.2 watts annually.

Solar panel discoloration and PV deterioration are directly related, according to a non-destructive assessment of encapsulant discoloration with crystalline silicon PV modules conducted by Sinha et al. [69]. They demonstrated that an electrical mismatch appeared to significantly speed up the encapsulant discoloration of the module. Non-uniform discoloration caused a significant loss in the fill factor, which in turn increased the series resistance of cell connections. To a lesser extent, the light reduction was directly responsible for the power degradation caused by discoloration. The electrical mismatch loss might result from encapsulant discoloration. Figure 4 shows the variation in the temperature of PV modules with and without discoloration in spatially resolved dark lock-in thermography (DLIT) pictures of two module pairs. The more brown the module is, the larger the mismatch loss [69]. When compared to similar non-brown modules (b and d) in the same module pair, the brown modules (a and c) show a larger temperature variance. By computing the standard deviation from the obtained pixel data of thermal pictures, the degree of mismatch was assessed. As they do not accurately represent mismatch-induced thermal effects, the extraordinarily hot pixels associated with severe localized faults were omitted from our calculations. The results demonstrate that, due to their discoloration, brown modules have larger electrical mismatches, which would also lead to a decrease in the FF and output power.

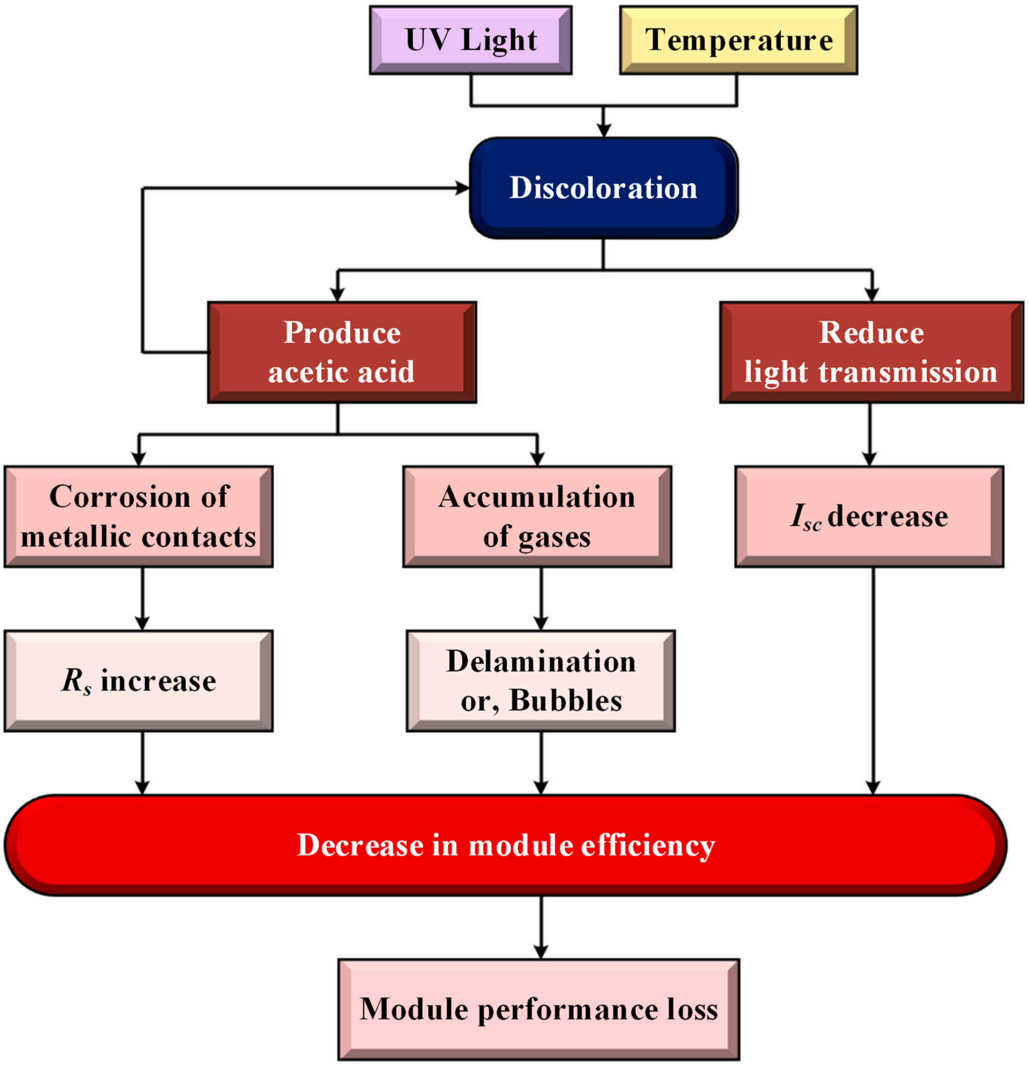
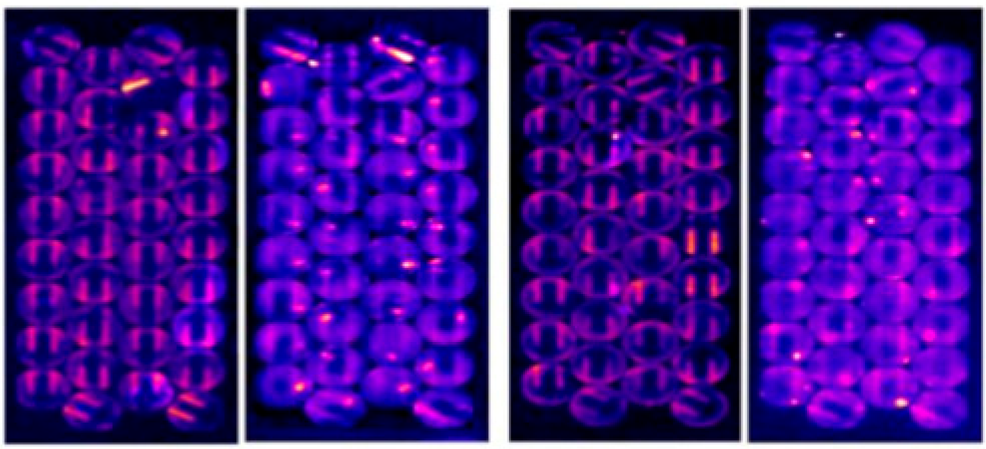


Figure 3. Flow chart of PV aging process through discoloration [69].



(**a**) (**b**) (**c**) (**d**)

Figure 4. Temperature variation in discolored and non-discolored PV modules [69].

In addition to Morocco, the deterioration and aging effects on PV performance were examined in Ghana, an African nation with a tropical climate, where 22 monocrystalline silicon modules were exposed for 16 years. The experiment was carried out by Quansah et al., who found that discoloration was a major factor in the module's maximum power being lowered by 24.6% [13]. With a growing proportion of cell discoloration, the PV cell performance degrades in terms of power output. The PV panel will eventually become completely ruined if the discoloration process continues to progress in it.

3.3. Cracks and Hotspots

The thickness of solar cells can vary depending on the specific type and design of the cell. However, crystalline silicon solar cells are typically between 150 and 200 µm (0.15–0.2 mm) thick. A hotspot is a localized area of elevated temperature on a solar photovoltaic (PV) panel that is brought on by a high resistance in one or more of the panel's cells. This can happen when a solar cell receives less sunlight than the other cells in the panel due to a shadow or other impediment partly covering a piece of the cell. Because of this, the shaded cell produces less energy than the other cells, which may result in a reverse current flow through the shaded cell, which might cause overheating and possibly irreparable harm [71,72]. When solar cells are exposed to changes in temperature, the materials they are made of can expand or contract. If the temperature changes are significant enough, this expansion or contraction can cause stress on the materials, which can lead to cracking or other forms of damage to the cell. The expansion and contraction of solar cell materials can also affect the overall integrity of the solar panel that the cell is a part of. If the solar panel is not designed to allow for thermal expansion and contraction, it can also be subjected to stress and damage. It is crucial to pick materials with great thermal stability when creating solar cells. Spotting hotspots early by obtaining infrared photos of modules can assist in boosting the power production and lifespan of the photovoltaic system. As a result, the use of focused solar radiation in photovoltaic installations can boost the specific power of photovoltaic modules while simultaneously maintaining the temperature of the solar cells within them. In silicon solar cells, hotspots can occur when a portion of the cell becomes shaded or otherwise blocked from the sun while the rest of the cell continues to generate power. This can cause the shaded area to become reverse-biased, which can lead to a buildup of heat and a potential hotspot. Hotspots in silicon cells can cause permanent damage to the cell and reduce the overall power output. In concentrating solar cells, hotspots can occur due to the concentration of sunlight onto a small area. This can cause high levels of heat to build up, leading to thermal stress and potential damage to the cell. Concentrating solar cells are particularly vulnerable to hotspots due to the high levels of concentration involved [73,74]. Hotspots can also develop as a result of manufacturing flaws or cell damage, including micro-cracks or faulty cell interconnections. These flaws might result in high resistance in the afflicted cells, which will heat up the area in question and perhaps harm the panel over the long run [75–77]. Another frequently occurring drawback of solar PV modules is cracking, which generally happens because of the expansion of the solar cell. During the day, the silicon cells, which are very thin, expand and contract because of higher temperatures, which cause small imperfections that lead to larger micro-cracks [78–80]. Cell cracks in solar photovoltaics can also occur while transporting or installing them; environmental factors such as snow, strong winds, and hailstorms can cause cracks in the solar panel as well [81,82]. Different types of cracks can occur in PV modules, including diagonal, parallel to the busbar, and perpendicular to the busbar. However, diagonal cracks cause significant degradation of the output power of solar photovoltaics over time, which can cause permanent aging. Furthermore, the number of PV panel fractures is a significant matter when the output power is reduced. The output power's deterioration is significantly impacted by only 60% of the total fractures [77]. Photovoltaic (PV) modules are subjected to mechanical and thermomechanical strains in outside settings, according to Niyaz et al., which causes the solar cells to develop fractures. Cracks can cause electrical outputs between cells to become imbalanced, which causes an uneven distribution of temperature and has a rapid impact on the performance and long-term dependability of PV modules [83]. Cracks make the solar cell uneven and serve as locations for carrier recombination that reduce EL emission. The results showed that micro-cracks in PV modules can cause power losses of 30% (Humaid Mohammed Niyaz). From the above literature, it can be stated that the classification of cracks based on their properties is the key to analyzing the effects of cracks on the temperature distribution of PV modules. Generally, cracks in PV modules are classified as micro-cracks and cracks based on UV-F (ultraviolet photoluminescence) and EL (electroluminescence) images. The foundation of UV-PL imaging is the idea that when exposed to UV radiation, damaged solar cells will produce less photoluminescence than undamaged ones. Using this method, UV light is used to ignite a solar cell, and a camera or other imaging device is used to record the photoluminescence that results. The resulting image can then be examined to find regions of decreased photoluminescence, which point to cell injury [84]. The EL imaging method is based on the idea that when a voltage is applied to a solar cell, damaged portions will release less light than undamaged ones. This method involves electrically biasing a solar cell to create an EL signal, which is then recorded by a camera or other imaging equipment. The resulting image can then be examined to find regions with a weaker EL signal, which indicates the existence of cell damage. The specific application and type of damage being identified determine the metrics utilized in UV-PL and EL imaging. The strength and dispersion of the photoluminescence or EL signal that is released, the homogeneity of the cell surface, and the presence of flaws or other irregularities in the cell structure are some frequent metrics employed in UV-PL and EL imaging. These metrics can be used to evaluate the overall performance and quality of a solar cell as well as to identify and measure the degree of damage in the cell [85]. Bdour et al. present a summary of data collected from various projects in Jordan to explain the impact of each micro-crack form on power loss and to guide decision-makers in replacing failed panels according to their terms of exchange [86]. Therefore, micro-cracks have different impacts on power loss, with polycrystalline technology having power reduction rates of 0.82–3.21%. The degradation variation depends on module conditions. For monocrystal technology, the power loss varied between 0.55% and 0.9%, except for some samples of both technologies, with effects other than micro-cracks severely affecting performance [44]. Gabor et al. showed that decomposition is largely related to recombination and shunting along cracks rather than the loss of active area [87]. Gabor et al. also presented a comparison of module efficiency and irradiance for three cases. As with single-cell coupons, after charging and cracking, the module had less irradiance than before charging, resulting in a significant drop in efficiency. An undamaged module dropped by 3.9% at 0.2 suns, while a charged module dropped by 9.2%. Interestingly, the efficiency further decreased under 1 sun after cycling, but the decrease was less severe at lower irradiances, so the module was more efficient under 0.2 suns than before cycling at 0.2 sunlight and only dropped by 5.6%. This can be explained by the fact that cyclic loading opened some cracks, effectively removing some areas of cells with internal cracks from the circuit. A shorter total length of cracks remaining in the active area of the cell results in recombination and less rapid decay at reduced irradiance, whereas a reduced active area results in lower efficiency at higher irradiances. Table 4 summarizes the crack and hotspot effects.

According to Dhimish et al., mechanical or thermal strains that partially or fully separate areas inside the solar cell are the major causes of fractures that commonly affect both solar cells in the millimeter to micron range [88]. Manufacturing, the process of transporting the module to the PV site, the installation procedure, a lot of snow, or physical damage to the module can all lead to stress. Cell tearing can be decreased by improving these procedures. Manufacturing will inevitably produce cracks. Dhimish et al. further point out that when the wafer thickness drops, the cracking issue in solar cells becomes worse. This is because the cells' lower thickness makes them more vulnerable to extra mechanical stress when they are put together into a complete PV module. In 60-cell PV modules, if the cell region is not insulated, this frequently results in cell cracking and a performance decrease of up to 2.5%. However, as fractures result in hotspots, several attempts have been made to reduce the impact of hotspot solar cells by employing power electronic devices to control the current delivered to the impacted cells. Similar to one another, these methods use a high-frequency switching component to adjust the module's current without disrupting the connection between the module and the power converter. PV module crack development is shown in Figure 5.

Table 4. Studies performed on crack and hotspot effects on solar PV.

Refs.	Objectives	Contribution	Identification Methods
[77]	Impact of a crack on PV performance	Only 60% of the total crack has a significant impact on the power deduction in the investigated PV modules	Statistical approach
[83]	Impact of cracks on crystalline silicon photovoltaic modules' temperature distribution	The temperature distribution in the PV module depends not only on the type of crack but also on the bias of cracked cells and the number of cracked cells. Shading of a cracked cell can lead to a temperature difference in the range of 10 °C to 26 °C.	Electro-thermal model
[86]	Impact of micro-cracks on PV power reduction	Micro-cracks reduce the power of polycrystalline PV modules by percentages of 0.82–3.21%. For monocrystalline PV modules, the rate varies between 0.55% and 0.9%.	EL imaging method
[87]	Impact of PV design factors on reducing the crack effect	From the cell design level to the system installation level, the authors proposed a broad range of solutions that can stop the crack's effect on PV modules, including thicker wafers, greater busbar input, parallel wiring of cells, etc.	Not applicable

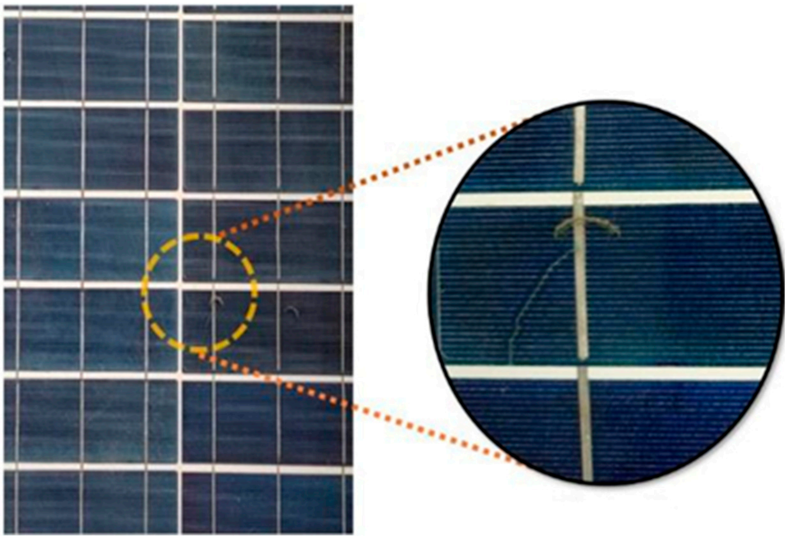


Figure 5. Formation of a crack in a PV module (this figure was developed from the original sample and experiments that were carried out in the laboratory).

3.4. Delamination

The phenomenon of delamination is the separation of laminated solar panel parts from one another. Due to delamination, the production output for the panels will considerably decrease. EVA (ethylene and vinyl acetate), glass, the back sheet, and other raw materials used to make solar photovoltaic modules can become contaminated and consequently delaminate. In addition, the delamination of panels is caused by the environment's high temperature. Other than that, a lot of evidence suggests that delamination is a sign of the solar panel manufacturer's shoddy manufacturing process. The delamination of solar panels causes degradation, which is usually seen after a long period of exposure and soars with time. Figure 6 presents the degradation process through delamination.

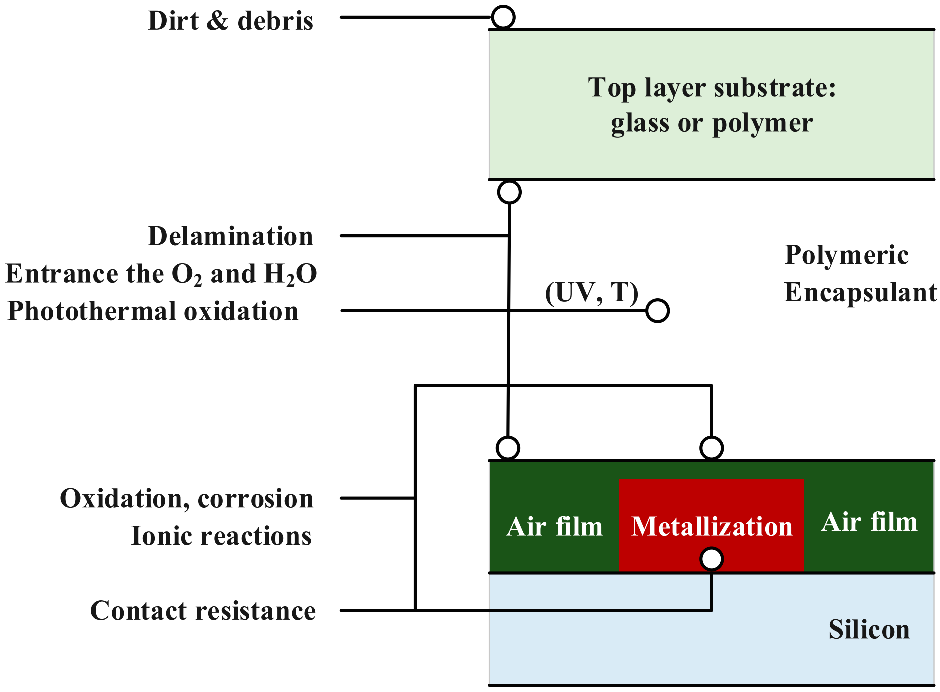


Figure 6. PV degradation process through delamination [89].

A review was presented by Oliveira et al. in which they discuss ethylene-vinyl acetate copolymer (EVA) deterioration in crystalline silicon photovoltaic modules, including its origins and consequences [89]. The generation of acetic acid and other hazardous gases is caused by the photodegradation of EVA by UV light, which also raises temperatures. These gases may result in bubble formation or delamination, which will lower the performance of the PV module. Figure 6 depicts the delamination-based deterioration process. Fonseca et al. performed a degradation analysis of a photovoltaic generator made up of 48 solar panels after it had been operating for 15 years in southern Brazil [4]. The results show that EVA darkening affected 100% of the module cells and produced a milky pattern. Twenty-four of its seventy-two cells were not functioning correctly because of a faulty internal electrical junction. The average installation power had decreased by 9.50%, or 0.7% annually, according to the electrical characterization of the I-V curve data gathered before and after the 15 years of operation for each of the 48 modules. The current decrease (9.19% and 9.12% for IMP and ISC, respectively) was mostly to blame for this power loss. In their experiment on the electrochemical processes of leakage-current-enhanced delamination and corrosion in Si photovoltaic modules, Li et al. demonstrated delamination on the metallization of an Arco Solar module after 27 years of field exposure [90]. The electrochemical reaction on cell metallization results in corrosion and delamination, which are influenced by leakage current, which can be produced by temperature, humidity, and contaminants. The ionic composition of the leakage current can trigger electrochemical reduction processes that result in hydrogen and hydroxide ions when the cell bias is negative. On the metal surface, hydrogen gas can build up, which encourages delamination and reduces the output power. Figure 7 shows a realistic representation of PV delamination.

In the western Himalayan area of India, Chandel et al. performed a degradation study of 28-year field-exposed mono-c-Si photovoltaic modules of a direct coupled solar water-pumping system [46]. PV modules visually displayed considerable cell delamination. Additionally, it was discovered that the PV deterioration rate had increased by 1.4% yearly, which is equal to India's 1.45% degradation rate for monocrystalline modules. Sequential and combined acceleration tests of crystalline Si photovoltaic modules were performed by Masuda et al. [91]. Several variables contribute to degradation when exposed to the elements outside, such as high temperatures, high levels of humidity, thermal cycling, UV rays, current flow, high voltage, salt spray, and mechanical stress. The results, however, indicated that Pmax only slightly degraded throughout the TC (thermal cycling) test, which also included the HF (Humidity Freeze) test, a delamination phenomenon frequently seen in PV modules exposed to the outdoors for an extended period. The delamination impacts are summarized in Table 5.

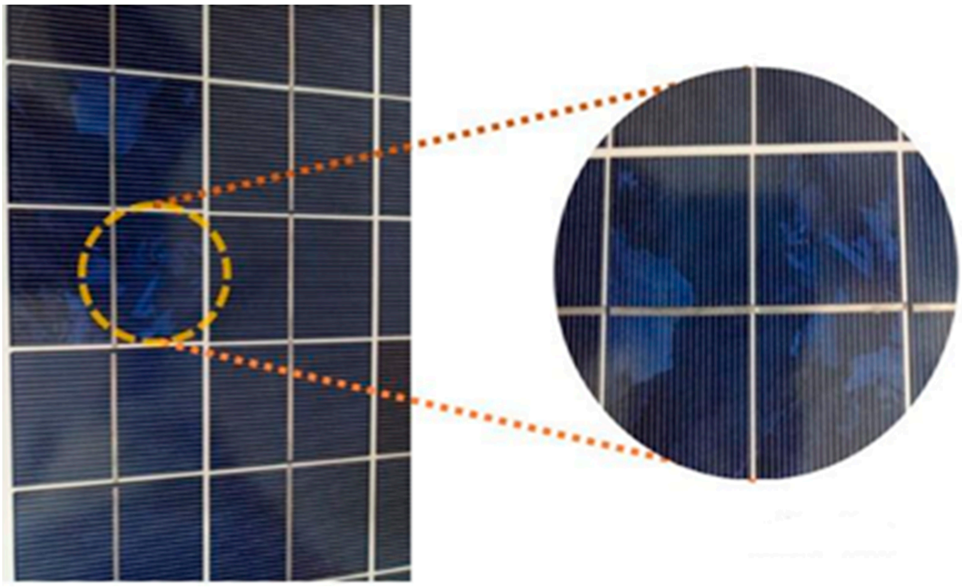


Figure 7. Delamination in solar panels (this figure was developed from the original sample and experiments that were carried out in the laboratory).

Table 5. Effect of delamination effect on PV aging.

Refs.	Objective	Contribution	Limitation
[89]	Cause and effect of EVA degradation	This study provides a thorough analysis of the research on EVA degradation and its effects.	Although aging is one of the key effects of EVA degradation, no precise rate of degradation owing to EVA failures has been determined, according to this study.
[30]	Degradation analysis of 15-year-old PV system	The most frequent defects found were browning (discoloration) and delamination. The average degradation rate was 0.7%/year.	This investigation only focused on discoloration and delamination; however, this PV system was affected by environmental factors too, which were not considered in detail in the discussion.
[90]	Electrochemical failures of Si PV modules due to delamination and corrosion	The electrochemical reaction on cell metallization results in corrosion and delamination, which are influenced by leakage current, which can be produced by temperature, humidity, and contaminants.	No specific degradation rate or relation between aging and delamination was shown.
[46]	Degradation analysis of 18-year-old PV system	Encapsulant discoloration, delamination, and oxidation were the principal flaws. The average power degradation was 1.4%/year.	This study was conducted in an irrigation field where dust is a prevalent component that affects PV modules. However, the authors failed to take this into account.

3.5. Temperature and Humidity

Kinetic energy is transferred from one thing to another through heat. Here, the heat comes from the sun, which is transferred to the PV panels and raises the temperature. Temperature is a measure used to describe how warm or cold something is. The environment's high temperature creates moisture or humidity, which is one of the main elements affecting how well the PV panels perform [92]. With the installation time, this impact grows.

Vásquez et al. experimented with the processing of global climate data and the mapping of the mechanisms and rates of PV module degradation [93]. The Köppen-Geiger-Photovoltaic (KGPV) climatic classification and the anticipated deterioration rates, according to Vásquez, have a direct association. The average rate of deterioration in Europe's hot temperate zones is around 0.5%. However, depending on the year, this figure might change. Additionally, this shows that climate change may influence the long-term effectiveness of PV systems. Another study was conducted by Dhimish et al. on the photovoltaic degradation rate affected by different weather conditions based on PV systems using the YOY (year-on-year) technique for more than 10 years (2008 to 2017) for six distinct photovoltaic (PV) sites in the UK, which is mostly influenced by cold weather conditions, and Australia, which is primarily affected by cold weather conditions. It was discovered that the UK sites' deterioration rates ranged from −1.05% to −1.16 %/year [94]. However, because the temperature is lower than in Australia, a greater deterioration of between −1.35% and −1.46%/year was seen for the PV sites deployed there [88]. Research on the effects of humidity on photovoltaic cell performance was presented by Hamdi et al. [95]. Water has an impact on photovoltaic units when it comes into contact with the cellular elements of the cell, causing its efficiency to decrease and lowering its electrical productivity. The efficiency of solar cells was significantly reduced when they worked in challenging conditions, such as high temperatures and relative humidity of more than 70%. The effects of various environmental and operational parameters on PV performance were reviewed by Hasan et al. [18]. According to their study, the PV module performance degrades with increasing module temperature. Without a cooling facility, the efficiency decreases by around 0.03% to 0.05% for every 1°C increase in temperature. They advise selecting materials carefully so that they can tolerate a humid environment since the corrosion of the PV panel is caused by moisture ingress in humid settings. Tripathi et al. evaluated the performance of solar PV panels in a humid environment [60]. The findings of the experiment show that a rise in the humidity of 50.15% caused a reduction in solar radiation of 24.05% on the panel surface. Additionally, this investigation demonstrated that a rise of 50.15% in relative humidity caused a loss of 36.22% in the panel's output power. However, when the humidity increased from 65.40% to 98.20%, the temperature of the PV panel was lowered by 11.40%, indicating an increase in output power. Table 6 presents a summary of these results.

Table 6. Effects of high temperature and humidity on PV degradation.

Refs.	Objective	Findings	Drawbacks
[93]	Global mapping of degradation and degradation rate of PV module based on temperature effect	The average degradation rate of PV modules in a hot climatic zone is 0.5%/year.	Although a great mapping of PV degradation is shown, aging factors such as cracks, dust, and delamination may have distinct effects that are not reflected in this global degradation map because the mapping is primarily based on temperature or climatic conditions.
[60]	Performance of PV module under humid atmospheric conditions	When the humidity level rises by 50.15 percent, the panel's power output falls by 34.22 percent	The experiment was conducted in a lab setting. It is still necessary to research how natural humidity will affect the results.
[95]	Impact of humidity on PV cell performance	When working in conditions of high air temperature and high humidity (above 70%), PV cells' efficiency is significantly reduced.	The temperature of the cell, which has a significant impact on PV deterioration and longevity as well, was not taken into consideration in this study, which was focused on the humidity effect on the PV cell.
[18]	Effect of environmental factors on PV degradation	Dust accumulation in humid circumstances produces sticky, adhesive mud, which lowers power output by 60% to 70%.	The technical problems with PV degradation, such as cracks, were not covered in this study's thorough analysis of PV degradation and associated mitigation strategies.

4. Impacts of Aging Factors on PV Module

4.1. Impact of Aging Factors on Lifespan

Generally, the life expectancy of solar panels is 20–30 years, and this period can be decreased by the influence of some aging factors. Aging factors influence the solar panel in such a way that it starts to slowly lose its power generation capability. The continuation of this process for a long period triggers the reduction in power generation and, after a time, the solar panel is fully degraded before its expected lifespan.

The performance of solar PV is significantly impacted by dust. The efficiency and output power of solar PV are reduced by the uniform deposition of dust on the surface. The type of dust and the length of time over which it builds depend on the solar PV system's lifetime; dust comes in many different forms, including biological dust, industrial dust, agricultural dust, and airborne dust [96]. Although the output power and efficiency of the solar panel are reduced by airborne dust accumulation, this can be improved by cleaning the PV module. However, if the panel is left dirty for an extended time, such as a year or more, this can affect the light transmission into solar cells because dust particles cause partial shedding, which causes the solar panel to mismatch and develop hotspots, which causes the PV module to age [97]. Bird droppings and other biological dust have a higher impact than airborne dust. Its increased size can result in a 31% reduction in transmittance, which leads to partial shedding and causes the panel to mismatch and develop hotspots [98]. For 15 g of dust deposition, agricultural dust such as mud, rice husk, compost, etc., can result in a maximum power loss of 51.82% [96]. On the other hand, industrial dust such as gypsum and coal can decrease a panel's efficiency by 64% and 42%, respectively [99]. Therefore, it is evident that this will decrease the PV panel's transmittance and result in partial shadowing, both of which will shorten the panel's lifespan [96]. The graph in Figure 8 was created after an in-depth study of Ref. [96], which shows the PV power loss caused by dust accumulation.

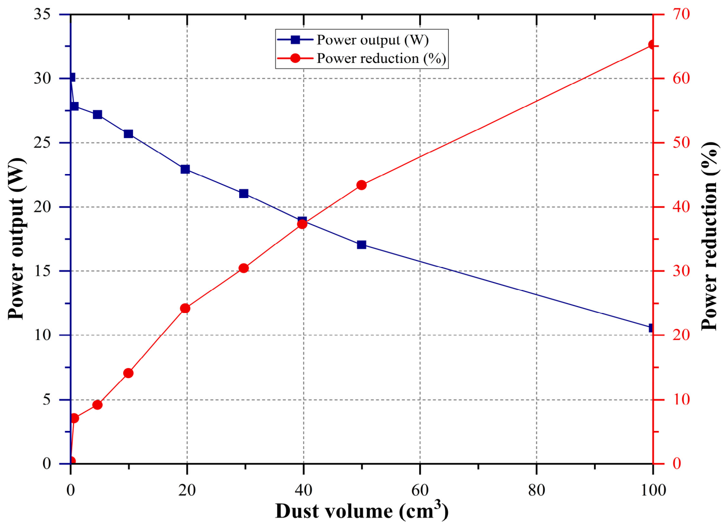


Figure 8. Reduction in PV output power due to the accumulation of dust panels.

Temperature and humidity have a variety of consequences on PV cells that can lead to cell failure and early panel deterioration. The bypass diode problems with PV panels are more prevalent in hot climates such as Australia than they are in cold climates. However, compared to hot tropical climate zones, PV panels installed in cold climate zones, such as the UK, exhibit more hotspots [100]. Rapid changes in the surrounding temperature can also lead to PV panel glass breakage. Due to thermomechanical stress, cracks in the solar cell can be seen. Solar cells with cracks in them can still produce a current, but the voltage will be lower and the output power will be reduced. With time, the percentage of cracks increases, increasing the number of damaged cells [101]. As a result, the PV panel deteriorates earlier than expected. Due to decreased light reflectance and transmittance caused by discoloration and delamination (D&D), which can cause both short-term and long-term deterioration, cell damage, and a reduction in maximum power, the PV panel degrades earlier than predicted [53].

4.2. Impact of Aging Factors on Efficiency

Age-related factors have a significant influence on the PV panel's efficiency. Dust can lower a panel's efficiency by 11.86% and the performance of the entire system by 7.4% [102]. In Nepal, the efficiency fell by 29.76% as a result of dust buildup [62]. Although other aging factors significantly contributed to the decline in solar panel efficiency, dust had a significant influence on the performance of solar PV. D&D reduced the output power by 17.9%, which had an impact on both the module's and the entire system's efficiency [103]. Temperature is one of the main environmental factors that influence efficiency and cause PV aging. The temperature may have a variety of effects on a PV panel's efficiency. Since the semiconductor is utilized to construct the PV cell, it may also result in additional PV failure concerns, including discoloration, delamination, and hotspots. The effect varies from region to region. With rising temperatures, PV panels' output current, voltage, power, and overall efficiency all drop. When the cell temperature drops below 25°C, the current decreases, while the voltage and output power rise. In general, a silicon solar PV module's efficiency can drop by 0.5% for every degree that the temperature rises. After careful analysis of Ref. [104], a graph was developed that shows the reduction in power due to dust. Some models can assess how the temperature affects photovoltaic properties. For evaluating PV performance, there are a number of cutting-edge modeling methodologies, including electrical, thermal, and coupled modeling. The dynamic electrical–thermal behaviors of PV devices can be predicted by a linked electrical–thermal model. In the coupled model, the electrical and thermal behaviors are predicted using a five-parameter SDM and a heat transfer PDE, respectively. Experimental I-V and P-V curves were used to first confirm the validity of the electrical sub-model. Based on this, the coupled model was completely validated using data from five consecutive summer days of field measurements [105].

4.3. Impact of Aging Factors on Material Degradation

A fundamental aspect of a PV cell's deterioration is material degradation or internal degradation, which may not be visible to the naked eye but affects solar PV's performance. The deterioration of solar cells is brought on by the reduction in the semiconductor band gap that occurs at increased ambient temperatures [106]. The gaps may be lowered by 1.569 eV to 1.508 eV for perovskite solar cells [107]. The reduction in PV panel output power caused by accumulation of dust is shown in Figure 9.

One of the biggest reasons why PV cells degrade is also due to the EVA encapsulant's change in color. Stress factors, including high temperatures and humidity, are significant in the case of EVA degradation, which causes cell aging to occur quicker than planned. Potential-Induced Deterioration (PID), which has a substantial impact on PV modules, is an additional cause of the significant degradation of PV modules. One of the aging variables that were significant in initiating the effect of PID is dust. The PV module's collected dust particles lower the irradiation. After 96 h of PID testing, it was demonstrated that the results are 2–4 times better at lower irradiances than at higher irradiances [108]. Table 7 illustrates the contributions of aging factors to PV degradation. In Table 8, a summary is provided.

Overall, dust accumulation on the surfaces of PV modules can reduce their efficiency by blocking sunlight and increasing the operating temperature, leading to thermal degradation. Discoloration caused by exposure to UV radiation can also reduce efficiency by absorbing less sunlight. The delamination of encapsulant layers can lead to moisture ingress, which can cause corrosion and ultimately lead to module failure. Hotspots, caused by shading or cell mismatch, can cause localized heating and material degradation, which can reduce the lifespan of the module. Cracks can also lead to reduced efficiency and material degradation by allowing moisture and other contaminants to enter the module. In addition, the mechanical stresses caused by thermal cycling and wind loading can exacerbate cracking and further reduce the module's lifespan. The degradation of photovoltaic (PV) modules due to various factors, such as dust, discoloration, delamination, hotspots, cracks, temperature, and humidity, can have a significant impact on their performance and lifespan. The following are some mitigation strategies to reduce the impact of these factors:

- Dust: Regularly cleaning PV modules is essential to prevent dust buildup, which can reduce the amount of sunlight reaching the cells. Cleaning can be performed using water or a soft brush, but care should be taken not to scratch the surface of the module.
- Discoloration: The discoloration of PV modules can be caused by various factors, such as exposure to UV radiation, extreme weather conditions, and chemical damage. To mitigate this, it is recommended to use high-quality materials with UV stabilizers and to avoid exposure to harsh chemicals. Regular maintenance and inspection can also help detect discoloration early and prevent it from spreading.
- Delamination: Delamination is the separation of layers in a PV module, which can lead to reduced performance and even complete failure. To mitigate this, it is essential to use high-quality materials and to ensure proper installation and maintenance. In the case of delamination, the affected area should be promptly repaired or replaced.
- Hotspots: Hotspots occur when a small area of a PV module generates more heat than the rest of the module, which can lead to reduced performance and even damage. To mitigate this, it is essential to use high-quality materials and to ensure proper installation and maintenance. Additionally, PV modules with bypass diodes can help prevent hotspots by redirecting the current around the affected cells.
- Cracks: Cracks in a PV module can reduce its performance and lifespan. To mitigate this, it is recommended to use high-quality materials and to ensure proper installation and maintenance. Regular inspections can help detect cracks early and prevent them from spreading.
- Temperature: High temperatures can reduce the performance of PV modules and shorten their lifespan. To mitigate this, it is recommended to use materials with high thermal conductivity and to ensure proper ventilation and shading. Additionally, PV modules with anti-reflective coatings can help reduce the amount of heat absorbed by the cells.
- Humidity: High humidity can lead to corrosion and other forms of damage in PV modules. To mitigate this, it is recommended to use materials that are resistant to corrosion and to ensure proper installation and maintenance. Additionally, regular inspections can help detect and prevent damage caused by humidity.

Table 7. Degradation rates of various aging factors.

Aging Factors	Degradation Rate	Area of Degradation
Dust [60]	5.88%	Efficiency
Discoloration [13]	24.6%	Maximum output power
Delamination [4]	9.50%,	Output power
Hotspot [77]	1.45%	Output power
Crack [89]	2.5%.	Performance ratio
Temperature [96]	0.5%	Efficiency
Humidity [61]	36.22%	Output power

Table 8. Impact summary of aging factors' contributions to PV aging.

Impacts	Reference	Effects	Contributions	Research Gaps
Efficiency	[98]	Solar PV systems' efficiency can be severely reduced by dust. Dust efficiency decreased by 64%, 42%, 30%, and 29% with various types of industrial dust, such as coal, aggregate, gypsum, and organic fertilizer, respectively.	The authors looked at many sorts of dust and discovered that of all the dust they looked into, coal had the greatest impact on efficiency loss. The authors also asserted that when the temperature rose, PV performance decreased because of heat loss caused by dust buildup.	The research noted that dust buildup raised the module's temperature, but no analysis of the effects of high temperatures or their relationship with dust accumulation was performed.
	[102]	Bird droppings, dust, and water droplets reduced the output power by 8.80% and the efficiency of solar PV by 11.86%.	Although environmental elements, including dust, moisture, and bird droppings, drastically affected efficiency, a water droplet on a PV module's surface lowered the temperature, which was able to increase the output power by 5.6%.	The influence of several environmental conditions on efficiency deterioration was demonstrated by the authors, but further research is still needed to determine how these factors affect other aging aspects in PV modules, such as discoloration or delamination.
Lifespan	[44]	Climate variables such as humidity and temperature affect how long solar panels last, and the rate of PV deterioration is higher in cold weather (UK) than it is in hot weather (Australia). For the UK and Australia, respectively, the deterioration rates range from 1.05% to 1.16%/year and 1.35% to 1.46%/year. Furthermore, the significant danger of glass breakage is brought on by the chilly climate.	The authors found that no bypass diodes were damaged in cold climatic conditions, and the number of hotspots found in cold climatic conditions (UK) was less than in hot climatic conditions (Australia).	The interrelationship between temperature and aging factors and how it affects the lifespan of PV modules is not thoroughly discussed, despite the authors' excellent investigation of PV degradation in two opposing climatic conditions, which revealed sporadic indications of various aging factors, such as hotspots and cracks.
	[101]	The possible impact of a crack and its position on output power degradation might significantly shorten the PV panel's expected lifetime.	The significance of a crack depends on the percentage of damage to a PV cell. This study found that 50% of damaged cells are cracked parallel to the busbar.	It was not thoroughly addressed how percentages of damaged cells, cracks, and crack orientation affect output power.
Material degradation	[106]	As the temperature rises, the lattice scattering worsens and the semiconductor's carrier mobility worsens. A high ambient temperature will widen the band gap on the PV surface, diminish photon absorption, and deteriorate the semiconductor.	When the temperature is increased to 30 °C and 70 °C, the electron mobility decreased from 114 $cm_2/(Vs)$ at temperature T = 0 °C to 98 °C and 82 $cm^2/(Vs)$, respectively.	Although the authors claimed that rising ambient temperatures increase band gaps, reduce electron mobility, and increase photon absorption, there is no clear evidence of how quickly materials degrade with each increase in temperature.
	[13]	The most common visibly noticeable flaws on the modules were encapsulant discoloration and junction-box adhesive deterioration.	Maximum power can be degraded by 18.2–38.8%. The annual linear degradation rate was 1.54%.	A 16-year-old PV module was studied by the authors, but further research is still needed to determine what would happen in the event of a relatively short exposure duration.

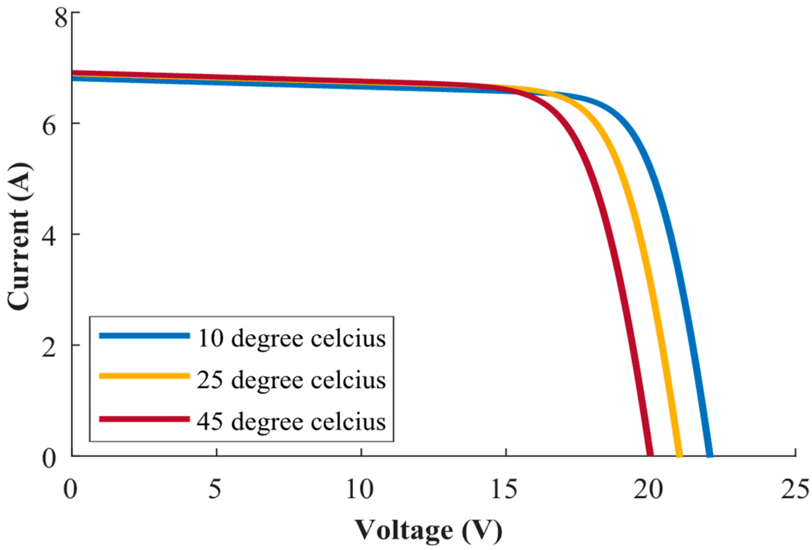


Figure 9. Reduction in PV output power due to the accumulation of dust panels.

5. Future Directions for Mitigating the Impacts of Aging Factors on PV Modules

Based on the critical discussion, information, and analysis, this study offers the following effective suggestions for sustainable energy management for solar PV.

- This study found that dust is one of the main components that accumulate on the PV module's surface and causes shedding, decreases photon absorption, and increases PV module degradation in a variety of ways, including output power reduction and efficiency degradation, which decrease the PV module's lifespan and efficiency as well. Therefore, more research is needed to understand how the form, size, and accumulation direction of dust particles impact the rate of deterioration and lifespan of PV modules.
- The encapsulant material's discoloration can reduce the module's transparency, which in turn reduces the quantity of light that reaches the solar cells and the module's total power production. Additionally, discoloration raises the module's temperature, making it more vulnerable to thermal stress, which can lead to cracking and other types of physical damage. As a result, the module's lifetime, power-generating capability, and efficiency may all decline. Hence, an in-depth investigation is necessary to prevent discoloration.
- A PV module's stability and structural integrity may be impacted by delamination, which happens when its layers split or detach from one another. By lowering the amount of light that reaches the solar cells and by raising the resistance in the module's electrical circuit, delamination can also result in a decrease in the performance of the module. This may cause the module's efficiency and power output to decline, which will lower its overall performance. To reduce the effect of delamination on the deterioration and longevity of PV modules, extensive investigation is required. It is also crucial to employ high-quality, long-lasting materials and construction methods, as well as to properly maintain and monitor the condition of the PV modules. Additionally, regular inspections and preventative maintenance can also help identify and address any delamination-related symptoms before they cause serious harm.
- The creation of fractures in solar cells because of mechanical and thermomechanical stresses causes the PV modules' electrical outputs to become imbalanced. According to this study, diagonal fractures significantly reduce the output power, efficiency, and lifespan of PV modules. The impact of cracks also depends on their direction. To reduce the effect of cracks on the deterioration and longevity of PV modules, further analysis is thus necessary. It is also crucial to employ high-quality, durable materials and construction processes, as well as to properly maintain and monitor the status

of the modules. Regular inspections and preventative maintenance can also aid in identifying and addressing any cracks before they cause serious harm.

- The materials used in the manufacturing of the module, such as the encapsulant material, solar cells, and metal frame, can experience thermal stress at high temperatures. This may result in physical damage, such as warping, cracking, and other issues. High temperatures can also slow down the deterioration of the module's materials and lower the danger of electrical failure. To reduce the effect of temperature and humidity on the deterioration and lifespan of PV modules, extensive research is required. It is also crucial to properly design and install the modules with the right ventilation and temperature control, as well as to regularly monitor and maintain the modules. The danger of degradation due to temperature and other environmental factors can also be decreased by using high-quality, long-lasting materials and building methods.
- Several variables, including climatic conditions, manufacturing flaws, and material aging, contribute to the decline in the performance of PV systems over time. As a result, it is crucial to identify and treat PV system aging to guarantee peak efficiency and lifetime. By identifying patterns in output power datasets, defect identification using sensor data analysis, and damage detection using picture analysis, artificial intelligence (AI) may play a significant role in the detection of PV system aging. For example, a solar energy company installs sensors on its PV panels to collect data on various parameters, such as voltage and current. These data are then fed into an AI-based system that uses machine learning algorithms to analyze the data and detect any anomalies or changes that may indicate the aging or degradation of the panels. The effectiveness and lifetime of PV systems, maintenance costs, and the adoption of renewable energy sources may all be improved with the application of AI in PV aging detection.
- Government policies and financial incentives can play a crucial role in preventing PV aging by encouraging the adoption of best practices in PV module manufacturing, installation, and maintenance. Governments can set minimum quality standards for PV modules and systems, which would encourage manufacturers and installers to adhere to best practices to ensure the longevity and reliability of their products. Governments can also fund research and development initiatives aiming at the development of new technologies and materials that can improve the durability and efficiency of PV modules and systems.
- Collaboration between researchers, industry stakeholders, and policymakers is crucial in preventing PV aging. Through collaboration, they can work together to develop and implement strategies for preventing PV aging, such as improving the quality of materials and construction methods, implementing regular maintenance and inspection programs, and providing financial incentives for the adoption of best practices. Additionally, collaboration can lead to the development of new technologies and innovations that can help to prevent PV aging, such as advanced materials and coatings that are more resistant to environmental factors such as dust, moisture, and temperature.
- New and emerging solar PV technologies, such as perovskite solar cells and bifacial modules, have the potential to address some of the degradation and aging issues associated with traditional solar PV modules. Perovskite solar cells are a type of thin-film solar cell that has demonstrated high efficiency and potential for low-cost production. These cells have shown promise in mitigating some of the degradation issues related to traditional solar cells, such as cracking and delamination. Bifacial modules, on the other hand, have the potential to increase the efficiency and energy output of solar PV systems. Bifacial modules can generate electricity from both sides, allowing them to capture light that is reflected from the ground or other surfaces. This can help reduce the impact of shading and soiling on the front surface of the module. Additionally, bifacial modules are less susceptible to hotspots and can help reduce temperature-related degradation.

The aforementioned analysis, critical evaluation, and constructive suggestions would be useful for conducting further exploration to overcome the concerns and challenges of the degradation and aging of solar PV toward sustainable energy management, creating a pathway to reduce global carbon emissions and achieve sustainable development goals (SDGs). By improving the efficiency and output power of PV modules, clean energy can be generated at a lower cost, making it more accessible and competitive with fossil fuels. This can help to promote the adoption of renewable energy sources and reduce dependence on non-renewable sources of energy (SDG 7). In addition, the development of the PV industry can lead to the creation of many job opportunities (SDG 8). Moreover, the need for replacement or additional PV modules can be reduced by extending their lifespan and efficiency, which will lessen their environmental impact and improve the sustainable use of resources (SDG 12). By improving the durability and stability of PV modules, the risks associated with climate-change-related events, such as extreme weather conditions, can be mitigated. This can help to combat the impacts of climate change (SDG 13).

6. Conclusions

Solar energy will be a future alternative energy source that the world realizes due to the global energy crisis and rise in carbon emissions over the past few decades. However, there are several key aspects that need to be taken into account for solar PV degradation. Due to the influence on longevity, material deterioration, and efficiency decrease, several aging elements, including dust, discoloration, delamination, temperature, humidity, fractures, and hotspots, were examined in this research. Firstly, the causes of degradation and the degradation rate were analyzed for different types of solar cells in different countries. Secondly, aging factors were introduced, followed by in-depth investigations regarding each of the aging factors. This analysis provides an overview of the current situation, the impact on performance, and the characteristics of the PV aging variables. Thirdly, a comprehensive assessment was conducted on the effects of aging variables on PV modules, including lifetime decrease, material degradation, and efficiency degradation. This investigation showed that each factor affecting aging has a distinct and varied effect on PV modules. According to reports, dust can decrease solar panels' effectiveness as it accumulates over time; nonetheless, dust's effect on the lifespan is less severe than that of other aging factors. Cracks and hotspots, on the other hand, have a significant influence on lifetime and efficiency deterioration; however, the rate of degradation is based on the proportion of afflicted PV cells. The solar PV's lifetime expectancy, material deterioration, and efficiency reduction are all impacted by both discoloration and delamination; nonetheless, delamination and discoloration caused by temperature and humidity are more severe. The effects of all aging variables were also demonstrated to linearly increase over time.

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