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Edgar Hernando Sepúlveda-Oviedo

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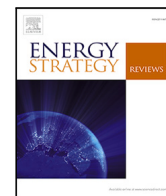
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Review article

Impact of environmental factors on photovoltaic system performance degradation

Edgar Hernando Sepúlveda-Oviedo 

LAAS-CNRS, Université Fédérale de Toulouse, CNRS, UPS, Toulouse, 31031, France

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ABSTRACT

The rapid expansion of photovoltaic (PV) systems underscores the need to understand environmental factors affecting their performance, degradation, and economic viability. This study comprehensively reviews 175 articles, classifying environmental factors such as atmospheric deposits (dust, sea salt, pollen), meteorological conditions (wind, temperature, humidity, rainfall, snowfall, hailstorms), shading, and solar irradiation variability. A novel multilevel classification of degradation modes is introduced, identifying failure mechanisms and their impacts. Key findings reveal performance losses of up to 60%–70% due to combined factors, while mitigation strategies, such as wind-induced cooling, can improve power output by 14.25%, and snow accumulation results in up to 12% annual energy losses. Performance metrics like Performance Loss Rate (PLR) and Degradation Rate (DR) are evaluated to quantify long-term impacts, with economic implications including potential revenue losses and maintenance costs. For instance, addressing dust accumulation in arid regions could save 20%–30% in annual cleaning costs while reducing energy inefficiencies. Recent advancements in AI-driven predictive maintenance are highlighted as pivotal for optimizing system performance and minimizing costs. This integrated analysis provides actionable insights for researchers, engineers, and policymakers, emphasizing the need for tailored strategies to enhance PV resilience and economic sustainability. By addressing the interaction of environmental factors and introducing standardized metrics, this study fills critical research gaps, offering a roadmap for improving PV system reliability, reducing operational costs, and supporting the transition to sustainable energy under diverse environmental conditions.

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1. Introduction

The significant increase in global energy demand and consumption, coupled with the generation of greenhouse gases from traditional fossil fuels and the depletion of these resources, has accelerated the exploration of renewable and environmentally friendly energy sources [1]. Photovoltaic (PV) systems have been at the forefront of this transition, focusing on continuous and efficient energy production [2]. Between 2010 and 2019, the cost of PV energy production dropped by 82% [3], leading to a global surge in installed PV capacity, growing from 1.3 GW in 2000 [4] to 627 GW by the end of 2019 [5]. This rapid growth has continued into the 2020s, with around 350 GW of PV capacity installed globally in 2023, marking a 50% increase compared to 2022, and projections indicating 390 GW of new installations in 2024 [6]. Analysts further estimate that by 2027, annual installations could reach up to 560 GW, driven by ongoing reductions in PV system costs, which have fallen by approximately 85% since 2010 [7]. As solar energy becomes one of the most promising and reliable energy sources of the 21st century [8], attention is increasingly being directed toward overcoming challenges that impact the long-term performance of these systems, including environmental and operational factors.

The considerable challenges that environmental factors present to the efficiency and reliability of PV systems [9]. These factors include atmospheric deposits such as dust, air pollution, sea salt, and organic debris [10], as well as meteorological conditions like wind speed, temperature fluctuations, humidity [11], rainfall, snowfall [12], and

hailstorms [13]. Shading from vegetation growth or wildfires, as well as variability in solar irradiation, further affect the performance of PV systems [14]. However, while many studies have examined individual factors, there is a lack of comprehensive research that integrates multiple environmental influences and their interactions. This gap motivates this study.

In the state of the art, many studies address the loss of efficiency in PV systems. However, most studies primarily focus on the effects of dust or specific environmental factors, with limited evaluation of the broader spectrum of factors that reduce system performance. For example, while Wan et al. [15] consider multiple environmental, financial, and non-performance-related factors, their analysis is limited to a narrow subset of environmental influences.

To the best of the authors' knowledge, no comprehensive study examines the wide range of environmental factors that affect PV systems as done in this study. This limitation is particularly concerning as future climate conditions, exacerbated by climate change, are expected to increase the complexity of PV system design, operation, and maintenance. Addressing this knowledge gap is crucial to ensuring maximum energy production and reliability in modern and next-generation PV installations.

This study aims to fill a critical gap in the literature by providing a comprehensive review of the environmental factors that affect PV system performance, their interactions, and their cumulative effects on system degradation and energy output. By systematically analyzing a wide range of factors – including atmospheric deposits, meteorological conditions, shading, and solar irradiation variability – this work

quantifies their impacts, proposes a novel classification framework for degradation modes, and compiles key performance metrics to measure efficiency losses. Additionally, it offers actionable insights to optimize PV system design, maintenance, and performance under diverse environmental conditions. Special attention is given to extreme environmental factors, such as snow and storms, which can lead to performance reductions of up to 54.5% [16], highlighting the importance of addressing these challenges as climate change exacerbates their effects globally.

This study makes several significant theoretical contributions to the field of PV system performance and energy management. **First**, this study compiles and evaluates the effects of various environmental factors, including dust, wind speed and direction, temperature, humidity, rainfall, snowfall, hailstorms, shading, and solar irradiation. **Second**, this study shows the need to propose a novel multilevel and multidomain classification for degradation modes in PV systems, which organizes failure modes based on their location of occurrence, external cause, or interaction with other faults. **Third**, the study emphasizes the need for standardized testing protocols, which are essential for producing reliable conclusions across different environmental and operational conditions. **Fourth** contribution involves providing key recommendations to improve maintenance strategies, installation protocols, and policy design for PV systems. Finally, **fifth** contribution integrates a detailed section on the metrics used to quantify performance loss due to environmental factors. These metrics are critical for accurately evaluating long-term system performance and guiding maintenance strategies.

This document is structured as follows: Section 2 discusses related work and the methodology employed. Section 3 examines the environmental factors affecting PV system performance. Section 4 focuses on the performance metrics used to evaluate PV degradation. Section 5 presents the discussion of this study, including the broader implications of the findings and key elements for sustainable energy generation, research challenges, and study limitations. Finally, Section 6 provides the conclusions drawn from this study.

2. Methodology and related work

This section outlines the studies documented in the literature concerning the area of interest, as well as the methodology employed to conduct this study.

2.1. Related work

Numerous studies have explored the factors that reduce the efficiency of photovoltaic (PV) solar modules, with a predominant focus on dust and its associated effects. Chanchangi et al. [17] review the literature on dust accumulation under the climatic conditions of Nigeria, emphasizing the need for further research to adapt PV design practices for enhanced soiling resistance. Their work highlights the interaction of dust with environmental factors such as wind, temperature, and humidity, as well as operational aspects like surface orientation, tilt angle, and installation characteristics. Similarly, Kazem et al. [18] provide an extensive review on dust deposition and cleaning techniques, estimating losses of up to 80% in desert regions. However, while these studies offer valuable insights into dust-related issues, they often neglect broader dimensions such as lifecycle implications, economic impacts, or comprehensive performance metrics.

Expanding beyond dust, Song et al. [19] analyze the combined effects of air pollution, dust, humidity, and ambient temperature on PV performance, incorporating operational parameters such as surface properties and tilt angles. Likewise, Pugesana et al. [20] and Salamah et al. [5] focus on performance losses due to factors like wind, humidity, and dust while exploring innovative self-cleaning technologies. Despite these contributions, these works do not address critical aspects

such as short- or long-term impacts, lifecycle analyses, or economic implications.

Khalid et al. [21] propose mathematical models for representing dust accumulation and studying potential cleaning mechanisms, while Jathar et al. [22] evaluate the combined effects of environmental factors like wind, temperature, shading, and humidity on PV performance. Although these studies provide valuable insights, they do not consider comprehensive performance metrics or mitigation strategies. Bamisile et al. [23] extend their analysis to include additional operational factors such as wildfires and hailstorms but similarly lack emphasis on economic or long-term performance assessments.

Hooshyar et al. [24] focus on the progress made in mitigation strategies for soiling, specifically examining cleaning mechanisms. Wan et al. [15] present a comprehensive survey on dust deposition, evaluating mechanisms, effects, mathematical modeling, cleaning methods, and monitoring systems. Their study also incorporates additional environmental factors such as rainfall, wind, humidity, and temperature, as well as operational characteristics like surface materials and tilt angles. Al-Sharaf et al. [25] contribute significantly by examining the economic implications of dust accumulation on PV systems. However, their work does not extend to other environmental factors or lifecycle assessments.

Patel et al. [26] and Conceição et al. [27] delve into specific mitigation strategies, including electrodynamic shields and the effects of soiling, with a particular focus on environmental interactions involving wind and humidity. In contrast, Laarabi et al. [28] take a broader approach by investigating dust interactions with various environmental factors such as rainfall, temperature, and humidity, alongside operational parameters like installation height, tilt angle, and orientation. Their study also evaluates the effectiveness of mitigation strategies, providing a more comprehensive perspective on soiling effects.

Table 1 provides a detailed comparison of the aspects addressed in these recent studies, focusing exclusively on works published from 2020 onward to ensure a contemporary framework for comparison. While these works significantly advance the understanding of specific factors, none comprehensively address short-term and long-term performance impacts, economic implications, or lifecycle analyses. Furthermore, this study introduces a set of metrics for assessing PV system performance, enabling a clearer understanding of performance losses and offering a unified framework, as outlined in the methodology presented in [29].

2.2. Methodology

The methodology consists of four phases: (i) identifying the need, (ii) formulating a search protocol, (iii) conducting a review of environmental factors that affect the performance of PV systems and metrics used to quantify performance loss, and (iv) analyzing the review (challenges and key elements in research and applications, discussion, and conclusions). Since the needs of phase (i) are defined in the introduction, the explanation of the phases continues from phase (ii), which involves formulating a search protocol.

First, it is crucial to establish the search equation for use in databases. This equation is developed from expert-derived keywords and enriched with relevant references related to the topic of interest. The use of keywords to construct the search equation is widely recognized as one of the most effective methods to initiate systematic research [32]. The resulting equation is presented in Eq. (1).

$$F = (A_1 \text{ OR } A_2) \text{ AND } (B_1 \text{ OR } B_2) \text{ AND } ((C_1 \text{ OR } C_2) \text{ AND } C_3) \text{ AND } (D_1 \text{ OR } D_2 \text{ OR } D_3 \text{ OR } D_4) \text{ AND } J_1, \quad (1)$$

where, A_1 to A_2 , B_1 to B_2 , C_1 to C_3 , D_1 to D_4 , and J_1 represent keywords as described in Table 2.

Table 1
Comparison of aspects addressed in this study with recent works (2020 onwards) [30,31].

Year →	2020	2020	2021	2021	2021	2021	2022	2022	2023	2023	2023	2023	2024	2024	2025	2025	2025	
Studies →	[17]	[18]	[19]	[20]	[30]	[28]	[5]	[27]	[21]	[22]	[26]	[31]	[15]	[25]	[23]	[24]	This study	
Factors																		
Dust	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Air Pollution	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	
Sea salt deposition	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	
Pollen/organic debris	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	
Wind	✓	✗	✗	✓	✓	✗	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗	✓	
Temperature	✓	✗	✓	✓	✓	✗	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗	✓	
Humidity	✓	✗	✓	✓	✓	✗	✗	✓	✗	✓	✗	✓	✓	✗	✓	✗	✓	
Rainfall	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓	
Snowfall	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	
Hailstorms	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	
Vegetation growth	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	
Wildfires	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✓	
Solar irradiation	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✓	✗	✓	
Impact																		
Short-term	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
Long-term	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓
Economic	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✓
Mitigation	✓	✓	✓	✗	✗	✓	✓	✓	✓	✗	✓	✗	✓	✗	✗	✓	✓	✓
Lifecycle	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓
Performance metrics	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓

Table 2
Terms of the search equation.

Tag	Keyword
A ₁	Factor
A ₂	Aspect
B ₁	Impact
B ₂	Effect
C ₁	Performance
C ₂	Efficiency
C ₃	Degradation
D ₁	photovoltaic
D ₂	System
D ₃	Cell
D ₄	Photovoltaic
J ₁	Environmental

Table 3
Criteria for inclusion of documents in this study.

Inclusion criteria
Article Published in peer Reviewed Journal
English language
Articles available in electronic format
Conference Papers

Eq. (1) is used in the search engines *Scopus* and *Web of Science* due to their significant advantages over other databases, as demonstrated in the article by Zhu [33]. Subsequently, a set of inclusion criteria is established, as presented in Table 3.

The documents retrieved from the *Scopus* and *Web of Science* databases are combined, and duplicate documents are removed using *Zotero* software [34]. These articles are then subjected to several stages of filtering. Additional articles are obtained using the “*Citation searching*” method [35], which aims to identify relevant research in a particular field or topic by analyzing references in existing articles. This second group of articles is also subject to filtering. Finally, a set of articles recommended by experts is included. The bibliography search process is detailed in Fig. 1.

At the end of the article filtering process, 175 pertinent articles are acquired for further examination.

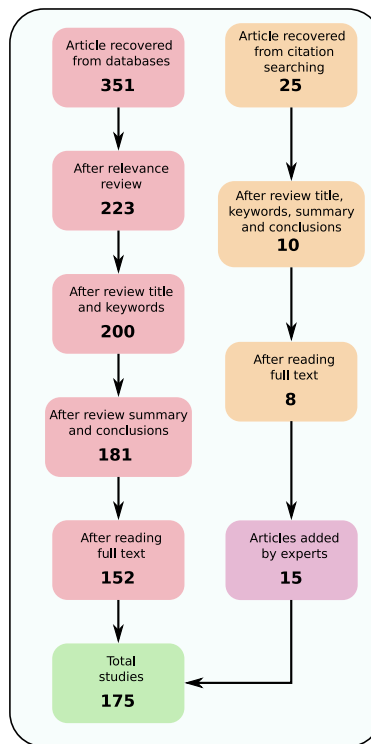


Fig. 1. Methodology employed to retrieve the researched articles. This methodology involves the utilization of documents obtained from *Databases*, “*Citation searching*”, and *Experts* to assemble a robust and relevant document set for this study. Multiple stages of filtering are conducted during the document selection process.

3. Environmental factors affecting photovoltaic system performance

The degradation of PV panels is influenced by a wide range of environmental factors. While the efficiency of PV systems is significantly dependent on the design and manufacturing characteristics of the cells, outdoor installations are exposed to various environmental

factors that can lead to both permanent and temporary faults [36]. Permanent faults, such as cracks or detachment of frames or glass in the PV panel [37], can result from extreme weather events, including lightning strikes [38], heavy snowfall [39], and hailstorms [39]. These physical damages allow the penetration of oxygen and humidity into the module, leading to corrosion of the internal circuits.

In addition to these permanent damages, PV systems are also susceptible to temporary faults. These are typically caused by the accumulation of environmental deposits or obstructions, such as leaves, dust, air pollution, bird droppings, and debris, as well as shading from nearby buildings, trees, and clouds [40]. Shading has been extensively studied due to its potential to create localized heating or “hotspots” [36]. If the temperature of the cell exceeds 150 °C, the module can suffer irreparable damage, and in extreme cases, may even catch fire [38].

This study focuses on the examination of the natural environmental factors affecting PV system performance, specifically: atmospheric deposits (dust, air pollution, sea salt, pollen, and organic debris), meteorological conditions (wind speed and direction, temperature, humidity, rainfall, snowfall, and hailstorms), shading factors (vegetation growth and wildfires), and irradiance-related factors, including solar irradiation. These environmental elements, either individually or in combination, can significantly reduce the overall performance of PV systems, and are considered major contributors to efficiency losses in PV installations.

In light of these challenges, the development of PV technology has evolved to address these environmental issues more effectively. Section 3.1 discusses the technological advancements made to mitigate the adverse effects of environmental factors, including innovations in materials and system design that enhance PV system resilience to environmental challenges. By understanding how different factors, such as temperature fluctuations, dust accumulation, and shading, affect the PV panels, advancements like Perovskite Solar Cells (PSCs), bifacial modules, and floating PV systems have been developed to optimize performance in hostile environments. Furthermore, the integration of PV systems with other renewable energy technologies, such as wind and energy storage, is becoming increasingly vital for creating hybrid systems capable of withstanding environmental variations.

In light of these challenges, the development of PV technology has evolved to address environmental issues more effectively. Section 3.1 discusses the technological advancements designed to mitigate the adverse effects of environmental factors, including innovations in materials, system design, and hybrid renewable energy integrations. Technologies such as PSCs, bifacial modules, floating PV systems, and hybrid PV-wind-storage solutions optimize performance under challenging environmental conditions, including dust accumulation, temperature fluctuations, and shading.

The subsequent subsections, ranging from Section 3.2 to Section 3.6, provide a detailed examination of specific environmental factors that influence PV system performance and degradation. These sections analyze the effects of atmospheric deposits such as dust, air pollution, and organic debris, meteorological conditions including temperature, humidity, and wind, as well as shading caused by vegetation or external obstructions. A comprehensive understanding of these factors is essential for identifying their combined impact on PV systems.

This exploration of environmental factors complements the technological advancements discussed earlier, underscoring the need for integrated approaches to enhance the resilience and efficiency of PV systems in diverse climatic regions. By addressing both the causes of degradation and the solutions to mitigate them, this study bridges the gap between environmental challenges and the development of robust, high-performance PV systems.

3.1. Development of photovoltaic technology and its role in addressing environmental challenges

The evolution of PV technology has enabled significant advancements to address the environmental challenges affecting system performance. This section explores the historical development of PV systems,

the role of Artificial Intelligence (AI), and the emerging innovations in materials and hybrid systems that enhance PV resilience against environmental factors.

3.1.1. Historical development of photovoltaic technology

The development of PV technology began with the discovery of the PV effect by Edmond Becquerel in 1839. Practical silicon-based solar cells were developed in the 1950s, achieving initial efficiencies between 6% and 10%, and were primarily used in space applications due to their reliability. Over the decades, advancements in materials, manufacturing processes, and system design have dramatically increased efficiencies and reduced costs, enabling widespread terrestrial deployment.

Single-crystalline Silicon (sc-Si) and Polycrystalline Silicon (pc-Si) technologies currently dominate the market, with efficiencies reaching 25% and 23.3%, respectively [41]. Thin-film technologies, such as Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS), offer alternatives with efficiencies up to 22.6% and 23.6%, while emerging PSCs demonstrate strong potential for further advancements, particularly under low-light and high-temperature conditions [41]. However, challenges remain in improving their stability and scalability [42].

Environmental factors such as dust accumulation, shading, and temperature variability significantly impact PV performance. Comparative studies indicate that Crystalline Silicon (c-Si) technologies experience fewer efficiency losses under dust exposure, while thin-film alternatives demonstrate better resilience to high temperatures due to their lower temperature coefficients [43]. For instance, Sc-Si cells report power output losses of $-0.1353 \text{ W}/^\circ\text{C}$, while thin-film technologies show lower sensitivity [44]. Fig. 2 illustrates the steady improvement in cell efficiencies across various PV technologies over time [41].

Innovations such as self-cleaning coatings, advanced encapsulation materials, and hybrid systems combining PV with energy storage or wind energy have further enhanced system durability and performance under harsh environmental conditions [45]. These advancements ensure the continued adaptability and sustainability of PV systems in addressing global energy demands.

3.1.2. The role of artificial intelligence in predicting degradation and optimizing maintenance

AI has emerged as a critical tool for improving the performance and durability of PV systems under the influence of environmental factors such as dust accumulation, shading, and temperature variability. By leveraging Machine Learning (ML) techniques and advanced algorithms, AI enables precise fault detection, predictive maintenance, and performance optimization.

Traditional AI models primarily focused on identifying severe degradation patterns or major faults. Recent advancements, however, have extended the focus to uncover the root causes of subtle, less-studied issues, such as snail trail faults, which significantly impact PV panel performance and longevity. For example, ensemble learning frameworks have demonstrated effectiveness in detecting and diagnosing snail trails, offering insights into fault initiation and progression mechanisms [46].

ML models have also been applied to analyze weather-related degradation, assessing the impact of temperature, humidity, and irradiance on the performance of the PV systems [47]. Comparative studies of ML techniques, including regression models and Neural Networks, have shown their ability to predict PV output under diverse climatic conditions, providing essential information for mitigating environmental factors [47]. These methods allow operators to anticipate performance losses due to extreme weather events and optimize maintenance schedules accordingly [48].

Furthermore, AI tools have advanced feature extraction techniques for identifying hidden patterns in system health data, enabling early detection of degradation processes. For instance, Convolutional Neural Networks (CNNs) and Support Vector Machines (SVMs) have proven

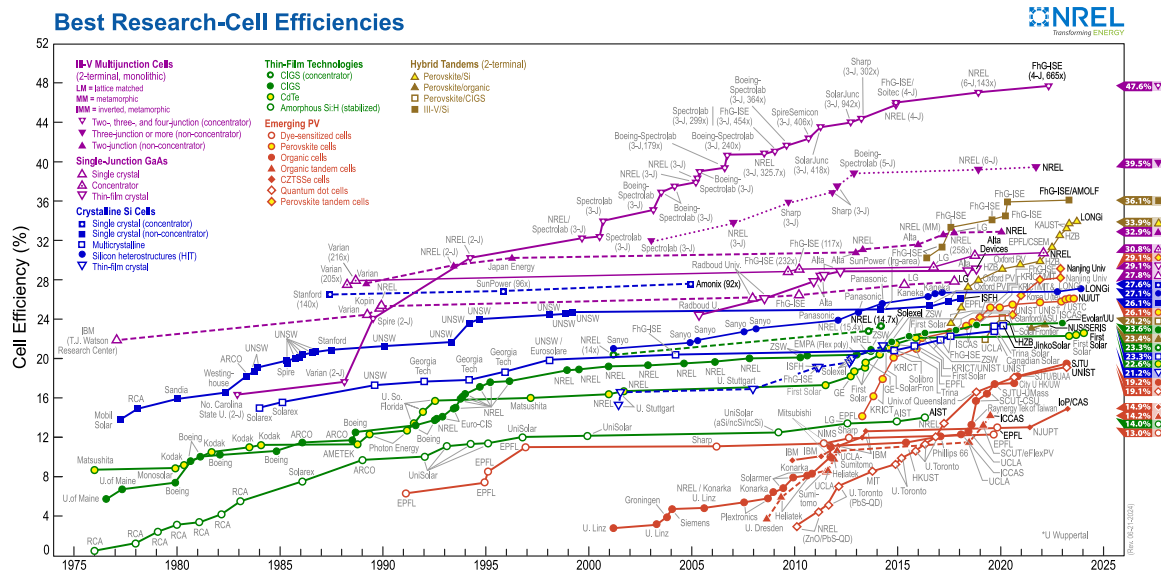


Fig. 2. Cell efficiency progress trend of various PV devices [41].

effective in diagnosing localized faults, such as hotspots or partial shading, which are often exacerbated by environmental factors like dust accumulation or bird droppings [49]. Feature extraction methods provide valuable metrics for assessing module health status and predicting long-term performance trends [48].

Real-time monitoring systems, enhanced by AI-driven predictive analytics, facilitate dynamic decision-making to address environmental challenges. For example, weather-based AI models can adapt maintenance protocols to account for seasonal variations in dust deposition, ensuring that PV systems maintain optimal efficiency in arid or high-dust regions [50]. Additionally, these tools can forecast degradation patterns caused by temperature variability, allowing for the implementation of cooling strategies to mitigate efficiency losses [29].

3.1.3. Advancements in perovskite solar cells

PSCs have emerged as a transformative technology in PV systems due to their high efficiencies, lightweight design, and cost-effective manufacturing processes. However, their performance and stability are significantly affected by environmental factors, including humidity, temperature fluctuations, Ultraviolet (UV) radiation, and airborne contaminants.

Exposure to high humidity accelerates the degradation of perovskite materials, compromising device efficiency. Recent research has introduced cyclodextrin-based supermolecules, which improve moisture resistance, preserving over 90% of the original efficiency under high humidity conditions [51]. Similarly, anti-solvent engineering has enhanced the structural and optical properties of perovskite thin films, enabling better performance under ambient conditions by reducing defects and improving film crystallinity [52]. Encapsulation technologies, including thin-film coatings, further enhance environmental stability, allowing PSCs to operate effectively in regions with relative humidity levels up to 50% [53].

Temperature variability poses another critical challenge, as it induces phase segregation and structural instability in the perovskite layer. Advanced passivation techniques, such as the integration of phosphorus-containing materials, stabilize grain boundaries and mitigate thermal damage, ensuring operational stability under fluctuating temperatures [54]. Experimental studies have demonstrated that PSCs parameters, including efficiency and Open Circuit Voltage (V_{oc}), exhibit significant temperature sensitivity, requiring optimized thermal management strategies to maintain consistent performance [55].

UV radiation accelerates the degradation of perovskite films, leading to a decline in light absorption efficiency. Plasma polymer-based encapsulation methods have been shown to enhance UV resistance while preserving optical transparency, significantly extending the operational lifespan of PSCs in high-radiation environments [56]. Additionally, surface coatings, such as Al_2O_3 treatments, have demonstrated hydrophobic and dust-repellent properties, reducing light obstruction caused by dust accumulation and preventing moisture ingress, particularly in arid regions [57].

Recent reviews highlight the ongoing advancements in PSCs technology, focusing on improving stability through material engineering and protective coatings to counteract environmental factors. These advancements address critical issues such as moisture-induced degradation, thermal instability, and UV-induced aging, positioning PSCs as viable solutions for real-world deployment in harsh environmental conditions [58]. Furthermore, optimized fabrication techniques, including anti-solvent treatments, continue to enhance perovskite film quality and resilience to ambient conditions [52].

These ongoing developments underscore the importance of mitigating environmental factors to enhance PSCs performance and durability. With continuous innovation in material design, passivation strategies, and encapsulation methods, PSCs hold substantial potential for achieving long-term stability and high efficiency in diverse climatic regions.

3.1.4. Bifacial modules and floating photovoltaic systems

Bifacial and floating PV systems have emerged as innovative technologies addressing environmental challenges and improving energy generation efficiency [59]. Bifacial modules capture solar radiation from both their front and rear surfaces, enhancing energy yields by leveraging high ground reflectance (albedo) in environments such as snow-covered, sandy, or water-rich regions. For instance, increasing the albedo to 0.5 and elevating bifacial modules above ground can boost energy yields by up to 30% [60]. These modules are particularly effective in mitigating shading effects by allowing reflected and diffuse light to contribute to energy generation, thereby improving system resilience under non-uniform illumination [61].

Floating PV systems, installed on water bodies such as lakes, reservoirs, and irrigation canals, provide significant advantages in land-constrained regions. Their natural cooling effect reduces module temperatures, mitigating efficiency losses caused by thermal stress and increasing energy output by up to 10% compared to land-based systems [62]. Moreover, floating PV systems reduce water evaporation,

improving water resource management in arid regions while limiting algae growth by reducing solar exposure on water surfaces [62].

The combination of bifacial modules and floating PV technology offers further opportunities for energy optimization. A recent study demonstrated that floating bifacial systems equipped with reflectors could achieve a bifacial gain of up to 18% by maximizing light capture and mitigating thermal losses [63]. However, environmental factors such as dust accumulation, bird droppings, and shading from nearby structures can reduce energy yields, emphasizing the need for innovative surface coatings and cleaning solutions to maintain performance under real-world conditions [64].

Innovative hybrid configurations integrating bifacial modules, floating PV systems, and other renewable energy technologies such as wind and energy storage systems can further address intermittency challenges. Such systems enhance reliability and efficiency, particularly in regions with fluctuating environmental conditions and high energy demands [60].

These advancements underscore the importance of optimizing bifacial and floating PV system designs to mitigate environmental factors and maximize energy production. With continued innovation in materials, system configurations, and maintenance strategies, bifacial and floating PV technologies represent promising solutions for sustainable and resilient energy generation in diverse climatic regions.

3.1.5. Integration of photovoltaic with hybrid renewable energy systems

The integration of PV systems with hybrid renewable energy technologies, such as wind turbines and energy storage systems, has emerged as a promising solution to mitigate energy intermittency and improve overall reliability. Hybrid systems harness the complementary nature of solar and wind resources, ensuring stable energy generation in regions prone to fluctuating irradiance, shading, or seasonal variations. Simulation studies have shown that hybrid solar-wind-storage systems can achieve consistent power outputs, particularly in sustainable campus scenarios where energy reliability is critical [65].

Energy storage plays a pivotal role in hybrid systems, as it mitigates variability by storing excess energy for later use. Lithium-ion batteries dominate energy storage applications due to their efficiency and long lifecycle, while advancements in thermal energy storage systems using Phase Change Materials (PCMs) offer additional flexibility in energy management [66]. These technologies enhance hybrid system resilience, particularly in off-grid or remote areas where environmental factors such as temperature fluctuations and dust storms impact performance.

Floating hybrid systems, which combine PV panels and wind turbines over water bodies, have gained prominence for their operational efficiency and land-use optimization. Such systems benefit from natural cooling effects, which reduce thermal losses, and have demonstrated enhanced performance in regions with high ambient temperatures. Studies have highlighted their potential to address limited land availability and deliver stable energy outputs in highly populated areas [67].

Recent advancements also focus on the development of control strategies and optimization techniques to improve hybrid system performance. Model predictive control and AI algorithms have been applied to optimize energy distribution, forecast environmental impacts, and enhance system efficiency under real-world conditions [66]. For example, predictive models allow systems to adapt dynamically to variable weather patterns, minimizing energy losses caused by environmental challenges like dust accumulation or shading [68].

3.2. Atmospheric deposits

Atmospheric deposits refer to the accumulation of various airborne particles and substances on the surface of PV panels, which can significantly impact their performance. These deposits, including dust, air pollution, sea salt, pollen, and organic debris, obstruct sunlight

from reaching the PV cells, leading to reduced energy generation. The extent of the performance reduction depends on the type, size, and density of the deposits, as well as environmental conditions such as wind speed and humidity, which can either exacerbate or mitigate the accumulation of these materials.

Dust, for example, is one of the most common atmospheric deposits and is particularly problematic in arid and semi-arid regions where frequent dust storms can cause energy losses of up to 50% [10]. Airborne pollutants from industrial areas, as well as smoke and ash from wildfires, can further decrease the transmittance of sunlight by settling on the module surfaces. Coastal areas are particularly affected by sea salt deposition, which not only blocks sunlight but can also corrode module surfaces, leading to long-term degradation.

Organic debris, such as pollen and leaves, is another common atmospheric deposit, especially in areas with dense vegetation. These organic materials can trap moisture and create localized shading, further reducing the efficiency of the PV system. In all cases, regular maintenance, including cleaning and preventive measures, is crucial to minimize the negative effects of atmospheric deposits and sustain optimal PV system performance.

3.2.1. Dust

Dust particles accumulate on the module surface, transported by changes in air speed and direction, humidity, dust storms, surface finish, elevation angle, soil type, gravity, and surrounding vegetation. Dust directly affects the optical, thermal, and electrical characteristics of PV surfaces [69]. For example, studies showed daily performance losses of up to 0.6%, particularly in the spectral range between 450 and 500 nm [70].

The accumulation of dust on PV surfaces also casts shadows on the PV panel, significantly reducing energy production [71]. Dust particles can create two types of shading: soft and intense shading. Soft shadows occur when minor particles, such as smog in the environment, dust on the surface of PV panels, fog, and smoke, decrease the total intensity of solar irradiance absorbed by the solar cells. Intense shadows occur when substances such as accumulated dust block sunlight distinctly and noticeably, as seen with dust masses, mud, snow, bird droppings, debris, leaves, among others.

Dust can originate from various sources such as fungi, bird nests or droppings, microfibers, plant debris, industrial coal, cement, limestone, airborne particles, carpet and fabric corrosion, among others. This generates a significant challenge, as most PV systems are located near industries, volcanic regions, and areas susceptible to dust storms, which contribute to the accumulation of dust in PV systems. For instance, in [72], authors measured the current, voltages, and power of six PV arrays situated in different locations in Oman. The study showed that the most critical contaminants found on PV surfaces are particles from the burning of fossil fuels in power plant chimneys, the foundries of the industrial city, and traffic. This energy reduction could reach 55%. In a recent study, the effects of various types of dust, including ash, sand, and cement, on the performance of photovoltaic modules were analyzed. The research found that ash had one of the most significant impacts on PV efficiency, causing a reduction of up to 24.5% under dry conditions [73]. This highlights the critical need for efficient cleaning strategies to mitigate the effects of dust accumulation.

In a study by Gholami et al. [74], the impact of dust on glass transmittance is examined in a 70-day experiment in Isfahan, Iran. During this study, the dust concentration ranged from 4.0599 g/m² when facing the northwest with a 90° tilt angle to 10.3129 g/m² when facing the north with a 15° tilt angle. This resulted in a reduction of 15% and 24.83% in glass transmittance, respectively.

In desert areas, dust deposition rates are markedly high [75], resulting in a reduction of approximately 40% in solar energy due to atmospheric dust particles [76]. In Saudi Arabia, studies have demonstrated that soiling can significantly impact PV system efficiency, with power drops reaching up to 50% after six months without cleaning

due to dust accumulation [77]. Similarly, experimental studies in Oman showed monthly energy generation losses ranging from 5.6% to 10.8% due to soiling, with cleaning intervals being a critical factor [78]. Research has also found that the characteristics of dust, such as particle size, composition, and geographical location, significantly affect the rate and severity of efficiency losses, with smaller particles causing more scattering of irradiance [79]. In a recent study, researchers identified a linear relationship between dust density and PV module efficiency, showing that a dust density of 10 g/m² could reduce the maximum power output of PV modules by approximately 34% [80]. This highlights the significant impact of dust on PV performance, particularly in exposed environments like deserts.

Regarding the exposure time, in [81], authors analyzed the effect of tilt angles and exposure time on dust accumulation on PV panels. It was observed that lower tilt angles promote more significant dust deposition, with a notable difference in dust accumulation between panels tilted at 0° and 45° during the first two weeks of exposure. This difference became less significant over time, stabilizing after 30 days. These findings emphasize the critical role of tilt angles in managing soiling rates. A study conducted in Oman analyzed the impact of dust accumulation on PV panels over several months. It found that dust particles with diameters between 0.3 and 1 μm caused the most significant reduction in irradiance, resulting in a power output loss of 42% at a dust density of 50 g/m² [79]. The study recommends cleaning intervals of one to two months to mitigate efficiency losses, particularly in desert regions where dust accumulation is a major issue. As a recommendation, the authors suggested a maximum interval of 3 months to clean the PV system. In [82], the authors observed a 12.7% increase in dust-induced losses when the dust density increased by 5.44 g/m² over a period of more than 5 months.

When analyzing the characteristics of the particle, studies such as [82] carried out in Sharjah, United Arab Emirates, focused on examining dust particles of varying shapes and sizes (1.61 – 38.40 μm). A linear relation is observed between dust density and normalized PV power, with a 1.7% reduction per g/m². In [82], the authors used a clean reference module and a module with varying levels of dust accumulation for these experiments. All experiments are carried out under identical conditions of irradiance, ambient temperature, and relative humidity.

The impact of dust depending on the type of particle is analyzed to evaluate the impact of dust on Short Circuit Current (I_{sc}), power output, solar radiation and Fill Factor (FF) in [75]. In that study the authors demonstrated that carbon particles measuring 5 μm in size, with a dust density of 28 g/m², significantly reduce the I_{sc} compared to higher densities of 73 g/m² (10 μm of cement), 168 g/m² (50 μm of limestone), 240 g/m² (60 μm of limestone), or 275 g/m² (80 μm of limestone). In the same study the authors demonstrated that finer dust particles quickly block the passage of light into the PV panel. This occurs because smaller dust particles are evenly dispersed, whereas larger dust particles leave enough gaps for sunlight to penetrate the PV panel. Finer particles have a significant impact on efficiency loss compared to larger particles. This is mainly due to the fact that fine particles block the passage of solar irradiance due to their smaller spacing between particles [82]. Studies indicate that fine dust particles (less than 1 μm in diameter) accumulate more rapidly than larger particles, significantly impacting PV efficiency due to their higher potential for creating surface shading. Additionally, research highlights that the degradation in PV panel performance is influenced not only by the density of accumulated dust but also by its morphological and chemical properties [83]. For example, dust with angular and rough morphologies causes more light scattering compared to smooth, spherical particles [84].

Several studies focused on specifically measuring the reduction in transmittance as a result of dust accumulation. In general terms, any particle with a diameter between 0.10 μm and 1000 μm [10] that accumulates on the surface of PV panels can absorb or reflect solar radiation, significantly affecting transmittance. In a study conducted

in Dhaka, Bangladesh, dust accumulation over four months resulted in a reduction in I_{sc} by up to 22.31% and a corresponding maximum energy loss of 35% during the dry season [85]. Shaik et al. [9] show that after 40 days of exposure, the transmitted permeability of coated glass decreased by 30%, while the transmitted permeability of uncoated glass decreased by 37% in Saudi Arabia). Olivares et al. [86] also demonstrated that particles sized between 20 μm and 60 μm, originating from mining activities, could allow to a reduction of up to 50% in transmittance. In [87], the authors affirmed that dust allows degradation of the solar spectrum reaching the module surface, altering its absorption, reflection, and light scattering characteristics throughout the solar range from UV to visible. Similarly, in Iraq, a particle-based model indicated that dust accumulation could lead to significant power losses, with smaller particles causing greater degradation due to their higher surface coverage potential [88]. Furthermore, in another study, it was demonstrated that transmittance reductions due to dust accumulation depend on particle size and type, with fine particles (< 1 μm) having a more significant impact [89].

Recent research has demonstrated that dust accumulation affects different PV technologies differently. For instance, CdTe modules were found to be more resistant to performance degradation caused by soiling compared to P-Si modules, with CdTe experiencing a 33% lower power loss under similar conditions [90]. This variation underscores the critical role of PV technology and coatings in determining the resilience of modules to environmental soiling. The performance of various types of PV cells composed of C-Si and CdTe under the influence of soiling is studied in [91]. These studies concluded that C-Si exhibits fewer losses under various environmental soiling conditions.

3.2.2. Air pollution

Air pollution, particularly in urban environments, has a significant impact on the performance of PV systems. Pollutants, such as dust, ash, and aerosols, deposit on the surface of PV panels, reducing their efficiency by blocking sunlight and increasing surface temperature. Some studies show that ash deposition from air pollution can significantly impact PV panel efficiency and energy production. For example, coal ash and fly ash deposited on PV panels near coal-fired power plants caused energy production losses of up to 15.82% and 13.16%, respectively, under outdoor natural sunlight conditions [92].

In heavily polluted regions, the effects of Particulate matter (PM) are even more pronounced. For example, research conducted in Shanghai found that particulate matter (PM_{2.5}) concentrations correlated exponentially with power reduction, with the worst cases showing a 35.2% reduction in power output [93]. Similarly, a study conducted in Kraków demonstrated that dust deposition densities could range from 25.8 to 277 mg/m² in a week, causing a power loss of up to 42.1% depending on exposure [94]. Dust and particulate matter in urban environments are particularly problematic, as pollution from anthropogenic sources exacerbates the issue.

The type of pollutant also influences the degree of performance degradation. For instance, a study investigating the effects of different dust types found that pollutants like limestone and carbon-based dust caused a higher reduction in efficiency compared to other pollutants, with losses reaching 20% after exposure to dense deposits [95]. These findings were supported by other research showing that coal dust deposits resulted in efficiency losses up to 44.14% after eight weeks of exposure [96].

Dust deposition is not the only factor; ambient air quality, particularly aerosol concentration, plays a key role in PV performance. For example, in Central Greece, aerosol scattering was found to reduce PV efficiency by up to 5.6% [97]. Similarly, in regions with high levels of air pollution, such as parts of India and China, reductions in solar energy production due to airborne PM_{2.5} have been reported to range between 17-25% [98]. This demonstrates the combined effects of soiling and reduced solar irradiance due to atmospheric pollution.

Humidity and wind speed significantly influence how dust and pollutants adhere to PV panels. A recent study showed that under high humidity conditions, capillary forces dominate particle adhesion, leading to increased soiling rates, while higher wind speeds reduce dust accumulation by up to 10.9% depending on the type of dust [88]. In desert regions like Oman, dust storms significantly impact PV system performance. A recent study showed that dust accumulation led to energy production losses of up to 32% following a major sandstorm. The deposited dust, primarily composed of silica, aluminum oxide, and iron oxide, reduced transmittance and efficiency due to decreased spectral transmissivity [99]. Dust accumulation on PV panels leads to increased surface temperatures, further degrading performance due to elevated thermal effects [100].

The composition of airborne dust is critical in determining its impact. In Saharan (Algeria) environment, sandstorms and dust accumulation have been shown to reduce PV output by as much as 34% [101]. Similarly, in Pakistan, PM10 and PM2.5 concentrations in regions near industrial zones caused energy generation losses ranging from 7.48% to 10.68%, depending on the season [102]. These findings underscore the importance of location-specific factors in evaluating the impact of air pollution on PV performance.

It is clear from the research that different environmental and geographical factors amplify the impact of air pollution on PV systems. In Iraq, where frequent dust storms are common, PV systems experienced a 25% reduction in energy output, leading researchers to recommend automated cleaning systems to mitigate losses [103]. Mostefaoui et al. [101] studied the impact of sand dust and sandstorms on the efficiency of PV panels in the desert region of Adrar, located in southern Algeria. In that study [101], the PV panels are left exposed to the elements for six months without cleaning. After this period, the modules are cleaned with a glass cleaner and water. The results of the study showed significant reductions in the current-voltage and power-voltage curves exceeding 50%. In desert environments, the accumulation of sand on PV panels significantly affects performance. A study conducted in Dubai revealed that sand accumulation caused glass abrasions and encapsulant discoloration, leading to power losses exceeding 30% after prolonged exposure [104].

Finally, long-term studies have revealed that the effects of dust and other pollutants are not only limited to efficiency losses but also contribute to the long-term degradation of PV panel materials. Research has shown that dust particles trap moisture, leading to corrosion and material degradation, which can reduce the operational lifespan of PV systems [105]. Therefore, addressing the impacts of air pollution on PV systems is crucial for maximizing both short-term energy production and long-term system durability.

3.2.3. Sea salt deposition

Sea salt deposition, common in coastal regions, can negatively affect the performance of PV systems by creating a corrosive environment on the module surface. Studies show that sea salt particles accumulate on the surface, leading to the degradation of PV panels. Research conducted in coastal regions has shown that high humidity and salt deposition accelerate the degradation of PV modules. In one study, the combination of salt spray and 85% relative humidity led to a 5% reduction in performance retention after 2500 h of exposure [106].

Further studies show that salt accumulation can significantly reduce the efficiency of PV panels. For instance, in Palembang, Indonesia, it was observed that PV panels exposed to sea salt showed an average output power reduction of 1.3778 W and a 0.948% drop in efficiency over a period of three days [107]. A study conducted on dust accumulation and its effects on PV systems demonstrated that fine dust particles with diameters smaller than 2 μm significantly reduced light transmittance and PV performance. Specifically, a reduction in power output of up to 35% was observed under simulated desert conditions, highlighting the severe impact of fine dust on optical properties [82]. In another study,

dust mixed with sea salt was shown to reduce spectral transmissivity from 91% to 46.09%, leading to a 44.14% reduction in efficiency [96].

Corrosion caused by sea salt aerosols has been extensively studied in coastal regions. Recent research using chloride distribution models revealed that the deposition rates of airborne salinity decrease exponentially with distance from the coast. Coastal areas experience the highest rates of salinity-driven atmospheric corrosion due to high levels of airborne chlorides and humidity, highlighting the significant risks for infrastructure in these zones [108]. Sea salt aerosols have been shown to accelerate the degradation of PV systems in coastal regions. Recent research highlights that exposure to salt aerosols can lead to Potential-induced degradation (PID) of polymeric backsheets, reducing their durability and increasing surface roughness over time. These effects are exacerbated by prolonged exposure to salt-mist environments, highlighting the necessity of robust materials for coastal PV installations [109].

Moreover, seawater exposure presents greater challenges for floating PV systems. Studies have indicated that corrosion under continuous sea salt exposure can cause delamination and degrade metal components, leading to significant power loss over time. One study showed that seawater exposure led to a 35% increase in corrosion rates in supporting devices after only eight days of testing [110]. Floating PV systems are particularly vulnerable due to constant exposure to seawater aerosols, which accelerate metal component degradation. Similarly, backsheets in coastal PV installations can suffer from salt damp-heat environments, which reduce the interface adhesion strength between backsheet and encapsulant materials by as much as 30% over several weeks of exposure [111]. This mechanical weakening can result in panel delamination, further reducing efficiency and increasing the risk of module failure.

Localized corrosion caused by salt deposition in marine environments has been extensively studied. A recent analysis showed that the deposition of sodium chloride aerosols significantly accelerates corrosion on metal substrates, particularly in coastal areas where airborne salinity and humidity levels are high. Corrosion initiation was observed within minutes under high salinity exposure, emphasizing the need for protective coatings and regular maintenance for materials exposed to marine environments [109]. Similarly, encapsulation materials such as ethylene-vinyl acetate can be prone to discoloration and delamination in coastal installations due to salt and moisture exposure, which accelerates module degradation [112]. These effects can result in a 2.3–3.7% annual power loss, as seen in long-term studies conducted in tropical and coastal environments [113].

The influence of salt and moisture can extend to encapsulation degradation and even metallization corrosion. In studies conducted on long-term PV installations, salt and moisture exposure led to encapsulant discoloration and microcracking, further compromising the efficiency of PV panels over time [114]. This degradation is particularly severe in tropical climates, where humidity accelerates the corrosion of internal PV components. Additionally, cracks formed in the encapsulation layers provide entry points for moisture and salt, leading to progressive material breakdown and irreversible efficiency losses.

In mitigate these effects, protective coatings have been developed to reduce the adhesion of salt particles and prevent corrosion. Superhydrophobic coatings, which reduce water and salt particle adhesion, have shown promise in preventing performance losses. A study found that PV panels treated with a superhydrophobic film experienced a 25% lower efficiency drop compared to untreated modules under salt deposition conditions [115]. Other protective strategies include the use of corrosion-resistant materials in module frames and junction boxes, as well as regular cleaning protocols to prevent salt buildup. Anti-corrosion coatings that contain silane and nanocomposite layers have also demonstrated effectiveness in reducing corrosion rates in salt-exposed environments [116].

Sea salt deposition poses a significant threat to the long-term performance and durability of PV systems in coastal and marine environments. With efficiency losses ranging from 5%–44% and the risk of

material degradation, strategies such as protective coatings, corrosion-resistant materials, and regular cleaning are essential for mitigating the effects of salt exposure. Addressing these challenges is crucial for maintaining the reliability and efficiency of PV systems in coastal regions, particularly as the demand for solar energy continues to grow in such areas.

3.2.4. Pollen and organic debris

Organic matter, such as pollen and other natural debris, can significantly affect the performance of PV systems, especially in areas with dense vegetation. A recent study in North Carolina, USA, observed that during peak pollen season, performance losses of over 15% were recorded at multiple utility-scale PV plants due to pollen accumulation. The study also highlighted that rainfall alone was insufficient to completely remove pollen from PV surfaces, emphasizing the need for manual cleaning [117]. Such deposits block light and trap moisture on the surface, contributing to long-term degradation if not managed properly.

Additionally, the impact of organic debris can be magnified when mixed with other contaminants. A study in Iraq showed that organic debris, such as pollen mixed with common dust, could cause energy losses of 35%–40% over a period of two months due to its ability to adhere strongly to the PV surface, particularly in high-humidity environments [118]. Similar results were observed in regions with high relative humidity, where organic material trapped moisture, exacerbating the efficiency losses. In India, fine organic matter deposits on PV panels were found to reduce power output by 10%, primarily due to reduced light transmittance [96].

The interaction between pollen and dust has also been studied, revealing additional impacts on performance. Research conducted in Greece showed that the combination of organic debris and fine dust particles reduced efficiency by 5.6% due to the scattering and absorption of sunlight [97]. This synergistic effect between different pollutants underscores the importance of regular cleaning and maintenance, particularly in areas where both pollen and dust levels are high.

Pollen can have a particularly detrimental impact on transmittance due to its fine, sticky nature. In an experiment conducted on PV panels in Spain, the presence of pollen reduced transmittance by up to 9.1 g/m^2 , causing significant performance degradation [119]. Pollen particles, especially from species like cypress, have been shown to stick to the surface of PV panels, causing substantial reductions in transmittance. This is especially problematic in areas with high pollen counts, as the accumulation of pollen particles over time can severely impact the ability of panels to capture sunlight efficiently.

Bird droppings represent another significant form of organic debris that can severely impact PV performance. Bird excrement creates localized shading and hotspots due to its dark and opaque nature, which disrupts the uniform absorption of sunlight and causes thermal stress on PV cells. Experimental analyses have shown that bird droppings can result in up to a 15% reduction in power output, depending on the size and distribution of the deposits [120]. Furthermore, the acidic nature of bird droppings can corrode module surfaces over time, accelerating material degradation and reducing the operational lifespan of PV panels. A systematic study in Western Rajasthan demonstrated that seasonal bird dropping accumulation caused significant reductions in energy yield, particularly in regions with specific tilt angles [121]. In regions with high bird populations, such as coastal or agricultural areas, the accumulation of bird droppings on PV systems is a recurring challenge that requires regular cleaning and maintenance. Frequent cleaning schedules and the use of hydrophobic coatings have been shown to significantly mitigate these impacts and restore energy yields to optimal levels [122].

Organic matter deposits, such as pollen and natural debris, not only reduce the efficiency of PV systems but also contribute to long-term material degradation. A study demonstrated that in humid environments, moisture within organic deposits accelerates encapsulant

degradation and corrosion of metallic components, leading to reduced system lifespan [38].

Moreover, organic debris deposits can exacerbate the effects of other environmental pollutants. Studies have demonstrated that when organic matter is combined with industrial pollutants, such as particulate matter or aerosols, the overall impact on PV performance can be much greater. For example, in industrial zones with high levels of aerosols, organic debris has been found to enhance the adherence of particulate matter to the panel surface, leading to a compounding effect on efficiency losses [123].

The presence of pollen, bird droppings, and other organic debris on PV systems can have substantial effects on their performance, particularly when combined with other pollutants or environmental factors. Regular cleaning and maintenance are essential to mitigate these effects, especially in areas with dense vegetation, high bird activity, or during seasons with elevated pollen counts. The accumulation of organic debris not only reduces energy output in the short term but also contributes to the long-term degradation of PV panels, potentially shortening their operational lifespan.

3.3. Meteorological conditions

Meteorological conditions play a critical role in determining the performance of PV systems. Factors such as wind speed and direction, ambient temperature, humidity, rainfall, snowfall, and hailstorms can all influence both the short-term and long-term efficiency of PV systems. These conditions can either enhance or reduce the energy output of PV systems by affecting how much solar irradiance reaches the panels, as well as how the system responds to environmental factors like heat, moisture, and mechanical damage.

For instance, wind speed can have a cooling effect on PV panels, improving their efficiency by reducing operating temperatures. In contrast, strong winds can also transport dust and debris, which accumulate on the panels and block sunlight. Temperature fluctuations are another key factor, as high temperatures typically reduce the efficiency of PV cells by increasing their internal resistance, while colder temperatures can improve performance by reducing thermal losses.

Humidity, rainfall, and snowfall primarily affect PV systems by introducing moisture, which can degrade panel materials over time, lead to corrosion, and reduce V_{oc} . While rain can have the benefit of naturally cleaning the panels by washing away dust and debris, it can also increase humidity levels, which negatively impact performance. In colder regions, snowfall can accumulate on panels, blocking sunlight and significantly reducing energy production until it melts or is removed. Hailstorms, though less frequent, can physically damage PV panels, leading to cracks and even complete failure of the panels.

Understanding and mitigating the effects of these meteorological conditions is essential for optimizing the performance and durability of PV systems in diverse environments.

3.3.1. Wind speed and wind direction

Wind speed and direction significantly influence PV panel performance by affecting temperature, dust deposition, and relative humidity. A recent study in Tehran demonstrated that wind speeds between 4.5 m/s and 6.5 m/s helped reduce dust accumulation, improving panel cleanliness and increasing output power by up to 12%. However, excessive wind speeds also promoted the redeposition of smaller particles, highlighting a complex relationship between wind and soiling [124].

Considering the effect of wind on temperature, a study demonstrated that wind speeds ranging from 6 to 13 m/s can reduce PV module temperatures by over $8 \text{ }^\circ\text{C}$ in hot desert climates. This cooling effect significantly improves module efficiency, emphasizing the importance of wind as a critical factor in PV system performance [125]. Shaik et al. [9] reported that a wind speed of 12 m/s can reduce temperatures in Slovenia by half their operating temperature and by $10 \text{ }^\circ\text{C}$ in Saudi Arabia.

Experimental studies, such as those of Zhe et al. [126], shown that the average operating temperature of a PV panel is 53.7 °C and can produce an average output power of 42.42 W even without wind. On the contrary, a PV panel exposed to the wind can generate an average output power of 49.47 W with an optimal operating temperature of 49.5 °C. In essence, wind exposure can reduce the operating temperature by approximately 4.2 °C and increase power output by 14.25%. Some studies even demonstrated performance improvements at 47 °C.

The operating temperature of a PV panel depends on the balance between heat generated by the module and heat exchanged with the environment through conduction, convection, and radiation. A recent study demonstrated that increasing air speed improves heat dissipation by reducing PV module temperatures by up to 8 °C, which significantly enhances efficiency [127].

Utilizing convective heat transfer through natural wind movement is the most cost-effective cooling approach [128]. Also, in a study by Ali et al. [129], simulations demonstrated that the wind is an effective cooling mechanism for PV surfaces, especially at moderate wind speeds. The authors found that the average temperature of Sc-Si modules decreased by up to 42% and 43% at wind speeds ranging from 5 to 15 m/s, for Sc-Si and Pc-Si modules, respectively, thus improving the performance of PV systems. In [129], the authors concluded that the overall performance of Sc-Si and Pc-Si modules improves as the wind speed and tilt angle increase.

The temperature elevation in PV cells is primarily influenced by wind speed. A recent study showed that increasing wind speed from 0.5 m/s to 6.5 m/s reduced PV cell surface temperatures from 84.8 °C to 49.81 °C, highlighting the strong cooling effect of higher wind velocities [130]. This cooling effect enhances PV efficiency, with diminishing returns observed at very high wind speeds.

The reduction in operating temperature induced by wind speed is directly correlated with the overall system efficiency of PV panels due to the temperature-dependent nature of their performance. Lower module temperatures reduce resistive losses and improve the power conversion efficiency, as quantified by the temperature coefficient of power (γ_p), which typically ranges between -0.4% and $-0.5\%/^{\circ}\text{C}$ for C-Si modules [131]. For instance, a temperature reduction of 10 °C, as observed in studies by Shaik et al. [9], would result in an approximate 4% to 5% increase in power output. Furthermore, the improved heat dissipation achieved through convective cooling also enhances the FF of solar cells, which positively impacts energy generation. This logical correlation underscores the critical role of wind as a natural cooling mechanism that not only mitigates temperature-induced losses but also contributes to the overall optimization of PV system performance.

The impact of wind on dust deposition can vary depending on environmental conditions. In desert regions, wind carrying dust and sand particles significantly reduces PV performance. For example, experimental studies showed that wind-sand erosion decreased PV module output by 19.02% at wind speeds of 15 m/s and tilt angles of 15° [132]. Conversely, in areas with fewer loose particles, wind can clean PV panel surfaces, mitigating soiling effects.

Recent studies have demonstrated that the wind speed required to remove dust from PV panels depends significantly on particle size and surface conditions. Smaller particles, with diameters less than 10 μm , require wind speeds exceeding 25 m/s for effective removal, while larger particles are removed at significantly lower speeds. Moreover, the electric field of the PV panel influences dust adhesion, with reduced electric fields during nighttime facilitating easier dust removal [133].

Wind speed can modulate the effect of relative humidity on PV systems. Higher wind speeds can disperse humid air, reducing relative humidity, or transport moisture from external sources, as observed in tropical or coastal regions. A study conducted in Al-Nasiriyah, Iraq, revealed that wind speeds significantly influence PV panel performance, with higher wind velocities reducing module temperatures and partially offsetting the negative effects of increased humidity [134]. The combination of wind and humidity factors can be decisive for

PV performance. While humidity alone tends to degrade performance, wind can partially offset this effect by cooling the panels. Nevertheless, in highly humid environments, even the cooling benefits of wind may not be enough to completely mitigate efficiency losses [135].

In tropical regions, wind speed variations significantly influence both humidity and solar radiation, directly affecting PV system performance. A study conducted in Indonesia highlighted that high wind speeds can disperse humid air, reducing relative humidity and enhancing solar irradiance levels, which improves PV output efficiency. However, under certain conditions, wind can also introduce moisture, complicating the overall performance of the system [136]. Similarly, studies in desert environments have shown that wind can reduce humidity by removing moist air and replacing it with drier air, leading to more favorable conditions for solar energy conversion [124]. Increased moisture in the air causes greater scattering and absorption of solar radiation before it reaches the PV panels, resulting in lower electricity generation [124].

The correlation between wind speed and relative humidity is particularly significant for the design and optimization of PV systems. By considering wind patterns and their effect on humidity, solar energy installations can be optimized to minimize the adverse effects of high relative humidity. For example, site selection in areas with lower humidity or predominant wind patterns that reduce local moisture can improve the overall energy yield of PV systems.

3.3.2. Temperature

The operating temperature of PV cells is one of the most critical factors affecting their efficiency and energy output. Studies have shown that for every 1 °C increase in PV module temperature, efficiency decreases by 0.5%, underscoring the negative impact of heat on performance. Cooling mechanisms, such as water cooling, have been found to improve electricity generation by up to 52.6% in regions with high ambient temperatures, making them an effective strategy for thermal management [137]. Additionally, wind speed plays a crucial role in modulating PV module temperatures. A study demonstrated that wind speeds between 6 and 15 m/s significantly reduced module temperatures, improving efficiency by up to 10% in hot climates. This cooling effect is particularly beneficial for high-efficiency PV technologies exposed to direct sunlight [138].

Temperature variations not only affect energy conversion efficiency but also introduce mechanical stresses within PV panels. These stresses arise from differences in the coefficients of thermal expansion between materials, such as encapsulants, solder joints, and silicon layers. Prolonged exposure to thermal cycling can cause delamination, crack propagation, and solder joint fatigue, leading to significant structural degradation [139]. For example, solder joints have been shown to experience coarsening and void formation under cyclic thermal stress, which reduces module efficiency and lifespan [140].

Furthermore, the efficiency of Sc-Si cells decreases by approximately 0.5% for every 1 °C increase in cell temperature [141]. Studies have shown that the operating temperature of PV cells significantly affects their efficiency. A temperature increase from 30 °C to 64.7 °C reduces module efficiency from 15.27% to 9.80%, underscoring the critical role of temperature management in maintaining PV performance [142]. Additionally, the implementation of cooling systems has proven effective in mitigating these losses, with water-cooling techniques reducing module temperatures by 12 °C and improving efficiency by up to 4.46% in Sc-Si PV modules [143].

Encapsulation materials are particularly vulnerable to high-temperature fluctuations. Ethylene Vinyl Acetate (EVA), one of the most widely used encapsulants, tends to discolor and degrade chemically under prolonged thermal stress, reducing its transmittance and mechanical stability [144]. In contrast, Thermoplastic Polyolefin (TPO) exhibit superior resistance to high temperatures, maintaining their structural integrity and reducing the frequency of encapsulant replacements [140].

The performance of Pc-Si PV systems is significantly influenced by temperature variations. Studies have shown that as module temperature increases from 25 °C to 65 °C, efficiency can decrease by approximately 10% due to thermal effects. Advanced cooling techniques, such as phase-change materials and heat sinks, have demonstrated a reduction in temperature by up to 11.9 °C, resulting in a 3.5% improvement in efficiency [145]. Similarly, in China, the performance of Pc-Si panels was observed to drop by 5% when the temperature increased from 14 °C to 27 °C during the summer, with corresponding increases in humidity [146]. Furthermore, in the same type of PV technology, it was demonstrated that for every 1 °C increase in temperature, the V_{oc} decreased by approximately 2 mV per cell, while the I_{sc} increased marginally by 0.05% [147].

The transmittance of PV systems is significantly influenced by temperature, which impacts the efficiency of energy conversion. A study on thermally resistive PV glazing demonstrated that by optimizing the thermal insulation properties of glazing systems, the transmittance of solar radiation can be enhanced, improving efficiency. The findings revealed that under controlled conditions, thermally optimized PV glazing achieved a significant reduction in heat transfer while maintaining high levels of visible light transmittance, supporting efficient energy and thermal management [148].

Moreover, experimental studies on dust deposition demonstrate that even a small increase in dust accumulation can reduce the transmittance by up to 20%, further exacerbating the effect of temperature on system performance [149]. This reduction in transmittance leads to lower output power, emphasizing the need for temperature control in PV systems to maintain optimal performance. The transmittance of PV systems can be significantly affected by environmental factors such as temperature and dust. A study demonstrated that industrial dust deposition on PV glazing materials caused efficiency losses ranging from 29% to 64%, depending on the type of dust and environmental conditions. This highlights the critical role of dust management and maintenance in sustaining the transmittance and performance of PV systems in tropical and industrial regions [150]. These studies make it evident that Temperature directly affects transmittance. However, research has shown that a 60%–65% transmittance loss can be mitigated by heating the surface of the PV cell during the night and early morning hours [151].

The Maximum Power Point Tracking (MPPT) of PV systems is significantly influenced by temperature variations, as increasing temperatures reduce the maximum power output due to the negative temperature coefficient of the V_{oc} and the Maximum Power Point Voltage (VMPP). An improved MPPT approach has been developed to enhance tracking performance under variable temperature conditions, reducing power losses and improving tracking efficiency. This method demonstrates increased accuracy and faster response times, even under dynamic temperature changes [152]. Studies have shown that for every 1 °C increase in temperature, the power output can drop by as much as 0.5% to 0.65%, which highlights the importance of precise MPPT algorithms that can adjust dynamically to temperature variations [153].

One innovative approach is a temperature-based MPPT algorithm that uses the temperature-dependent optimal current–voltage curve to track the maximum power point with higher stability and accuracy compared to conventional algorithms [153]. Additionally, glowworm swarm optimization-based methods have shown promising results in handling temperature variations and partial shading conditions, offering an efficient way to maintain maximum power output despite fluctuating environmental factors [154].

An experiment is conducted to study the change in the maximum power point of the PV system at various temperatures in [155]. In that study, the authors demonstrate that as temperature increases, module power increases accordingly, as seen in the shift of the maximum power point. However, this behavior only occurs until the maximum operating

temperature is reached. If the temperature continues to increase beyond this value, the power of the module begins to decrease.

The effect of temperature on the generation of electricity from PV panels is linked to its impact on current and voltage. As temperature increases, the band gap of PV cells decreases, leading to a reduction in V_{oc} and an increase in reverse saturation current, which diminishes the overall efficiency of the cell. This phenomenon was observed across multiple PV technologies, including Sc-Si and Pc-Si, with efficiency reductions ranging from 10% to 15% at elevated temperatures [156].

The effect of temperature on the performance of PV panels significantly influences current, voltage, and efficiency. A study demonstrated that increasing the operating temperature from 25 °C to 65 °C results in a significant decline in PV module efficiency due to a reduction in V_{oc} and increased current, highlighting the importance of thermal management strategies. Cooling systems can mitigate these losses, improving efficiency by up to 11.9% [157].

The correlation between temperature and dust deposition on PV surfaces has been extensively studied. A recent study highlighted that thermophoresis – caused by temperature gradients between the PV panel surface and the ambient air – reduces the accumulation of submicrometer dust particles. When the PV panel temperature exceeds ambient air by several degrees, a thermophoretic force develops, creating a dust-free region near the panel surface. This effect is particularly effective for submicron particles, enhancing panel cleanliness and performance [158]. According to Gupta et al. [75], when the temperature of the PV panel is below 40 °C, this force results in an increase in the density of deposited dust. In contrast, when the temperature exceeds 60 °C, the effect of thermophoresis becomes negligible compared to other forces such as gravity and Brownian motion.

Although high module temperature, resulting from ambient temperature, significantly reduces energy conversion, various studies reported that a substantial temperature difference between ambient air and the surface of the PV panel helps to reduce dust accumulation on the module glass cover [159].

Economic analyses reveal that failures due to thermal cycling, such as solder joint fatigue and encapsulant degradation, incur substantial maintenance costs. For a utility-scale 1 MW PV system, replacing encapsulants or solder joints can cost up to \$30,000 annually [140]. However, adopting high-temperature-resistant materials, such as reinforced solder joints or advanced encapsulants like TPO, reduces long-term maintenance expenses by 20%–25%, offsetting their higher upfront costs [144]. Lifecycle cost analyses further highlight the economic benefits of integrating temperature-resistant materials, ensuring consistent performance and minimizing downtime [139].

3.3.3. Humidity

The direct effect of humidity on PV power is challenging to quantify in a standardized way. For instance, dropwise condensation, such as dew formation, improves the performance of PV cells, whereas dew deposition in the form of a film reduces the efficiency of PV cells [160]. Atmospheric humidity affects the performance of PV cells, although to a smaller extent. In warm and humid climates, the impact of humidity on PV module degradation is significant. High humidity accelerates PID and corrosion, particularly in C-Si cells. A study demonstrated that exposure to high humidity and temperatures leads to interconnection failures and cracks, reducing module efficiency by up to 15% over extended periods [161].

The effect of humidity and precipitation on PV energy production has been widely studied. A study conducted in Benin found that relative humidity, with an average value of 80.14%, negatively impacts PV performance, with a correlation coefficient of -0.42 between humidity and energy generation [162]. In another study conducted in arid regions of Northwest China, precipitation and humidity were found to influence PV performance, with areas experiencing high precipitation and humidity showing significant variations in energy generation [163].

The effect of relative humidity and precipitation on PV performance is significant. A study revealed that an increase in relative humidity from 65% to 98% reduced PV panel power output by 34.22%, primarily due to reduced solar insolation and increased dust adhesion [164]. Additionally, research in polluted and desert regions showed that precipitation alone is insufficient for maintaining PV cleanliness, with soiling causing up to a 50% reduction in energy generation without active cleaning measures [165].

Humidity can alter the irradiance level of incident light and significantly affect PV performance. A study highlighted that increased humidity levels reduced PV efficiency due to scattering effects caused by water vapor particles, resulting in lower irradiance on the panel surface. Experimental analysis in floating PV systems demonstrated that high humidity levels negatively influenced voltage output but also helped reduce ambient temperatures, creating a complex interplay between temperature and humidity effects [136]. Additionally, environmental studies in India confirmed that relative humidity has a strong inverse correlation with irradiance, further emphasizing the importance of site-specific analysis for optimal PV performance [166].

An increase in relative humidity significantly reduces the amount of visible solar radiation reaching PV panels, thereby lowering energy output. Recent studies confirm that high humidity levels scatter solar radiation and decrease irradiance on the PV panel surface, leading to reduced power generation efficiency [167]. Relative humidity negatively affected output power by reducing solar radiation transmission [124]. Similarly, in humid regions like Malaysia, wind was found to improve the output of PV systems by counteracting the heat generated during operation, although high humidity remained a limiting factor for maximum efficiency [168].

The effect of humidity on the current and voltage of PV systems is significant and can impact the overall performance of PV systems. Studies show that as relative humidity increases, both the current and voltage generated by PV systems tend to decrease. For instance, experimental data reveal that relative humidity ranging from 65% to 75% leads to a decrease in output current and efficiency, particularly in Pc-Si PV systems [169]. In high-humidity environments, the voltage output of PV panels tends to remain stable, while current and power generation are significantly affected. A study demonstrated that elevated humidity levels can increase moisture ingress into PV cells, reducing insulation resistance and contributing to performance losses. This emphasizes the importance of implementing strategies such as advanced encapsulation materials to mitigate humidity-related issues [170].

The impact of humidity on the current parameters of PV cells, specifically I_{sc} and V_{oc} , is significant and leads to measurable performance losses. Experimental studies have demonstrated that increasing relative humidity negatively affects both I_{sc} and V_{oc} in PV panels. For instance, in tropical climates, damp-heat conditions – caused by high humidity combined with elevated temperatures – reduce I_{sc} by up to 7.14% and V_{oc} by 0.66% over time due to resistive losses and material degradation [171]. Additionally, Pc-Si modules have been shown to be particularly sensitive to moisture ingress, with increased humidity leading to substantial losses in optical performance and overall efficiency [172].

High-humidity environments, particularly when relative humidity exceeds 70%, can exacerbate leakage currents and further reduce both I_{sc} and V_{oc} . This effect has also been observed in PSCs, where elevated relative humidity disrupts crystallization processes, thereby lowering power output [173]. These findings underscore the importance of developing advanced encapsulation strategies and material engineering solutions to mitigate humidity-induced losses in PV systems.

Moreover, prolonged exposure to humid conditions accelerates moisture penetration into the module, which reduces electrical output and increases surface conductivity [174]. Experimental evaluations have quantified these losses, indicating a linear decrease in power output of 3%–5% for every 10% increase in relative humidity [175].

These effects are further amplified in regions with high ambient temperatures, where the combined influence of thermal stress and moisture ingress accelerates degradation mechanisms such as corrosion and delamination of PV panel components [176]. Additionally, the negative impact of humidity on PV systems is more prominent in regions with high humidity, where corrosion and insulation degradation further affect the current and voltage characteristics over time [135].

Some authors suggested a linear relation between relative humidity and current, relative humidity and voltage, and relative humidity and power [124]. The problem with humidity on PV surfaces is twofold. First, sunlight refracted, reflected, or diffracted away by water droplets reduces the direct impact on solar cells, diminishing electricity generation. Second, moisture retention in the module increases electrical conductivity, leading to leakage currents. A study demonstrated that high humidity levels significantly increase leakage currents, which exacerbate PID in PV modules [177]. Additionally, moisture ingress has been shown to reduce the efficiency of PV cells and promote internal corrosion, which further degrades system performance [170].

Humidity plays a significant role in the degradation of PV system components, particularly through mechanisms like corrosion, delamination, and encapsulant discoloration. A recent review found that moisture ingress into PV modules accelerates encapsulant yellowing, delamination, and contact corrosion, significantly reducing module efficiency and lifespan. Advanced encapsulation materials and moisture-resistant designs are critical to mitigating these effects [178]. Moisture ingress into the PV panel accelerates several degradation processes [179]. For instance, it leads to delamination of the EVA acetate encapsulant from the silicon PV cell, as the adhesive strength between these materials weakens under humid conditions [180]. This delamination often initiates at the interface between the EVA and metallization, where corrosion can also occur due to the accumulation of water and ions, further promoting module degradation [181].

Corrosion in thin-film PV panels has been attributed to moisture ingress, particularly through module edges, leading to delamination and the degradation of encapsulant and metallic layers. A recent study demonstrated that moisture-induced degradation in CIGS modules includes delamination, acetic acid formation, and contact corrosion, which significantly reduce electrical performance by increasing series resistance and decreasing V_{oc} [182]. Additionally, the presence of moisture exacerbates electrochemical reactions at the metal contacts, such as the formation of silver sulfide and silver oxide, which degrade the electrical performance of the module [183]. Additionally, experimental studies revealed that discoloration patterns significantly impact I_{sc} , with modules installed at specific tilt angles experiencing accelerated degradation [184].

Vapor condensation on PV panels significantly impacts dust adhesion and accumulation. Experimental studies demonstrated that condensation forms capillary bridges between dust particles and the panel surface, increasing adhesion forces and promoting particle agglomeration. This process reduces panel efficiency by limiting light transmission and increasing soiling rates [185]. Advanced coatings, such as hydrophobic treatments, have been shown to mitigate condensation-related dust adhesion, improving panel cleanliness and efficiency [186].

In [11], the mechanism of adhesion forces (capillary, electrostatic, and van der Waals forces) between dust particles and PV surfaces is studied in detail. The authors experimentally demonstrate that under conditions of high relative humidity, the capillary force accounts for 98% of the total forces that contribute to adhesion. They also show that under dry conditions, dust adhesion is mainly due to van der Waals forces.

In humid environments, dust particles accumulate on PV surfaces and collect moisture from the surrounding atmosphere, forming a sticky and adhesive mud that significantly reduces energy output. This mud formation increases dust adhesion due to capillary forces and hinders natural cleaning by light rain, further exacerbating soiling effects. A study demonstrated that humidity enhances the adhesion of

dust particles to PV panels, increasing cleaning difficulty and reducing power output by up to 30% in humid tropical environments [187]. Furthermore, controlled experiments have shown that relative humidity correlates strongly with dust adhesion, with performance losses intensifying as moisture levels rise [188].

3.3.4. Rainfall

Rainfall can have both positive and negative effects on PV system performance, depending on the intensity, duration, and frequency of rainfall. On one hand, rain can naturally clean the surface of PV panels by washing away dust and debris, improving their performance. However, excessive rainfall, high humidity, and water ingress can lead to various issues, including reduced voltage output and long-term system degradation.

In regions with frequent rainfall, the cooling effect of rainwater on PV panels can slightly enhance their performance by reducing surface temperatures. For instance, in high-altitude regions like the Andean area of Juliaca, Peru, where rainfall is frequent, the reduction in temperature due to rain improved energy capture efficiency by up to 5.6% during certain periods [189]. Similarly, research in India demonstrated that following rainfall events, the removal of dust and debris from PV panels restored output power by approximately 7%–8%, particularly in tropical regions where dust accumulation was significant before rainfall [190].

The impact of rainfall on PV system performance depends on the intensity and consistency of the rain. Light or intermittent rainfall may not effectively clean PV panels, allowing fine dust particles to accumulate and reduce energy output. However, studies show that heavy rainfall events can help remove these deposits and restore module performance. For instance, the presence of droplets can negatively affect energy production under certain conditions, but heavy rain can also improve performance by cleaning the modules and reducing surface temperatures, as observed in temperate climates [191].

In some regions, however, excessive or prolonged rainfall can result in adverse effects, such as water ingress and corrosion of metallic components. In a study conducted in Malaysia, researchers found that frequent and intense rain, coupled with high humidity, led to water ingress into PV junction boxes, which caused electrical faults and a 12% reduction in system efficiency over a year [192]. This problem is particularly prevalent in regions where the seals and enclosures of PV systems are not designed to withstand prolonged exposure to water and humidity.

Another study conducted in Iran demonstrated that while rainfall effectively cleans PV surfaces, frequent rainstorms combined with wind-driven dust lead to fluctuating performance levels. The study found that rain combined with high dust levels reduced the power output by as much as 8%–12% per month, despite regular rainfall events [124]. Thus, while rain helps clean PV panels, it may not fully restore performance in areas with frequent dust storms or rapid dust accumulation.

Research has also indicated that in arid regions where rainfall is scarce, artificial cleaning systems may be required to remove dust and dirt effectively. In studies conducted in Qatar and Saudi Arabia, automated water systems were shown to restore up to 27% of power output by washing off accumulated dust [193], highlighting the necessity for such systems in regions with minimal rainfall. Rainfall can be both a benefit and a detriment to PV system performance. While it can clean the surface of PV panels and slightly enhance performance through cooling effects, excessive rainfall and humidity can lead to voltage losses, water ingress, and long-term degradation. Thus, regular maintenance and proper system design to handle water exposure are critical in regions with frequent rainfall.

3.3.5. Snowfall

Snowfall significantly reduces the energy output of PV systems by blocking sunlight and decreasing irradiance. A study demonstrated that annual energy losses due to snow can range from 1% to 12%, depending on the geographic location and snow conditions, emphasizing the economic and operational challenges snow poses to PV installations [194]. Additionally, non-uniform snow coverage has been shown to create significant inefficiencies, with bypass diodes in PV arrays playing a critical role in mitigating the impact [195].

These findings underline the importance of snow removal strategies to minimize energy loss and maintain PV system performance during the winter months. In a study conducted in Calgary, Canada, it was found that snow accumulation can lead to an annual energy loss of approximately 9% in PV systems. This loss was particularly evident in systems without bypass diodes, where snow significantly hinders energy production during the winter months [196]. These findings underscore the importance of incorporating snow removal strategies and system designs that can mitigate the effects of snow on energy yield, especially in regions prone to heavy snowfall.

In snowy regions, non-uniform snow coverage and buildup on the panels can cause a considerable drop in performance. For instance, in simulations and field experiments, it was found that when snow thickness reaches 1 cm, the power generation efficiency of the PV panel drops to approximately 7.1% of its normal output [197]. A study analyzing snow-related energy losses in PV systems found that modules placed at elevated positions experience annual losses of 1% to 9%, while those closer to the ground suffer losses of up to 29% due to snow accumulation and ground interference. These findings highlight the importance of ground clearance and module placement in mitigating snow-related performance losses [198].

The presence of snowfall significantly affects the incident irradiation on PV panels, leading to energy losses due to snow coverage and increased reflection. Studies indicate that snow-covered modules can experience daily energy losses of up to 93%, depending on the duration and intensity of the snowfall [199]. For example, in a PV system located in Konya, Turkey, the monthly energy loss in periods of heavy snowfall reached as high as 18%. Over the course of a year, the total energy loss due to snow coverage was found to vary between 1% and 2% [199]. The same study showed that during heavy snowfall, daily energy losses could exceed 93%, with monthly energy losses reaching 18% during periods of significant snow coverage [199].

A study using a modeling approach based on the Bouguer–Lambert Law found that snow coverage on PV panels could reduce the incident irradiance by as much as 80% to 90% during heavy snow conditions, depending on the snow properties and coverage [200]. This blockage is primarily due to the reflective and absorptive properties of snow, which prevents direct sunlight from reaching the solar cells. The reduction in irradiance subsequently decreases the power output of PV systems in snowy environments.

Snowfall can cause various types of mechanical damage and degradation to PV panels. One of the primary forms of damage is due to the mechanical stress from snow loads, which can lead to microcracks in the PV cells [10].

A study analyzing the long-term performance of PV panels found that extreme weather events, including snow and high mechanical loads, caused significant cracking and damage, leading to power degradation over time. Hail, high winds, and heavy snow loads were identified as key contributors to increased degradation rates, emphasizing the need for robust module designs to resist environmental factors [201]. In another study, snow load simulations showed that mechanical stresses induced by heavy snow caused the propagation of existing cracks and initiation of new ones, with modules experiencing up to a 3.19% reduction in power output after repeated snow load cycles [202].

The impact of snow on PV modules has been shown to accelerate delamination, which further reduces module performance by degrading

encapsulation materials. A study demonstrated that encapsulant delamination caused by environmental factors, such as snow and temperature fluctuations, significantly reduces optical transmittance and adhesion, leading to decreased energy output and module lifespan [112].

Experimental studies compared the performance of PV panels with snow cover at various tilt angles [12]. In this study, the authors compared regularly cleaned modules with those left unclear after exposure to a snow layer. The study showed a decrease in annual energy production due to snow of 12%, 15%, and 18% for tilt angles of 39°, 24°, and 0°, respectively. An important aspect highlighted in that article is that the reduction in energy loss is dependent on the snow layer on the surface of the PV panel and the angle of tilt of the PV array.

A study analyzing snow-related energy losses in PV systems emphasized that module tilt angles significantly influence snow shedding and performance losses. Systems with steep tilt angles (30°–50°) showed reduced annual losses of 5%–10%, while modules closer to the ground experienced higher losses of up to 34% due to snow accumulation and limited airflow. These findings underscore the critical role of module positioning in mitigating snow-related energy losses [203].

Increased albedo caused by snow accumulation on the ground can partially offset energy losses in PV systems by reflecting more sunlight onto the panels. This effect is more pronounced in systems with higher tilt angles, where increased ground reflectivity improves energy capture and system efficiency. A study demonstrated that ground albedo values exceeding 0.7 significantly enhance energy generation, particularly for bifacial modules with optimal tilt angles [204].

3.3.6. Hailstorms

Hailstorms significantly impact PV systems, causing cracking, microcracking, and other forms of damage to solar cells. A study demonstrated that hail impacts result in mechanical stresses that propagate pre-existing cracks and create new microcracks, reducing PV module efficiency. Modules with front glass thicknesses of 4.0 mm were found to have greater resistance to hail impacts, mitigating the extent of damage and improving long-term performance [205].

In a similar study, conducted by Muehleisen et al. [13], the impact of hail on the degradation of three PV systems in southern Austria was experimentally monitored. These PV plants are impacted by hail with a diameter of 40 mm. UV fluorescence images and electroluminescence measurements confirmed multiple fractured PV cells, linear cracks, and cross-shaped microcracks. They also determined energy losses of approximately 30%. Other studies reported losses ranging from 10% to 20% due to hailstorms [13]. Another study investigating hail impacts using simulations found that PV panels with a glass thickness of 4.0 mm were highly resistant to hail damage. Modules with thinner glass were more susceptible to micro-cracks, which can lead to power losses. The results suggested that thicker glass can prevent severe damage from hailstones up to 25 mm in diameter, which is within the standard hail size resistance guaranteed by most manufacturers [206]. A simulation study analyzing the mechanical impacts of hail confirmed that deformation and internal stresses caused by hailstones could lead to significant structural damage to PV module glass, reducing power output. Experimental methods validated that hail sizes above 25 mm significantly increased module performance loss rates, underscoring the importance of improved hail resistance standards for PV systems [201].

One study conducted simulations using Ansys Workbench software to analyze the hail impact on the glass cover of PV panels. The results showed that hailstones of up to 25 mm in diameter caused material deformation and stress, leading to micro-cracks in the solar cells, which can reduce power output by up to 4.83% [207]. In another experimental study, the simulation of hailstones on solar cells revealed that impacts from ice balls with diameters up to 25 mm caused micro-cracks, resulting in up to 4% reduction in module performance [208]. Simulations of hail impact on thin-film PV panels revealed that even small cracks initially had minimal effect on performance but could

worsen over time due to moisture penetration, ultimately affecting electrical output [209].

A experimental research paper on the mechanical effects of hail indicated that modules subjected to repeated dynamic loads during hail simulations experienced stress levels ranging from 236 kN/m² to 109.8 kN/m². These forces propagated existing cracks and introduced new ones, leading to reductions in power generation of 2.33% to 4.83% [210]. In a study assessing PV panels after exposure to golf-ball sized hail (approximately 4.4 cm in diameter), the hail-damaged modules exhibited 3% to 4% less power output than undamaged ones. This loss persisted over a four-year period without further degradation, indicating that the hailstorm had caused an initial, permanent reduction in performance [211].

A study analyzing the hail impact on tempered glass used in PV modules demonstrated that glass thickness is a crucial factor in mitigating damage. Tempered glass with a thickness of 3 mm resisted impacts from hailstones measuring 25 mm at speeds up to 52 mph without visible damage or power loss, confirming its effectiveness in improving PV durability against extreme weather [212].

In another study, electroluminescence imaging was used to predict the electrical loss caused by hail-damaged modules. The electroluminescence method predicted power losses within 4.3% accuracy at the maximum power point, demonstrating its effectiveness for assessing damage after hailstorms [213].

A novel approach to improve PV durability against hailstorms was tested with lightweight, glass-free modules. This innovative design used a multi-layer polymer frontsheet, which proved capable of withstanding hail impact, reducing the risk of mechanical failure while maintaining energy output efficiency. The new design showed better durability compared to standard glass modules, especially under extreme weather conditions [214].

A data-driven approach using hail size and frequency data was proposed for risk quantification, aiming to predict the likelihood of hail damage in regions prone to hailstorms. This highlights the need for more stringent hail tests than those currently outlined in the International Electrotechnical Commission (IEC) standards [215]. Further analysis of lightweight silicon PV panels with polymer composites showed that such materials could withstand higher hail impacts compared to conventional glass-covered modules, providing better long-term performance [216].

Recent studies have confirmed that the resistance of PV modules to hail impacts is significantly influenced by the material used for the front surface. Tempered glass provides superior resistance to hail impacts compared to other materials such as polymers or acrylics, ensuring minimal damage under standard hail testing conditions. This highlights the importance of material selection for PV module durability [217].

3.4. Shading factors

Shading is one of the most significant environmental factors that can drastically reduce the performance of PV systems. When sunlight is partially or completely blocked from reaching the PV systems, the energy output decreases, often disproportionately compared to the shaded area. Shading can be caused by various factors, including vegetation growth, buildings, nearby structures, and natural elements like clouds or smoke from wildfires. Even small areas of shading on a PV panel can result in significant power losses due to the way solar cells are interconnected.

Recent studies have demonstrated that shading can result in substantial power losses depending on the severity and distribution of shadows. Partial shading, caused by nearby objects, vegetation, or terrain irregularities, can lead to power losses ranging from 45% to 85%, depending on the extent of coverage. This occurs due to the mismatch in current across interconnected cells, forcing bypass diodes to activate, which further reduces the output power and generates localized heating that accelerates module degradation [218].

For PV/thermal systems, shading effects are even more pronounced due to their reliance on both electrical and thermal outputs. A study demonstrated that optimized reconfiguration techniques, such as the Total Cross Tied (TCT) and SuDoKu patterns, can reduce shading-induced power losses by up to 20%, thereby maintaining system efficiency even under irregular shading conditions [219]. Similarly, novel reconfiguration strategies, like Skyscraper arrangements, have shown potential in mitigating losses by redistributing shading effects evenly across the PV panels, increasing power yields [220].

The impact of cloud-induced transient shading has also been examined, revealing that short-term shading can disrupt energy generation patterns. Advanced power electronics, such as MPPT techniques, are critical in mitigating these losses, particularly in regions with frequent cloud cover [221].

Performance assessments highlight the necessity of optimizing system design and placement to minimize shading effects. For example, in urban environments, simulations have shown that strategic placement of rooftop PV panels can mitigate shadowing from Heating, Ventilation, and Air Conditioning (HVAC) systems and structures, reducing power losses by up to 25% [222]. These findings underscore the importance of combining reconfiguration strategies with site-specific planning to ensure reliable energy generation in shaded environments.

Vegetation growth, particularly from trees or tall plants near PV installations, can cause partial or full shading of the panels. Studies show that shading can reduce the power output by more than 90% if a large portion of the PV array is shaded. Seasonal growth patterns and poor maintenance can exacerbate these effects, making vegetation management critical for maintaining optimal energy production.

In contrast, wildfires release significant amounts of smoke and particulate matter into the atmosphere, which can travel long distances and obstruct sunlight. This results in temporary reductions in solar irradiance reaching the PV panels, with losses of up to 37% recorded during heavy smoke conditions. Shading from smoke is particularly problematic in regions prone to frequent wildfires, where the effect may persist for days or weeks.

Shading also generates localized heating, commonly known as “hotspots”, which can degrade the affected PV cells over time. This thermal stress accelerates the aging of the modules, reducing their lifespan and efficiency. Mitigating shading effects is essential to maximizing the performance of PV systems, and methods such as site planning, vegetation control, and advanced power electronics like maximum power point tracking can help minimize the impact of shading on energy production.

3.4.1. Vegetation growth

Vegetation growth near PV installations can lead to significant shading issues, which drastically reduce energy production. Research has shown that partial shading caused by trees, tall grasses, or other vegetation can decrease power output by as much as 92.6% when three-quarters of the PV panel surface is shaded [40]. To avoid these severe losses, it is critical to maintain vegetation near installations to ensure maximum exposure to sunlight. A study from Romania also demonstrated that even partial shading on a small portion of a PV array could result in losses between 5% and 20%, depending on the shading intensity and duration [223]. The presence of surrounding vegetation significantly influences these effects, with shading during peak sun hours being particularly detrimental. In these cases, energy production is reduced not only by shading but also by localized heating effects, which reduce the overall system efficiency.

Shading caused by vegetation not only reduces incident sunlight on PV panels but also creates temperature imbalances across the module surface, known as “hotspots”, which accelerate degradation. A study highlighted that hotspots formed due to partial shading can increase cell temperatures by over 20 °C compared to unshaded cells, significantly reducing efficiency and accelerating damage [224]. Additionally, enhanced circuit designs have been proposed to mitigate hot spot effects and reduce mismatch losses caused by shading [225].

The type and density of vegetation significantly influence shading losses in PV systems. A study analyzing shading in various environments found that dense vegetation causes annual solar irradiation losses of up to 12%, with losses being most pronounced during summer months. Optimized placement and strategic vegetation management can mitigate these effects and improve energy output [226].

This research also demonstrated that while urban areas with dense trees were most affected by vegetation shading, even rural and sub-urban installations experienced losses due to overgrown vegetation. In contrast, deserts and barren regions are less affected by vegetation but still experience shading losses due to shrub growth. Horizontal shading from vegetation, which typically covers the entire panel surface, is particularly detrimental. In extreme cases, horizontal shading caused by tall trees or dense forests can reduce PV output by up to 100% if not addressed in a timely manner [227]. Vertical shading, while less impactful, can still result in power losses ranging from 30% to 50% when applied to large portions of the array.

In addition to losses caused by shading, the presence of vegetation near PV systems can affect maintenance costs. Regular trimming and vegetation control are required to prevent shading issues, and the cost of this maintenance is not negligible. Studies have shown that utility-scale PV sites with native or pollinator-friendly vegetation tend to have lower per-acre maintenance costs compared to sites with turfgrass, which require more frequent mowing and herbicide application [228]. However, poorly managed vegetation can lead to much higher costs in the long term due to the impact of shading. Mitigating the effects of vegetation growth on PV performance involves careful site selection and shading analysis before installation.

Shading mitigation techniques have advanced significantly in recent years, incorporating novel optimization algorithms for MPPT. For example, the Harris Hawk Optimization (HHO)-based MPPT has been shown to effectively track maximum power under partial shading conditions, achieving a 10%–30% improvement in tracking speed and reducing random oscillations by over 90%, demonstrating its robustness and efficiency [229]. Similarly, bio-inspired algorithms like the Squirrel Search Algorithm (SSA) have achieved efficiency levels above 99% while minimizing power oscillations under shaded conditions [230].

Recent advancements in agrivoltaic systems, which integrate crop production with solar energy harvesting, have also offered insights into how vegetation and PV systems can coexist effectively. Studies conducted in Italy demonstrated that agrivoltaic systems with controlled vegetation under PV panels increased land-use efficiency by up to 25%, while reducing shading losses and generating income through crop production [231]. By carefully managing vegetation growth and maintaining adequate spacing between crops and PV systems, agrivoltaic systems can minimize shading impacts while providing additional environmental and economic benefits.

Overall, vegetation growth near PV systems is both a challenge and an opportunity. While unchecked growth can lead to severe shading losses, proper vegetation management and mitigation techniques can reduce these impacts. Incorporating vegetation into the design of PV systems, particularly in agrivoltaic setups, offers a sustainable approach to land-use that balances renewable energy production with environmental conservation.

3.4.2. Wildfires

Wildfires release large amounts of soot, ash, and other particulate matter into the atmosphere, which can accumulate on PV panels and drastically reduce their performance. Studies have shown that energy production can be reduced by as much as 8.3% on average during high smoke days at PV sites as compared to similar conditions without smoke present [232]. This effect is compounded by the fact that wildfire regions tend to have long periods without rain, meaning these particles remain on the panels for extended periods, further reducing efficiency.

A more detailed analysis in the Western Mediterranean revealed that smoke from wildfires can lead to up to 43% daily energy loss for PV systems due to high aerosol optical depth values reaching as high as 6.0 [233]. Research in the western United States quantified wildfire-induced reductions in PV production, with findings showing a 9.4%–37.8% decrease in output on smoky days [234]. Wildfire smoke can travel hundreds of kilometers from the source, affecting PV systems in regions far removed from the fire itself.

Particulate matter from wildfires, especially fine PM_{2.5}, significantly impacts PV performance due to its ability to adhere to panel surfaces and reduce transmittance. In California, PM_{2.5} from wildfire smoke caused a 35.7% reduction in PV production during peak smoke events [235]. This is particularly concerning in areas with frequent wildfires and low precipitation, where particles remain on the panels for long periods, exacerbating efficiency losses.

Additionally, the type of PV technology plays a role in determining the extent of the impact. Research indicates that different types of PV cells (e.g., Sc-Si vs. Pc-Si) have varying sensitivities to smoke, with power reductions ranging from 12.5% to 37.8% depending on the cell type and severity of the wildfire smoke [105].

In Australia, the 2019–2020 Black Summer wildfires led to a significant reduction in PV generation, with some rooftop PV systems in New South Wales experiencing energy losses as high as 65% on days of intense smoke activity [236]. Additionally, fine particles from wildfires can remain in the atmosphere for extended periods, with reductions in PV output persisting for weeks after the fire has been contained.

Wildfires also affect the local climate, influencing irradiance levels and further impacting solar energy production. In the 2020 wildfire season in Washington State, PV production was severely reduced due to high smoke concentrations and low wind speeds, resulting in diminished irradiance. This led to a significant decline in PV energy output, with reductions of up to 20% across affected regions [237]. The radiative impact of smoke also results in a local cooling effect, further lowering the energy available for PV conversion.

Given the increased frequency and intensity of wildfires globally, the cumulative impact on PV systems is becoming more concerning. Long-term exposure to wildfire smoke not only reduces energy production but also accelerates system degradation, leading to higher maintenance costs and shorter operational lifespans. This highlights the need for improved forecasting, maintenance, and protection strategies for PV systems in regions affected by wildfires.

3.5. Irradiance related factors

The performance of PV systems is directly tied to the amount of solar irradiance that reaches the surface of the PV systems. Irradiance-related factors encompass the natural variability in sunlight, which can be influenced by geographic location, time of year, weather conditions, and atmospheric composition. Solar irradiance is the primary driver of energy production in PV systems, and any factor that alters the intensity or quality of sunlight can significantly impact the overall energy yield.

Fluctuations in solar irradiance can occur due to natural atmospheric conditions such as cloud cover, atmospheric dust, and aerosols, which scatter and absorb sunlight, reducing the amount of direct irradiance that reaches the PV panels. Variations in the position of the sun throughout the day and across seasons also affect the angle at which sunlight strikes the panels, influencing the efficiency of energy conversion. In some regions, air pollution and wildfire smoke can further reduce irradiance by increasing the aerosol optical depth, which leads to a significant drop in energy production.

In addition to these natural variations, solar irradiance can be affected by man-made structures that cast shadows on PV installations, such as buildings or towers. The precise alignment and tilt of PV panels are essential for maximizing the capture of irradiance, especially in regions with high seasonal variability in sunlight. Technologies such

as solar tracking systems and optimized panel orientation can help mitigate the losses caused by suboptimal irradiance angles.

Understanding and accounting for irradiance-related factors is crucial for accurately predicting the performance of PV systems and optimizing their design and operation. By analyzing solar potential at specific locations and employing technologies to mitigate irradiance variability, PV installations can be better adapted to their environment, ensuring more consistent and efficient energy production.

3.5.1. Solar irradiation

The amount of energy entering a specific horizontal region at a given wavelength and time is called irradiance [238]. Solar energy, or solar irradiance, significantly impacts PV panel production due to the unpredictability of solar resources caused by weather conditions (seasons) or variations in the altitude of the Sun due to its movement throughout the day. In cases of shading, solar irradiance still reaches unshaded cells, significantly reducing module voltage but not the current. Consequently, the current generated in unshaded cells flows to shaded cells, causing the latter to operate in a negative voltage zone and lose energy instead of producing it. Some shading effects can be gradual due to the angle of the sun during the day, while others can be rapid due to cloud movement [239]. Moreover, the effects of partial shading due to irradiance changes can result in significant power losses. Experiments show that at 75% shading, the impact factor on power output is reduced to 0.86, highlighting the critical impact shading has on system performance [240].

The solar energy incident on a surface consists of three types of radiation: direct, diffuse, and reflected. Each type of radiation plays a significant role in determining the efficiency of PV systems. For instance, direct radiation is crucial for concentrated solar power generation, while diffuse radiation can enhance PV performance under cloudy conditions by providing scattered light. Studies have shown that optimizing PV design for all three radiation types can significantly improve energy yields [241].

Therefore, the maximum solar irradiance for a module occurs when the module surface is oriented perpendicular to the sun direction. According to various studies, every degree of deviation from south results in a 0.08% reduction in productivity, especially in the azimuthal position [17]. Thus, the optimal tilt angle is generally determined using the latitude angle of the location. Studies have shown that adjusting tilt angles for summer and winter significantly enhances energy capture, with deviations of up to 15° optimizing irradiance during colder months. Seasonal adjustments can increase energy yield by up to 10%, emphasizing the importance of such configurations [242].

It is also important to consider that PV panels receive direct sunlight from the sun and scattered light from the sky, ground, and nearby objects [238]. Calculating incident irradiance becomes more complex when nearby objects cast shadows or reflect sunlight onto the PV panels. Furthermore, it is necessary to account for the fact that the intensity of solar irradiation varies throughout the day, typically peaking at mid-afternoon. In [243], the authors showed that cloudy conditions are the main cause of irradiance value changes. The power-voltage or current-voltage curves of a PV panel work as a visual representation of its characteristics.

The energy generated by a PV panel increases with higher solar irradiance, as this provides more photons to excite electrons from the valence band to the conduction band, leading to increased current production. A recent study demonstrated the critical impact of solar irradiance on PV performance, validating that precise predictions are challenging due to environmental variability. Advanced simulation techniques confirmed a direct relationship between irradiance and energy output, emphasizing the need for adaptable system designs [244].

Furthermore, various studies confirm that higher levels of irradiation positively affect PV panel performance, but excessive heat generated during high irradiation can reduce efficiency. For instance, when irradiation levels increase from 1000 to 3000 W/m², power

generation increases by approximately 190 W while the thermal energy absorbed by the module rises by around 996 W, leading to efficiency drops due to overheating [245]. Furthermore, various studies confirm that higher levels of irradiation positively affect PV panel performance, but excessive heat generated during high irradiation can reduce efficiency. To counter this, water-cooling systems have been shown to significantly improve performance. For example, a study demonstrated that water cooling reduced panel temperature by up to 37.67%, resulting in an efficiency increase of 13.4% during periods of high solar irradiance [246].

High-concentration PV systems, which operate under intense solar irradiation, show significant increases in electrical output but are highly sensitive to angular misalignment. Studies show that even small angular deviations can result in significant reductions in efficiency, underscoring the need for precise tracking systems. This sensitivity makes it crucial to optimize alignment mechanisms to maintain system performance under concentrated irradiation [247].

In low-irradiation conditions, performance remains consistent, but high irradiance fluctuations can cause notable degradation in performance ratios and increase harmonic distortions [248]. Additionally, shading plays a crucial role in affecting irradiance levels and consequently, power output. Studies show that partial shading can cause reductions of up to 92.6% in power production when three-quarters of the PV surface is shaded [40]. This impact highlights the importance of optimizing irradiance and mitigating factors like shading to improve module performance.

Further analysis into the impact of irradiation on the performance ratio of PV panels revealed that as irradiance increased, energy production also increased proportionally. At an irradiance level of 230 W/m², the performance ratio dropped to 16.5%, demonstrating that lower irradiance can drastically reduce system efficiency [249]. Low irradiance conditions also negatively affect PV systems, as shown by studies quantifying energy losses in C-Si modules.

At locations experiencing low irradiance conditions, PV systems face significant energy losses. A study evaluating PV performance in Sub-Saharan Africa highlighted that energy losses due to insufficient solar irradiance could reach up to 3.8%, depending on site-specific environmental conditions and panel configurations. These findings underscore the importance of site-specific designs to mitigate irradiance losses [250]. This is consistent with large-scale case studies where seasonal variations in irradiance caused fluctuations in performance ratios. During high irradiance periods in spring and summer, performance ratios were higher, whereas they were significantly lower in the autumn and winter months due to reduced solar exposure and irradiance [251].

Other conditions can also affect the effect of solar irradiation on PV systems. High-altitude locations experience different effects, where dust reduced system performance by around 3%, while rain improved efficiency by cooling the module, mitigating temperature effects caused by high irradiance [189]. Implementing water-cooling systems can mitigate this heat, increasing power output by 27.33% under high irradiation conditions of 1000 W/m² [252].

3.6. Environmental factor-induced failures in photovoltaic systems

Environmental factors impacting PV systems can be systematically categorized into distinct groups based on their nature and influence. This study proposes a classification framework that organizes these factors into four primary categories: **atmospheric deposits**, **meteorological conditions**, **shading factors**, and **irradiance-related factors**. These categories represent the main pathways through which environmental factors degrade PV performance, encompassing **physical**, **chemical**, and **operational** impacts.

In this framework, the impacts of environmental factors are further analyzed based on their temporal dimension. **Short-term impacts** refer to immediate consequences, such as efficiency losses or structural damage, while **long-term impacts** involve cumulative degradation,

irreversible failures, and associated lifecycle costs. Understanding this temporal distinction is crucial for prioritizing mitigation strategies and optimizing the lifecycle performance of PV systems.

Moreover, many of these factors interact, compounding their effects on PV system performance. For instance, dust deposition (a physical impact) can exacerbate chemical degradation by trapping moisture or pollutants, accelerating material corrosion. Similarly, shading caused by vegetation (an operational impact) can lead to localized overheating (physical impact), which, over time, degrades module materials (chemical impact).

This study emphasizes that all proposed mitigation strategies are supported by lifecycle cost analyses, ensuring their economic and operational viability over the lifespan of the system [253]. Fig. 3 illustrates the classification of environmental factors and their primary impacts on PV systems, while Table 4 provides a comprehensive summary of these factors, their associated failure mechanisms, impacts, and mitigation strategies. Together, these tools offer a robust framework for understanding the diverse ways in which environmental factors degrade PV system performance and identifying priority areas for intervention.

3.6.1. Physical impacts

Physical impacts on PV systems arise from external forces and environmental factors that cause structural damage. These impacts can be categorized into short-term effects, such as immediate efficiency losses or material damage, and long-term effects, including cumulative wear or component failure.

Hailstorms are a prominent source of physical damage, often resulting in shattered glass or module cracks, with replacement costs ranging from \$150 to \$400 per module, depending on severity [13]. Microcracks caused by hail propagate over time, reducing the operational lifespan of modules and necessitating replacements that can add \$50,000 to \$100,000 to the lifecycle costs of a 1 MW installation [254]. Lifecycle cost analyses suggest that investing in hail-resistant glass or protective barriers, while incurring an initial cost increase, reduces long-term costs by minimizing replacements and downtime.

Dust accumulation, especially in arid regions, reduces light transmittance and leads to efficiency losses of up to 30% [255]. Cleaning costs range from \$0.10 to \$0.25 per square meter per cycle [194], translating to annual expenses of \$2000 to \$5000 for a 1 MW installation. Advanced hydrophobic coatings, costing between \$3 and \$5 per square meter, reduce dust adhesion and extend cleaning intervals, decreasing maintenance costs by 25% [18]. Robotic cleaning systems, priced between \$500 and \$1000 per robot, further lower cleaning expenses by up to 40% annually [256]. When evaluated over a 20-year system lifespan, these technologies provide net savings that outweigh their upfront costs, enhancing overall system efficiency.

Snowfall presents another challenge, causing efficiency losses through shading and structural stress over time. Annual snow removal costs for a 1 MW installation range from \$5000 to \$15,000 [194]. Snow-shedding coatings, costing \$1 to \$2 per square meter, reduce these expenses by 30%, while robotic snow removal systems offer automated solutions that minimize labor costs [40]. Lifecycle cost analyses reveal that combining snow-shedding coatings with automated systems optimizes long-term savings by ensuring consistent energy output during winter months.

Wind events pose significant risks to PV systems, including misalignment and surface abrasion caused by high-speed wind-driven particles. A study highlights that wind speeds exceeding 50 km/h significantly increase the risk of panel misalignment and mechanical surface damage, underscoring the importance of robust mounting systems and protective coatings [257]. Robust mounting systems, aerodynamic designs, and wind barriers mitigate these effects, preserving system integrity in high-risk regions [258]. These measures, while requiring higher upfront investments, significantly reduce repair costs and operational disruptions, contributing to a lower total cost of ownership over the lifecycle of the system.

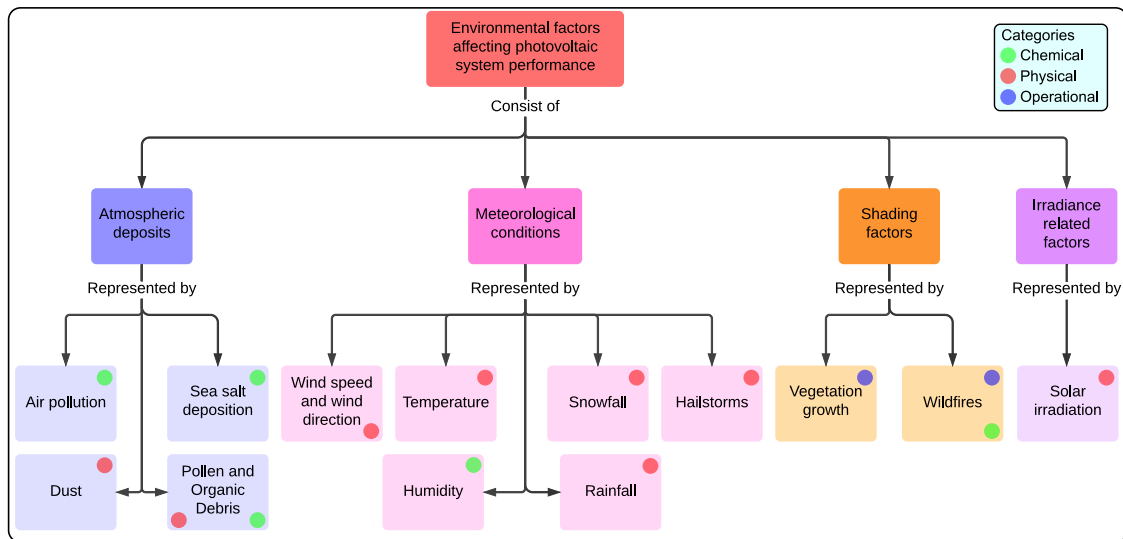


Fig. 3. Classification of environmental factors and their primary impacts (physical, chemical, or operational) on PV systems.

3.6.2. Chemical impacts

Chemical impacts on PV systems result from environmental factors such as humidity, air pollution, and sea salt deposition, which primarily affect the structural and chemical integrity of the modules. These factors accelerate degradation processes that lead to increased maintenance costs and reduced operational efficiency. Similar to physical impacts, chemical impacts can also be classified into short-term and long-term effects.

In coastal regions, salt deposition is a significant challenge, as it accelerates metal corrosion and encapsulant delamination. Annual maintenance costs to address salt-induced damage, including the application of anti-corrosion coatings, range from \$10 to \$25 per square meter [259]. Air pollution, particularly in urban and industrial zones, introduces sulfur and nitrogen compounds that exacerbate material degradation. This results in cleaning expenses of \$30 to \$50 per module annually [260], translating to \$10,000 to \$20,000 annually for a 1 MW installation, depending on pollutant levels [259].

Over time, chemical degradation leads to encapsulant discoloration and delamination, which can compromise the performance and lifespan of the module. Replacing modules affected by these issues can cost between \$150 and \$300 per module [261], adding up to lifetime replacement costs of \$100,000 to \$200,000 for a 1 MW installation. However, advanced encapsulants with pollutant-resistant properties, priced at \$50 to \$100 per module, can reduce these costs by 15 to 20 percent over a 20-year operational period [262].

Preventative measures, such as hydrophobic coatings costing between \$3 and \$5 per square meter, reduce the frequency of cleaning and lead to annual savings of up to 25% in maintenance budgets [40]. Combined with regular inspections, priced between \$1000 and \$3000 annually for a 1 MW installation, these strategies ensure early detection of degradation, preventing costly repairs and replacements [263].

3.6.3. Operational impacts

Operational impacts arise from inefficiencies in PV system performance due to shading, soiling, and variability in solar irradiation. These impacts can be classified into short-term effects, such as immediate power losses, and long-term effects, including module degradation and reduced system lifespan. Both types of impacts contribute to significant maintenance costs and economic losses over the lifecycle of PV installations.

Shading from vegetation, for instance, leads to short-term power loss and requires regular maintenance to mitigate its effects. Vegetation management costs range from \$0.15 to \$0.30 per square meter

per cycle, resulting in annual expenses of \$5000 to \$15,000 for a 1 MW installation, depending on vegetation density and geographic location [228]. Similarly, wildfire events contribute to shading through ash deposition, causing immediate power losses and increasing the risk of long-term corrosion due to chemical residues [264]. Persistent soiling, if not addressed promptly, can add \$2000 to \$4000 annually in cleaning costs for the same installation size [263]. Advanced anti-soiling coatings, costing between \$0.50 and \$2 per square meter, can decrease cleaning frequency by up to 25%, saving \$2000 to \$5000 annually for medium-sized installations [18].

Over time, operational inefficiencies such as soiling and shading exacerbate long-term impacts, including module degradation and hotspot formation, which increase repair costs. Hotspots typically require module replacements, with costs ranging from \$50 to \$80 per module [265]. For large-scale installations, these inefficiencies result in additional lifecycle expenses of \$10,000 to \$30,000. Furthermore, revenue losses due to unmitigated operational inefficiencies can exceed \$50,000 to \$100,000 annually for utility-scale PV systems [266]. These economic impacts highlight the need for comprehensive strategies to mitigate both short-term and long-term operational impacts.

Mitigation measures tailored to operational impacts can effectively reduce costs and extend system lifespans. Automated cleaning systems, which require an upfront investment of \$500 to \$1000 per robot, lower annual cleaning expenses by approximately 40%, translating to savings of \$4000 to \$8000 per year for a 1 MW installation [256]. In agricultural regions, integrating PV systems with solar irrigation practices has proven highly effective, offering annual net savings ranging between \$1255/ha and \$68,582/ha due to diesel replacement and reduced maintenance costs, with an average payback period of 2.88 years [263].

Real-time monitoring systems, priced between \$100 and \$300 per module, enable proactive identification of shading, soiling, or degradation issues, preventing revenue losses and reducing maintenance expenses by \$10,000 to \$20,000 annually for utility-scale PV installations [253]. Additionally, hybrid cleaning schedules, combining routine and performance-based cleaning, can lower overall operational costs by 15%, saving \$7000 to \$12,000 annually for a 1 MW installation [267].

Lifecycle cost analyses further highlight the importance of integrating real-time monitoring systems with preventative maintenance strategies. Such combinations not only optimize energy output but also reduce long-term operational expenses, ensuring sustained performance and economic viability over the lifespan of the system [253]. By adopting advanced operational practices and technologies, PV systems can achieve significant savings while maintaining reliability and efficiency.

Table 4
Summary of environmental factors, categories, associated failures, impacts, and mitigation strategies in PV systems.

Factor	Category	Failure description and reference	Impact	Mitigation strategies
Dust	Physical	Reduced Transmittance: Dust reduces sunlight absorption, lowering efficiency by up to 30% [255]. Surface Abrasion: Dust particles erode module surfaces over time [94].	Short: Immediate efficiency loss Long: Surface damage	Regular cleaning, anti-soiling coatings, electrostatic removal systems.
Air Pollution	Chemical	Corrosion: Sulfur/nitrogen compounds promote material corrosion [260]. Residue Build-Up: Pollutants form hard-to-remove layers, reducing efficiency [165].	Short: Contamination reduces efficiency Long: Encapsulation damage	Anti-corrosion coatings, pollutant-resistant materials, periodic cleaning.
Sea Salt Deposition	Chemical	Corrosion: Salt accelerates metal corrosion and delamination [268]. Weakening: Salt spray weakens module integrity [269].	Short: Corrosion initiation Long: Structural failures	Anti-corrosion treatments, salt-resistant materials, cleaning systems.
Pollen and Organic Debris	Physical/Chemical	Blockage: Pollen reduces light transmission during peak seasons [119]. Reactions: Organic residues degrade surfaces under humidity [119].	Short: Light blockage Long: Surface degradation	Regular cleaning, self-cleaning coatings, anti-adhesive surfaces.
Wind Speed and Direction	Physical	Mechanical Stress: Strong winds misalign panels or cause cracks [270]. Surface Erosion: Wind-driven particles wear surfaces [258].	Short: Structural stress Long: Surface erosion	Robust mounts, aerodynamic designs, wind barriers.
Temperature	Physical	Thermal Degradation: Heat accelerates PV material aging [271]. Connector Failures: Cyclic expansion damages connectors [94].	Short: Efficiency loss Long: Material failure	Heat-dissipating materials, passive cooling, PCMs.
Humidity	Chemical	Corrosion: Moisture corrodes metal contacts [268]. Delamination: Humidity weakens encapsulants [96].	Short: Power loss Long: Encapsulation failure	Moisture barriers, improved sealing, corrosion-resistant designs.
Rainfall	Physical/Chemical	Cleaning Effect: Rain removes surface dust, improving performance [272]. Corrosion: Polluted rain accelerates surface aging [268].	Short: Cleaning improves output Long: Corrosion in polluted areas	Anti-corrosion coatings, water management systems, inspections.
Snowfall	Physical	Stress: Snow weight causes structural cracking [273]. Power Loss: Snow blocks light, reducing generation [194].	Short: Output reduction Long: Structural fatigue	Snow-shedding coatings, heating systems, mechanical snow removal.
Hailstorms	Physical	Glass Breakage: Hailstones shatter protective glass [96]. Microcracks: Hailstones cause long-term cracks [94].	Short: Structural damage Long: Gradual efficiency loss	Hail-resistant glass, protective barriers, optimized angles.
Vegetation Growth	Operational	Shading: Vegetation reduces sunlight exposure [258]. Costs: Trimming adds maintenance expenses [228].	Short: Power reduction Long: Hotspot damage	Automated trimming, vegetation management plans, elevated panels.
Wildfires	Physical/Chemical	Ash Deposition: Ash reduces sunlight absorption [264]. Corrosion: Smoke chemicals accelerate surface degradation [264].	Short: Immediate power loss Long: Corrosion damage	Anti-adhesive coatings, post-fire cleaning, corrosion-resistant materials.
Solar Irradiation	Physical/Chemical	PID: High irradiation causes ion migration [255]. UV Degradation: UV light weakens encapsulants [94].	Short: Efficiency drop Long: Material aging	PID-resistant materials, UV-protective coatings, durable encapsulants.

Table 4 consolidates the detailed information discussed in this section, summarizing the environmental factors, their associated failure mechanisms, economic impacts, and mitigation strategies. This summary serves as a practical reference for understanding the diverse ways in which these factors interact and the corresponding measures to optimize PV system performance across their lifecycle.

4. Performance metrics for photovoltaic systems

PV systems are exposed to a variety of environmental factors, which lead to performance degradation over time. To accurately assess, monitor, and improve the efficiency and longevity of these systems, a set of performance metrics is employed. These metrics provide valuable

insights into how well the system operates, how it degrades under specific environmental conditions, and the overall energy production.

The main objective of utilizing these metrics is to quantify losses in performance, evaluate the efficiency of energy production, and guide decision-making for system maintenance and improvement. This section outlines key performance metrics, such as the *Performance Loss Rate (PLR)*, *Performance Ratio (PR)*, *Degradation Rate (DR)*, and *Energy Payback Time (EPBT)*, among others. These metrics are critical for understanding how environmental factors impact PV systems, and they play a fundamental role in developing strategies to mitigate performance losses and extend the operational life of the systems.

4.1. Performance loss rate

The PLR is a key metric used to quantify the degradation of PV system performance over time. It represents the annual percentage decrease in the efficiency of the system or output power and is crucial for predicting the long-term reliability and economic viability of PV installations. The primary objective of calculating the PLR is to assess the reduction in the energy-generating capacity of PV systems due to various factors such as environmental degradation, module aging, and operational conditions. Understanding the PLR helps in estimating the lifespan of PV systems and in planning maintenance and replacement strategies. The PLR is typically derived from long-term performance data collected from PV systems. This data can be obtained through various methods, including:

- **Field Measurements:** Continuous monitoring of PV systems in operational conditions, where data on output power, irradiance, and temperature are recorded over several years.
- **Simulations:** Using software tools to simulate the performance of PV panels under different degradation scenarios and environmental conditions.
- **Statistical Analysis:** Historical data is analyzed using statistical techniques to isolate the effects of different degradation mechanisms.

A common approach to calculate the PLR is through linear regression of performance data over time. The PLR can be expressed mathematically as in Eq. (2).

$$PLR = \frac{1}{T} \times \left(\frac{P_0 - P_T}{P_0} \right) \times 100, \quad (2)$$

where P_0 is the initial performance (e.g., power output or efficiency) at time $t = 0$, P_T is the performance at time $t = T$ years later and T is the number of years over which the performance data is collected.

It is essential to note that several methodologies are employed to ensure robust and accurate estimations. Common approaches include Year-on-Year regression (YoY) regression, Classical Seasonal Decomposition (CSD), and advanced techniques such as Autoregressive Integrated Moving Average (ARIMA) and LOcally wEighted Scatterplot Smoothing (LOESS) to account for seasonal variations and non-linear trends. For instance, CSD and ARIMA are particularly effective in minimizing uncertainty and addressing seasonality in performance data [274]. Furthermore, international efforts such as the IEA PVPS Task 13 initiative emphasize the need for data cleaning, filtering, and selection of performance metrics to derive reproducible PLR values [275]. These methodologies aim to align with best practices and reduce variability caused by environmental conditions and data noise, enabling industry-wide standardization and actionable insights for system maintenance.

A typical PLR value for PV systems ranges from 0.5% to 1.0% annually for C-Si modules, depending on factors such as technology, environmental conditions, and maintenance practices. A lower PLR indicates that the system is degrading slowly, which suggests better long-term reliability and efficiency. Conversely, a higher PLR indicates more rapid degradation, which can be caused by harsh environmental conditions such as high temperatures, dust accumulation, or improper maintenance, ultimately reducing the operational lifespan of the system and economic viability. Eq. (2) is widely used for determining the PLR of PV systems and has been employed in several studies, including those focused on analyzing long-term field performance and laboratory-tested modules [131]. Studies have shown that the PLR can vary significantly depending on the type of PV technology, environmental conditions, and maintenance practices. For example, C-Si modules typically exhibit a PLR of around 0.5% to 1.0% per year, while thin-film technologies may experience higher DRs.

In an empirical study by Deceglie et al. (2023), the PLR for a large set of PV systems was analyzed using field data spanning multiple years.

The results indicated a median PLR of approximately 0.8% per year for C-Si modules. The study also highlighted that the PLR can increase in harsher environmental conditions, such as high temperatures or high levels of soiling, which accelerate the degradation of PV panels [276]. Another study by Lindig et al. (2022) evaluated the best practices for PLR calculations and highlighted the challenges of deriving reliable PLR estimates due to nonlinear degradation patterns and the importance of distinguishing between recoverable and nonrecoverable losses [274].

Recent studies comparing PV technologies have confirmed that thin-film systems exhibit higher PLR than C-Si systems. For example, thin-film technologies showed annual PLRs averaging 3.21%, significantly higher than C-Si systems, which reported annual PLRs of approximately 1.01%, highlighting the need for robust degradation mitigation strategies in thin-film systems [277].

4.2. Performance ratio

The PR is a widely used metric that evaluates the quality of the performance of a PV system by comparing the actual energy output to the theoretical energy output that would be expected under ideal conditions. PR is dimensionless and is typically expressed as a percentage, making it a crucial indicator of the overall efficiency and effectiveness of PV systems. The primary objective of calculating the PR is to assess how efficiently a PV system is converting available solar energy into usable electrical energy, taking into account all losses, including those due to inefficiencies in components, shading, temperature effects, and soiling. The PR helps to identify performance issues that are not directly related to the solar resource but to system design, installation quality, and operational conditions. The Performance Ratio is calculated using Eq. (3).

$$PR = \frac{E_{AC}}{G_{ref} \times P_{STC}}, \quad (3)$$

where E_{AC} is the actual energy output of the PV system (in kWh or MWh), G_{ref} is the global irradiation on the PV plane (in kWh/m²), and $P_{StandardTestConditions(STC)}$ is the nominal power of the PV system at Standard Test Conditions (STC) (in kWp).

To enhance the context and provide more information on the calculation and standardization of the PR, it is worth noting that PR calculations often integrate adjustments for temperature and irradiance effects to improve accuracy. Advanced methodologies, such as those suggested by Rupnik and Westbrook, emphasize temperature corrections in PR calculations, reducing the error caused by seasonal variations [278]. Additionally, Dhimish showed that the incorporation of regional environmental factors, such as shading and soiling, into PR assessments significantly enhances the reliability of the metric for system evaluation [251]. Furthermore, Oglari et al. analyzed different PR formulations, comparing temperature-corrected and weather-corrected PR to mitigate seasonal variations and standardize PR calculations [279].

This ratio is often calculated over a specific period, such as daily, monthly, or yearly, to monitor and compare system performance under varying environmental conditions. A typical PR value for well-functioning PV systems ranges between 75% and 90%, depending on the system design and location. A PR closer to 100% would indicate a near-ideal system with minimal losses, whereas a lower PR suggests significant performance issues.

In a study by Dhimish (2020), the PR was evaluated across 8000 PV installations to assess how temperature fluctuations impact system performance. The findings demonstrated that PR values decrease in regions with high temperatures, suggesting that thermal regulation and control mechanisms are essential for optimizing performance in such climates [251]. Ambient temperature corrections are critical for accurate PR calculations in PV systems. A recent study demonstrated that using experimental temperature coefficients instead of standard datasheet values significantly reduces seasonal PR variations, improving the accuracy of long-term performance assessments [280].

Matsumoto et al. (2020) also studied how soiling on PV panels influences PR, showing that accumulation of dust and dirt can significantly reduce PR values, especially in arid regions. Their work emphasized the importance of regular cleaning schedules to maintain optimal PR levels [281].

4.3. Array performance ratio

The Array Performance Ratio (PRA) is a specific metric used to evaluate the performance of a PV array, which is a collection of interconnected PV panels. This metric is similar to the general PR but focuses more closely on the array level, providing insights into the efficiency and effectiveness of the array in converting solar energy into electrical energy under real operating conditions. The primary goal of calculating the PRA is to monitor the performance of the PV array by comparing the actual energy produced by the array to the theoretical energy that could be produced under ideal conditions. This allows operators to identify inefficiencies within the array that may be due to shading, module mismatch, soiling, or other factors that affect performance. The PRA is calculated using Eq. (4).

$$PRA = \frac{E_{Array}}{G_{Array} \times A \times \eta_{STC}}, \quad (4)$$

where E_{Array} is the actual energy output of the PV array (in kWh or MWh), G_{Array} is the global irradiation on the array plane (in kWh/m²), A is the area of the PV array (in m²), and η_{STC} is the efficiency of the PV panels at STC.

The PRA has evolved to include more advanced methodologies to ensure precise evaluations. Studies such as those by Mamun et al. have highlighted the importance of accounting for partial shading and its impact on PV panel performance, particularly in varying irradiance conditions. Their research demonstrates how the shading of PV arrays can lead to significant reductions in efficiency and long-term degradation if not properly managed [240]. Furthermore, Ogliari et al. demonstrated the advantages of using temperature-corrected PRA formulations to standardize performance assessments across varying climatic conditions, ensuring consistent comparisons between different installations [279]. These approaches are becoming standardized in the PV industry, improving the comparability and reliability of PRA metrics across installations.

A typical PRA value for well-functioning PV arrays generally ranges between 70% and 90%, depending on factors such as the design of the array, location, and environmental conditions. A PRA closer to 100% suggests that the array is operating near its maximum efficiency with minimal losses due to shading, soiling, or module mismatches. Conversely, a lower PRA indicates that there are significant inefficiencies within the array, likely caused by environmental or operational factors such as dirt accumulation, shading, or misalignment, which negatively affect energy output.

Several studies have explored the effects of partial shading, soiling, and array configurations on PRA. For instance, research on PV systems under dynamic partial shading conditions showed that optimized array reconfiguration techniques, such as TCT and SuDoKu patterns, significantly reduce power losses and improve PRA by evenly distributing shading effects across the array [222]. PRA is a valuable metric for monitoring and optimizing the performance of PV arrays. By focusing on array-specific factors, such as shading and soiling, PRA provides detailed insights that can help improve the efficiency and reliability of large-scale PV installations. As shown in these studies, consistent monitoring and tailored maintenance strategies are essential for ensuring optimal array performance, especially in environments with high shading or soiling potential [282].

Several studies have explored the effects of partial shading, soiling, and array configurations on PRA. For example, Ramanan et al. (2019) conducted a detailed performance analysis of grid-connected PV systems in hot and humid climates. The study highlighted how

environmental conditions, especially high temperature and humidity, along with shading and soiling, can lead to significant variations in PRA values. Their results indicated that CIGS arrays generally performed better than Pc-Si arrays under such conditions due to their improved efficiency in low-light and high-temperature environments [283].

4.4. Array photovoltaic for utility systems applications

The Array PV for Photovoltaic for Utility Systems Applications (PVUSA) is a specific performance metric designed to evaluate the performance of PV systems, particularly in large-scale utility applications. This metric was developed as part of the PVUSA project in the United States to provide a standardized way to compare the performance of different PV systems under varying environmental conditions. The PVUSA model is unique because it takes into account both the irradiance and the ambient temperature, adjusting the expected power output accordingly. This adjustment allows for a more accurate assessment of the performance of a PV system under real-world operating conditions. The PVUSA metric is calculated using Eq. (5).

$$P = a + b \times G + c \times T, \quad (5)$$

where P is the power output of the PV system (in kW), G is the solar irradiance (in W/m²), T is the ambient temperature (in °C), and a , b , and c are empirically determined coefficients specific to the PV system.

The PVUSA model provides a standardized framework for evaluating the performance of PV systems by incorporating environmental corrections, such as irradiance and temperature. Recent advancements have focused on refining the PVUSA methodology for enhanced forecasting accuracy and adaptability to real-world conditions. For instance, Shah et al. developed a grey-box neural network based on the PVUSA model to improve power forecasting, demonstrating a significant reduction in prediction errors for grid-connected PV systems [284].

Shah et al. [284] evaluated multiple performance models for PV systems and highlighted that advanced models, such as PVUSA, demonstrate superior performance in predicting energy yield, particularly under variable climatic conditions. A recent analysis validated that the PVUSA model predictions have a mean absolute error of less than 1%, making it highly reliable for large-scale applications.

The PVUSA metric is particularly useful for large-scale utility applications as it accounts for both irradiance and temperature, two critical factors influencing PV system performance. A higher PVUSA value indicates that the system is operating efficiently under real-world conditions, while a lower value may point to inefficiencies caused by suboptimal alignment, shading, or poor thermal management. By adjusting the expected power output based on environmental variables, the PVUSA metric provides a more accurate representation of the operational performance of a system compared to theoretical maximums. This makes it a valuable tool for utility operators and engineers to optimize PV system configurations and assess performance across different environmental conditions.

The PVUSA metric has been successfully applied in recent studies to enhance the evaluation of performance loss rates and long-term reliability of PV systems. For instance, advanced statistical approaches integrating PVUSA significantly reduce variability in degradation rate estimates, providing robust and accurate performance assessments over multi-annual periods [285]. Additionally, PVUSA has been integrated into advanced degradation models for more precise lifetime predictions, ensuring reliable system operation under diverse environmental conditions [277].

4.5. Energy payback time

The EPBT is a critical metric used to evaluate the sustainability and efficiency of PV systems. EPBT is defined as the amount of time

required for a PV system to generate the amount of energy equivalent to the energy consumed during its production, installation, and operational phases. This metric is crucial for assessing the long-term viability of renewable energy technologies, particularly in determining their overall environmental impact and energy efficiency. The EPBT is calculated using Eq. (6).

$$EPBT = \frac{E_{\text{input}}}{E_{\text{output}}}, \quad (6)$$

where E_{input} is the total energy consumed during the production, installation, and operation of the PV system, and E_{output} is the annual energy generated by the PV system. An EPBT of less than 1 year indicates that the PV system generates more energy in a year than was used in its production, while a higher EPBT suggests a longer time to offset the energy invested.

Recent advancements in EPBT methodologies have refined lifecycle assessments for enhanced precision and standardization. For instance, Shah et al. (2023) conducted a lifecycle assessment of Pc-Si PV systems in Pakistan and reported EPBT values between 2.5 and 3.5 years, demonstrating the importance of regional factors in manufacturing and energy generation [286]. Similarly, Hadi and Heidari (2021) compared various façade-integrated PV systems, finding EPBT values as low as 0.6 years for perovskite systems, highlighting the potential of novel technologies for sustainable energy solutions [287]. Another study by Rao et al. (2022) analyzed thin-film PV/thermal systems in tropical regions, reporting CO₂ emissions reductions and EPBT values ranging from 1.21 to 1.57 years for CdTe and Dye-Sensitized Solar Cells (DSS) systems, respectively [288].

4.6. Energy production factor

The Energy Production Factor (EPF) is a key performance metric used to evaluate the efficiency and productivity of PV systems. EPF measures the ratio of the energy generated by a PV system over its lifetime to the energy consumed in producing, installing, operating, and maintaining the system. It is an important metric for assessing the overall energy efficiency and sustainability of renewable energy systems. The EPF is calculated using Eq. (7).

$$EPF = \frac{E_{\text{output, lifetime}}}{E_{\text{input}}}, \quad (7)$$

where $E_{\text{output, lifetime}}$ is the total energy generated by the PV system over its entire operational life, and E_{input} is the total energy consumed during the production, installation, operation, and maintenance of the PV system. An EPF greater than 1 indicates that the system produces more energy over its lifetime than the energy consumed in its entire lifecycle, making it an efficient and sustainable option.

The EPF has been increasingly studied to establish industry-standard methods of calculation. Casula et al. explored EPF variations across silicon-based and thin-film PV technologies in different geographic regions, showing that thin-film systems generally exhibit higher EPF values due to lower material and production energy requirements, making them more favorable for long-term energy production in high-irradiance regions [289]. Piano et al. proposed integrating cooling mechanisms in floating PV systems to enhance EPF, demonstrating that water cooling significantly increases energy yield, particularly in warm climates where heat dissipation is crucial [290].

Recent studies have analyzed the performance of PV panels in specific applications like greenhouses, showing that C-Si modules exhibit superior EPF compared to other technologies. This makes C-Si modules the most efficient choice for environments where optimal light transmission and energy generation are critical. These findings highlight the adaptability of C-Si modules to diverse environmental conditions and their potential to maximize energy output [291].

4.7. Life cycle conversion efficiency

The Life Cycle Conversion Efficiency (LCCE) is a crucial metric for evaluating the overall efficiency of PV systems, considering their entire life cycle from manufacturing to disposal. LCCE measures the ratio of the total energy output of a PV system over its lifetime to the total energy consumed throughout its life cycle, including production, installation, operation, maintenance, and end-of-life disposal. The LCCE is calculated using Eq. (8).

$$LCCE = \frac{E_{\text{output, lifetime}}}{E_{\text{input, total}}}, \quad (8)$$

where $E_{\text{output, lifetime}}$ is the total energy generated by the PV system over its entire operational life, and $E_{\text{input, total}}$ is the sum of all energy inputs required for the production, installation, operation, maintenance, and end-of-life disposal of the PV system. A higher LCCE indicates a more efficient and sustainable PV system, as it signifies a greater energy return over the life cycle relative of the system to the energy invested.

Recent studies have emphasized the importance of LCCE in PV systems, particularly in addressing energy-intensive stages such as material processing and end-of-life disposal. For instance, Singh et al. (2020) highlighted that the number of collectors in solar desalination systems significantly impacts LCCE, with increases in collector numbers improving efficiency [292]. Furthermore, comprehensive lifecycle analyses of recycling processes for end-of-life PV panels demonstrated reductions in carbon emissions and environmental impacts, underscoring the role of sustainable disposal practices in enhancing LCCE [293]. Additionally, lifecycle assessments integrating circular economy principles have been shown to extend PV system lifespans, improving energy output efficiency and reducing environmental footprints [286].

4.8. Cleanliness index

The Cleanliness Index (CI) or ΔCI is a metric used to quantify the impact of soiling on the performance of PV systems. Soiling refers to the accumulation of dust, dirt, and other particulate matter on the surface of PV panels, which can significantly reduce their efficiency by blocking sunlight. ΔCI measures the relative decrease in performance caused by soiling, providing an important tool for assessing the need for cleaning and maintenance of PV systems. The CI is calculated using Eq. (9).

$$\Delta CI = \frac{P_{\text{clean}} - P_{\text{soiled}}}{P_{\text{clean}}} \times 100, \quad (9)$$

where P_{clean} is the power output of the PV system under clean conditions, and P_{soiled} is the power output of the PV system under soiled conditions.

The CI provides a critical assessment of soiling impact on PV performance, with methodologies evolving to ensure standardized and accurate measurement. Recent advancements propose the integration of ML models to predict ΔCI changes using environmental variables. Tovilović et al. demonstrated that introducing the CI into tree-based ML models significantly improves the accuracy of power forecasting in PV systems [294]. Additionally, Javed et al. applied Artificial Neural Networks (ANNs) to model the relationship between ΔCI and environmental variables, such as PM10, relative humidity, and wind speed, achieving better prediction accuracy compared to traditional linear regression models [295]. These developments underline the importance of advanced predictive tools for optimizing cleaning schedules and mitigating soiling losses in PV systems.

A higher ΔCI indicates a greater loss in performance due to soiling, suggesting that the efficiency of the system is being significantly impacted by accumulated dust or debris. For example, a ΔCI value of 30% implies that the output of the PV system has decreased by 30% due to soiling. In such cases, immediate cleaning or maintenance may be necessary to restore optimal performance. In contrast, a low ΔCI

value, such as 5%, suggests that the system is relatively clean and operating close to its full capacity, with minimal performance losses due to soiling.

Several studies have demonstrated the importance of monitoring the CI in PV systems. For example, Pagani et al. (2021) developed a soiling index model that uses solar radiation and current to monitor PV efficiency, offering a low-error alternative for establishing cleaning schedules [296]. In a related study by Javed et al. (2017), an ANNs model was used to predict daily changes in the CI, showing that environmental variables such as PM10, wind speed, and relative humidity significantly influence soiling levels on PV panels [295].

4.9. Daily change in cleanness index

The Daily ΔCI , or Daily Change in CI, is a metric used to assess the day to day variation in the performance of PV systems due to soiling. It provides a finer resolution of how soiling accumulates on PV panels over time and how it affects their efficiency on a daily basis. This metric is particularly useful in environments where soiling rates can vary significantly from day to day due to weather conditions, industrial activity, or other environmental factors. The Daily ΔCI is calculated using Eq. (10).

$$\text{Daily } \Delta CI = \frac{\Delta CI_{\text{today}} - \Delta CI_{\text{yesterday}}}{\Delta CI_{\text{yesterday}}} \times 100, \quad (10)$$

where ΔCI_{today} is the CI measured for the current day, and $\Delta CI_{\text{yesterday}}$ is the CI measured for the previous day.

Daily ΔCI calculations have been refined through predictive modeling techniques that leverage environmental and meteorological data to enhance precision. Guo et al. demonstrated a strong correlation between dust accumulation and the Daily ΔCI , highlighting the impact of weather events like dust storms and rainfall on soiling rates and removal efficiency. Recent studies validate this finding by showing that dust accumulation significantly affects PV output, reducing power by up to 35% under high dust deposition, with cleaning cycles playing a critical role in mitigating these losses [81].

Micheli et al. expanded on these findings by introducing ML algorithms to predict daily soiling rates, integrating factors such as PM10 levels, humidity, and wind speed. Their work highlighted the effectiveness of these models in improving cleaning schedules and mitigating soiling-related performance losses [297]. In subsequent research, Micheli et al. further refined these models, incorporating methods to detect cleaning events and seasonal soiling accumulation patterns, which directly impact the accuracy of ΔCI measurements and maintenance strategies [298]. These advancements collectively contribute to a more robust framework for improving the precision of ΔCI calculations and optimizing PV system performance under varying environmental conditions.

4.10. Module degradation factor

The Module Degradation Factor (MDF) is a metric used to quantify the reduction in performance of PV panels over time due to various factors such as environmental exposure, material degradation, and operational wear and tear. It is a crucial metric for assessing the long-term reliability and durability of PV systems. The MDF is typically calculated using Eq. (11).

$$\text{MDF} = \frac{P_{\text{initial}} - P_{\text{current}}}{P_{\text{initial}}} \times 100, \quad (11)$$

where P_{initial} is the initial power output of the PV panel at the time of installation, and P_{current} is the current power output of the PV panel after a certain period of operation. This equation expresses the MDF as a percentage, indicating the proportion of power loss relative to the initial performance of the module. A higher MDF value suggests significant degradation, which may be caused by environmental stresses,

such as temperature fluctuations, humidity, UV radiation, and dust accumulation.

The MDF has been extensively studied to standardize its calculation and identify key factors affecting PV panel performance over time. Diallo et al. reviewed the impact of environmental factors, such as UV radiation and temperature fluctuations, highlighting their significant role in accelerating material deterioration and reducing module efficiency [38]. Lillo-Sánchez et al. conducted long-term studies on PV panels, revealing that cell browning and metallization oxidation contribute to a 30.9% degradation after 22 years of operation [299]. Subramaniyan et al. complemented these findings by developing data-driven models to predict long-term DRs based on environmental factors like UV exposure and temperature variations, providing valuable tools for anticipating performance losses and planning maintenance strategies [300]. These studies collectively establish benchmarks for monitoring and predicting degradation, enabling the industry to improve the reliability and longevity of PV systems.

4.11. Array yield and final yield

Array Yield (Y_A) and Final Yield (Y_F) are important metrics used to evaluate the energy production efficiency of PV systems. These metrics are crucial for understanding the performance of PV systems in relation to their installed capacity and the available solar energy.

4.11.1. Array yield

Y_A (Y_A) is defined as the ratio of the energy output from the PV array to the rated power of the array at STC. It is typically expressed in hours per day, indicating how many hours the PV array would need to operate at its rated capacity to produce the observed energy output. The equation for Y_A is given by Eq. (12).

$$Y_A = \frac{E_{\text{array}}}{P_{\text{STC}}}, \quad (12)$$

where E_{array} is the energy output from the PV array (in kWh), and P_{STC} is the rated power of the PV array at STC (in kW).

Y_A metrics have been enhanced by incorporating system-specific environmental adjustments to improve accuracy and reliability. Ding et al. proposed health-based performance evaluations that account for shading and faults, demonstrating how these factors significantly impact Y_A and highlighting the importance of continuous performance monitoring to ensure optimal energy generation [301].

Recent studies have demonstrated that site-specific factors, such as tilt angle and irradiance levels, significantly impact the energy yield and overall efficiency of grid-connected PV systems. For example, research using seasonal tilt optimization showed that adjusting tilt angles monthly or seasonally improves Y_A by up to 5.82% compared to fixed annual tilt angles [302]. Similarly, a study in Iraq emphasized the importance of site-specific tilt angle adjustments, reporting a 38.3° optimal tilt angle for maximizing annual PV output [303].

4.11.2. Final yield

Y_F is another performance metric that accounts for the overall energy production of the PV system relative to its installed capacity. It includes the effects of all system losses, including those from inverters, cabling, and shading. The equation for Y_F is given by Eq. (13).

$$Y_F = \frac{E_{\text{total}}}{P_{\text{STC}}}, \quad (13)$$

where E_{total} is the total energy output of the PV system after all losses (in kWh), and P_{STC} is the rated power of the PV array at STC (in kW).

Y_F methodologies often include corrections for inverter losses and other system inefficiencies to improve accuracy in performance evaluations. Sahouane et al. analyzed a 28 kWp system in the Saharan region of Algeria, highlighting the significant impact of harsh environmental conditions, such as high temperatures and dust accumulation, on Y_F .

values. They reported a maximum Y_F of 5.3 h/day under optimal conditions, emphasizing the need for temperature and dust corrections in Y_F assessments [304]. Similarly, Seme et al. evaluated PV systems in Slovenia, demonstrating how design and operational factors, such as tilt and azimuth angles, significantly influence Y_F and overall energy output. Their findings provide a framework for optimizing system efficiency by incorporating these factors into Y_F calculations [305]. These studies collectively highlight the importance of environmental and design considerations in improving the reliability of Y_F as a metric for PV system performance.

4.12. Capacity utilization factor

The Capacity Utilization Factor (CUF) is a key performance metric used to assess the efficiency and effectiveness of a PV system. CUF is defined as the ratio of the actual energy output from the PV system over a given period to the maximum possible energy output if the system operated at its full rated capacity for the same period. This metric provides insights into how well the PV system is being utilized in comparison to its potential. The equation for CUF is given by Eq. (14).

$$CUF = \frac{E_{\text{actual}}}{P_{\text{rated}} \times T}, \quad (14)$$

where E_{actual} is the actual energy output of the PV system (in kWh), P_{rated} is the rated power capacity of the PV system (in kW), and T is the total time period considered (in h).

The CUF has been refined through the integration of environmental and operational adjustments to improve its accuracy in assessing PV system efficiency. Aslam et al. discussed advancements in PV technology and management practices, emphasizing their role in overcoming challenges posed by high temperatures, dust accumulation, and system inefficiencies. They noted that continuous technological improvements can significantly enhance CUF, with well-managed systems typically achieving values between 15% and 25% [306]. Similarly, Muhammad et al. explored the influence of environmental factors such as temperature, dust, and humidity on CUF, highlighting the need for site-specific strategies to address these variables and maximize system performance [307].

Recent studies have emphasized the critical role of site conditions, tracking systems, and plant availability in determining CUF. For example, a detailed performance review of a 467.2 kWp PV system demonstrated that factors such as array design, tracking systems, and environmental conditions significantly influence CUF, which ranged between 17% and 20% depending on site-specific parameters [308]. Similarly, an analysis of a utility-scale PV plant in a dry climate reported CUF values between 15% and 20%, underscoring the importance of optimized tilt angles and climate adaptability [309].

4.13. Degradation rate

The DR is an essential metric used to quantify the decline in performance of a PV system over time. This metric is crucial for understanding the long-term reliability and efficiency of PV systems, as it directly impacts the overall energy yield and economic viability of the installation. The DR is typically expressed as a percentage per year and represents the annual reduction in the maximum power output of the system due to factors such as material aging, environmental factors, and system inefficiencies. The equation for calculating the DR is given by Eq. (15).

$$DR = \frac{P_{\text{initial}} - P_{\text{final}}}{P_{\text{initial}} \times T} \times 100, \quad (15)$$

where P_{initial} is the initial power output of the PV system (in kW or MW), P_{final} is the power output of the PV system after time T years (in kW or MW), and T is the time period in years. A low DR (closer to 0.5% per year) indicates that the system is aging slowly and maintaining most of its original efficiency, which leads to a more

extended useful life and higher cumulative energy output. In contrast, a high DR (greater than 1.5% per year) suggests rapid performance decline, necessitating frequent maintenance or early replacement of components to sustain optimal energy production.

The DR quantifies the annual reduction in PV system performance and is a critical metric for evaluating long-term reliability. Recent studies have demonstrated that DR values vary significantly across PV technologies and climatic conditions. For instance, C-Si systems typically exhibit annual DR values between 0.18% and 1.01%, while thin-film technologies, such as CIGS and Amorphous Silicon (a-Si), show higher DR values ranging from 3.21% to 6.53% per year, particularly in harsh climatic environments [277]. Furthermore, location dependency plays a significant role, with systems in warmer regions experiencing accelerated degradation compared to those in moderate climates [310].

Advanced statistical techniques, such as Seasonal and Trend Decomposition by LOESS - Trend Decomposition (STL), have been increasingly employed to improve DR estimation accuracy. These methods enable better differentiation between reversible effects, such as soiling or shading, and intrinsic degradation processes [311].

A recent meta-analysis of 99 primary studies comprising 837 degradation rate estimates reveals a median degradation rate of 1% per year, with photovoltaic module technology and climatic conditions being the main drivers of these differences [312]. Frick et al. (2020) further investigated the influence of climatic conditions on DRs, showing that systems in warmer climates often experience accelerated degradation. This study emphasized that Pc-Si systems in hotter regions are particularly susceptible to higher DRs, reaching up to 1% per year [310].

4.14. Visual loss factor

The Visual Loss Factor (VLF) is a metric used to quantify the reduction in the perceived output of PV systems due to non-uniform soiling, shading, or other visual impairments on the PV panels. Unlike metrics that measure overall performance losses, VLF focuses specifically on losses that can be observed visually, which often correlate with the partial shading of the modules or the presence of debris that unevenly covers the surface of the PV cells. The VLF can be expressed as in Eq. (16).

$$VLF = \frac{P_{\text{max, clean}} - P_{\text{max, impaired}}}{P_{\text{max, clean}}}, \quad (16)$$

where $P_{\text{max, clean}}$ is the maximum power output of the PV panel under clean, unimpaired conditions, and $P_{\text{max, impaired}}$ is the maximum power output of the PV panel when visually impaired by factors such as partial shading, soiling, or other obstructions. A high VLF indicates significant visual impairments, such as heavy shading or soiling, which cause substantial losses in power output. In contrast, a low VLF suggests that the visual obstructions are minimal and that the system is operating closer to its clean state. Monitoring the VLF can help in scheduling maintenance or cleaning routines to restore optimal PV performance.

The VLF quantifies power losses due to non-uniform soiling and shading, providing critical insights into the performance of PV systems under real-world conditions. Recent advancements in modeling techniques have improved the accuracy of VLF assessments. For instance, Ghosh et al. developed a methodology using PV yield data to estimate soiling and shading losses without additional sensors, demonstrating the significant impact of non-uniform soiling on energy output [313]. Similarly, Kappler et al. integrated shading and soiling data into ML models to enhance PV performance predictions, reducing forecast errors and improving system efficiency [314]. Doll et al. explored the use of luminescence imaging to detect and quantify soft and hard soiling on PV panels, highlighting its potential for automated VLF monitoring and loss quantification [315]. These advancements enable more precise identification and mitigation of visual impairments, ensuring optimal PV system performance.

Studies like those by Honnurvali et al. (2020) explored the modeling and simulation of PV DRs, incorporating VLFs into performance calculations, highlighting the importance of addressing these factors to minimize power losses [316]. Recent research has emphasized the impact of visual factors, such as reflection losses, on PV panel efficiency. For instance, a study investigating the use of anti-reflective coatings found that panels with SiO₂ nanomaterial coatings improved efficiency by up to 19.73%, significantly reducing reflection losses and enhancing energy capture [317]. This underscores the importance of optimizing PV systems to minimize optical losses and improve overall performance. Lastly, Deline et al. (2020) studied nonuniform irradiance and mismatch losses, which align with the visual loss concept, demonstrating how partial shading contributes to measurable losses [318].

5. Discussion

This study provides a comprehensive assessment of the key environmental factors and their influence on the performance degradation of PV systems. The findings highlight specific mechanisms through which these factors – including atmospheric deposits, meteorological conditions, shading, and irradiance – reduce system efficiency and reliability. For instance, dust accumulation leads to a 20%–30% reduction in light transmittance, while temperature fluctuations accelerate material degradation and increase the risk of delamination (Section 3.6). These findings form the basis for actionable recommendations aimed at mitigating these impacts through advanced materials, predictive maintenance, and policy interventions tailored to local conditions. Additionally, the study highlights the importance of performance metrics—such as the PLR and PR—which quantify the extent of performance loss over time.

The findings of this study provide actionable insights that have significant implications for real-world applications. By identifying and classifying the environmental factors that influence PV system performance, this review offers a foundation for improving maintenance strategies and informing policy-making efforts. For instance, the adoption of AI-driven system monitoring can enable predictive maintenance, ensuring timely interventions that minimize degradation and energy losses [319]. The results of this study demonstrate that dust accumulation can reduce light transmittance by 20%–30% (Section 3.6), while high temperatures contribute to encapsulant degradation and delamination, particularly in regions with significant thermal fluctuations. Policymakers can utilize these findings to develop localized regulations that mandate the use of self-cleaning coatings to minimize dust-related efficiency losses and advanced cooling systems to mitigate temperature-induced degradation [20]. For example, regions with arid climates could benefit from promoting the adoption of nanotechnology-based self-cleaning surfaces, while coastal regions might prioritize encapsulants resistant to humidity and corrosion. Similarly, engineers can incorporate smart tracking systems and resilient designs to address specific environmental challenges identified in this study. For instance, shading caused by vegetation and wildfires leads to significant reductions in energy output and encapsulant degradation due to heat exposure (Section 3.6). Smart tracking systems equipped with ML algorithms can dynamically adjust panel angles to optimize energy capture, while resilient designs can mitigate damage from extreme weather conditions, such as heavy snowfall or hail. These interventions are essential for sustaining energy generation in diverse environments.

5.1. Environmental factors and induced failures

The environmental factors analyzed in this study not only reduce the energy output of PV systems but also contribute to mechanical and electrical failures over time, as summarized in Table 4. This table provides a detailed overview of the specific failure modes induced by

environmental factors, highlighting their varied impacts on PV system components.

Atmospheric deposits, including dust, air pollution, sea salt, and organic debris, are among the most significant contributors to PV performance degradation. Dust accumulation can lead to a 20%–30% reduction in light transmittance and create localized hotspots due to uneven shading [78]. Additionally, air pollution exacerbates surface degradation through chemical interactions with PV materials, particularly in urban environments. Sea salt, especially in coastal areas, accelerates corrosion, reducing system longevity [320], while organic matter, such as pollen and debris, leads to sticky contamination, further hindering light absorption [321]. The failures induced by these atmospheric deposits, including surface erosion and corrosion, are detailed in Table 4.

Meteorological conditions, including wind, temperature, humidity, precipitation, snow, and hail, also contribute significantly to PV system degradation. While wind can have a cooling effect, it poses risks of mechanical damage and surface erosion due to wind-driven particles [322]. Temperature fluctuations accelerate the degradation of module materials as shown in Table 4. High humidity, particularly when combined with sea salt deposition, promotes corrosion and delamination, particularly in coastal regions [323]. Precipitation, including rain, snow, and ice, further contributes to mechanical stress, as snow accumulation can block sunlight and cause cracks during freeze-thaw cycles [324]. These specific weather-induced failures, such as glass breakage and connector corrosion, are detailed in Table 4.

Shading factors, such as those caused by vegetation growth and wildfires, also contribute to performance degradation. Vegetation causes shading, which leads to a disproportionate reduction in energy output. Wildfires not only cause shading due to ash but also expose PV systems to intense heat, which can degrade the encapsulant materials [325]. Table 4 summarizes the potential impacts of these shading factors on system performance.

Irradiance-related factors, such as UV radiation and PID, further impact PV system efficiency. Prolonged exposure to UV radiation causes yellowing of the encapsulant, which reduces light absorption [326]. High irradiance levels accelerate the ion migration within PV cells, leading to PID and efficiency losses over time [327]. These irradiance-related failures are documented in Table 4.

Combined effects: The interaction between these environmental factors often exacerbates their individual impacts. For example, dust accumulation combined with high humidity increases particle adhesion, making it more difficult for natural cleaning processes like wind or rain to remove debris. As summarized in Table 4, these combined effects accelerate degradation, highlighting the importance of integrated maintenance strategies to address multiple environmental factors simultaneously.

5.2. Importance of performance metrics

In addition to the analysis of environmental factors, this study emphasizes the use of performance metrics such as the PLR and PR to quantify degradation. The PLR measures the annual percentage decrease in system performance due to environmental degradation and aging. The findings of this study highlight that PLR values for C-Si PV systems typically range from 0.5% to 1.0% per year (Section 4), with higher values observed in harsher environments such as coastal or arid regions. For instance, areas with significant dust accumulation and high humidity exhibit elevated degradation rates due to particle adhesion and corrosion. Monitoring PLR trends enables operators to implement targeted maintenance strategies and evaluate the effectiveness of mitigation technologies, such as anti-soiling coatings or robotic cleaning systems. For example, field data shows that PLR values typically range from 0.5% to 1.0% per year for C-Si PV systems [276], with harsher environments leading to higher DRs. This metric is essential for predicting the long-term reliability of PV systems and optimizing maintenance schedules.

The PR is another critical metric that compares the actual energy output to the theoretical output under ideal conditions. PR values typically range between 75% and 90%, with lower values indicating that environmental factors such as soiling, shading, and temperature are significantly reducing system efficiency [251]. By monitoring these metrics, operators can identify when systems are underperforming and implement targeted interventions to mitigate further degradation.

Additional metrics, such as the EPBT, the PRa, and the Δ CI, provide further insights into the efficiency and sustainability of PV systems over their lifecycle. These metrics, discussed in Section 4, are essential for evaluating how environmental factors reduce energy production and for determining the economic viability of PV installations in different environments.

5.3. Recommendations for sustainable energy generation

The rapid advancements in PV technology and the findings of this study highlight the importance of adopting innovative strategies to enhance PV system performance and longevity. By addressing environmental factors and integrating cutting-edge technologies, stakeholders can optimize system efficiency, reduce maintenance efforts, and ensure sustainability in renewable energy infrastructure. The following recommendations outline practical and forward-looking measures:

- **Environmental impact assessments:** Conduct assessments for PV installations, considering local factors such as dust accumulation, humidity, wind conditions, and shading to tailor system designs for specific environments. Studies show that environmental conditions significantly affect system efficiency and should be included in planning and risk analysis [328].
- **Self-cleaning and anti-soiling coatings:** Implement advanced coatings, including nanotechnology-based self-cleaning surfaces, to mitigate soiling losses and reduce manual cleaning frequency, particularly in dust-prone areas [20].
- **AI-driven system monitoring:** The findings of this study emphasize the importance of deploying AI-based predictive maintenance systems to address degradation mechanisms identified in PV systems. For example, real-time monitoring of dust deposition rates and hotspot formation can reduce the risk of efficiency losses caused by uneven shading and localized heating (Section 3.6). By integrating ML models with real-time sensor data, operators can optimize cleaning schedules and predict material degradation, minimizing downtime and extending system lifespan [319].
- **Advanced cooling systems:** Integrate passive cooling methods, such as heat-dissipating surfaces, and active solutions like PCMs or liquid cooling to counteract temperature-induced efficiency losses [101].
- **Automated robotic cleaning:** Invest in robotic cleaning technologies equipped with water-efficient systems or dry cleaning techniques to maintain performance in regions with frequent soiling and water scarcity. Robotic cleaning systems have demonstrated the potential to minimize energy losses due to dust accumulation while conserving water resources in arid climates [20].
- **Smart tracking systems:** Incorporate dual-axis solar tracking systems with ML algorithms to optimize the angle of PV systems dynamically and maximize solar irradiation capture. These systems have been shown to increase energy yields significantly, particularly in regions with high variability in solar angles [319].
- **Resilient system design:** Engineer PV systems to withstand extreme mechanical stress caused by strong winds, heavy snowfall, or hailstorms, ensuring durability and long-term performance. Studies have emphasized the importance of robust system architecture to mitigate damage from extreme weather events and climate variability [45].

- **Performance metrics and benchmarking:** Utilize standardized performance metrics such as the PLR and PR to monitor degradation trends and enable proactive interventions. Regular performance monitoring has been highlighted as essential for early fault detection and improved maintenance strategies [40].
- **Energy storage integration:** Enhance energy reliability by integrating advanced energy storage systems, such as lithium-ion batteries and emerging solid-state batteries, to mitigate the effects of solar variability. Research highlights the increasing role of energy storage solutions in ensuring stable energy supply for PV systems under intermittent solar irradiation [329].
- **Self-healing materials:** Utilize self-healing materials capable of repairing microcracks and surface damage autonomously, thereby extending the operational lifespan of PV panels [45].
- **Nanotechnology-driven solutions:** Explore nanoparticle-based coatings that can improve light absorption, reduce contamination, and enhance energy yield efficiency [20].

5.4. Challenges and key elements in research and applications

To fully address the environmental challenges discussed in this study, several key research areas and opportunities must be pursued to enhance PV system performance, resilience, and sustainability under diverse environmental conditions.

Integrated environmental models: The findings of this study underscore the need for comprehensive models that integrate multiple environmental factors to predict their combined impact on PV systems. For example, the interaction between dust accumulation and high humidity increases particle adhesion, exacerbating soiling losses and accelerating surface degradation (Section 3.6). While current research often focuses on isolated factors, such as the effects of temperature on power output, the combined impact of these variables remains underexplored. Developing integrated models that account for these synergies will enable more accurate predictions of degradation patterns and inform the design of robust PV systems tailored to specific climatic conditions. For instance, studies have shown that the interaction between dust and high humidity can exacerbate soiling losses due to the formation of sticky layers on PV surfaces, which are more difficult to clean [40]. While individual models for specific factors exist, such as the impact of temperature on power output, integrated models remain limited in their ability to predict the synergetic effects of these factors under real-world conditions. Developing such models would enable more accurate assessments of degradation patterns and provide a foundation for optimizing PV designs for specific climates.

Real-time monitoring systems: Advanced sensors that provide real-time monitoring of environmental conditions, such as wind speed, temperature, and dust deposition rates, are essential for optimizing system operations. Recent developments in low-cost Internet of Things (IoT) technologies have made it feasible to deploy distributed sensor networks for PV systems, allowing operators to dynamically adjust maintenance schedules and cleaning cycles based on real-time data [330]. For example, sensors that detect early signs of partial shading or hotspot formation can reduce efficiency losses by enabling timely interventions. Integrating these systems with ML algorithms for anomaly detection further enhances their capability to mitigate energy losses and extend system lifespan.

AI-driven tools: AI is revolutionizing the maintenance and performance optimization of PV systems by enabling real-time fault detection, predictive maintenance, and degradation forecasting. For instance, ML models trained on historical data can predict performance losses due to weather variations and environmental factors with high accuracy [46]. Emerging AI applications are also exploring fault diagnosis for less obvious degradation mechanisms, such as “snail trails” on PV cells, which are associated with microcrack formation and material discoloration [46]. Continued advancements in AI algorithms, particularly

for detecting subtle degradation patterns, are critical for reducing operational costs and minimizing downtime in PV systems.

Standardization of metrics: Establishing standardized performance metrics, such as the PLR, PR, and DRs, is vital for benchmarking PV system performance across diverse environmental conditions. For example, the PLR metric provides insights into annual efficiency losses, which can vary significantly depending on climatic factors and maintenance practices. Recent studies have highlighted the challenges in achieving accurate and reproducible PLR calculations, emphasizing the need for robust methodologies that can account for non-linear trends and other variabilities [274]. Standardization would not only improve cross-regional comparisons but also aid policymakers and engineers in identifying best practices for system optimization. Furthermore, the adoption of these metrics can drive the development of international guidelines for PV system testing and certification under various environmental conditions.

Advanced fault diagnosis for emerging issues: Research into advanced diagnostic methods is essential for identifying faults in their early stages, particularly those caused by complex environmental interactions. Faults such as microcracks, partial shading, and PID often develop gradually and can go undetected until they cause significant efficiency losses. Recent advancements in ML and feature extraction techniques have shown promise in detecting these issues before they escalate [48]. For instance, algorithms capable of distinguishing between transient and permanent faults have been developed, providing operators with actionable insights to implement targeted interventions. Furthermore, the application of ensemble learning frameworks is expanding the scope of fault diagnosis by addressing less-understood degradation phenomena, such as discoloration and snail trails [46]. These innovative diagnostic methods are critical for optimizing maintenance strategies, minimizing downtime, and extending the operational lifespan of PV systems.

Low-cost, embedded diagnostic algorithms: The development of low-cost, embedded diagnostic tools is pivotal for scaling advanced monitoring capabilities to large-scale and distributed PV systems. Embedded systems equipped with real-time diagnostic algorithms can provide continuous monitoring without the need for expensive external equipment. For example, recent research demonstrated a novel embedded system leveraging infrared thermography and ML to diagnose faults such as dirt accumulation, degradation, and overheating in PV panels [331]. This system integrates Tiny Convolutional Neural Networks (TinyCNNs) into a low-power microcontroller, offering real-time fault detection at an average cost of approximately \$120. These tools not only reduce the operational expenses associated with maintenance but also democratize access to advanced diagnostic technologies for smaller operators and off-grid installations. By embedding these algorithms directly into PV systems, stakeholders can achieve a balance between cost-efficiency and reliability, ensuring sustainable energy production even under challenging environmental conditions.

Material resilience and emerging technologies: The development of resilient materials and innovative technologies, such as PSCs and bifacial modules, offers promising avenues for addressing environmental factors. PSCs, for example, demonstrate superior performance in high-temperature and low-light conditions, but their sensitivity to moisture and thermal instability remains a significant challenge [332]. Similarly, bifacial modules, which capture solar energy on both sides, have shown potential for increased energy output in regions with high albedo surfaces, such as deserts or snowy areas. These modules, leveraging advanced materials for both durability and efficiency, are designed to maximize the bifacial gain, with studies highlighting energy yield improvements of up to 30% compared to monofacial counterparts [332]. Advanced material coatings, including anti-soiling and self-healing technologies, further enhance the durability of PV panels by mitigating degradation caused by dust and other environmental factors. These innovations ensure the adaptability of PV systems to extreme climates while reducing long-term maintenance costs.

In addition to their technical benefits, understanding the cost trends of these emerging technologies is essential to accelerating their adoption. While the upfront costs of advanced materials and technologies, such as bifacial modules and self-cleaning coatings, can be significant, they offer substantial financial benefits over their lifecycle. For instance, self-cleaning coatings not only reduce soiling losses but also minimize the need for frequent manual cleaning, leading to operational cost savings [333]. Similarly, the enhanced energy output of bifacial modules can offset their higher initial investment by improving overall system efficiency and revenue generation. Future research should prioritize cost-benefit analyses to quantify these financial advantages, providing stakeholders with the necessary insights to adopt these technologies effectively and sustainably.

Hybrid renewable energy systems: Integrating PV systems with hybrid renewable energy solutions, such as wind power and advanced energy storage, offers a robust approach to ensuring energy reliability under variable environmental conditions. Hybrid systems mitigate the effects of solar intermittency by complementing PV generation with other renewable sources that operate under differing climatic conditions. For example, wind power typically peaks during the evening or storms, balancing PV generation, which is highest during sunny hours [334].

Additionally, energy storage technologies, including lithium-ion batteries, flow batteries, and thermal storage, are crucial for storing surplus energy generated during peak sunlight hours for later use, thus ensuring a steady energy supply [334]. Hybrid configurations combining PV with wind and energy storage have demonstrated the potential to significantly reduce supply fluctuations and improve system efficiency. Future research should focus on optimizing these systems to enhance their scalability and cost-effectiveness, making them accessible for broader adoption.

Advanced cooling and cleaning systems: Addressing environmental factors such as high temperatures and dust accumulation requires innovations in cooling and cleaning technologies to maintain PV system efficiency. Passive cooling techniques, including the use of heat-dissipating surfaces and thermally conductive encapsulation materials, reduce the adverse effects of temperature-induced performance losses. Active cooling methods, such as PCMs and liquid cooling systems, have also demonstrated significant potential in regions with extreme heat [335]. Simultaneously, robotic cleaning technologies are emerging as a viable solution for addressing soiling losses in dusty and arid environments. These systems are equipped with water-efficient or dry-cleaning mechanisms, which minimize the use of scarce resources while maintaining performance. Self-cleaning coatings incorporating nanotechnology have also been shown to reduce surface contamination effectively, decreasing the frequency of manual cleaning interventions [335]. Together, these advanced cooling and cleaning systems ensure the operational efficiency of PV systems under challenging environmental conditions, paving the way for greater energy reliability and cost savings.

Maintenance strategies for environmental mitigation: While this study does not focus on maintenance strategies, it is essential to highlight the importance of exploring practical solutions to mitigate the impacts of environmental factors on PV systems. Effective maintenance strategies, such as routine cleaning methods, self-cleaning coatings, and advanced material technologies, play a critical role in sustaining system performance and extending operational lifespans. For instance, automated cleaning systems and self-cleaning coatings incorporating nanotechnology have demonstrated potential for reducing soiling losses, especially in regions with high dust or pollen levels [333]. Moreover, addressing the economic aspects of maintenance strategies, such as cost-benefit analyses comparing periodic cleaning costs to efficiency losses, can provide valuable insights for stakeholders. Recent research has highlighted the financial benefits of investing in self-cleaning technologies and automated systems, which, while involving higher initial

costs, offer significant long-term savings by reducing manual interventions and improving energy yields. These strategies represent a key avenue for future research and development, bridging the gap between academic insights and practical applications in the industry.

Impact of deposits on encapsulation and energy generation: Atmospheric deposits, such as dust, sea salt, and pollen, pose significant challenges to PV systems by obstructing sunlight transmittance and accelerating long-term degradation. Recent studies have shown that dust accumulation can reduce PV power output by up to 30% in high-soiling regions. Additionally, factors such as dust particle size, composition (e.g., SiO_2 and CaCO_3), and climatic conditions further exacerbate these losses, highlighting the importance of regular cleaning and system maintenance [333].

This immediate reduction in power output directly impacts system performance and financial returns. In addition to performance losses, the prolonged presence of deposits severely affects the encapsulation materials of PV panels. Dust and pollen increase surface roughness, promote microcrack formation, and enhance moisture ingress, all of which compromise the structural integrity of PV systems. In coastal environments, sea salt exacerbates these effects by inducing surface corrosion, which leads to encapsulation delamination and yellowing, further diminishing performance over time [333].

The economic implications of these challenges are considerable. Revenue losses of up to 30% annually have been reported in regions with severe soiling, highlighting the urgent need for effective mitigation strategies. Furthermore, the costs associated with repairing or replacing degraded encapsulation materials range from \$10 to \$25 per square meter annually, depending on environmental conditions and exposure severity [336]. These financial burdens underscore the necessity for innovative solutions, such as self-cleaning coatings and automated cleaning systems, to minimize energy losses and reduce maintenance costs.

5.5. Implications for stakeholders

The findings of this study provide actionable insights that can benefit various stakeholders in the PV sector. For **engineers and technicians**, the proposed classification framework and performance metrics serve as tools to identify, diagnose, and mitigate degradation mechanisms, enabling the optimization of PV system design and maintenance protocols. Environmental factors such as dust accumulation, temperature variability, and shading have been shown to significantly impact PV panel performance, particularly in arid and semi-arid regions [319]. By understanding the effects of these factors, engineers can implement mitigation strategies, such as anti-soiling coatings or enhanced cooling systems, to improve system efficiency [40].

Policymakers can leverage this synthesis to develop standardized testing protocols, improve installation regulations, and implement policies that address the long-term impacts of environmental factors. For instance, integrating dust mitigation strategies into installation guidelines in high-dust regions has been proposed as a necessary step to ensure reliable PV performance [20]. Additionally, addressing climate-specific factors such as humidity and rainfall can support policies that promote resilient PV installations [101].

For the **research community**, this comprehensive review highlights key research gaps, such as the interactions of multiple factors under real-world conditions and the cumulative impacts on long-term degradation. Existing studies often focus on isolated factors like dust or thermal effects, but the need for integrated studies remains critical [45]. This study provides a roadmap for future studies, encouraging interdisciplinary approaches to advance knowledge in PV performance and reliability under diverse environmental conditions.

Economic challenges for operators: The economic implications of environmental factors on PV systems are considerable. Dust accumulation, for instance, can result in efficiency losses of up to 30%,

leading to substantial revenue reductions in high-soiling regions. Furthermore, the financial burden associated with repairing or replacing degraded encapsulation materials due to environmental factors, such as sea salt corrosion or microcrack propagation, can significantly impact operational costs. For example, a study on the energy and economic losses caused by dust has revealed that dust accumulation led to power output reductions of up to 8% in tropical climates and associated cleaning costs significantly added to the economic burden [83]. These findings underscore the importance of investing in advanced mitigation strategies, such as automated cleaning systems, to enhance system resilience and reduce operational expenses.

Policy recommendations for economic sustainability: Policymakers should consider incentivizing the adoption of technologies that mitigate these challenges, such as anti-soiling coatings, robotic cleaning systems, and advanced encapsulation materials. For instance, policies promoting the integration of optimized cleaning schedules and low-cost maintenance strategies tailored to regional conditions have been shown to reduce both energy losses and maintenance expenses [84]. Supporting further research and implementation of cost-effective mitigation technologies could significantly alleviate the economic challenges faced by PV operators in environmentally stressed regions.

5.6. Study limitations

This study provides a detailed analysis of the environmental factors affecting PV systems, but it has some limitations. First, the dataset used for performance analysis does not include all geographic regions, particularly those in tropical and polar climates. Future research should expand the geographic scope to include more diverse environmental conditions. Second, while the study highlights the importance of performance metrics, it does not fully explore the economic implications of degradation. Further research is needed to integrate economic modeling with performance metrics to evaluate the cost-effectiveness of different mitigation strategies. Third, the interaction between environmental factors – such as dust, humidity, and temperature – requires further exploration through long-term studies. While this study provides evidence of the combined effects of environmental factors, such as the interaction between dust and humidity leading to sticky deposits (Section 3.6), further long-term studies are necessary to quantify these synergies across diverse climatic conditions. Expanding the geographic scope of data collection, particularly in tropical and polar regions, will improve the generalizability of the findings and support the development of globally applicable mitigation strategies.

Additionally, as this is a review-based study, it is acknowledged that the generalizability of the findings may be influenced by key assumptions and limitations inherent to the reviewed literature. For instance, some studies did not specify the geographical location or the type of PV systems considered, while others were conducted in controlled laboratory environments that may not fully represent real-world operating conditions. Furthermore, the diversity in environmental conditions, such as irradiance, temperature, and humidity, across different regions complicates direct comparisons or universal generalizations.

Significant efforts were made to highlight trends and insights applicable across PV technologies and environmental conditions; however, the variability in experimental designs and reported parameters introduces challenges in standardizing results. These limitations reflect the broader context of PV research and emphasize the importance of future studies incorporating consistent reporting standards regarding geographical focus and system specifications to enhance comparability and applicability.

6. Conclusions

This study provides a comprehensive analysis of the environmental factors that affect the performance of PV systems, as well as the critical performance metrics used to quantify degradation over time.

By considering a wide range of environmental conditions – including atmospheric deposits, meteorological conditions, shading factors, and irradiance-related factors – this research offers a holistic understanding of the challenges that PV systems face in diverse environments. Unlike previous studies that often focus on individual factors, this study emphasizes the collective and interactive effects of multiple factors on PV performance. Several important findings emerged from this analysis:

- PV efficiency can decrease by 35% to 50% in standard environments, while under more extreme conditions, efficiency losses can reach 60% to 70%, primarily due to dust accumulation, temperature fluctuations, and shading factors (see Section 3).
- The accumulation of dust leads to significant daily efficiency reductions, approximately 0.05% under normal conditions. If not regularly cleaned, dust can reduce light transmittance by up to 37%, as outlined in Table 4.
- Environmental conditions such as wind, which can cool PV modules, and precipitation, which naturally cleans module surfaces, can have dual impacts. Wind speeds between 2.8 m/s and 10 m/s, for example, can lower module temperatures by up to 10 °C, mitigating overheating (see Section 3.3.1), while heavy snow accumulation can reduce energy production by 40% to 90%, emphasizing the need for effective snow management (see Section 3.3.5).
- Temperature has a pronounced effect on PV performance, with crystalline cells experiencing a 0.5% decrease in efficiency for every 1 °C increase in cell temperature. In extreme cases, efficiency can drop to 69% at 64 °C (see Section 3.3.2).
- Economic impacts are significant, with dust accumulation alone causing revenue losses of up to 30% annually in high-soiling regions. The costs associated with cleaning and maintenance can range from \$10 to \$25 per square meter annually, depending on environmental severity (see Section 5.5).
- Failure mechanisms induced by environmental factors – such as corrosion, delamination, and surface erosion – require targeted mitigation strategies, as summarized in Table 4, to ensure system longevity and reduce operational costs.
- The adoption of advanced technologies, such as self-cleaning coatings, automated robotic cleaning systems, and smart tracking mechanisms, can mitigate efficiency losses by up to 15% to 20% under challenging environmental conditions (see Section 5.3).
- Integrated renewable energy solutions, combining PV systems with wind power and advanced energy storage, have shown potential to significantly reduce supply fluctuations and improve overall energy reliability, particularly in regions with variable climatic conditions (see Section 5.4).
- Performance metrics, including the PLR, PR, and ΔCI , are critical for monitoring system efficiency and degradation trends. These metrics enable proactive maintenance and provide valuable insights into the economic and operational impacts of environmental factors (see Section 4).

This study also stresses the importance of integrating performance metrics—such as the PLR, PR, ΔCI , and DR—to accurately monitor and evaluate the long-term behavior of PV systems. These metrics, discussed in Section 4, provide valuable insights into how environmental factors accelerate degradation and reduce energy production. For example, the PLR offers a way to quantify annual performance losses, while the CI enables operators to assess the impact of soiling on system efficiency. By incorporating these metrics into routine system monitoring, stakeholders can make informed decisions about maintenance, technology selection, and system design.

The findings from this research underscore the complexity of the interactions between environmental factors and PV system performance. The results not only address the stated objectives but also highlight actionable insights for stakeholders, including engineers, policymakers,

and researchers. The synthesis of findings provides a robust framework for guiding maintenance strategies, policy recommendations, and future research efforts.

Finally, while this study emphasizes the need for a holistic approach to PV system design and management, the detailed perspectives for future research outlined in Section 5.4 should guide subsequent efforts. These include developing integrated environmental models, advancing AI-driven fault diagnosis, and optimizing hybrid renewable systems. By addressing these areas, the resilience and sustainability of PV systems can be further enhanced, ensuring their long-term viability as a cornerstone of the renewable energy transition.

Acronyms

I_{sc}	Short Circuit Current
V_{oc}	Open Circuit Voltage
Y_A	Array Yield
Y_F	Final Yield
a-Si	Amorphous Silicon
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
ARIMA	Autoregressive Integrated Moving Average
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CI	Cleanness Index
CIGS	Copper Indium Gallium Selenide
CNNs	Convolutional Neural Networks
CSD	Classical Seasonal Decomposition
CUF	Capacity Utilization Factor
DR	Degradation Rate
DSS	Dye-Sensitized Solar Cells
EPBT	Energy Payback Time
EPF	Energy Production Factor
EVA	Ethylene Vinyl Acetate
FF	Fill Factor
HHO	Harris Hawk Optimization
IEC	International Electrotechnical Commission
IoT	Internet of Things
LCCE	Life Cycle Conversion Efficiency
LOESS	LOcally wEighted Scatterplot Smoothing
MDF	Module Degradation Factor
ML	Machine Learning
MPPT	Maximum Power Point Tracking
pc-Si	Polycrystalline Silicon
PCMs	Phase Change Materials
PID	potential-induced degradation
PLR	Performance Loss Rate
PM	particulate matter
PR	Performance Ratio
PRa	Array Performance Ratio
PSCs	Perovskite Solar Cells
PV	Photovoltaic
PVUSA	Photovoltaic for Utility Systems Applications
sc-Si	Single-crystalline Silicon
SSA	Squirrel Search Algorithm
STC	Standard Test Conditions
STL	Trend Decomposition
SVMs	Support Vector Machines
TCT	Total Cross Tied
TinyCNNs	Tiny Convolutional Neural Networks
TPO	Thermoplastic Polyolefin
UV	Ultraviolet
VLF	Visual Loss Factor
VMPP	Maximum Power Point Voltage
YoY	Year-on-Year regression

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Data availability

Data will be made available on request.

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