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Article
Progress in Improving Photovoltaics Longevity

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Featured Application: Improving the longevity of photovoltaics (PV) is essential in the TW solar age, especially towards their integration into urban infrastructure and for building components for city decarbonization. Despite continuous product changes, the physical triangle based on field observations, data analysis, and testing, and applicable from the nanoscale of solar cells to the kilometer scale of utility PV installations, has substantially improved PV reliability and lifespan to more than 30 years. Here, we present the progress in our scientific understanding of PV degradation processes, the influence of key factors, field and remote operation monitoring methods, approaches for improving PV longevity, and the scientific research needs that arise from the incomplete identification of these degradation processes. We propose appropriate mitigation strategies for enhancing the longevity of PV and building-integrated photovoltaics (BIPV), and we discuss the feasibility of achieving PV longevity values of 50 years by reducing the PV degradation rate to 0.2%/year.

Abstract: With the increase of photovoltaic (PV) penetration in the power grid, the reliability and longevity of PV modules are important for improving their payback period and reducing recycling needs. Although the performance of PV systems has been optimized to achieve a multi-fold increase in their electricity generation compared to ten years ago, improvements in lifespan have received less attention. Appropriate operation and maintenance measures are required to mitigate their aging. PV cells and modules are subject to various degradation mechanisms, which impact their long-term performance and reliability. Understanding these degradation processes is crucial for improving the lifetime and sustainability of solar energy systems. In this context, this review summarizes the current knowledge on key degradation mechanisms (intrinsic, extrinsic, and specific) affecting PV modules, as well as on-site and remote sensing methods for detecting PV module defects and the mitigation strategies employed for enhancing their operational lifetime under different climatic conditions in the global environment.

Keywords: photovoltaics; PV longevity; PV lifetime; BIPV; PV degradation mechanisms; PV operation monitoring

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1. Introduction

The global deployment of photovoltaics (PV) has seen remarkable growth in the last few years, with cumulative capacity reaching 1.6 TW in 2023 from 1.2 TW in 2022 [1]. In 2023, almost 450 GW of new PV systems were installed globally, showing the sector's fast expansion despite challenges such as supply chain disruptions and fluctuating material availability and costs. This increase, expected to reach a capacity of 2.4 TW by 2025 [2], is driven by a combination of increasing demand for renewable energy sources to support the clean energy transition, technological advancements in photovoltaics properties such as more efficient solar cells, the declining costs of modules, and improved energy storage solutions. For example, the efficiency of solar cells has increased with modification techniques such as PERC (Passivated Emitter and Rear Cell) developed by Prof. Green and his team, which enhances light absorption and electron collection [3], novel cell architectures such as TOPCON (Tunnel Oxide Passivated Contact) with an innovative electron collection mechanism [4], new cell structures such as SHJ (Silicon Heterojunction) [5], and module arrangements (half cells, bifacial) [6]. Moreover, the efficiency of photovoltaics is continuously increasing with emerging and novel tandem cells, with a trend to reach 30% efficiency by 2030 [7].

Although research efforts have been mainly focused on improving the efficiency of photovoltaics, PV longevity is also becoming critical in their massive deployment. As the number of solar installations grows globally, the volume of end-of-life panels also increases and will require extensive recycling management. It is estimated that 1.7–8 million tons by 2030 and 60–78 million tons by 2050 of solar panel waste will need to be addressed worldwide [8]. China, the United States, Japan, Germany, and India are estimated to be the top five PV panel waste countries, and concerns are raised about the management of waste PV modules in the realms of environmental preservation and resource recovery [9–11].

Despite the advancements in PV technology, several barriers hinder effective recycling and the overall sustainability of solar energy systems [12]. The complexity of dismantling integrated systems, coupled with the economic feasibility of recycling processes, presents significant challenges [13]. Currently, many recycling methods are still in developmental stages, and existing mechanical recycling processes often yield materials that lack the purity required for reuse in new PV products [13]. This situation is exacerbated by a lack of standardized procedures for end-of-life management, which can lead to inconsistencies in recycling practices across different regions [14]. Furthermore, the current market dynamics leading to lower module prices may discourage investment in recycling technologies and infrastructure. As a result, many countries are still developing policies to address the growing issue of solar panel waste, which complicates the transition to a circular economy in the solar sector [12,15]. Research gaps persist in the fields of PV technology and recycling, particularly regarding the development of materials that enhance durability and facilitate easier recycling [12,16].

Therefore, not only do efficient, economical, and environmentally friendly recycling technology systems need to be developed, but PV lifetimes must also be improved in order to reduce module waste and recycling needs. This necessitates a shift toward more durable materials and designs that can withstand environmental stresses while maintaining high efficiency over time. In particular, building-integrated photovoltaics (BIPV) must prioritize longevity to ensure their economic viability and effectiveness as components of the building envelope [17]. The integration of PV technology into building materials presents unique challenges, including the need for aesthetic compatibility and structural integrity, which can complicate maintenance and replacement strategies. Enhancing the durability of BIPV systems helps to maintain their performance and reduces the frequency of costly replacements, thus improving the overall sustainability of these systems.

In this context, understanding the parameters affecting degradation rates and PV lifetime becomes crucial as the energy transition to PV systems accelerates. The lifespan of solar modules is typically 25 to 30 years during which they experience a gradual degradation in efficiency. A frequently used definition of lifetime for modules/systems refers to a threshold (power loss beyond a defined limit) corresponding to 80% of the initial nominal power of the device.

Typical median degradation rates of 0.5–0.6%/year range with the mean in the 0.8–0.9%/year range are reported for the conventional crystalline silicon (c-Si) modules [18]. The high-efficiency silicon heterojunction modules expected to enter the GW manufacturing scale show median and average performance loss rate values of 0.80%/year and 0.83%/year, respectively [19].

In order to increase lifetimes and decrease degradation rate, the reasons modules degrade and fail should be comprehensively understood, and designs and materials should be selected to minimize degradation and failures [20]. Each design choice impacts lifetime differently in different climates since degradation can vary significantly based on environmental factors such as temperature, humidity, and exposure to ultraviolet radiation. For instance, modules installed in hotter climates may experience degradation rates nearly double those found in cooler regions. By the end of their expected lifespan, solar panels may operate at approximately 80% of their original efficiency, still contributing to electricity generation but at a reduced capacity. However, the extreme weather climates the world experiences in the climate crisis affect the lifetime of PV modules [21]. Hence, it is essential to understand the degradation mechanisms and the effect of local climatic conditions on the longevity of PV technologies. In this context, manufacturers can be assisted in developing mitigation strategies and climate-proofing PV technologies for the most significant environmental stressors such as the temperature rise of the modules. Enhancing the durability of solar modules will not only maximize energy production but will also reduce waste and environmental impact associated with the disposal of aging systems.

While several comprehensive studies have been published in the literature on PV degradation mechanisms, assessments on the factors affecting the longevity of photovoltaics, especially in building-integrated PV modules, are limited.

In view of the above, this work aims to review and synthesize existing research on the factors influencing the longevity of PV systems. Through the analysis of the degradation mechanisms of solar modules, the paper provides a comprehensive overview of the lessons learned so far and identifies the research gaps and open questions. In addition, the innovative materials and technologies developed for enhancing the longevity of PV systems are assessed. This includes the advancement of solar cell materials and cooling methods as well as the best installation and maintenance practices with innovative PV inspection and cleaning methods.

The remainder of the manuscript is organized as follows. Section 2 outlines the methodology for this work, while Section 3 is devoted to a concise overview of the theoretical framework regarding PV output dependence on intrinsic and environmental parameters. PV physical degradation rate is also discussed due to its pivotal role in improving PV longevity. The results are divided according to the specific objectives of the analysis and are presented in Section 4. In this section, a particular emphasis is put on highlighting the need for BIPV longevity improvement. Results are discussed in Section 5, and the main conclusions of this study are summarized in Section 6.

2. Methodology

The methodology for this work was structured to ensure a comprehensive and systematic examination of the literature on PV module longevity, focusing on the key degradation mechanisms, detection methods, and mitigation strategies. The following steps outline the approach taken and are schematically depicted in Figure 1:

1. The initial step involved defining the key terms and concepts critical to PV system longevity. These include degradation mechanisms (categorized as intrinsic, extrinsic, and specific), operational monitoring techniques, and maintenance strategies. The review was restricted to studies published over the past two decades, capturing the most recent advancements in PV technology and longevity improvements.
2. A thorough literature search was conducted using Scopus. Keywords including "Photovoltaics", "PV lifetime", "PV degradation mechanisms", and "PV longevity" were used in various combinations to identify relevant research articles, resulting in an initial dataset of 1148 articles.
3. The initial dataset was screened by title and abstract to exclude irrelevant studies, resulting in a narrowed selection of 133 articles. The search was restricted to peer-reviewed journal articles, review papers, and conference proceedings in English. Additionally, references from key articles were reviewed to ensure comprehensive topic coverage.
4. The full text of the selected articles was analyzed to extract specific information related to degradation mechanisms, monitoring methods, and mitigation strategies. The articles were then categorized into thematic groups, focusing on intrinsic, extrinsic, and specific degradation modes, along with innovative materials, technologies, and best practices in operation and maintenance. The classification was based on identifying

frequent failure patterns and stress factors impacting PV modules' thermal cycling performance.

5. The final step involved identifying research gaps and open questions within the literature. This included areas where further investigation is needed, such as the long-term effects of environmental stressors under different climatic conditions, the development of advanced materials, and the optimization of operation and maintenance (O&M) practices. The review also highlights innovative technologies and approaches that promise to improve PV systems' longevity.

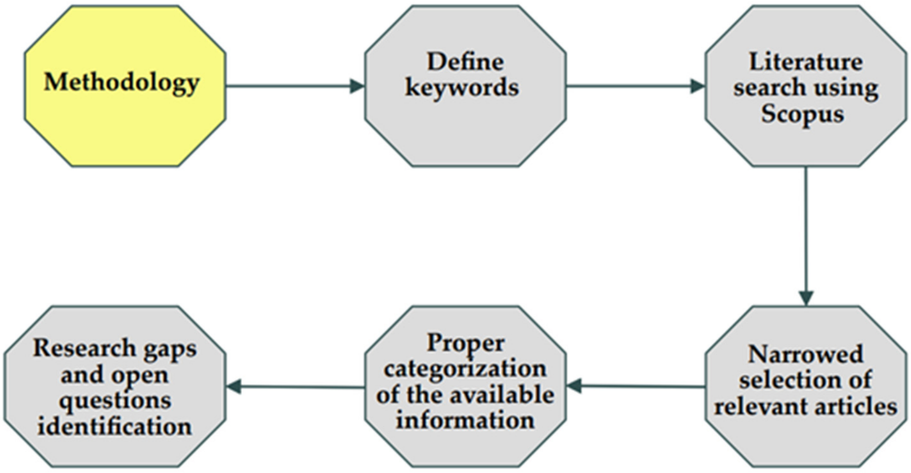

Figure 1. Schematic illustration of the methodology that the review followed.

Results were summarized in tables to categorize degradation modes and their corresponding mitigation techniques, while a chart illustrated trends over time. The systematic approach employed in this review aims to provide a thorough and critical assessment of the current progress in improving the longevity of PV systems, offering valuable insights for both researchers and practitioners in the field of solar energy.

3. Theory: PV Electricity Generation and Degradation Rate

3.1. PV Electricity Generation

The total irradiance, G_F, on the PV surface is given by adding the beam component, G_b, to the diffuse component, G_d:

$$G_F = G_b + G_d. \quad (1)$$

Lu et al. [22], in their recent publication, analytically calculate the direct irradiance component with the assistance of an optical model [23]. Then, based on the Perez model [24], they determine the diffuse component.

The solar position algorithm [25], developed by the National Renewable Energy Laboratory (NREL), provides precise solar path data, such as zenith (z), elevation angles (θ), and solar azimuth (γ_s), at any time and geographical coordinate. Alternatively, these parameters can be calculated by [26] for typical cities in Europe. The optical model is based on two irradiance components: beam and diffuse. A clear schematic illustration of these components for a PV module is presented in Figure 2.

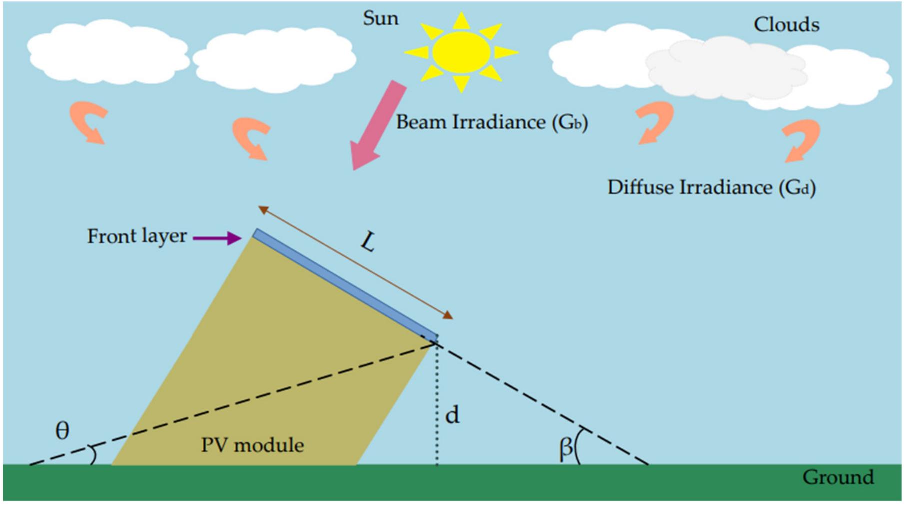

Figure 2. Schematic illustration of the incident irradiance with the two components (beam and diffuse) on the photovoltaic (PV) front surface. The module has a ground clearance of d, a length of L, and a tilt angle of β.

From the total solar power incident on the module, the absorbed portion is given as follows:

$$P_{sun} = a_m G_F, \tag{2}$$

where a_m is the absorptivity of the module, weighted by the solar spectrum (e.g., AM1.5 or ASTM G173-03 [27] simulated spectrum).

For typical PV modules, which consist of N_s cells connected in series and N_p cells connected in parallel, the relationship between current and voltage is given as follows:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(VN_p + R_s I)}{N_s N_p n k_B T} \right) - 1 \right] - \frac{VN_p + R_s I}{N_s N_p R_p}, \tag{3}$$

where I is the output current and V the output voltage. I_{ph}, I_0, N_s, N_p, R_s, and R_p represent the photocurrent, the diode saturation current, the number of cells in series and in parallel, the series resistance, and the parallel resistance, respectively, $q = 1.602 \times 10^{-19}$ C is the charge of the electron, $k_B = 1.381 \times 10^{-23}$ J/K is the Boltzmann's constant, T is the temperature, and n is the diode ideality factor. It is evident from this equation that the intrinsic parameters affecting PV output are the series and parallel resistances as well as the temperature of the PV module affected by the absorbed solar irradiation given by Equation (2).

On the assumption of no other loss occurrence, the maximum power output of a PV module is calculated by data from its current–voltage (I–V) characteristic curve, which is as follows:

$$P_m = I_{MPP} V_{MPP}, \tag{4}$$

where the subscript "MPP" refers to the corresponding values at the maximum power point.

From the incident irradiance on the module, a small portion is the final power output, while the remainder is mainly converted into thermal energy. Among all PV components, solar cells with a high absorptivity coefficient are the ones with the highest temperature. Then, via conduction, heat is transferred from the solar cell to the front glass surface, which in turn exchanges heat with the environment. This heat dissipation takes place through convection and radiation. Thermal radiation, which occurs among the PV module, atmosphere, and sun, significantly impacts its performance. The description of the thermal behavior and characteristics of the PV module is beyond the objectives of this review and can be found in detail in recent studies [22].

3.2. Degradation Rate Model for PV Modules

In order to evaluate the effect of stress variables on the PV module's performance degradation, a model for these degradation rates needs to be established. Over the past few decades, especially for the most common degradation mechanisms, several models that study the electrical behavior of the module components under climatic stress conditions have been developed [28]. Dirawi et al. [29], using the model proposed by Kaaya et al. [30], focused on determining outdoor degradation rate. In outdoor conditions, PV modules are mostly susceptible to the impact of temperature, ultraviolet (UV) irradiance, and relative humidity. These three factors were thoroughly examined by Kaaya et al. [30], who proposed a model for a quantitative description of the physical degradation rate.

According to this model [29,30], three key degradation processes related to climatic conditions and stresses occur on a PV module during its real-world operation: hydrolysis, photo-degradation, and thermo-mechanical degradation. The export of an aggregate model is based on the proper combination of individual models for each degradation factor. Thus, the total physical degradation rate is given as follows:

$$K_T = A_N \cdot (1 + k_H) \cdot (1 + k_P) \cdot (1 + k_{Tm}) - 1, \tag{5}$$

where K_T $\left[\text{year}^{-1}\right]$ and A_N $\left[\text{year}^{-2}\right]$ being the total degradation rate and the normalization constant, respectively. By k_{Tm}, k_H and k_P, respectively, the thermo-mechanical, hydrolysis, and photo-degradation rates are denoted. The expressions for the aforementioned degradation processes are given below:

$$k_{Tm} = A_t \cdot C_N \cdot (273.15 + \Delta T)^{\theta} \cdot \exp\left(\frac{-E_{at}}{k_B T_{max}}\right),\ \Delta T = T_{max} - T_{min}, \tag{6}$$

$$k_H = A_h \cdot RH^n \cdot \exp\left(\frac{-E_{ah}}{k_B T_{mod}}\right), \tag{7}$$

$$k_P = A_p \cdot UV^X \cdot (1 + RH^n) \cdot \exp\left(\frac{-E_{ap}}{k_B T_{mod}}\right), \tag{8}$$

where A_t $\left[{}^{\circ}\text{C}^{-1}\text{cycle}^{-1}\right]$, A_h $\left[\text{year}^{-1}\right]$ and A_p $\left[\text{m}^2/\text{kWh}\right]$ are the thermo-mechanical, hydrolysis, and photo-degradation pre-exponential constants, respectively. By E_{at} [eV], E_{ah} [eV], E_{ap} [eV] the activation energies of power degradation induced by the thermo-mechanical, hydrolysis and photo-degradation processes, respectively, are denoted, while k_B is the Boltzmann constant. T_{mod} [K], T_{max} [K], and T_{min} [K] are the PV module temperature, the maximum temperature of the module, and the minimum temperature of the module, respectively. UV and RH are the integral UV dose $\left[\text{kW}/\text{m}^2\right]$ and the relative humidity, respectively, and X, n, and C_N [cycles/year] are model parameters related to UV irradiation dose and relative humidity on the power degradation and cycling rate, respectively.

Having calculated the total physical degradation rate, K_T $\left[\text{year}^{-1}\right]$, the model also provides an estimation of the lifespan of a PV module. To achieve this, the failure time t_f [years] is calculated by considering a loss of the order of 20% in the initial maximum output power according to the manufacturer and is given as follows [31]:

$$t_f = \frac{\Gamma}{K_T \cdot [|\log(0.2)|]^{\frac{1}{\mu}}}, \tag{9}$$

where Γ and μ are model parameters for the construction material and the shape of the module, respectively.

4. Results

4.1. PV Degradation Mechanisms

After their installation and commencement, the interaction between PV modules and their ambient is inevitable. The effect of prolonged exposure to environmental and weather conditions and the limited viability of construction materials lead to the gradual degradation of the module. This decline can severely impact the efficiency, performance parameters, operating characteristics, and estimated lifespan over time. Gaining a clear insight into these degradation processes and developing effective mitigation strategies is crucial for enhancing the sustainability and cost-effectiveness of solar energy technologies.

Recent surveys and research have made remarkable progress in identifying the key degradation mechanisms impacting PV modules and implementing measures to enhance their longevity. According to Table 1, these mechanisms can be broadly categorized into three main types: intrinsic degradation in the dark, extrinsic degradation caused mainly by environmental stress factors, such as photo-induced degradation and chemical reactions with water and oxygen, and other factors, and specific degradation from mechanical load and other modes. In the present subsection, an analysis of the internal, external, and specific degradation mechanisms that affect a PV module is examined.

Table 1. Degradation mechanisms affecting a photovoltaic (PV) module.

PV Degradation Mode	Degradation Mechanism	Description	References
Intrinsic	Decrease in shunt resistance (Rsh)	Due to metal migration through the p-n junction	[32–34]
	Antireflection coating deterioration	Reduces light absorption	[35–39]
	Hot-spot failures	Caused by mismatched, cracked, or shaded cells	[40–42]
	Module delamination	Caused by reductions in bond strength	[40,43,44]
Extrinsic	Bubble formation in encapsulants	Leads to delamination and hot spots	[40,45,46]
	Corrosion and decreased adherence to contacts	Increases series resistance (Rs)	[47–49]
	Backsheet discoloration and cracking	Reduces power output	[40,43,50–53]
	Potential-induced degradation (PID)	Affects solar cell performance	[40,43,54–58]
	Light-induced degradation (LID)	Particularly prevalent in organic photovoltaics (OPVs)	[40,43,59–63]
	By-pass diode failure	Due to overheating	[40,44,64]
	Encapsulant failure	Due to UV degradation and depletion of stabilizers	[40,44,65–67]
Specific	Cell cracking	Caused by thermal stress, hail, or damage during processing	[40,43,44,68–70]
	Interconnect open-circuit failures	Due to fatigue from cyclic thermal stress and wind loading	[40,44,71,72]
	Module glass breakage	Due to vandalism, thermal stress, handling, wind or hail	[40,43,44,73,74]

4.1.1. Intrinsic Degradation (Internal Stress Factors)

Intrinsic degradation [40] is related to processes that can occur even in the absence of light in the internal of the module. These internal factors include processing effects, module architectural and manufacturing techniques, and PV component compatibility. Intrinsic degradation can be addressed by selecting materials with glass transition temperatures above 100 °C to improve stability at functioning temperatures.

- **Processing**. One of the main causes of intrinsic degradation is poor processing, which can occur in module manufacturing or at a more fundamental level, namely in module components. Indicatively, we mention that immoderate thermal stressing of ethylene-vinyl acetate (EVA) during lamination can lead to solar cell dislocation or cracking [75]. Lamination warpage can be induced when the laminate is left to cool down to room temperature [76]. The installation of poorly crosslinked modules is also a significant factor to evaluate. For example, the utilization of poorly crosslinked EVA can increase the susceptibility toward corrosion and potential-induced degradation (PID) [77,78] and induce full curing in operating conditions or even delamination, as it attenuates the bonding strength between EVA and all the neighboring module components [66].
- **Module architecture**. The module architecture and design principles are considered to be of particular importance regarding the effect of intrinsic degradation. Transport and

physical properties of packaging materials, such as oxygen, water vapor, and acetic acid transmission rates, are inseparably related to oxidation phenomena, moisture ingress, acetic acid evaporation [79], etc. The structural materials of a PV module hold a pivotal role in managing the different parameters that can contribute to degradation modes, such as oxygen, gas transmission, moisture, and water vapor [80]. For instance, in an unbreathable module construction, the choice of a packaging material with a relatively low water-vapor transmission rate may significantly restrict the moisture penetration, but it does not allow all gas-form degradation by-products to escape from the module, with all the entailed problems. Contrariwise, in a breathable module construction, a packaging material with a relatively high water-vapor transmission rate allows the uneventful movement of moisture from the unit to the environment and vice versa due to concentration gradients, which vary according to temperature's and relative humidity's seasonal and daily cycles.

- **PV components compatibility**. The proper design and subsequent matching of all adjacent PV components is vital for the reliability, flawless performance, and extended lifespan of the module. Among all relevant components of the PV module, the back-sheet and the encapsulant are more prone to degradation effects. It is, therefore, crucial to find a way to properly exploit the thermo-mechanical properties of these components [81]. In the primary stages of PV module operation, material incompatibilities included delamination, metal corrosion, and discoloration, i.e., yellowing [82]. However, over the past few years, the incorporation of new materials in PV field technologies has led to the expansion of material incompatibilities. For instance, specific combinations of polypropylene-based backsheets and polyethylene-based encapsulants comprise adhesion failures [83], while acetic acid accumulation was connected to cracking formation and propagation [84]. In order to limit—or even eliminate, if possible—the compatibility problems inside a module, it is imperative to modify the already existing encapsulant-backsheet combinations or turn to the quest for new, well-promising ones with reinforced properties.

4.1.2. Extrinsic Degradation (External Stress Factors)

Extrinsic degradation [40] is a separate, broad category of degradation modes occurring on PV modules, which significantly influence their performance and long-term effectiveness during real-world operation. Bubble formation in encapsulants, which leads to delamination and hot spots, can be mitigated by using encapsulation materials with very low permeation rates for oxygen and water.

Environmental Stress Factors

- **Irradiance**. The incidence of solar irradiance on PV modules can be described in terms of power, angle of incidence, and spectral distribution, which is a function of geographical features, weather conditions, climatic variations, and air pollution. Polymeric materials, with a resounding presence in PV modules, can be severely damaged by the long-term effect of ultraviolet (UV) photons (280–400 nm), as their energy is sufficient enough to provoke scissions in the element sequence (bonds between carbon and/or oxygen) of the polymer main chain. Extended exposure to UV light inevitably leads to fragility and discoloration of the polymer [77]. More specifically, despite its small power fraction in comparison with UVA (315–400 nm), UVB radiation (280–315 nm) is the most devastating for polymers in PV modules, and it can accelerate the degradation process, especially during summer at lower latitudes, when the module's exposure to the sun is prolonged.
- **Temperature**. Temperature is one of the root causes of environmental stress factors related to external degradation in PV modules. Not only does it intervene in the electric behavior of the module, but it is also responsible for additional mechanical stresses, as the individual elements of the modules are characterized by different thermal expansion coefficients. Temperature is also a key factor for speeding up diffusion and

chemical reactions in materials, as well as degradation mechanisms on the modules. The phenomena of metallic elements corrosion and degradation of backsheets and encapsulants are found to be in full agreement with the Arrhenius model [85].

Due to the incidence of solar irradiance on a module, a gradient in temperature between the cell or the module and the outer environment is developed. The heat flux distribution in the outer part of the cell is closely related to the geometrical and thermal properties of the neighboring materials. As previously stated, temperature variations affect the expansion and contraction of the module units in a different manner, resulting in thermo-mechanical [86] stresses, which depend on the diurnal, seasonal, and annual temperature and, consequently, appear in a periodic pattern. They can cause deformation, delamination, fatigue failures, cell cracking, and malfunctions in general in the different module components.

- **Moisture**. Moisture also has a negative impact on the proper operation of PV modules, as it can cause adhesion issues among the components, corrosion of metallic materials, and delamination. In ambient conditions, moisture can be tracked in different states of matter, namely gas (humidity, water vapor), liquid (rain, water, dew, or condensed humidity), and solid (ice).

  Moisture in gas form can ingress through polymeric materials and concentrate in the interior of the module, causing complications and degradation of its components. In liquid forms such as rain, dew, or condensed humidity, moisture can be absorbed by the module and induce additive mechanical stresses. Among the adverse effects of liquid moisture, one can point out the erosion of surrounding materials, leakage current, and weakening of the electrical insulation of dielectric materials. Solid moisture as ice can produce mechanical stresses in the outer part of the module, delamination, or further damage to the frame and the front glass. The accumulation of snow or the formation of ice on the front side of the module provokes extra mechanical stresses, leading to possible irreparable damage, cell cracking, and even detachment of the frame [87–89].

  The PV module is characterized by a moisture saturation limit, which can be exceeded with a decrease in temperature. This excess causes the creation of droplets at the interfaces, metallic elements, and cell surfaces, which, in turn, lead to reduced module performance and losses. From a manufacturing point of view, modules contain low water levels, but on a long-term scale and in operating conditions, internal moisture levels will increase. In order to extend the lifespan of PV modules, the attention must be focused on the time needed to achieve the equilibrium moisture concentration. This temporal limit is calculated up to a week and to several years for a glass/backsheet module (breathable construction) and a glass/glass module (unbreathable construction), respectively [90,91]. This specific difference is directly associated with the ease or difficulty in moisture movement from the module to the environment and vice versa.
- **Soiling**. Soiling [92,93] is a very broad category of PV module degradation that affects its performance and effectiveness. It may arise from the accumulation of dust and bird droppings on the surfaces, or it can be attributed to air pollution. The level of soiling is a complicated function of the properties and the location of the surface, the height from the ground in which the module has been installed, and the way all components of the modules have been implemented. The climate conditions are also a key parameter to the degree of soiling, as they can obstruct the path of light into the cell. For example, in desert climates [94], levels of dust soiling are extremely high.

  A uniform distribution of biological soiling or dust does not weaken the reliability of PV modules on a long-term scale, but it can significantly impact the performance of the module on the field. However, bird droppings, with an irregular shape and a random distribution on the front surface, can interrupt the light transmission of the module, leading to reliability and performance failures [95]. More specifically, this type of soiling can induce the formation of hot spots, localized areas where temperatures are particularly high (on the order of hundreds of degrees). Due to their catastrophic impact on the module packaging and the solar cell, sources of soiling must be treated with particular attention, including frequent cleaning procedures.

- **Air Pollutants**. Air pollutants [96–98] of natural or artificial/industrial origin in a high concentration can significantly degrade the performance of the various components of a PV module, such as backsheets, junction boxes, connectors, and wiring. Different kinds of pollutants are dominant in various regions: ammonia in rural areas and salt mist in coastal areas. This type of extrinsic degradation also raises legitimate concerns about the safety of the PV modules, as problems with decreased electrical insulation may arise.

Summarizing results are presented in Table 2.

Table 2. The effects of various environmental factors on photovoltaic (PV) modules.

Environmental Factor	Description	Effects on PV Modules	References
Irradiance	Solar irradiance is influenced by power, angle of incidence, and spectral distribution, depending on geographical features, weather, climate, and air pollution	– Long-term UV exposure leads to polymer degradation. – UVB radiation (280–315 nm) is particularly damaging, causing fragility and discoloration.	[77]
Temperature	Temperature affects electrical behavior and introduces mechanical stresses due to different thermal expansion coefficients in module materials	– Accelerates diffusion and chemical reactions. – Causes thermal stresses leading to deformation, delamination, cell cracking, and malfunctions.	[85,86]
Moisture	Moisture exists in gas (humidity), liquid (rain), and solid (ice) forms, affecting adhesion and causing corrosion	– Gas moisture can ingress through materials, causing degradation. – Liquid moisture induces mechanical stresses and leakage currents. – Solid moisture can cause delamination and structural damage.	[87–91]
Soiling	Accumulation of dust, bird droppings, or air pollution affects light transmission to PV cells	– Dust accumulation may not weaken reliability but impacts performance. – Bird droppings can create hot spots leading to significant performance failures.	[92–95]
Air pollutants	High concentrations of natural or industrial pollutants degrade PV components like backsheets and connectors	– Different pollutants affect regions differently (e.g., ammonia in rural areas). – Decreased electrical insulation raises safety concerns.	[96–98]

Other

Besides environmental stress factors, extrinsic degradation in a PV module can emerge from many other causes during operation.

- **Bubble formation**. Apart from delamination, the deterioration of EVA adhesion is responsible for the formation of bubbles in the encapsulant of the module. Chemical reactions that take place in the interior of lamination films of a PV module, triggered by thermal decomposition, give gaseous products that provoke swelling of any delaminated gadgets at the front or at the back surface of the module on the one hand and bubble formation [43,46] on the other. Due to air entrapment inside the bubbles, the heat dissipation mechanism, which is responsible for balancing temperature differences and natural cooling of the PV modules, is disordered. This disorder can have a deleterious effect on the module performance as severe spectral losses can be manifested. Ineffective heat dissipation and bubble formation lead to overheating phenomena in the solar cell, which jeopardize both their performance and lifespan.

Increased temperature can, in most cases, cause solar cell bonding issues, which explains bubble formation near the interfaces between different solar cells. It should be mentioned that the appearance of bubbles increases the reflectance of solar irradiance, which further degrades the PV module's performance.

- **Corrosion and decreased adherence to contacts**. Metal corrosion and poor adherence of contacts are two of the most frequent degradation modes a solar module can face. Corrosion can be caused by the permeation of oxygen and moisture through the laminated edges of a PV module [47]. The entry of moisture can furthermore lead to current leakage, which diminishes power, weakens metal contacts of the junction box, and increases series resistance (Rs). In order for corrosion to take place in a PV panel, a metallic element, an electrolyte, and an oxidation factor should coexist [48]. Although being a long process, the impact of aging on the PV components, especially the encapsulant and the backsheet, can gradually lead to corrosion. Poor cell interconnection, deterioration of frames, and increased Rs [49] are only some of the remarkable consequences of corrosion related to encapsulant degradation.
- **Backsheet discoloration and cracking**. Due to the variety and possible combinations of the composition materials, the degree to which degradation mechanisms affect the backsheet of a PV module depends on its manufacturing characteristics. Backsheet degradation mainly includes discoloration and cracking.
  Discoloration. In operating conditions, the production of chromophores, which are by-products released in chemical reactions, adds a yellow tint to the backsheet [50,51]. The appearance of the yellow color in the backsheet foreshadows reduced power output on a long-term scale, as it entails amendments in the polymer structure. In order to combat the undesirable impact of UV irradiance on the module, it is a common practice to insert colorants in the polymers. The gradual deterioration of the outer polymer layer of the backsheet can lead to a local gathering of these colorants, which adds a chalky tint to the module. Backsheet discoloration is more likely to cause delamination and cracking.
  Cracking. Backsheet cracking [52] can be observed in either the outer or the inner layer and is identified as one of the most frequent problems in a PV module, which is directly linked to safety issues. Due to weakened electrical insulation, current leakage and ground faults can arise. Cracking can, furthermore, expedite the entry of moisture, water, chemical substances, and oxygen into the internal part of the module, putting an obvious risk to all its components. Weather conditions also exert a major influence on cracking initiation, as they undermine the stability of the polymer chains and abet fragility. Once created, mechanical stresses lead to rapid crack sprawl, with a rate related to environmental conditions and material processing [53].
- **Potential-induced degradation (PID)**. The term "potential induced degradation" has been introduced to describe all the degradation phenomena that can occur on a PV module due to high levels of voltage. The series connection of modules in solar power plants leads to the measured voltage on the order of kilovolts in operation service. More specifically, these high electrical potential levels are developed between solar cells and frames, with the latter being grounded in accordance with safety protocols and regulations. The aforementioned potential difference leads to an inevitable leakage current between the encapsulant of the module and the grounded frame.
  Regardless of the manufacturing techniques and architecture, all PV modules are prone to PID, while the development of this degradation mechanism depends on the selection of construction materials. Although PID can be subserved by climate conditions and environmental agents, such as temperature and relative humidity, potential bias remains its main cause. The magnitude of the effects is strongly associated with the polarity of the applied voltage. For instance, in c-Si-based modules, two different PID mechanisms have been detected [54]: surface polarization (PID-p) and shunting (PID-s). PID-p is a high voltage creepage-related phenomenon that arises from surface polarization as an extension effect of net charge hoarding in the

dielectric stack that separates the cell and the frame of the module. This phenomenon occurs more frequently in the cases of a positive biased n-type wafer. The gathered charge changes the surface field distribution of the solar cell, enhancing the surface recombination processes, which significantly diminish both the short circuit current and open circuit voltage. The complete understanding of the PID-p phenomenon, along with a coherent interpretation of the responsible physical mechanisms, remains a challenge for scientists.

On the other hand, in PID-s [99], local shunts over the emitter are created. This phenomenon is more likely to be found in a negative p-type wafer, mainly because the external bias pushes the sodium ions to move from the cover glass to the cell and turn into metallic sodium in the emitter.

PID in a PV module is inextricably linked to increased recombination and shunt formation, which negatively affect the proper functioning of solar cells. In addition, it can cause considerable power losses due to the decrease in efficiency and performance. PID exhibits reversibility, provided it is detected in time. Once the phenomenon is identified, the module is unshackled from the potential and is left to naturally cool to room temperature in order to restrict power loss [57]. Alternatively, the recovery procedure is focused on a reverse bias application and was estimated at 100 h, as found by Pingel et al. [58]. The supervision of the PID effects during stress tests in the laboratory is often carried out by electroluminescence (EL) imaging.

- **Light-induced degradation (LID)**. Light-induced degradation (LID) refers to the degradation of a PV module due to exposure to solar light. LID occurs in either thin-film [100] or mono-crystalline Si solar cells and directly or indirectly impacts all module components. The magnitude of the effect is relatively small, measuring up to 5% of total module power. The injurious outcomes caused by LID could be summarized as the appearance of metastabilities in the semiconductor layers, which are induced by high-temperature processing and diffusion phenomena among the different layers [59].

  The two main recognized causes of LID in c-Si PV modules are the Czochralski process utilized for cell construction [60,101] and iron-boron pair dissociation [62]. In the first case, the crystal lattice is enriched with oxygen atoms, while the doping process with boron atoms leads to boron-oxygen complex formation on the wafer. A prerequisite for the formation of these defects is light exposure, with subsidiary action of recombination carrier-triggered mechanisms. This effect results in a decreased minority-carrier lifespan in the layers of the cells. In the second case, the interstitial iron impurities contained in c-Si solar cells create pairs with boron atoms. Light exposure causes pair dissociation and interstitial iron as defects are found in the lattice, acting as recombination centers.

  The performance of the module can, in most cases, partially recover during summer [102], while in winter, a further decrease is observed. The LID degradation effect can be identified by constant monitoring of the module and continuous comparison of its I–V characteristic curves, which provide information about the current and the voltage of the module. The LID stabilization procedure, although it requires a long period of time, has proven promising for the efficiency of the module.
- **By-pass diode failure**. The installation of bypass diodes [40,64], often integrated with the junction box, is of utmost importance in the attempt to moderate the losses when the module operates in the reversed-bias mode, allowing the current to circulate by bypassing the bad cells. In cases of significant differences in short circuit current among some cells, those with the lowest values of current can experience reverse bias and, consequently, overheating. The phenomenon can be observed either in the case of a shaded cell, where the cell is illuminated by less light than it is designed for, or in a damaged cell/internal electric circuit. Bypass diodes not only serve an instrumental role in the degradation of the performance of the module, but they are also prone to safety issues, as they exhibit a variety of failure modes, such as thermal leakage,

electrostatic discharge, and arching [103].
In extreme weather conditions, like thunderbolts and lightning, the increased electrostatic discharge leads to a high current flowing through the diode in a short time frame. As a result, thermal runaway takes place, and the diode in the cell gradually overheats until it is permanently damaged. Thermal leakage can also occur when the heat dissipation mechanism is not successful, and the non-countered high temperature will eventually cause cessation of the diode operation. Furthermore, an open circuit failure can arise in the case of a damaged or disconnected diode, exposing the module to the risk of overheating or even fire. A short circuit failure can occur due to high voltage when the diode has been either installed incorrectly or shortened. Besides these examples, bypass diode degradation can come out of high-temperature operating conditions, leading to semiconductor malfunctions [104,105].

- **Encapsulants failure**. Encapsulants are elastomeric materials, usually made of EVA or alternative encapsulation materials such as thermoplastic polyolefins, ionomers, and polyolefin elastomers [106,107]. The dominant degradation modes of encapsulants in a PV module are UV degradation, depletion of stabilizers, discoloration, and delamination. They also indirectly affect the degradation rate of the adjacent module components.
  Discoloration. Encapsulant discoloration is attributed to EVA degradation, which occurs due to the module's exposure to UV light. The presence of incompatible additives in the EVA leads to acetic acid formation, and the encapsulant is colored with a brown or yellow hue. The temperature factor also reinforces the phenomenon [44]. Modern encapsulant manufacturing techniques are based on lower additive concentration in EVA [65] or the utilization of additives with enhanced stability.
  Delamination. Encapsulant delamination is also a common failure mode that appears at the interfaces of the laminated layers. The term is used to describe detachment between different elements of the module and adhesion loss. Adhesion strength is affected by the aging of the encapsulant as well as all the chemical and physical procedures that take place [66,67]. Delamination is proven to be hazardous for both the internal circuit and the solar cell, as it smooths the way for moisture or water inflow.

Summarizing results are presented in Table 3.

Table 3. Key points regarding extrinsic degradation mechanisms affecting PV modules.

Degradation Cause	Description	Effects on PV Modules	References
Bubble formation	Deterioration of ethylene-vinyl acetate (EVA) adhesion leads to bubble formation due to thermal decomposition and gaseous products	– Disrupts heat dissipation, leading to overheating – Increases reflectance of solar irradiance, degrading performance	[43,46]
Corrosion and decreased adherence to contacts	Caused by moisture permeation through laminated edges, leading to weak metallic connections	– Results in current leakage, diminished power output, and increased series resistance (Rs) – Corrosion accelerates due to EVA degradation and moisture entry	[47–49]
Backsheet discoloration	Backsheets are multilayered; discoloration occurs from chemical reactions producing chromophores	– Yellow tint indicates reduced power output over time – Can lead to delamination and cracking due to polymer structure changes	[50,51]

Table 3. *Cont.*

Degradation Cause	Description	Effects on PV Modules	References
Backsheet cracking	Cracking can occur in either outer or inner layers, affecting electrical insulation	– Weakens insulation leading to current leakage and risks of ground faults – Facilitates moisture entry, risking internal components	[52,53]
Potential-Induced Degradation (PID)	Occurs due to high voltage levels between solar cells and grounded frames	– Causes leakage currents and can significantly decrease efficiency – Associated with shunting and surface polarization mechanisms	[54,57,58,99]
Light-Induced Degradation (LID)	Degradation from exposure to solar light during initial stabilization phase	– Reduces module performance by up to 5% due to metastabilities in semiconductor layers – Affected by manufacturing processes like Czochralski and iron-boron pair dissociation	[59,60,62,100–102]
Bypass diode failure	Bypass diodes prevent losses during reverse-bias operation; prone to various failure modes and affected by extreme weathers and overheating	– Can lead to overheating and potential fire hazards – Failure modes include thermal leakage and open/short circuit failures	[40,64,103–105]
Encapsulant failure	Encapsulants (often EVA) degrade due to UV exposure and aging	– Leads to discoloration and delamination – Impacts the performance of solar cells and overall module integrity	[44,65–67,106,107]

4.1.3. Specific Degradation (Mechanical/Other)

- **Cell cracking**. Due to the fragile nature of the semiconductors and their small thickness, cell cracking is a frequently reported concern for PV modules. Cracking can occur during the manufacturing process and is mainly due to mechanical stresses induced by handling, lamination, transportation [108], and implementation. It can also be caused by mechanical loads in operating conditions, weather conditions, such as snow and wind, or thermomechanical stresses and temperature cycles, which are related to climate alterations and environmental factors [68].
  Cracks obstruct the electrical conductivity in the cell, leading to decreased short circuit current and shunt resistance (Rsh) and increased Rs. Köntges et al. divided cell cracks into three main categories, type A, B, and C, according to their severity [69], while Ennemri et al., in their review, studied the cracks observed in c-Si solar cells [70]. The size, orientation, number, and position of cracks on a PV module can vary, and therefore, their impact on module performance is evaluated as severe or less severe. If cell cracking occurs in the field, other degradation modes, such as PID and delamination, may arise or accelerate. An additional consequence of cell cracking is a non-uniform current distribution across the PV module. Near the cracks, a localized heat accumulation is developed, leading to the formation of hot spots. The forthcoming temperature increase could even cause encapsulant delamination.
  The detection of these cracks can be conducted either by visual inspection, if the crack has sufficient dimensions, or by applying testing techniques such as electroluminescence (EL) imaging [109], I–V characteristic curves, hot-spot endurance tests [110,111], or UVF [112] in the case of micro-cracks, which are invisible to the naked eye.
- **Interconnect open-circuit failure**. The internal electrical circuit of a PV module consists of solar cell metallization and interconnect wiring. The circuit can face a variety of failures due to construction or processing errors. Weakening of wiring and metallization does not directly affect the module unless the resistance of these components increases significantly. In this case, the degradation of the module, as well as safety issues, are imminent [71,72]. As soon as the module is set to operation, the internal circuit, along with its joints, are under the influence of thermo-mechanical stresses, which are attributed to an increment in Rs and cause power losses. The extent

of the degradation depends on different parameters, such as environmental conditions, the module's construction features, and the selection of materials used. Over time, the circuit is subjected to fatigue from cyclic thermal stress and wind loading, resulting in progressive PV module degradation.

- **Module glass breakage**. Low-iron glass has been established as the first choice for substrate material in PV modules due to its multiple advantages: low cost, high transparency index, low permeation rate, good electrical insulation, and enhanced mechanical resilience. Glass breakage is a common failure and can occur in several stages: during transportation, installation, or operation. The latter case is especially attributed to thermal or mechanical stresses and loads. Weather conditions, such as wind or hail, can also cause glass breakage. Regardless of the cause of the breakage, broken glass in a PV module can have an immediate impact on the solar cell or on its circuit. It may also affect the electrical insulation of the glass or its impermeability to moisture and gases [74]. In all cases, glass breakage can act as an auxiliary on the degradation of the encapsulant or other components of the module and is more likely to occur on an unbreathable module (glass/glass), as glass edges are unshielded [73].

In Figure 3, images retrieved via Red–Green–Blue (RGB), infrared (IR), and ultraviolet fluorescence (UVF) methods from a PV module susceptible to cracks (horizontal and diagonal), delamination, and discoloration are depicted. The different techniques showcase, in a unique way, the effect of each degradation mechanism.

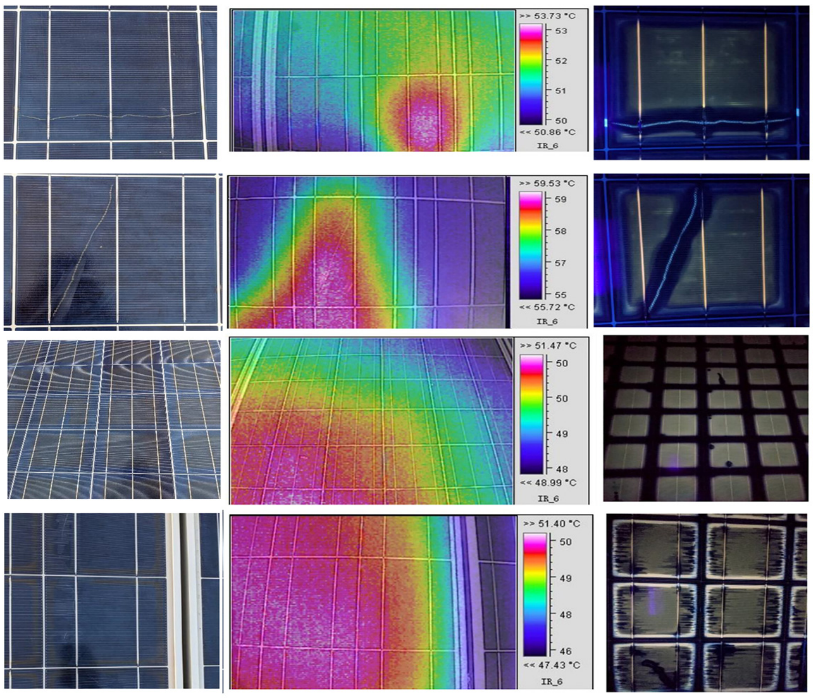

Figure 3. From top to bottom: Red–Green–Blue (RGB-left), Infrared (IR-middle), and ultraviolet fluorescence (UVF-right) images of a PV module affected by horizontal cracks, diagonal cracks, discoloration, and delamination, respectively [113].

4.2. PV Modules Failures (Not Only Degradation but Failure in Working)

Although the technology used for the construction of solar cells can differ, their main components and design materials exhibit common properties and characteristics. These components are not only subject to degradation processes but are also prone to failures in their operation, as they strongly affect the performance of the PV module. Table 4 lists and summarizes the degradation mechanisms and failure modes that can occur on the different module components and highlights their impact on the PV system [40]. It is worth mentioning that, in many cases, the boundaries between failure and degradation are not clearly defined.

Table 4. Degradation and failure modes of PV module performance and their impact on the performance characteristics of the PV system [40].

Module Component	Degradation Modes	Failure Modes	Impact/Effects
Backsheets	Hydrolysis, photo-oxidation	Discoloration, chalking, cracking, delamination	Reduced power output, corrosion
By-pass diodes	Overheating	Arcing, thermal leakage, electrostatic discharge	Safety risks, performance losses
Encapsulant	Photo-oxidation, corrosion	Discoloration, delamination, material interactions	Demeaned current
Frame	Corrosion	Loosening, deformation	Increased hazard of cell/module damage
Frontsheets	Photo-oxidation, hydrolysis	Discoloration, cracking, delamination	Reduced power output, corrosion, optical losses
Glass	Glass corrosion	Breakage, coating erosion	Cell or circuit damage, hot-spots emergence, moisture ingress
Internal circuitry and wiring	Corrosion of metallization	Cracking, fatigue, contact failure	Degraded current, cell isolation, hot-spots generation
Junction box	Corrosion, detachment	Insufficient sealing, arcs, delamination	Increased power losses, safety issues, high current
Solar cells	LID, PID, Light- and elevated temperature-induced degradation (LETID)	Cracking	Hot-spots creation, reduced power

4.3. PV Operation Monitoring

In order to evaluate the durability, long-term reliability, and proper operation—even in extreme weather conditions—of the PV modules, they must undergo accelerated testing procedures on a regular basis. These tests have a broader purpose of exposing PV modules to high-level stress conditions. The avoidance of failure modes presupposes that the majority of the degradation modes are detected in an initial phase. Consequently, the importance of continuous checks on the field-exposed modules is undeniable. Over the past few decades, a variety of techniques for detecting the different degradation modes affecting a PV module have been established. This subsection contains information on all—fields and remote- monitoring of PV operations. In Figure 4, we present a schematic illustration of field and remote methods of PV operation monitoring. Table 5 summarizes typical field monitoring methods and required equipment. In relation to Table 5, Table 6 synopsizes the well-known methods of remote PV operation monitoring, the required equipment and their usefulness, as well as some references that readers can consult for further exploration.

4.3.1. Field Monitoring Methods

Field monitoring methods [43,44], which are commonly applied for monitoring PV operations, are described in Table 5. The most common field monitoring method is visual inspection, which is a very popular, easy, and straightforward way to detect defects in a PV module, as it allows data collection and visual observations in a wide range. Although its detectability imposes restrictions due to the fact that several complications occurring in a material go unnoticed by the naked eye, this technique is effective, rapid, and does not require specialized equipment.

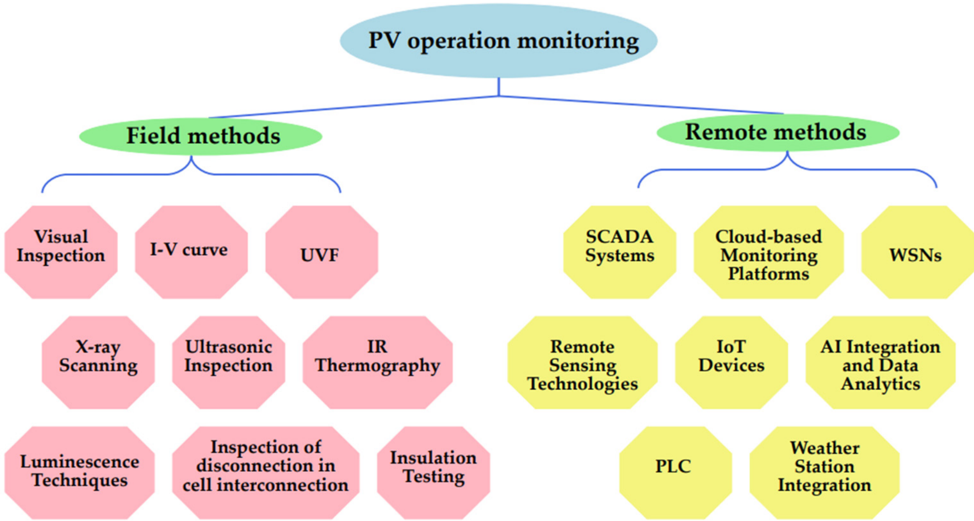

Figure 4. Schematic illustration of field and remote methods for PV operation monitoring.

Another valuable test tool for ensuring the proper operation of PV modules is the I–V curve. This method is applied to monitor and evaluate the electrical output of the module under different operating circumstances, such as levels of irradiance and variations in temperature. The parameters of the I–V curves are strongly connected to the electrical profile of the module. Discoloration, delamination, and glass corrosion can cause a drop in short-circuit current, while losses in open circuit voltage are often the result of PID, temperature-induced degradation (TID), LID, or a breakage in the cell interconnections. The slopes in each case denote an increase in shunt and series resistance, respectively. The I–V curves can be used to evaluate both the annual rate and the percentage of the degradation of the PV module.

The ultraviolet fluorescence (UVF) technique is widely used to measure degradation in c-Si-based solar cells. The application of the technique requires a spectrometer and a UV irradiation source, which can be used to detect cell cracks, hot spots, and EVA degradation. The method is mainly used for an in-depth examination of the encapsulation material of a PV module [112], which is typically EVA, along with various additives, such as oxidation stabilizers and UV absorbers, and acts as an accumulation region for fluorophores.

X-ray scanning is a non-destructive method applied to detect delamination and incoherence among the elements of a PV module in two-dimensional (2-D) images. Similar to the X-ray scanning method, ultrasonic inspection is based on scanning the PV module with the assistance of a moving ultrasonic transducer with an integrated X-Y indicator. Thermal or infrared imaging (IR-T) is one of the most well-known testing techniques for the detection of potential thermal abnormalities and electrical failures in a PV module. The method is non-destructive, contactless, and yields fast results, while it only requires a DC power supply and an IR camera with a spectral range between 8 and 14 µm. During PV operation, a localized heating increase is mainly caused by current runaway and broken or loosened contacts.

Luminescence techniques are based on light emitted by radiative recombination of charge carriers in semiconducting materials. The techniques used to trigger luminescence radiation can be divided into two categories: electroluminescence (EL) and photoluminescence (PL). In electroluminescence (EL), the capture of an EL image provides information and a quantitative explanation of several cell properties, including shunt and series resistance, diffusion length, and minority carrier lifespan. Besides this, a qualitative examination of an EL image intends to detect easily recognizable signs of possible degradation processes and aging effects in PV modules, which could, in the immediate future, question the durability and reliability of the module [114]. Furthermore, EL imaging can accurately identify cracked cells, hot spots, and shunts in c-Si cells, as well as corrosion and delamination signatures in thin-film solar cells. Daylight photoluminescence (dPL) can identify cell cracks and monitor material characteristics, while it is also crucial for the detection of open circuit faults in bypass diodes and the evaluation of the I–V curves of single solar cells.

Inspection of disconnection in cell interconnection is widely used as a means of evaluating the condition and effectiveness of the interconnection between PV modules and/or solar cells [115]. Its application requires an interconnect breakage tester, which can detect possible breakages in the interconnection system. This device can identify interconnection damages and faults, which can cause efficiency problems in the PV modules. Insulation testing [115] is a technique used to examine the condition of insulation materials, which are integrated with the electrical components of a PV module. The method requires an insulation resistance tester, which evaluates the effectiveness of the insulation. This device can detect potential insulation faults and defects in connections and wiring, which can induce safety issues and electrical faults.

A detailed analysis of the field monitoring methods is included in the Supplementary File. Table 5 below summarizes typical field monitoring methods and required equipment.

Table 5. Field monitoring methods used in photovoltaic (PV) operation.

Method	Description	Key Features	References
Visual inspection/assessment	A simple method for detecting defects in PV modules through visual observation	– Identifies obvious degradation signs such as corrosion, discoloration, and cracks – Requires no specialized equipment – Essential after PV module manufacturing	[43,74,116]
Current–Voltage curve (I–V characterization)	Evaluates electrical output under varying conditions	– Requires illumination, a DC power supply, and an I–V curve tracer – Reveals performance parameters like maximum power and voltage – Used to compare aged modules with reference values to assess degradation	[116]
Ultraviolet Fluorescence (UVF)	Measures degradation in c-Si solar cells through fluorescence emitted when UV light is absorbed	– Requires a spectrometer and UV source – Detects issues like cell cracks and EVA degradation – Fluorescence signals indicate degradation after about 1.5 years of outdoor exposure	[112]
X-ray Scanning	Non-destructive method for detecting delamination and component misalignment in PV modules	– Produces 2-D images to analyze structural integrity – Helps identify potential issues without damaging the module	[117]
Ultrasonic inspection	Non-destructive method that combines transmission and echo pulse techniques to locate defects in PV modules	– Uses ultrasonic transducers for scanning – Can define dimensions and locations of defects based on reflected pulses and beam diversion	[118]
Infrared Thermography (IR-T)	Detects thermal abnormalities and electrical failures through thermal imaging	– Non-destructive and fast; requires an IR camera and DC power supply – Effective for large-scale arrays; visualizes temperature distribution to identify hot spots indicating issues like current runaway or loose contacts	[119,120]

Table 5. *Cont.*

Method	Description	Key Features	References
Luminescence techniques	Measures light emitted from semiconductors to assess solar cell characteristics	– Includes Electroluminescence (EL), which uses a DC source to stimulate luminescence, and Daylight Photoluminescence (dPL), which uses sunlight during operation – Useful for identifying defects like cracks and shunts, as well as assessing material characteristics without disrupting the electrical circuit	[114,121–124]
Inspection of disconnection in cell interconnection	Evaluates the effectiveness of interconnections between PV modules or cells using a breakage tester	– Identifies possible breakages that could affect efficiency	[115]
Insulation testing	Examines insulation materials in PV modules using an insulation resistance tester to detect faults that could lead to safety issues	– Ensures the effectiveness of insulation against electrical faults and defects in connections or wiring	[115]

4.3.2. Remote Monitoring Methods

In the following Table 6, the most common methods for remote PV operation monitoring are presented [125].

Table 6. Remote methods, alongside equipment and usefulness, for PV operation monitoring.

Method	Required Equipment	Usefulness	References
Supervisory Control and Data Acquisition (SCADA) Systems	SCADA software, data loggers, sensors	Real-time data gathering on system performance and automated operation control, vital for large-scale installations	[126–128]
Cloud-based Monitoring Platforms	Data transmission units, cloud servers	Remote access to performance data, centralized monitoring systems, and real-time data analysis, crucial for multiple sites	[129]
Wireless Sensor Networks (WSNs)	Data collection units, wireless sensors, gateways	Installation of multiple wireless sensors across the PV system, simultaneous monitoring of different performance parameters, data analysis in centralized systems, critical for large and complex PV systems in difficult-wiring areas	[130–133]
Remote Sensing Technologies (satellites, drones)	Environmental sensors, aerial drones, satellite data	Long-term and large-scale monitoring, remote images and data collection, identification of possible issues that go unnoticed by other methods	[134,135]
Internet of Things (IoT) Devices	Cloud storage, IoT gateways, smart sensors	Data collection and processing from different sources, predictive maintenance capability, real-time automated monitoring, integrated with machine learning and AI	[136–139]
Artificial Intelligence (AI) Integration and Data Analytics	Analytics software, large datasets, AI algorithms	Predictive maintenance and fault detection through pattern identification, performance optimization, and advanced data analytics, Useful for extending PV longevity	[140–142]
Power Line Communication (PLC)	Modems, communication network	Cabling-free remote monitoring, easy data transmission, valuable for upgrading PV systems	[143]
Weather Station Integration	Data loggers, various sensors (for temperature, wind speed, and irradiance) incorporated in the weather station	Comparison and contrast of weather conditions with PV performance, useful for degradation signs detection	[144]

4.4. PV Longevity Improvement

By understanding the key degradation mechanisms and implementing appropriate mitigation strategies [145], the long-term reliability and cost-effectiveness of photovoltaic technology can be significantly improved, contributing to the widespread adoption of solar energy as a sustainable and reliable source of electricity. The pursuit of adopting solar energy for meeting electricity requirements in the near future ignites interest and presupposes not only the utilization, to the maximum degree, of the already existing knowledge and technology for PV modules and cells but also the search for new technology and techniques in order to extend their lifetime. This section is divided into two subsections. In the first one, we summarize the knowledge, based on literature, about the PV module lifespan, and we describe scientific gaps in the comprehension of degradation mechanisms and material technology improvements. In the second one, we present numerous mitigation strategies that have been applied in order to decelerate the effects of degradation mechanisms and ensure the stability and longevity of PV modules.

4.4.1. Knowledge Improvement

The first commercial PV modules, back in the 1980s, had an estimated operational lifetime of 10 to 15 years [146,147]. In the 1990s, the average lifetime was increased to around 20 years, mainly due to the transition from mono(poly)crystalline Si to thin-film materials, such as CIGS (Copper Indium Gallium Selenide), CdTe (Cadmium Telluride) and amorphous silicon (Si) [148]. This technological leap, in combination with advances in manufacturing protocols and enhanced encapsulation materials, upgraded the durability of PV modules. The establishment of testing procedures in the early 2000s for the evaluation of the reliability of PV modules led to a lifetime of 20 to 25 years [149,150], as the majority of degradation mechanisms, such as environmental stress factors, could be detected at an initial phase. In the 2010s, the PV industry witnessed huge improvements and innovations, with the introduction of bifacial modules, perovskite materials, and enhanced anti-reflective coatings, which promised improved efficiency and lower degradation rates. These breakthroughs raised the expected lifetime of the PV modules from 25 to 30 years [151,152]. Nowadays, PV manufacturers constantly attempt to further expand the boundaries of the module's lifetime. Higher efficiency and durability are ensured by data analysis, field and remote real-time monitoring, as well as maintenance procedures. The progress made so far, as well as the advancements that are yet to be achieved, aim at extending the PV module's lifespans into the 30–40-year range [153,154].

In Tables 7 and 8, a synopsis of photovoltaic systems' lifetime data over time is presented, based on literature sources and references and warranty data from different manufacturing companies [155], respectively. In Figure 5, the data for PV module lifetime from Tables 7 and 8 in a common diagram are depicted. The time axis is divided into decades, and the selected data points are depicted with corresponding error bars in both horizontal and vertical axes. The increasing trend of the curves reflects the ongoing development efforts and research focused on PV technology. The two curves have good correspondence, and now the scientific community is eager to observe whether the projected PV lifetime will live up to its expectations and break the 30–40-year barrier. Despite progress and advancements, numerous challenges along with scientific gaps remain, indicating the areas where both the available bibliography and the scientific research are incomplete. The longevity of a PV module has great expansion potential under the prism of knowledge improvement and overall design, which could guarantee enhanced cost-effectiveness and sustainability.

Table 7. The increment in PV module's lifetime over time, according to literature sources.

Decade	Lifetime According to Literature [Years]	References
1980–1990	10–15	[146,147]
1990–2000	15–20	[148]
2000–2010	20–25	[149,150]
2010–2020	25–30	[151,152]
2020–2030	30–35 (the range 30–40 years is the desirable goal)	[153,154]

Table 8. The increment in PV module's lifetime over time, according to warranty data from different manufacturing companies [155].

Decade	Warranty PV Lifetime Data [Years]	References
1980–1990	5–15	[155]
1990–2000	15–25	
2000–2010	~25	
2010–2020	25–30	
2020–2030	30–35	

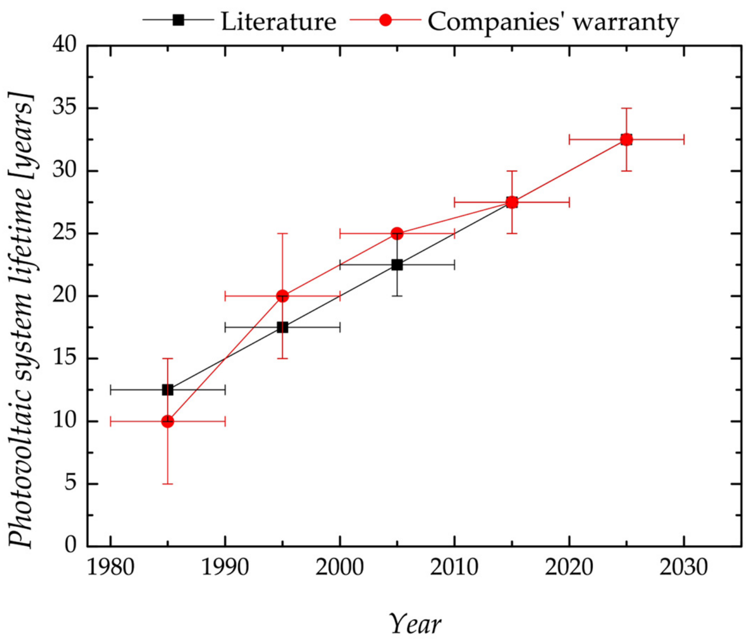

Figure 5. Progress in photovoltaic system's lifetime over the years, according to literature sources. Warranty lifetime data for PV modules over time are also shown [155].

Detailed insight and a full understanding of some degradation mechanisms, such as PID, TID, UV exposure, and LID, are still lacking. The key to improving PV module longevity is identifying these degradation processes and employing appropriate mitigation strategies. In Table 9, a comprehensive overview of the incomplete knowledge of these degradation mechanisms is presented, while several material advancements for their mitigation are also highlighted.

Table 9. Incomplete knowledge and corresponding material advancements that have been introduced as a result of continuous research regarding PID, TID, UV exposure, and LID.

Degradation Mechanism	Incomplete Knowledge	Material Advancements	References
PID	A fully microscopic interpretation of the phenomenon, materials components' behavior under high voltage stresses, appropriate material selection, and cost-effectiveness	Polyolefin elastomer (POE) encapsulants (higher volumetric resistance), fluoropolymer backsheets (limited moisture ingress)	[58,156,157]
Temperature-induced degradation (TID)	Effects of thermal fatigue on PV module's components, precise models for the development and enlargement of the cracks	Polyolefin encapsulants (increased hydrolytic degradation resistance and enhanced thermal stability), polyamide and PET (Poly-Ethylene Terepthalate)-based backsheets (increased thermal stability), fluoropolymer backsheets (increased thermal stability), advanced anti-reflecting coatings	[158–161]

Table 9. *Cont.*

Degradation Mechanism	Incomplete Knowledge	Material Advancements	References
UV exposure	Comprehensive understanding of the impact of UV irradiance on backsheets and encapsulants, durability and performance of the PV module, and interactions between different UV stabilizers	Highly resistant to UV irradiance encapsulants and backsheets, UV resistance coatings	[162–165]
LID	Inadequate interpretation of the underlying physical and chemical mechanisms behind the formation of boron-oxygen complexes, the role and accurate contribution of metal impurities and other defect compounds	Performance tests under varying doping percentages, progressive removal process of a boron-rich layer on the emitter, boron-doped Si PV cells	[166–168]

4.4.2. Mitigation Strategies

PV Modules

To mitigate these degradation processes and improve the long-term stability and lifetime of PV modules, several strategies have been employed [169]. These include appropriate material selection, updated manufacturing processes, and meticulous testing protocols in both field and laboratory. In Figure 6, a schematic diagram, including several mitigation strategies at both the module and operation–maintenance level, is depicted.

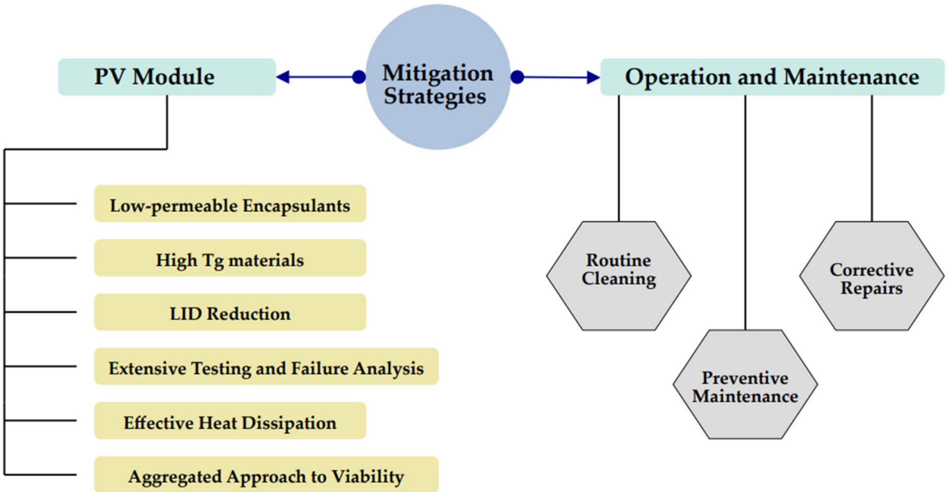

Figure 6. Mitigation strategies on both PV module and operation–maintenance level.

- **Encapsulation materials with low permeation rates**. Choosing encapsulants with a low permeation index is vital, as they can mitigate the ingress of harmful for the module's environmental and atmospheric constituents. The optimization of the encapsulants can, on a long-term scale, prevent delamination, discoloration, corrosion, and other degradation phenomena that pose a threat to the lifespan and performance of PV modules [170]. Despite their satisfactory performance in normal operation service and cost-effectiveness, typical EVA encapsulants show significant drawbacks and easy degradation and, as a consequence, require redesign and reformulation [171]. Seeking other economically beneficial encapsulation materials, polyolefins provide lower oxygen and water permeation rates, good UV resistance, stable chemical properties, and reduced degradation tendencies [172]. Ionomers [173] also have a prominent position in encapsulation manufacturing. While their design has proven costly, their superior characteristics, including high UV resistance, low moisture transmission, and improved adhesion to the adjacent components of the module, promise to ensure longevity, especially for modules based on thin-film technology.

- **Materials with high glass transition temperature (Tg)**. The glass transition temperature (Tg) is an important feature of backsheets and encapsulants integrated into PV modules. During operation, the temperature of the module rises significantly, and a plethora of temperature-related degradation phenomena begin to appear and escalate. For proper performance, PV module materials must be able to encounter high temperatures and secure their structure's stability under extreme thermal stresses. Encapsulants and backsheet materials with high Tg values above 100 °C are selected to maintain thermal stability and mechanical incorruptibility at operating temperatures. High-Tg materials remain unaffected under temperature elevations in outdoor conditions and show lower sensitivity to temperature-induced degradation (TID) mechanisms. These properties moderate the impacts of degradation on the PV modules and offer great potential for longevity. Typical examples of materials with high Tg values include polyolefins, polyamides, and polyimides. Polyolefins are more thermally resistant than EVA and are mainly used as encapsulation materials [106]. Polyamides are a well-considered choice for backsheets, providing enhanced properties and long-term reliability under thermal stress regimes [161]. Polyimides, with Tg on the order of 300 °C, are preferably selected when thermal stresses are extremely high and exceptionally high stability is a first priority [174,175].
- **Reduction in photo-induced burn-in effects**. Photo-induced burn-in effects refer to degradation signs and drops in the performance of PV modules immediately after their installation and first interaction with solar irradiance. Defects, impurities, and disordered film morphological patterns are recognized as the responsible mechanisms. A widespread mitigation strategy applied to reduce these effects is the use of pure materials with dense and ordered film morphologies [176]. Current research has revealed that perovskite materials are ideal candidates in the attempt to limit photodegradation and improve the longevity of PV modules, provided that during their manufacture process, high-ordered crystal lattices are created [177,178]. In traditional c-Si solar cell technology, the utilization of Si with a high purity index, thereby lowering defects and impurity concentration, can reduce the susceptibility to PID. A well-promising technology with great potential for constant improvement is the thin-film PV [179]. This field includes CIGS and CdTe materials, which have a dense structure and are suggested for mitigating burn-in effects.
- **Extensive testing and failure analysis**. Extensive testing and failure analysis [180] are an integral part of the vision to expand the lifespan of PV modules and can be carried out by a combination of different methods and practices. Accelerated testing aims to investigate long-term exposure to scaled stress conditions, such as high humidity condensation, high temperature, or high percentage of UV irradiance. Typical aspects of this method comprise damp heat testing, interaction with increased UV radiation, thermal cycling, and mechanical load testing. In the case of stressful situations that are difficult to simulate, such as in installation areas with different climates, field testing is employed, and perpetual inspection of the module is carried out. This method offers a deep insight into the effect of long-term operation on the PV module's performance and confirms the findings of the laboratory tests.

  A typical aspect of failure analysis is root cause analysis [181,182]. This method is used in the case of existing damage and failures and is intended for the methodical examination and identification of the responsible cause. By studying damaged connections, malfunctioning materials, and faulty interfaces, both on a macroscopic and microscopic scale, the precise reasons for degradation and possible defects can be detected. Additionally, failure analysis is a valuable tool for mapping and recognizing imprints of specific degradation mechanisms, such as LID, TID, and PID.
- **Effective heat dissipation**. The genuine challenge for the prosperity and advancement of PV technology is ensuring effective heat dissipation mechanisms. During operation, elevated temperatures within the module are raised, causing a drop in its power output and accelerating the degradation of its components and materials.

These detrimental effects of high temperatures can drastically lower its lifespan. The development and subsequent establishment of mitigation techniques that guarantee effective heat management is crucial for the longevity of PV modules. Toward this purpose, different cooling technologies have emerged and are constantly being improved—passive cooling, active cooling, and hybrid cooling methods—which are a combination of the two previous ones.

Passive cooling, which is mainly applied in large-scale installations, is an energy-beneficial system, as it does not require additional energy. In this technique, heat dissipation is based on the natural transfer of the stored heat to the ambient via conduction, convection, radiation, and evaporation. This process is significantly facilitated by the quality and the properties of the module's overall design. For example, bifacial modules, which ensure unobstructed air circulation, or modules with advanced airflow systems can provide useful guidelines for the improvements of passive cooling technology. Ramkiran et al. presented interesting experimental results of a comparative analysis among various passive cooling methods, including greenhouse cooling, plant cooling, and a combination of the two aforementioned phase change materials, which are cooling and coir pith [183]. Based on their outcomes, the achieved reduction in temperature is not strongly related to an increase in power and efficiency for all the techniques. They suggest that the selection of the appropriate cooling method depends on the environmental and climate conditions. Mahdavi et al., in their recent work, delve into a thorough study of the available literature regarding passive cooling methods and devices, summarizing their advantages and underlining the remaining research gaps [184].

In contrast to passive cooling, active cooling systems require an electrical power supply or external energy consumption. These approaches need a coolant element to operate, which includes a pump or a fan, and are efficient, especially in the desert and arid regions or in areas with hot climate conditions. Dwivedi et al. studied the various water-based cooling techniques to mitigate the elevated internal temperature of the PV module and noted the merits and demerits of each one in terms of temperature reduction [185]. Nowadays, as the need for enhanced cooling systems continues to grow, promising hybrid methods combining passive and active cooling have come to the forefront. Gharzi et al. conducted a comprehensive analysis of different cooling system categories, presenting their key traits and functionalities [186]. Their conclusions highlighted the hybrid cooling strategy as the optimum solution in terms of proper management of thermal energy, as well as both sustainable performance and long-term viability of PV technology.

Although a wide range of cooling methods are commercially available, the viability and performance effectiveness of each one need to be further examined. All methods require rigorous tests and advancements in order to fulfill their purpose and be implemented in large-scale solar systems. The optimum choice among all the proposed cooling methods is yet to be identified due to the lack of experimental and economic investment data. The vision of effective heat dissipation directs future research toward deeper insight into the hybrid cooling approaches, which have enhanced the potential of maintaining the internal temperature of the modules at the desirable levels. This intervention for the correct temperature regulation, as well as its contribution to the longevity of the PV modules, requires a more thorough investigation.

- **Aggregated approach to PV module viability**. Performance, cost, and reliability are the triptychs for ensuring PV module sustainability. A holistic strategy is based on the balanced impact of these three parameters, and its overarching purpose can be synopsized to enhance the operational lifetime of solar energy systems. The concept behind this endeavor lies in minimizing material costs and, simultaneously, guaranteeing a high level of performance and long-term reliability by optimizing the module design practices and manufacturing protocols. Efficiency and performance improvements need to be prioritized. The focus ought to be placed on maximizing the energy conversion inside the module. This requires the utilization of highly efficient solar cells, the attempt to adjust new material technology, such as perovskites, and the expectation of optimum resistance to environmental stress factors and degradation mechanisms. Another key factor is the automation of manufacturing and processing techniques to limit waste in raw materials and energy. The fulfillment of high-reliability requirements is based on establishing high-quality tests, both in the field and in laboratory conditions. Besides these, the longevity and durability of PV systems can be benefited by studying the sustainability of the modules in a more theoretical frame with the development of advanced predictive models and algorithms, which will be able to calculate the lifetime and the rate of degradation. In general, an aggregated approach to PV sustainability is the key to the emergence of solar energy as a profitable solution in terms of economic viability and environmental impact [187].

Strategies employed to enhance the longevity and stability of PV modules are summarized in Table 10.

Table 10. Mitigation strategies to enhance the longevity and stability of photovoltaic (PV) modules, emphasizing material selection, testing protocols, heat management techniques, and holistic approaches for sustainability in solar energy systems.

PV Longevity Enhancement Strategy	Description	Key Features	References
Material selection	Choosing appropriate materials to mitigate degradation and enhance stability	– Focus on encapsulants with low permeation rates to protect against environmental stresses – Use of additives and cross-linking agents to improve thermal stability – Exploration of polyolefins and ionomers for better performance and longevity	[170–173]
High glass transition temperature (Tg) materials	Selecting materials with high Tg values for backsheets and encapsulants to maintain structural integrity under thermal stress	– High Tg materials (>100 °C) resist temperature-induced degradation – Examples include polyolefins, polyamides, and polyimides, which offer enhanced thermal stability and reliability – Polyimides are preferred for extreme thermal conditions due to their high Tg (~300 °C)	[106,161,181,182]
Reduction of photo-induced burn-in effects	Addressing performance drops immediately after installation due to defects and impurities in materials	– Use of pure materials with dense film morphologies to minimize degradation – Perovskite materials show promise in limiting photo-degradation when produced with high-ordered crystal lattices – High-purity silicon reduces susceptibility to performance drops in traditional c-Si technology	[176–179]
Extensive testing and failure analysis	Implementing rigorous testing protocols to identify potential degradation early on	– Combination of accelerated laboratory tests and field testing to simulate real-world conditions – Methods include damp heat testing, thermal cycling, and mechanical load testing – Root cause analysis helps identify specific degradation mechanisms like LID, TID, and PID through detailed examination of failures	[180–182]

Table 10. *Cont.*

PV Longevity Enhancement Strategy	Description	Key Features	References
Effective heat dissipation	Ensuring proper heat management to prevent performance drops due to elevated temperatures during operation	– Development of cooling technologies: passive (natural heat transfer), active (requires energy), and hybrid methods (combines both) – Passive cooling benefits from module design, while active cooling is effective in hot climates – Hybrid systems are emerging as optimal solutions for thermal management in PV modules	[183–186]
Aggregated approach to viability	Balancing performance, cost, and reliability for sustainable PV module operation	– Focus on minimizing material costs while maximizing performance through optimized design and manufacturing practices – Emphasis on using efficient solar cells and new material technologies like perovskites – Development of predictive models to estimate lifetime and degradation rates enhances economic viability and environmental impact of solar energy systems	[187]

Operation and Maintenance (O&M)

PV system longevity can be considerably increased by following appropriate operation and maintenance (O&M) practices, in addition to material selection and testing procedures [188]. Routine cleaning, preventive maintenance, and corrective repairs can boost productivity, reduce downtime, and significantly prolong the PV system's lifetime.

Routine cleaning is a maintenance task that ensures high-efficiency operation for the PV module, manually or automatically. Manual cleaning is carried out by water and special equipment, such as soft brushes, and aims at careful removal of soiling without causing scratches or damage. This technique is more beneficial when the temperature is at low levels, especially in areas with high percentages of dust or drought. In the case of large installations, robotic cleaning devices are utilized, which do not require water and are capable of extensive cleaning, even in arid areas.

As a proactive mitigation strategy, preventive maintenance is based on constant servicing and inspection of the PV module to ensure its proper operation, stable performance, and prolonged lifespan. Hot spots, cracks, discoloration signs, and delamination or corrosion marks identification are the ultimate targets. Inverters, electrical wiring, and connection checking are of primary significance, as they can cause safety concerns, apart from reduced efficiency and performance. Suitability, proper operation of cleaning filters, and effective ventilation to avert overheating are crucial.

Corrective repairs describe the maintenance actions applied on a PV module as soon as a failure or a noticeable drop in performance is observed. In contrast to preventive maintenance, these procedures are exceptional measures to address identified flaws from escalating to complete failure and to fully recover the system. During operation, the degradation rates and indications vary among the PV module components. By replacing the vulnerable components, a high-level operation can be maintained, and an unrecoverable performance decrease can be avoided.

4.5. BIPV Longevity Improvement

Building-integrated photovoltaics (BIPV) represent a major advancement in solar technology by integrating PV modules directly into the building structure, serving dual purposes as both power generators and functional building materials as part of the roof, façade, or windows [189]. While this dual functionality is advantageous, it also introduces unique challenges that can affect the durability and performance of BIPV systems, necessitating targeted strategies to extend their operational lifespan.

Prolonging the lifetime of BIPV modules is essential for lowering the Levelized Cost of Energy (LCOE) and maximizing the value for key stakeholders. Unlike traditional PV installations, BIPV systems are often installed in orientations and environments that are not ideal, leading to various performance issues [190]. A primary concern is the higher operating temperatures that BIPV modules often experience due to inadequate rear-side ventilation compared to standalone PV systems [191]. This can result in hot spots [192], energy losses, and shorter operational lifespans. Additionally, BIPV modules are exposed to various environmental stressors [145], including humidity, high winds, snow loads, and other weather-related factors, similar to traditional PV systems.

The BIPV degradation mechanism may differ from those in standalone PV systems since they are usually exposed to building-specific factors such as structural loads, temperature changes from building heating and cooling, and shading from architectural elements. Additionally, the aesthetic requirements of BIPV systems often necessitate using semi-transparent or colored PV modules, which may have different aging profiles compared to standard modules [193].

One of the primary concerns is thermal stress, as these modules undergo significant temperature variations due to their integration into building structures. Poor ventilation can exacerbate thermal degradation, leading to material fatigue and delamination [88]. Moisture ingress is another critical issue, particularly for modules installed on façades or roofs. Exposure to rain, snow, or condensation can lead to the degradation of encapsulants, corrosion of electrical contacts, and PID. As modules age, particularly beyond their warranty period, problems such as severe delamination or microcracks can accelerate, resulting in a rapid decline in power output. Regular monitoring, especially after 15 years, and prompt detection of issues like junction box failures or corrosion are crucial for prolonging module life [194].

BIPV modules, as part of the building envelope, are subject to additional mechanical stresses [195] from wind, snow, debris, etc. This can result in microcracks, cell fractures, and other mechanical failures. Innovative mounting systems, such as the one proposed by [196], offer improved stiffness and adaptive control of panel gaps, which can enhance durability. Furthermore, Budiman et al. have developed a polycarbonate-sandwiched laminate design that permits the curving of silicon photovoltaics [197]. This design reduces tensile stresses and enhances compressive strengths in typically brittle silicon cells, thereby improving fracture resistance. These innovations enable more flexible and aesthetically pleasing designs and address long-term reliability, contributing to more robust and adaptable BIPV solutions.

Mitigation Strategies for BIPV Longevity

To enhance the longevity of BIPV systems, selecting robust materials with high thermal stability and low moisture permeability is essential. Advanced encapsulants such as EVA offer protection against UV radiation and moisture ingress, extending the module's lifespan [198]. Additionally, glass/glass module designs and the integration of nanomaterials improve durability and resistance to environmental factors. Flexible or laminated BIPV modules are better at absorbing and distributing mechanical loads, reducing the risk of damage. Protective coatings [199] that enhance UV resistance and minimize water permeation further contribute to module longevity [200]. Proper sealing of module edges and electrical junctions is crucial for preventing moisture ingress, particularly in humid climates. Reflective coatings can also help reduce heat absorption, thus mitigating thermal stress and prolonging the life of BIPV systems.

Effective thermal management is crucial for optimizing the performance and longevity of BIPV modules. Passive cooling techniques, such as ventilated façades and thermally conductive backsheets, can help regulate operating temperatures. Integrating radiative cooling coatings and phase change materials (PCMs) [201] or proper heat dissipation, such as air gaps, heat sinks, and ventilation, is essential to avoid excessive heat buildup. Kaaya et al. [202] indicate that well-ventilated BIPV systems can exceed their 25-year warranty across various climates, while inadequate ventilation, particularly in hot and humid regions, can significantly shorten module lifespans.

BIPV systems often experience higher temperatures due to limited rear-side ventilation, increasing thermo-mechanical stresses, and accelerating degradation. Ozkalay et al. [203] observed that BIPV modules in Southern Switzerland operated at temperatures 20–30 °C higher than those in open-rack systems, with daily temperature swings up to 25 °C more, underscoring the need for more stringent indoor qualification and safety tests, especially for modules exposed to extreme temperatures beyond standard International Electrotechnical Commission's (IEC) guidelines.

Innovative cooling solutions, such as the closed-loop photovoltaic cooling system developed by Dirawi et al. [29], have significantly improved PV module lifespan and efficiency, particularly in hot and arid regions. This system, designed to operate continuously, reduces temperature fluctuations and enhances performance, achieving an 8.2% increase in module lifespan compared to conventional designs. Additionally, Moghaddam et al. [204] introduced a BIPV system that enhances passive cooling through increased surface emissivity beneath PV panels, resulting in a 3 K reduction in operating temperature, which boosts efficiency and extends module lifespan by up to 21%.

Proper O&M practices are essential to ensure the long-term reliability of BIPV systems. Routine inspections should focus on detecting moisture ingress, checking for signs of delamination and discoloration, and the effectiveness of thermal management systems. Preventive maintenance, such as regularly cleaning modules to remove dust and debris, is crucial for optimal performance. Using both experimental and simulated data, Lee et al. [205] underscored the importance of addressing crack issues during installation and maintenance to preserve BIPV system longevity, noting that such damage can cause output reductions of up to 43%.

Enhancing the longevity of BIPV systems requires a holistic approach that considers the unique degradation mechanisms associated with building integration. Adopting advanced material solutions, effective thermal management strategies, protective measures, and robust O&M practices can significantly extend the operational lifetime of BIPV systems. This not only contributes to the sustainability of building-integrated renewable energy solutions but also improves their cost-effectiveness. The Net Present Value (NPV) index, estimated as the sum of present incoming (benefits) and outgoing (expenditures) cash flows over the lifetime of the investment, is dramatically increased by improving the longevity of the BIPV systems, as can be observed in Figure 7. Future design improvements should focus on mitigating heat and noise transmission, as well as corrosion. Ongoing research should aim to understand the impact of temperature on the electrical properties of BIPV modules, considering factors like material layers and installation angles while also comparing the long-term thermal and electrical performance of BIPV products with conventional building materials [206].

Table 11 summarizes the key aspects related to improving the longevity of BIPV, highlighting the material selection, thermal management, and operational practices, as well as future research directions necessary for enhancing the durability and efficiency of these systems in building applications.

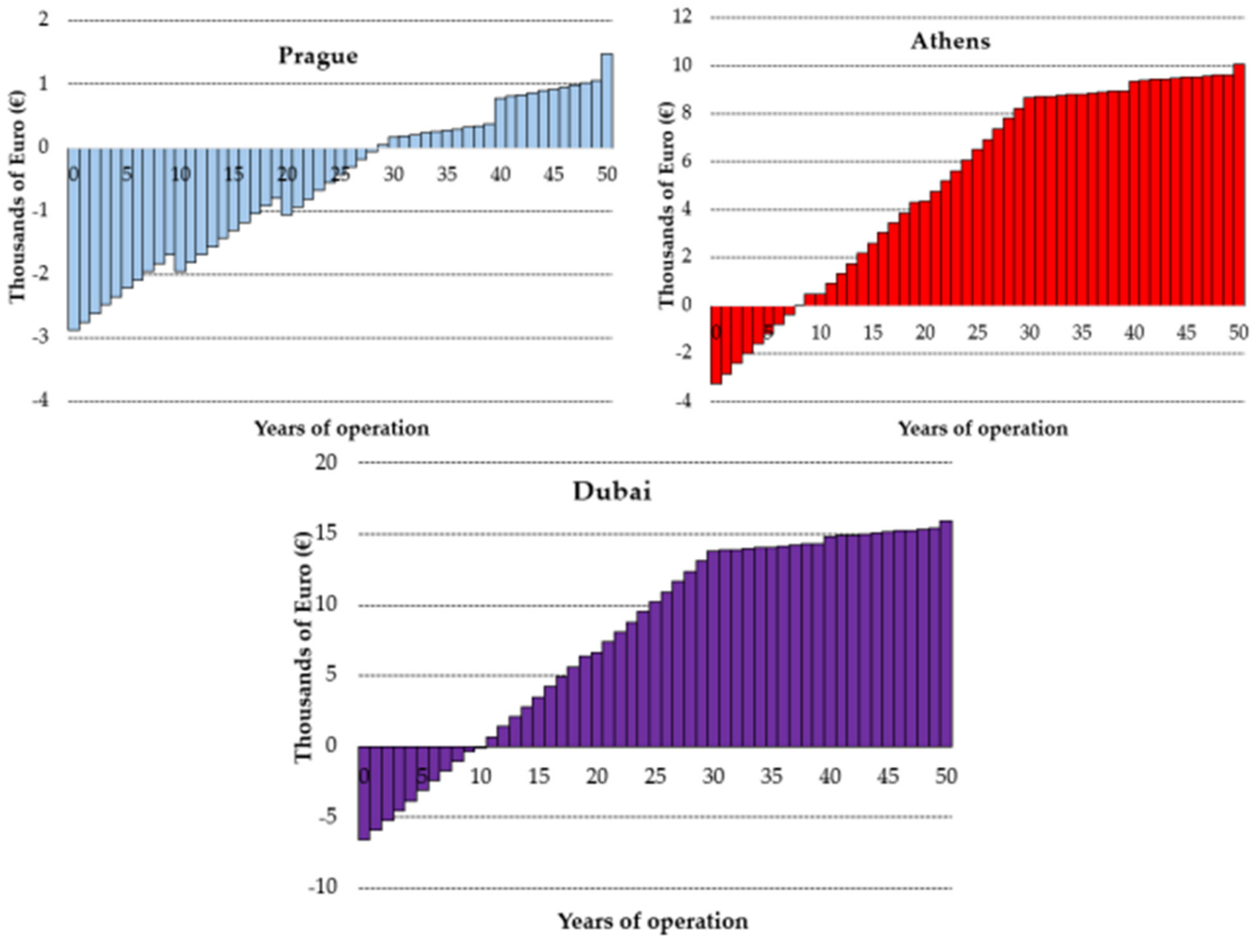

Figure 7. Net Present Value (NPV) index of building-integrated photovoltaics (BIPV) systems by improving their longevity to more than 30 years at three climate zones (Prague, Athens, and Dubai), based on the analysis of Skandalos and Karamanis [207].

Table 11. Building-integrated photovoltaic (BIPV) longevity improvement strategies.

BIPV Longevity Enhancement Strategy	Description	Key Features	References
Material selection	Selecting materials with high thermal stability and low moisture permeability is crucial for BIPV longevity.	– Advanced encapsulants protect against environmental stressors – Flexible or laminated designs distribute mechanical loads better – Protective coatings enhance UV resistance and reduce water permeation	[198–200]
Thermal management	Effective thermal management strategies are essential for optimizing BIPV performance and lifespan.	– Passive cooling methods like ventilated façades help regulate temperatures – Innovative cooling solutions can reduce temperature fluctuations significantly, improving lifespan by up to 21% – Regular inspections are necessary to identify thermal stress issues early on	[29,201–204]

Table 11. *Cont.*

BIPV Longevity Enhancement Strategy	Description	Key Features	References
Operational practices	Proper operation and maintenance (O&M) practices are vital for ensuring long-term reliability of BIPV systems.	– Routine inspections should focus on moisture ingress, delamination, and thermal management effectiveness – Preventive maintenance includes cleaning modules regularly to maintain performance levels – Addressing installation-related crack issues is critical for preserving module longevity, as damage can lead to significant output reductions	
Future directions	Future improvements should focus on innovative designs that mitigate heat transmission, noise, and corrosion while enhancing overall reliability of BIPV systems.	– Ongoing research should explore the impact of temperature on electrical properties of BIPV modules – Comparison with conventional building materials will help refine design approaches for better performance in various environments – Emphasis on developing predictive models for estimating lifespan and degradation rates will enhance economic viability of BIPV solutions	[205,206]

5. Discussion

The present paper's objective is, on the one hand, to summarize the current knowledge on key degradation mechanisms affecting PV modules and remote and on-field monitoring methods for identifying failures and, on the other hand, to present a series of mitigation strategies employed to prolong their sustainability and life expectancy. The first step toward this direction is an in-depth understanding of the degradation modes and their correlation with the different climatic and environmental conditions across the globe. Regional and geographic characteristics of the location of PV systems deployment pose multiple challenges to their performance, efficiency, and longevity, as the overall degradation effect is climate-dependent. A thorough insight into the intricate relationship between environmental stress factors and PV module reliability presupposes a correlation among degradation mechanisms, climate patterns, and weather conditions. Table 12 below provides a detailed overview of the association between the dominant degradation mechanism and the climate and regional factors.

In the vast majority of cases, the occurrence of degradation emerges as a complex combination of multiple stresses and not due to the effect of a single mechanism. During real-world operation, PV systems are susceptible to the effect of the superposition of all the aforementioned degradation mechanisms, depending on the climate and region of installation. A promising mitigation strategy aiming at enhancing the longevity of PV modules is the development of new, hybrid accelerated test setups and the establishment of protocols, the so-called agnostic tests, which will simulate this complex interaction. This approach was examined by Owen-Bellini and Hacke et al. [208,209] in their work, who achieved an accurate replicate of a combined stress situation by exposing the module to combined or sequential stress factors and evaluating their durability.

Table 12. Comprehensive overview of dominant PV degradation mechanisms across diverse climates and regional characteristics.

Dominant Degradation Mechanism	Weather/Climate Conditions	Regional Characteristics
PID	High humidity percentage, elevated temperature	Tropical and coastal regions
LID	High solar exposure, sunlight fluctuations	Sunny and desert areas
TID	Elevated operational temperature, intense diurnal and seasonal temperature variations	Arid, desert, continental, and temperate regions
UV Degradation	High UV irradiance exposure	Sunbelt regions, desert areas, high-altitude areas
Moisture Ingress	Frequent rainfalls, high humidity	Tropical and subtropical regions, coastal regions
Mechanical Stresses (snow, ice, wind, hail)	Heavy snowfalls, intense storms, ice accumulation, high wind speeds, hailstorms	Polar and high-altitude regions, mountainous areas, stormy regions, regions with extreme weather conditions (hurricanes, tornadoes, hailstorms)
Corrosion/Salt Mist Corrosion	High humidity, saline	Coastal regions, areas with salt-laden air or acid rain
Delamination	Thermal cycling, high moisture concentration	Humid areas, areas with intense temperature fluctuations
Soiling	Pollution (natural or industrial), dust accumulation, sandstorms, sand abrasion	Industrial areas and zones, urban areas, deserts, arid/semi-arid regions, areas with high dust levels and sandstorms
Hot Spots	Cell mismatch, partial shading phenomena	Regions with vigorous vegetation, urban areas with shading from buildings

After focusing on the different degradation mechanisms that strongly impact PV modules installed in various climates and regions across the globe, it is worth discussing the different degradation challenges faced by different PV technologies and several subsequent mitigation strategies that have been developed.

Different PV technologies are prone to specific degradation challenges that significantly impact their long-term effectiveness and durability. Silicon-based modules, which hold a dominant position on the market, are primarily susceptible to PID and LID. Secondarily, they are affected by moisture, corrosion, delamination, and thermo-mechanical stresses triggered by temperature fluctuations. Combined, these factors contribute to the gradual decline in performance reliability and longevity of silicon PV systems over time. Perovskite-based solar cells offer enhanced efficiency and low production costs, but their instability when exposed to heat, moisture, and UV radiation necessitates further and targeted research. Perovskites exhibit a high sensitivity to environmental factors, such as oxygen and moisture, which induce rapid degradation of their layer. As an inevitable result, their long-term performance and their effective large-scale deployment are questioned.

Organic PV cells (OPVs) also experience significant degradation issues. These solar cells are susceptible to PID, where sunlight exposure alongside oxygen can have a destructive impact on their organic components. Degradation processes are accelerated by their lower thermal stability and high moisture sensitivity, eliminating their long-term performance and durability. Despite their advantageous lightweight and flexibility, the reliability and stability of organic solar cells continue to pose a roadblock for their widespread adoption. Next-generation PV technologies, such as tandem [210] and multi-junction [211] solar cells, show promise in addressing some of the aforementioned challenges as they combine layers of different materials with supplementary properties. However, the widespread incorporation of these materials, as well as their cost-effectiveness and ensured stability, remains a crucial area of ongoing research.

The challenging task of mitigating degradation issues across different PV technologies (silicon, perovskite, organic) is ongoing. Numerous practical solutions have either been developed and are under constant testing or are currently in development. For typical silicon-based PV modules, the emphasis is given to advanced encapsulation materials and enhanced coatings that aim at minimizing moisture ingress and limiting PID, respectively.

LID can be significantly restricted by ensuring enhanced stability and quality control in the initial phase of manufacturing. Longevity and highly efficient performance can be achieved by developing optimized system designs that mitigate high system voltages and eliminate extreme thermal stresses.

Research targeted to organic and perovskite solar cells is more demanding. Advanced encapsulation techniques are of foremost importance in shielding these high-sensitive materials from environmental agents. Additionally, the development of thermally stable polymers and improved UV-blocking layers can prove to be valuable allies in mitigating heat and UV irradiance exposure, respectively. Especially for the OPVs, new organic materials with enhanced properties, advanced stability, and high-flexibility barrier coatings are being designed and constructed to address the multiple degradation challenges.

Based on the theory presented in Section 3 and according to Equation (9), the failure time of a PV module is inversely proportional to the physical degradation rate. Due to the dynamic form of the environmental conditions, namely transient solar irradiance, fluctuations in temperature, and variable humidity content, physical degradation includes the total effect of thermo-mechanical, hydrolysis, and photo-degradation rates. Extending the lifespan of PV modules requires the reduction of these factors' contribution as much as possible.

To enhance both PV module power output and solar cell service lifetime, advanced cooling methods need to be developed in order to maintain the internal cell temperature at low values. Defining an economical, profitable, attainable, and practically applicable cooling method across various climatic features remains a demanding challenge. Among other passive cooling techniques, radiative cooling [212] is an appealing method as heat dissipation to the environment and outer space requires no additional energy or material support. Due to its simplicity, economic viability, and great perspectives, efficient thermal management of PV modules through radiative cooling has begun to monopolize the scientific interest. However, several obstacles still need to be overcome, and further research in this direction remains essential. For typical c-Si solar cells, electron excitation occurs when the energy of the incident photons surpasses the semiconductor bandgap ($E_g \approx 1.1$ eV for Silicon). In contrast, energy below the bandgap is converted into heat, resulting in an increase in the cell temperature. Consequently, reduction in sub-bandgap absorption is vital for ensuring effective radiative cooling. An optimized solution for thermal management and extended lifetime for PV systems is the proper combination of eliminated sub-bandgap absorption and radiative cooling.

Alongside effective heat dissipation, impactful management of the hydrolysis rate is also beneficial. Hydrolysis is a chemical reaction activated by moisture, which deteriorates the polymer layers and structure of the PV module. A seemingly successful way to mitigate hydrolysis is the incorporation of innovative hydrophobic materials for coatings and encapsulants. These materials, which include water-resistant coatings and fluoropolymers, significantly limit the entry of moisture and water by offering a protective barrier. This approach can be profitable for the module's performance and operational lifetime, especially in wet and humid areas.

Local climate conditions affect the performance operation of solar cells and can reduce up to 70% of the output in harsh environments of high temperatures and relative humidity [213]. This result is mainly related to temperature increase as an intrinsic PV parameter and less related to humidity effect due to water vapor condensation at the PV front surface, the reflection of incident radiation, or the reduction of the direct and the increase of the diffuse component of solar radiation in a humid climate. For example, at the moderate climate of Brighton with global horizontal irradiation of 1195 $kWh/m^2/year$, the correlation coefficient between PV output, absolute, or normalized to incident radiation and low humidity increase has not been found significant [214].

However, humidity is an important parameter of solar module degradation. Intense degradation in hot and humid areas with high humidity and temperature has been observed for c-Si modules [215]. As moisture infiltrates into the PV panel, EVA, the most common encapsulant for c-Si, is hydrolyzed with acetic acid by-product, causing corrosion of silver grids and an increase in the Rsh of PV modules. Also, sticky and cementing dust layers are created on PV surfaces in high relative humidity conditions, resulting in soiling and lower output, which can be recovered by proper cleaning methods. Therefore, long-term PV exposure in a humid atmosphere can lead to the corrosion of the modules due to moisture ingress into the solar cell.

Successful mitigation of photo-degradation, particularly due to UV exposure, is crucial for the long-term stability of PV systems. To reduce the photo-degradation rate, an optimization of the material bandgap of the cells for the minimization of UV light absorption is suggested. Advanced materials with a tailored bandgap for the absorption of visible and IR light and the reflection or inhibition of UV radiation are essential. Additionally, glass layers or UV-blocking coatings offer a combination of enhanced protection against harmful UV rays and maintenance of solar cells' integrity. The application of these strategies can prolong the expected lifetime of PV modules and ensure their quality performance, particularly in areas with intense UV exposure.

Another ongoing challenge is adopting a holistic approach to PV systems in terms of cost-effectiveness and reliability. Material selection and innovative manufacturing technologies are extremely complicated, and their interaction and seamless integration with the adjacent module components should be properly evaluated. The current focus in the PV technology sector is on balancing cost-effectiveness. Prioritizing advanced technology that exhibits either lower cost at the same efficiency level or higher efficiency at the same cost is vital for ensuring PV longevity [216].

Achieving a longer lifespan of PV modules can also limit their environmental impact to a great extent by diminishing the need for new module production for replacement purposes. A longer lifetime will be proven an environmentally friendly investment by significantly reducing module recycling and PV waste. As PV technology continues to evolve and new materials are introduced, a detailed understanding and evaluation of the module's reliability remains crucial. The constant emphasis on testing procedures and identification of potential failure modules is the key to ensuring that technological breakthroughs enhance the longevity of solar energy systems.

The implementation of the PV reliability learning cycle, depicted in Figure 8, is a standard procedure for increasing the PV lifespan and improving their longevity [153]. The cycle starts with the observation and diagnosis of PV product operations in the field, followed by failure analysis and modeling to understand the degradation mechanisms. This leads to the development of physical models, new characterization and prognostic tests, and the design of new products. However, the long period of each learning cycle does not coincide with the short-length period of new cells and modules and necessitates reliable accelerated tests, advancing monitoring methods with sensible and embedded sensors, and feedback loops of big data analysis with the help of artificial intelligent methods.

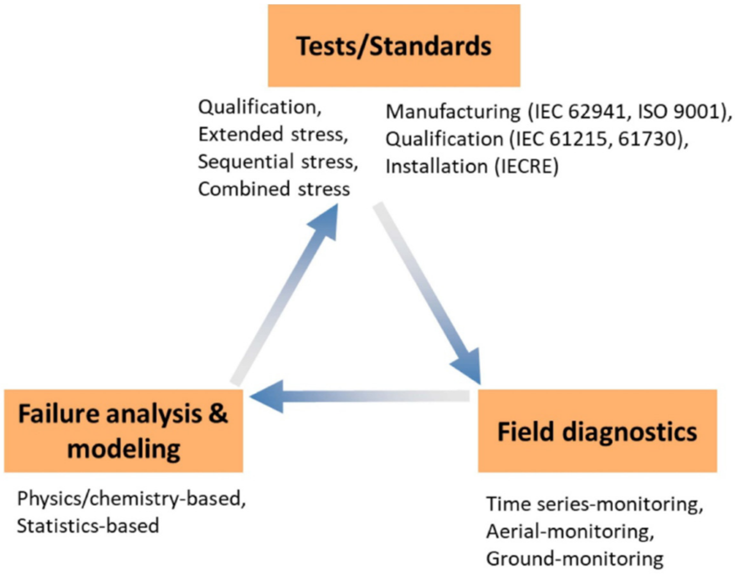

Figure 8. The PV reliability learning cycle for continuous improvement aims to maintain quality despite continuous changes [153]. This cycle aligns with key standards in photovoltaic (PV) module manufacturing and quality management, including EN IEC 62941:2020 for PV module quality systems [217], ISO 9001:2015 for quality management systems [218], IEC 61215-1:2016 for PV design qualification and type approval [219], IEC 61730-1:2016 for PV safety qualification requirements [220], and IEC 61215:2016 for crystalline silicon PV module qualification [221].

Although the operational guarantee of current photovoltaics is 30 to 35 years, PV modules continue to operate at high fractions of their expected outcome and are economically viable even after this period [37]. Therefore, the retirement of PV after reaching the limit of 80% is not an option when the photovoltaic operation is economically viable and profitable. In this context, warranties for an operational lifetime of 40 years and up to 70% of initial performance have been started to be offered by PV companies. Moreover, improving the performance during operation can enhance the lifetime duration of the warranty. Since the degradation rate is the most influential factor in the PV threshold performance and replacement, reducing it by appropriate methods will improve their lifetime with an even higher period of operation and affordable electricity generation. This is especially important for a building's integration of photovoltaics, where a replacement may not be easy and given that building components are constructed for longer operation periods. For example, building skin PV integration with limited or low rates of back-side PV ventilation results in higher module temperatures and higher thermo-mechanical stresses [88]. Therefore, degradation rates can be enhanced with a reduction of the BIPV component lifetime, a result that can be amplified due to urban overheating and climate change, while drastically affecting BIPV operation, especially in hot climatic conditions. In addition, improving PV modules' lifetimes will extend the period needed for developing the appropriate PV recycling infrastructure in their large-scale implementation with a sustainable reduction in the necessary resources needed for recycling [222]. As it is fully evident from the data assessment of the parameters affecting the degradation rate analyzed in this study, heat accumulation and temperature overheating of PV modules are detrimental factors in their operational phase. Therefore, research in developing efficient and easy-to-install PV coolers or reducing required resources and simplifying the operation of photovoltaic thermal (PVT) solar systems should be among the research priorities in the tens of TW of PV installation required for the energy transition [223].

To achieve a sustainable cycle of PV systems, future research should head toward the implementation of recycling strategies [12] for PV module waste. One promising approach is the establishment of specialized recycling facilities, where targeted recovery of valuable materials, including glass, silver, aluminum, and silicon, will be carried out. The dismantling of PV panels includes appropriate material separation through chemical, mechanical, and thermal processes. It ensures that worthwhile resources are being reused, significantly limiting the environmental impact of the solar industry. Moreover, the integration of closed-loop recycling systems provides the reassurance that the recovered materials are then reintroduced into the production process, reducing the dependence on raw resources and materials. The adoption of eco-design principles, which enable the incorporation of easy-to-recycle materials in PV module manufacturing technology, is also suggested, as it will embrace end-of-life recycling.

Supplementary, enhanced techniques, including the recovery of specialty metals from thin-film modules, continue to evolve, enhancing the efficiency and economic feasibility of the recycling processes [224]. The superposition of all these concerted efforts reveals a broader purpose of creating a circular economy for PV systems, promoting resource conservation, and minimizing waste. The establishment of revised and updated regulatory frameworks will also motivate the PV manufacturing sector to invest in sustainable and environmentally friendly recycling initiatives.

The goal of achieving sustainability in PV systems has led to the investigation of environmentally friendly materials capable of both eliminating the environmental footprint and improving efficiency. Traditional PV modules often rely on scarce or even toxic materials, such as lead and cadmium, and their utilization raises legitimate concerns about their long-term environmental impact. Therefore, a gradual transition to non-toxic, easily recyclable, and plentiful materials is deemed necessary. Improving the recyclability of silicon-based PV systems can promote a more robust lifecycle for the solar technology industry. Organic PV cells also offer a viable alternative, as their construction requires carbon-based components that are both easily recyclable and abundant as resources.

Perovskites and tandem cells are also emerging powerfully as attractive alternatives in PV systems, providing environmental benefits and excellent mechanical flexibility. Perovskite-based solar cells are known for their low production expenses and high efficiency, and they can be manufactured at lower temperatures. This capability is lucrative in terms of energy consumption and emissions generation. Additionally, their enhanced flexibility provides the opportunity for bendable and lightweight solar panels, making perovskites the ideal candidates for integration into various surfaces, such as building façades, windows, and roofs. Tandem cells, on the other hand, are hybrid stratified structures consisting of different material layers, such as silicon and perovskites, and promise increased efficiency, as they are capable of capturing a broader spectrum of sunlight. This property indirectly reduces the overall material use, as the energy generated per panel is maximized. As current research is oriented toward lead-free perovskites and easily recyclable materials for PV systems, future efforts should prioritize efficiency and diminishing the environmental footprint. On the one hand, this approach will ensure the sustainable character of PV manufacturing and disposal processes and, on the other hand, will pave the way for a greener, circular, and environmentally friendly solar energy industry.

Another intriguing challenge that attracts the interest of the scientific community is the stability of the PV system. Improving the long-term stability of emerging solar cells, such as perovskite solar cells, is critical to the deployment of this technology [225]. Besides qualification standards based on the International Electrotechnical Commission (IEC), mainly developed to address the field performance of silicon panels, protocols such as those developed by the International Summit on Organic PV Stability (ISOS) are useful in unifying the procedures to assess the stability of emerging solar cells and understand the mechanisms that affect their operational stability and failure modes [225]. In Figure 9, a schematic representation of the stress factors that impact solar cells in different ISOS protocols is presented, emphasizing and comparing the results of various aging procedures with each other. The ISOS protocols involve controlled combinations of key stress factors, including light exposure (visible and UV, dark or 1-sun equivalent), ambient temperature (65 °C or 85 °C), atmosphere (inert, ambient, controlled humidity), and electrical bias (open circuit, MPP tracking, or fixed voltage), to rigorously assess the stability of emerging solar cells.

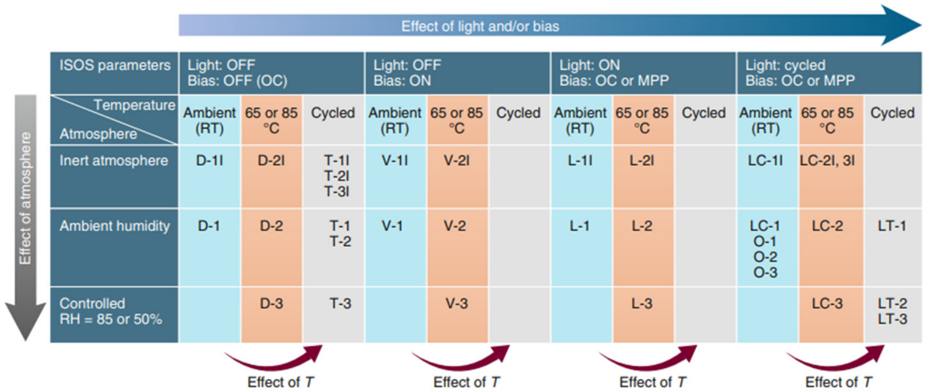

Figure 9. Stress factors affecting solar cells in different ISOS (International Summit on Organic PV Stability) protocols [225].

These protocols are categorized into five aging testing groups, ISOS-D (dark-storage/shelf-life), ISOS-L (light-soaking), ISOS-O (outdoor testing), ISOS-T (thermal cycling), and ISOS-LT (light-humidity-thermal cycling). Each of these groups evaluates specific stress conditions to simulate a real-world environment where emerging PV technologies are deployed. Future stability studies are suggested to include ISOS protocols to understand the impact of the stress factors, enabling better comparison across different aging procedures and promoting the standardization of stability assessments in the field [225].

It should be noted that the main aim of this work was to assess the progress in knowledge improvement of PV longevity. Due to BIPV's importance in the energy transition, a comprehensive assessment of their design, engineering, and maintenance costs should be performed toward the extension of their lifetime deployment. This future evaluation should focus on the investigation and introduction of enhanced materials, advanced architectural protocols and designs, and pioneering implementation techniques in order to achieve both optimum energy output and minimum degradation [7]. Routine maintenance procedures must be incorporated into the cost models to realistically replicate or even prevent system failures and malfunctions. By evaluating ongoing and upfront costs simultaneously, the suggested comprehensive assessment will undoubtedly be at the forefront of sustainable and well-informed investment plans and decisions that can enhance the performance and longevity of BIPV systems.

6. Conclusions

In addition to the research race in developing new technologies for photovoltaic (PV) modules, an assessment of the already operational technologies with feedback information on the impact of environmental stressors is required. This should be combined with efforts to improve both the longevity of operational modules and the resilience of new conventional installations, as well as the design of novel and robust PV systems.

While the global PV market is still expanding, addressing the challenges of degradation, enhancing the longevity of solar systems, and overcoming barriers to recycling are critical for the future sustainability of photovoltaic technology. Continued research and development in these areas will be vital for optimizing the performance and environmental impact of solar energy systems.

Monitoring feedback from modules has been found to considerably increase the lifetime span of photovoltaics. Data from more sensors will enable faster responses to degradation mechanisms and failures that arise from current and future extreme weather events. Proactively addressing field degradation and failures before they occur will decrease operational and maintenance expenses while increasing total electricity generation over the performance period.

New remote sensing methods have advanced detailed observations and can reduce failure rates. Combined with artificial intelligence (AI) opportunities for machine learning algorithms in failure detection, these advancements could significantly contribute to manufacturing and building more robust systems with increased residual value, reduced degradation rates, and prolonged PV lifespan benefits.

To achieve PV longevity values of 50 years by lowering the PV degradation rate to 0.2%/year, systems engineering improvements are required from the nanoscale to kilometer scales. Through thorough assessments from atomic interfaces to module design and the testing, installation, maintenance, monitoring, and proactive measures for failure avoidance, the reduction in degradation rates and increase in PV longevity can be feasible. In this context, research on improving the longevity of utility-scale and building-integrated photovoltaics (BIPV) should be considered at the same scale, while efforts focused on reducing costs and increasing efficiency intensify in solar cells and PV modules. Especially in BIPV applications, high PV operating temperatures and overheating of BIPV modules compared to open-field PV installations can lead to more rapid photo-thermal degradation. This necessitates natural or forced ventilation of BIPV skin modules and/or the implementation of efficient and low-cost PV cooling methods. Although research on these effects of BIPV has just started to be conducted and more research is imperative, increasing BIPV longevity is essential for transforming buildings into zero-energy structures and cities into carbon-neutral environments, with sustainable and resilient solutions that utilize fewer resources.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app142210373/s1, This section provides a comprehensive overview of essential field monitoring methods for photovoltaic (PV) modules, highlighting key inspection and diagnostic techniques for assessing module health and performance over time. These methods deliver critical insights into defect detection, degradation patterns, and efficiency metrics, enabling effective monitoring and maintenance of PV modules in real-world conditions.

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