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Assessment of Environmental and Operational Impacts on Photovoltaic System Performance Degradation

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تقييم الآثار البيئية والتشغيلية على تدهور أداء أنظمة الخلايا الكهروضوئية

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Abstract:
Photovoltaic (PV) system performance in real operating conditions is governed by the coupled effects of environmental variability, system design choices, and long-term operational and degradation mechanisms. Variations in solar irradiance intensity and spectral composition, driven by cloud dynamics, atmospheric conditions, and air mass, cause technology-dependent deviations from rated output and introduce spectral mismatch losses. Thermal behavior further constrains PV efficiency, as elevated ambient and cell temperatures reduce voltage, decrease conversion efficiency, and accelerate material aging, particularly in hot climates. These effects are compounded by soiling and surface contamination, where dust deposition, pollution, and organic residues reduce optical transmittance and energy yield in a strongly site-specific manner, necessitating adaptive cleaning schedules and advanced anti-soiling or self-cleaning solutions. In parallel, shading, orientation, and system configuration critically shape energy harvest under non-uniform conditions; partial and dynamic shading amplify mismatch losses and complicate power–voltage characteristics, while optimized tilt, azimuth, array layout, and module-level power electronics improve resilience and yield. Over the system lifetime, operational practices and degradation pathways, including inverter efficiency losses, grid interaction constraints, PID, delamination, and UV-induced aging, progressively affect reliability and lifetime energy production. Collectively, these findings emphasize the need for an integrated, systems-oriented framework that combines climate-aware design, shading-robust architectures, effective soiling mitigation, and data-driven monitoring and predictive maintenance to reduce performance uncertainty and maximize PV lifetime energy yield across diverse deployment contexts.

Keywords: Photovoltaic performance; Environmental effects; Thermal behavior; Soiling and shading losses; System degradation.

الملخص:
يخضع أداء أنظمة الطاقة الكهروضوئية (PV) في ظروف التشغيل الفعلية لتأثيرات مترابطة ناتجة عن التغيرات البيئية، وخيارات تصميم النظام، وآليات التشغيل طويلة الأمد والتدهور التدريجي. حيث تؤدي التغيرات في شدة الإشعاع الشمسي وتركيبه الطيفي، الناتجة عن ديناميكيات السحب والظروف الجوية وكتلة الهواء، إلى انحرافات تعتمد على نوع التقنية مقارنةً بالقدرة الاسمية، كما تُسبب خسائر ناتجة عن عدم التطابق الطيفي. كما يفرض السلوك الحراري قيودًا إضافية على كفاءة الأنظمة الكهروضوئية، إذ تؤدي درجات الحرارة المرتفعة للبيئة المحيطة والخلايا إلى انخفاض الجهد وتقليل كفاءة

التحويل وتسريع شيخوخة المواد، خاصةً في المناخات الحارة. وتتفاقم هذه التأثيرات نتيجة الاتساخ وتلوث الأسطح، حيث يؤدي تراكم الغبار والملوثات والبقايا العضوية إلى تقليل النفاذية الضوئية وانخفاض إنتاج الطاقة، وذلك بطريقة تعتمد بشكل كبير على خصائص الموقع، مما يستلزم تطبيق جداول تنظيف تكيفية واستخدام حلول متقدمة مقاومة للاتساخ أو ذاتية التنظيف. وبالتوازي مع ذلك، يلعب التظليل واتجاه النظام وتكوينه دورًا حاسمًا في تحديد كمية الطاقة المحصودة في ظل ظروف غير منتظمة؛ إذ يؤدي التظليل الجزئي والديناميكي إلى زيادة خسائر عدم التطابق وتعقيد خصائص القدرة–الجهد، في حين يُسهم تحسين زاوية الميل والسمت وتخطيط المصفوفة واستخدام إلكترونيات القدرة على مستوى الوحدة في تعزيز مرونة النظام وزيادة إنتاجيته. وعلى مدى العمر التشغيلي للنظام، تؤثر ممارسات التشغيل ومسارات التدهور المختلفة، بما في ذلك خسائر كفاءة العاكس، وقيود التفاعل مع الشبكة، وظاهرة التدهور الناتج عن الجهد المستحث(PID) ، والانفصال الطبقي، والشيخوخة الناتجة عن الأشعة فوق البنفسجية، بشكل تدريجي على موثوقية النظام وإجمالي إنتاج الطاقة على مدى عمره. وبشكل عام، تؤكد هذه النتائج على أهمية اعتماد إطار متكامل قائم على منهجية الأنظمة، يجمع بين التصميم الواعي بالظروف المناخية، والهندسة المقاومة للتظليل، واستراتيجيات فعالة للحد من الاتساخ، إلى جانب المراقبة المعتمدة على البيانات والصيانة التنبؤية، وذلك بهدف تقليل عدم اليقين في الأداء وتعظيم إنتاج الطاقة الكهروضوئية على مدى العمر التشغيلي في مختلف بيئات النشر.

الكلمات المفتاحية :أداء الأنظمة الكهروضوئية؛ التأثيرات البيئية؛ السلوك الحراري؛ خسائر الاتساخ والتظليل؛ تدهور الأنظمة.

Introduction:

Photovoltaic (PV) systems operate under a wide range of environmental conditions that fundamentally shape their instantaneous and long-term performance [5,6]. Solar irradiance variability, driven by cloud dynamics, atmospheric composition, and seasonal solar geometry, directly influences the amount and spectral quality of radiation incident on PV modules. Deviations from standard test conditions introduce spectral mismatch losses that vary across PV technologies, leading to discrepancies between rated and actual power output. These environmental fluctuations establish the primary boundary conditions for PV energy conversion and create inherent uncertainty in short-term power generation and long-term yield prediction [7,8].

Thermal effects represent a persistent source of performance loss in PV systems, particularly in regions characterized by high ambient temperatures and intense solar exposure [9]. Elevated cell operating temperatures reduce open-circuit voltage and conversion efficiency while accelerating thermally induced material degradation [10]. The cumulative impact of thermal stress over time contributes to gradual power degradation and reduced component lifetime. Effective heat dissipation, appropriate module selection based on temperature coefficients, and climate-aware system design are therefore critical for mitigating temperature-related losses and sustaining performance [11].

Soiling and surface contamination further exacerbate environmental performance losses by reducing the optical transmittance of the module surface. Dust deposition, pollution, organic residues, and salt accumulation attenuate incident radiation and may introduce partial shading, leading to both uniform power reductions and localized mismatch losses. These effects are highly site-specific and influenced by climatic conditions such as aridity, humidity, and proximity to pollution sources. Without systematic cleaning and surface protection strategies, soiling can become a dominant contributor to annual energy yield losses, particularly in desert and coastal environments. Figure 1 presents photographs of the soiling measurement systems installed at deferent sites, Arica, Calama, Copiapó, La Serena, and Santiago.

Figure 1. Photographs of the soiling measurement systems installed at deferent sites [12].

The systems were deployed at airports/airfields in Calama, Copiapó, and La Serena, whereas installations in Arica, Iquique, and Santiago were located on university campuses. All sites were deliberately selected to minimize or eliminate shading effects. In addition, given the absence of significant agricultural activity in the Atacama Desert and the placement of systems at a considerable distance from major industrial sources, local contamination from farming and heavy industry was expected to be negligible.

Beyond environmental exposure, system design and configuration significantly affect how PV systems respond to non-uniform operating conditions [13]. Partial and dynamic shading, suboptimal tilt and azimuth orientation, and dense array layouts can amplify mismatch losses and trigger bypass diode activation, resulting in complex power–voltage behavior [14]. Conversely, optimized orientation strategies, adequate row spacing, and the use of module-level power electronics, such as power optimizers and microinverters, can enhance energy harvest and improve resilience to shading-induced losses [15,16]. These design choices play a pivotal role in translating available solar resources into usable electrical energy.

Several studies have investigated the influence of environmental conditions on photovoltaic system performance, emphasizing irradiance variability, temperature effects, and spectral influences. For example, earlier experimental and simulation-based studies demonstrated that deviations from standard test conditions due to cloud cover, air mass variation, and atmospheric aerosols lead to significant reductions in PV output power and conversion efficiency [17-20]. These studies highlighted that spectral mismatch losses are technology-dependent, with thin-film and multi-junction PV modules showing greater sensitivity to changes in spectral distribution compared to crystalline silicon technologies.

A substantial body of literature [21-24] has focused on the impact of temperature and thermal behavior on PV performance. Previous research consistently reported a linear decrease in open-circuit voltage and overall efficiency with increasing cell temperature, particularly in hot and arid climates. Long-term field studies further showed that sustained thermal stress accelerates material degradation mechanisms, such as solder joint fatigue and encapsulant discoloration, ultimately reducing module lifetime and energy yield. These findings underscored the importance of temperature coefficients, thermal management strategies, and climate-adapted system design.

Other studies [25-27] have extensively examined soiling, dust accumulation, and surface degradation as major contributors to performance losses in PV systems. Field measurements conducted in desert, coastal, and urban environments revealed that soiling losses can range from a few percent to more than 30% annually, depending on local conditions and maintenance practices. Researchers also identified the role of cemented dust, salt deposition, and organic residues in causing persistent optical losses and localized shading, leading to hotspots and accelerated degradation. These studies emphasized the effectiveness of optimized cleaning schedules, anti-soiling coatings, and self-cleaning technologies in mitigating soiling-related losses.

More recent research has addressed the role of system configuration and operational factors in enhancing PV performance under non-uniform conditions. Comparative analyses showed that partial shading and suboptimal orientation significantly increase mismatch losses in conventional string inverter systems. In contrast, systems employing module-level power electronics, such as power optimizers and microinverters, demonstrated improved energy harvest, enhanced monitoring capability, and greater resilience to shading. Additionally, operational studies highlighted that proactive maintenance, performance monitoring, and data-driven fault detection are critical for minimizing long-term degradation and sustaining lifetime energy yield.

This manuscript provides a comprehensive and integrated assessment of the key environmental, design, and operational factors that drive performance losses in photovoltaic (PV) systems under real-world conditions. By systematically synthesizing the effects of solar irradiance variability and spectral mismatch, temperature-induced efficiency degradation, soiling and surface contamination, shading and system configuration, and long-term operational and aging mechanisms, the study moves beyond isolated analyses to present a holistic, systems-level perspective on PV performance. The manuscript elucidates how these factors interact cumulatively over time, influencing not only instantaneous power output but also reliability, degradation rates, and lifetime energy yield. Furthermore, the work highlights the critical role of climate-aware system design, shading-resilient configurations, and advanced operational strategies in mitigating performance losses. By emphasizing data-driven performance monitoring, fault detection, and predictive maintenance, the manuscript contributes actionable insights for improving long-term PV system operation and durability. Collectively, these contributions offer a unified framework that supports more accurate performance prediction, informed technology selection, and optimized operation and maintenance practices, thereby advancing the reliable and sustainable deployment of photovoltaic systems across diverse climatic and operational contexts.

Solar Irradiance Variability and Spectral Effects

Solar irradiance variability is a primary determinant of photovoltaic (PV) system performance, as the electrical output of PV modules is directly proportional to the intensity of incident solar radiation. Temporal fluctuations in irradiance, caused by diurnal cycles, seasonal changes, and transient weather conditions, lead to corresponding variations in generated current and power output. Rapid irradiance changes due to passing clouds can induce short-term power intermittency, affecting system stability and energy yield forecasting, particularly in grid-connected PV installations [28]. The angle of incidence of solar radiation on the PV module surface plays a critical role in determining the effective irradiance absorbed by the cells. As the sun's position changes throughout the day and across seasons, variations in incidence angle alter the amount of radiation reflected from the module surface and transmitted into the semiconductor material [29,30]. High incidence angles, especially during early morning and late afternoon hours, increase optical losses and reduce conversion efficiency, highlighting the importance of optimal tilt, tracking systems, and anti-reflective coatings in maximizing energy capture.

Beyond irradiance magnitude, the spectral distribution of sunlight significantly influences PV performance, as different PV technologies respond selectively to specific wavelength ranges. Changes in atmospheric composition, cloud thickness, and aerosol concentration modify the solar spectrum reaching the module surface [31,32]. These spectral shifts can lead to spectral mismatch losses when the incident spectrum deviates from the standard test conditions (STC), under which PV modules are typically rated, resulting in discrepancies between nominal and real-world performance.

Atmospheric conditions and air mass effects further compound spectral variability and irradiance attenuation. As air mass increases with lower solar elevation angles, shorter wavelengths are more strongly scattered, while longer wavelengths dominate the incident spectrum [33,34]. This phenomenon disproportionately affects PV technologies with narrow spectral response ranges, such as amorphous silicon or multi-junction cells, compared to crystalline silicon modules, which exhibit broader spectral sensitivity [35,36]. Consequently, geographical location and seasonal solar geometry play a decisive role in technology-specific performance outcomes. To summarize, the combined effects of irradiance variability, incidence angle, and spectral changes underscore the necessity of incorporating spectral-aware modeling and site-specific environmental data in PV performance assessment.

Temperature Effects and Thermal Behavior of PV Modules

Temperature is one of the most influential environmental factors affecting the performance, reliability, and long-term durability of photovoltaic (PV) modules. Unlike standard test conditions (STC), which assume a fixed cell temperature of 25 °C, PV systems in real-world operation are continuously exposed to varying thermal conditions driven by ambient temperature, solar irradiance, wind speed, and mounting configuration [37,38]. As a result, the actual operating temperature of PV cells often exceeds ambient levels, leading to pronounced deviations between rated and field performance. Understanding the thermal behavior of PV modules is therefore essential for accurate performance prediction, technology selection, and system optimization, particularly in hot and arid climates. Figure 2 shows thermal factor. The electrical characteristics of PV modules are inherently temperature-dependent, with increases in cell temperature primarily causing voltage degradation and efficiency losses.

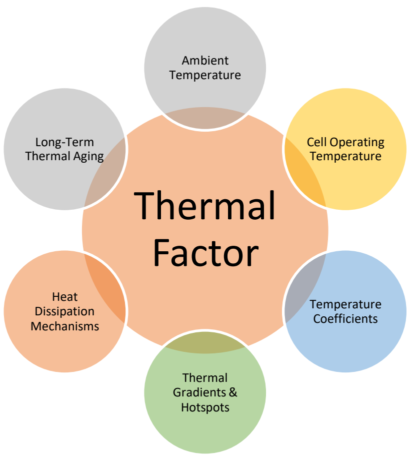

Figure 2. Thermal Factor

Table 1: Temperature effects and thermal behavior of PV Modules [41-46].

Thermal Factor	Description	Impact on Electrical Characteristics	Performance Consequences	Mitigation / Control Strategies	Notes
Ambient Temperature	Surrounding air temperature affecting module heat exchange	Indirect increase in cell temperature; reduction in open-circuit voltage (Voc)	Lower efficiency and power output in hot climates	Improved ventilation, elevated mounting, climate-aware design	Cell temperature typically 20–30°C above ambient
Cell Operating Temperature	Actual operating temperature of PV cells during energy conversion	Linear decrease in Voc and fill factor; slight increase in Isc	Net power and efficiency loss relative to STC	Modules with low temperature coefficients; cooling systems	Critical parameter for real-field performance
Temperature Coefficients	Rate of change of power, voltage, and current with temperature	Higher negative coefficients increase thermal sensitivity	Technology-dependent degradation (Si > thin-film)	Selection of PV technology with favorable coefficients	Typical power coefficient: −0.3 to −0.5 %/°C
Thermal Gradients & Hotspots	Non-uniform temperature due to shading or defects	Localized current mismatch and resistance increase	Accelerated aging and potential module failure	Bypass diodes, uniform layout, thermal imaging	Hotspots may exceed 100°C locally
Heat Dissipation Mechanisms	Processes removing excess heat from modules	Stabilizes voltage and electrical output	Improved efficiency and extended lifetime	Passive (heat sinks, PCM); Active (air/water cooling)	Design-dependent effectiveness
Long-Term Thermal Aging	Cumulative exposure to elevated temperatures	Material degradation and increased failure rates	Reduced lifetime energy yield	Durable encapsulation, preventive maintenance	Strongly climate-dependent

The first factor highlighted in Table 1 is ambient temperature, which governs the heat exchange between the PV module and its surrounding environment. Although ambient temperature does not directly determine electrical output, it strongly influences cell operating temperature through convection and radiation mechanisms. In hot climates, elevated ambient temperatures limit heat dissipation, causing higher cell temperatures and consequently lower open-circuit voltage. This explains the reduced energy yield commonly observed in desert and tropical regions despite high solar irradiance levels.

Closely related to ambient conditions is the cell operating temperature, which represents the actual temperature of the PV cells during energy conversion. Table 1 shows that increased cell temperature leads to a near-linear reduction in open-circuit voltage and fill factor, while only marginally increasing short-circuit current. Since voltage losses dominate, the net effect is a decline in output power and conversion efficiency. This behavior underscores why PV modules often perform below their nominal ratings in real operating conditions and highlights the importance of minimizing cell temperature through appropriate system design.

The temperature coefficients listed in the article quantify the sensitivity of PV electrical parameters to temperature variations. These coefficients are technology-dependent, with crystalline silicon modules typically exhibiting higher negative power coefficients than thin-film technologies. As indicated, higher negative coefficients translate into greater efficiency losses under high-temperature operation. Therefore, temperature coefficients serve as a critical criterion in PV technology selection, especially for installations in regions characterized by sustained high operating temperatures.

Another critical aspect discussed is the presence of thermal gradients and hotspots, which arise from partial shading, manufacturing defects, or non-uniform cooling. Table 1 illustrates how localized temperature increases can induce current mismatch, raise series resistance, and trigger hotspot formation. These localized thermal stresses not only reduce instantaneous power output but also accelerate module degradation and increase the risk of irreversible damage. Mitigation measures such as bypass diodes, uniform array layout, and infrared thermal inspections are therefore essential for maintaining system reliability.

The article further addresses heat dissipation mechanisms, including conduction, convection, and radiation, as fundamental processes governing module thermal regulation. Effective heat dissipation stabilizes operating temperature, improves voltage output, and enhances overall efficiency. Passive cooling techniques, such as optimized mounting, heat sinks, and phase-change materials, are often favored due to their simplicity and reliability, while active cooling methods can offer additional performance gains in high-temperature environments, albeit with increased system complexity. Finally, the article emphasizes long-term thermal aging, which captures the cumulative effects of sustained thermal exposure over the system lifetime. Elevated operating temperatures accelerate degradation mechanisms such as potential-induced degradation, encapsulant discoloration, delamination, and solder joint fatigue. These processes ultimately reduce lifetime energy yield and compromise system durability. Preventive maintenance, robust material selection, and climate-adapted design practices are therefore essential to mitigate long-term thermal impacts and ensure the economic viability of PV installations.

Effects of pollution, dust accumulation, and surface deterioration on the performance of photovoltaic cells

Soiling, dust accumulation, and surface degradation represent some of the most persistent non-electrical loss mechanisms affecting photovoltaic (PV) system performance, particularly in regions characterized by arid, coastal, or highly polluted environments. Unlike temperature or irradiance effects, soiling losses are largely site-specific and strongly influenced by local environmental conditions such as dust composition, wind patterns, humidity, and proximity to urban or industrial activities. The accumulation of contaminants on the PV module surface reduces optical transmittance, limits the amount of solar radiation reaching the photovoltaic cells, and consequently lowers energy yield and system efficiency [47,48].

In addition to uniform dust deposition, localized contaminants such as bird droppings, organic residues, and cemented dust layers can induce partial shading and current mismatch, leading to disproportionate power losses and the formation of hotspots. Over time, persistent soiling and abrasive particles may also contribute to surface degradation, including glass abrasion, coating deterioration, and chemical corrosion, which can permanently impair module performance [49,50]. Therefore, understanding the mechanisms of soiling and surface degradation is essential for accurate performance assessment, reliable energy yield prediction, and the development of effective operation and maintenance (O&M) strategies as illustrated in Table 2.

Table 2. Soiling, dust accumulation, and surface degradation [51-59].

Factor / Source	Description	Primary Mechanism	Impact on PV Performance	Key Indicators / Metrics	Mitigation & Management Strategies
Dust deposition	Accumulation of airborne particles on module glass, common in arid regions	Reduced optical transmittance and increased reflection	Reduction in Isc and power output; mismatch losses	Soiling ratio (SR), transmittance loss (%)	Scheduled cleaning, optimized tilt angle, robotic cleaning
Pollution & aerosols	Urban/industrial particulate matter and chemical aerosols	Optical attenuation and chemical interaction with glass	Gradual energy yield reduction and surface haze	PM concentration correlation, SR trend	Periodic washing, pollution-resistant coatings
Bird droppings & organic residues	Localized sticky contaminants causing partial shading	Shading-induced current mismatch and hotspots	Disproportionate power loss and reliability risk	Hotspot detection (IR), bypass diode activation	Targeted cleaning, bird deterrents, rapid inspection
Mud & cementation	Dust mixed with moisture forming hard crust	Strong adhesion reduces light transmission	Persistent power loss, difficult cleaning	SR recovery after cleaning, adhesion index	Hydrophobic coatings, soft-brush cleaning

Salt deposition (coastal)	Salt spray and crystallization on glass surface	Optical loss and corrosion risk	Power reduction and long-term reliability issues	Salt density, insulation resistance	Frequent rinsing, marine-grade components
Surface abrasion	Wind-driven sand erosion of glass	Micro-scratches increase scattering	Permanent efficiency loss	Haze index, surface roughness	Anti-abrasion glass, wind barriers
Cleaning frequency & schedule	Maintenance strategy balancing cost and yield	Restoration of transmittance	Improved annual energy yield	Performance ratio (PR), SR recovery	Data-driven cleaning optimization
Anti-soiling coatings	Hydrophobic or photocatalytic surface treatments	Reduced dust adhesion	Lower soiling rates and O&M costs	Soiling rate (SR/day), contact angle	Climate-validated durable coatings
Self-cleaning technologies	Robotic or electrostatic cleaning systems	Active removal of contaminants	Stable yield in high-soiling areas	Energy recovery vs O&M cost	Deploy in water-scarce regions

Soiling-related losses originate primarily from the deposition of airborne particles on the protective glass surface of PV modules, which reduces optical transmittance and limits the amount of solar radiation reaching the photovoltaic cells. Fine dust particles increase light scattering and reflection, while coarser particles can cause partial shading of individual cells. As indicated in the table 2, this reduction in incident irradiance is manifested mainly as a decrease in short-circuit current, leading to an overall decline in power output and energy yield. In arid and semi-arid regions, daily soiling rates can be significant due to frequent dust storms and limited natural cleaning by rainfall, making soiling one of the dominant loss mechanisms in such environments. Moreover, Urban and industrial pollution introduces an additional layer of complexity to soiling behavior. Pollutants such as soot, particulate matter, and chemical aerosols form thin films on the module surface that not only attenuate light but may also chemically interact with the glass or anti-reflective coatings. These interactions can result in persistent haze or surface discoloration that is not fully reversible through standard cleaning. Over time, this form of contamination leads to a gradual but sustained reduction in energy yield, emphasizing the importance of pollution-resistant surface treatments and appropriate cleaning agents in densely populated or industrialized areas.

Localized contaminants, particularly bird droppings and organic residues, have a disproportionately large impact on PV performance compared to uniform dust layers. Even small shaded areas can force current mismatch within a module or string, activating bypass diodes and causing localized heating. Such hotspots elevate thermal stress, accelerate encapsulant degradation, and increase the risk of irreversible cell damage. The table 2 highlights infrared thermal imaging and hotspot monitoring as essential diagnostic tools, enabling early detection and targeted maintenance before localized soiling evolves into long-term reliability issues. In humid and coastal environments, the interaction between dust and moisture often results in mud formation or cemented layers on the module surface. These hardened deposits adhere strongly to the glass, significantly reducing optical transmittance and making cleaning more difficult and water-intensive. Salt deposition in coastal regions further exacerbates performance degradation by introducing both optical losses and corrosion risks at module frames, connectors, and mounting structures. Frequent rinsing with appropriate water quality and the use of marine-grade components are therefore critical for sustaining PV system performance in such climates.

Surface degradation represents the cumulative, often irreversible consequence of prolonged soiling exposure and environmental stressors. Wind-driven sand particles can cause micro-abrasions on the glass surface, increasing surface roughness and light scattering. Similarly, repeated exposure to aggressive pollutants or improper cleaning chemicals may degrade anti-reflective or anti-soiling coatings. These processes lead to permanent reductions in transmittance and cannot be fully mitigated through routine maintenance, underscoring the importance of durable materials and protective coatings during the module selection and design stages.

Operational strategies, particularly cleaning frequency and scheduling play a central role in managing soiling losses. Excessive cleaning increases operational costs and may accelerate surface wear, whereas insufficient cleaning allows performance losses to accumulate. The data-driven approaches that monitor soiling ratios, performance ratios, and environmental conditions enable optimized cleaning schedules that balance energy recovery against maintenance expenses. In water-scarce regions, robotic and electrostatic self-cleaning technologies offer promising alternatives by maintaining stable energy yield while reducing water consumption and labor requirements. Overall, the detailed mechanisms and impacts summarized in the table 2 demonstrate that soiling and surface degradation are multifaceted challenges requiring integrated technical, environmental, and operational solutions. Effective mitigation depends on understanding site-specific conditions, selecting appropriate materials and technologies, and implementing intelligent O&M strategies. Addressing these factors holistically is essential for maximizing PV system efficiency, reliability, and long-term economic performance across diverse deployment environments.

Shading, Orientation, And System Configuration

Shading, orientation, and system configuration are among the most influential design and environmental factors governing the performance, reliability, and energy yield of photovoltaic (PV) systems [58-63]. Unlike uniform irradiance conditions assumed under standard test conditions, real-world PV installations frequently operate under non-uniform solar exposure due to partial and dynamic shading from surrounding structures, vegetation, terrain, and atmospheric variability [64-66]. These effects interact strongly with module tilt angle, azimuth orientation, and array layout, leading to electrical mismatch, reduced power output, and increased complexity in system operation and control as demonstrated Figure 3.

Moreover, the electrical configuration of PV systems, including string sizing, inverter architecture, and the use of module-level power electronics, plays a critical role in determining the system's resilience to shading and orientation-related losses. Design choices such as the placement of bypass diodes, adoption of power optimizers, or deployment of microinverters can significantly mitigate mismatch effects and enhance energy harvest under non-uniform conditions. Consequently, a comprehensive assessment of shading behavior, orientation strategies, and system configuration is essential for optimizing PV system performance, improving reliability, and ensuring economic viability across diverse installation environments [64-72].

A. Partial and Dynamic Shading Impacts on Electrical Performance

Partial shading introduces severe non-uniformity in irradiance distribution across PV modules and strings, leading to disproportionate power losses relative to the shaded area. In series-connected PV strings, the current is constrained by the lowest-irradiated cell, resulting in significant mismatch losses even under limited shading conditions. Dynamic shading, caused by moving clouds, surrounding structures, or vegetation growth, induces rapid fluctuations in power output that complicate performance forecasting and real-time control. These transient effects are particularly critical in grid-connected systems with high PV penetration, where power variability can affect voltage regulation, frequency stability, and inverter operation. Accurate modeling of partial and dynamic shading is therefore essential for realistic energy yield prediction and resilient PV system design.

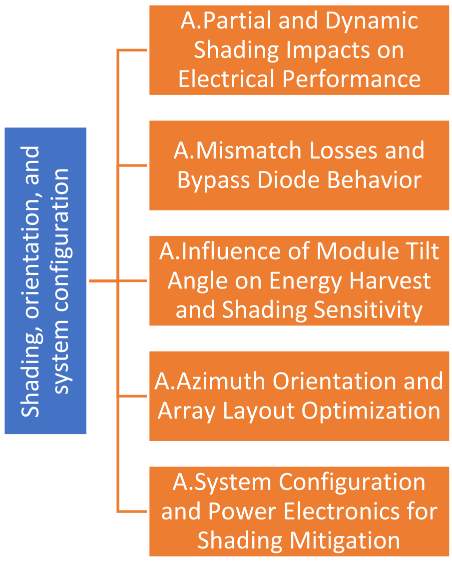

Figure 3. Shading, orientation, and system configuration.

B. Mismatch Losses and Bypass Diode Behavior

Electrical mismatch arises when PV modules or cells operate under unequal irradiance or temperature conditions, causing deviations in their current–voltage characteristics. Bypass diodes are integrated into PV modules to mitigate the adverse effects of shading by providing alternative current paths around shaded cell groups, thereby preventing excessive reverse biasing and hotspot formation. However, diode activation leads to stepwise voltage reductions and partial loss of available power. Under complex shading scenarios, multiple bypass diodes may activate intermittently, producing multi-peak power–voltage curves that challenge conventional maximum power point tracking (MPPT) algorithms. This behavior underscores the importance of advanced MPPT techniques and careful system design to balance protection, efficiency, and long-term reliability.

C. Influence of Module Tilt Angle on Energy Harvest and Shading Sensitivity

The tilt angle of PV modules directly affects the magnitude and temporal distribution of incident solar irradiance, influencing both annual energy yield and shading exposure. Optimally selected tilt angles maximize solar capture based on latitude and seasonal sun paths, while also reducing reflection losses at high incidence angles. In addition, increased tilt angles can mitigate shading from nearby obstacles during early morning and late afternoon periods and promote natural cleaning by rainfall, indirectly reducing soiling losses. Conversely, suboptimal or uniform tilt angles in densely packed arrays may increase self-shading, particularly during winter months when solar elevation is low. Therefore, tilt optimization must consider not only irradiance maximization but also shading geometry, land use constraints, and maintenance implications.

D. Azimuth Orientation and Array Layout Optimization

Azimuth orientation and array layout are fundamental design parameters that shape the spatial and temporal distribution of PV power generation. South-facing arrays typically maximize annual energy yield in the northern hemisphere, while east–west configurations offer flatter daily generation profiles and improved alignment with load demand. Array layout parameters such as row spacing, ground coverage ratio, and inter-row height differences determine the extent of mutual shading between module rows, particularly in large-scale ground-mounted systems. Inadequate spacing increases shading losses, whereas excessive spacing reduces land-use efficiency and raises installation costs. Optimized layout design therefore requires a multi-objective approach that balances energy yield, shading tolerance, land availability, and economic performance.

E. System Configuration and Power Electronics for Shading Mitigation

System-level configuration plays a decisive role in mitigating shading-induced losses and enhancing energy harvest under non-uniform operating conditions. Traditional centralized and string inverter architectures are more susceptible to mismatch losses because shaded modules limit the performance of entire strings. In contrast, module-level power electronics, such as power optimizers and microinverters, enable independent maximum power point tracking at the module level, significantly reducing shading sensitivity and improving overall energy yield. These technologies also enhance monitoring resolution, fault detection, and system flexibility. However, their adoption involves trade-offs related to higher initial costs, increased component count, and potential reliability considerations. Consequently, the selection of system configuration must be guided by site-specific shading conditions, system scale, economic constraints, and long-term performance objectives.

The combined effects of shading, orientation, and system configuration fundamentally shape the operational performance of photovoltaic systems under real-world conditions. Partial and dynamic shading introduce severe mismatch losses that cannot be accurately captured by simplified performance models, while suboptimal tilt and azimuth orientations further exacerbate energy yield reductions. Bypass diodes provide essential protection against hotspot formation, but their activation introduces voltage losses and complex power–voltage characteristics that demand advanced control strategies.

Effective mitigation of these challenges requires an integrated design approach that aligns physical layout optimization with appropriate electrical configuration and power electronics selection. Optimized tilt angles, well-designed array layouts, and site-specific orientation strategies can significantly reduce shading exposure, while module-level power electronics enhance system resilience and maximize energy harvest under non-uniform irradiance. Ultimately, incorporating shading-aware design principles and configuration strategies is critical for achieving high-efficiency, reliable, and economically sustainable PV systems across a wide range of climatic and deployment scenarios.

Operational, Aging, And Degradation Factors

The long-term performance and reliability of photovoltaic (PV) systems are governed not only by environmental conditions but also by operational practices, component aging, and inherent degradation mechanisms. While PV modules are generally designed for multi-decade operation, real-world performance often deviates from nominal expectations due to operational inefficiencies, grid interaction challenges, and progressive material degradation [73-75]. Factors such as inverter efficiency, load matching, maintenance quality, and grid compliance directly influence daily energy production, while aging phenomena, including potential-induced degradation (PID), delamination, ultraviolet (UV) exposure, and thermal cycling, gradually reduce system output over time [76,77]. Figure 4 outlines operational, aging, and degradation factors.

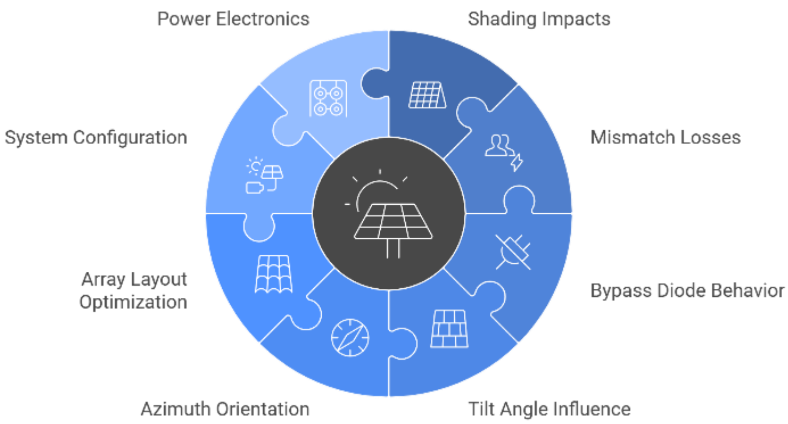

Figure 4. Operational, aging, and degradation factors.

Understanding the interplay between operational conditions and degradation processes is therefore essential for accurate lifetime energy yield assessment and sustainable PV system deployment. Advances in performance monitoring, fault detection, and data analytics provide new opportunities to identify early signs of degradation, optimize maintenance strategies, and extend component lifetimes. This section addresses the key operational, aging, and degradation factors affecting PV systems and emphasizes the role of proactive, data-driven management in ensuring long-term reliability and economic viability [78-83].

A. Operational Efficiency and Inverter Performance

Inverter performance is central to the operational efficiency of PV systems, as inverters govern the conversion of direct current generated by PV modules into grid-compatible alternating current. Inverter efficiency is not constant but varies with operating conditions, particularly irradiance level, temperature, and loading ratio. Under partial-load operation, common during early morning, late afternoon, and cloudy conditions, conversion losses can increase, reducing effective energy yield. Additionally, thermal stress on inverter components accelerates aging of power electronics, potentially leading to efficiency degradation and premature failure. Advanced maximum power point tracking (MPPT) algorithms, appropriate inverter sizing, and thermal management strategies are therefore critical to maintaining high operational efficiency throughout the system lifetime.

B. Load Matching, Grid Interaction, and Power Quality

The interaction between PV generation, local load demand, and the electrical grid significantly influences system performance and reliability. Mismatches between generation and consumption can result in energy curtailment, increased reliance on the grid, or reduced self-consumption efficiency in behind-the-meter systems. Grid interaction introduces additional constraints, including voltage rise, frequency deviations, and reactive power requirements, especially in weak or distribution-level grids with high PV penetration. Compliance with grid codes necessitates advanced inverter functionalities such as voltage support, reactive power control, and fault ride-through capability. These operational demands not only affect instantaneous performance but also impose additional stress on inverters and grid-connected components, influencing long-term reliability.

C. Maintenance Practices and Operational Reliability

Maintenance practices play a decisive role in sustaining PV system performance and minimizing degradation-related losses. Preventive maintenance activities, such as regular inspections, cleaning, electrical testing, and thermographic analysis, help identify early signs of component failure and performance degradation. In contrast, inadequate or reactive maintenance can allow minor faults to escalate into major failures, increasing downtime and reducing lifetime energy yield. Operational reliability is particularly sensitive to balance-of-system components, including inverters, cabling, connectors, and mounting structures, which often exhibit higher failure rates than PV modules themselves. Well-structured operation and maintenance (O&M) strategies are therefore essential for ensuring system availability and economic viability.

D. Aging Mechanisms and Long-Term Degradation of PV Components

PV systems are subject to multiple aging and degradation mechanisms that progressively reduce performance over time. Potential-induced degradation (PID) arises from high system voltages and moisture ingress, leading to leakage currents and power loss. Delamination and encapsulant discoloration degrade optical properties and electrical insulation, while prolonged ultraviolet (UV) exposure accelerates polymer aging and material embrittlement. Thermal cycling and humidity further exacerbate mechanical stress and solder joint fatigue.

E. Performance Monitoring, Fault Detection, and Data-Driven Maintenance

Advanced performance monitoring and fault detection systems are increasingly recognized as essential tools for sustaining long-term PV system performance. Key performance indicators such as performance ratio, capacity factor, and degradation rate enable continuous assessment of system health. Modern monitoring platforms integrate high-resolution sensor data, inverter diagnostics, and weather information to detect anomalies indicative of faults or degradation. Data-driven maintenance strategies, including machine learning and predictive analytics, allow operators to anticipate failures, optimize maintenance scheduling, and reduce operational costs. By shifting from reactive to predictive maintenance, PV systems can achieve higher reliability, improved lifetime energy yield, and enhanced economic performance.

Conclusion

The comprehensive analysis encapsulated within the five agendas highlights that photovoltaic (PV) system performance is the outcome of interdependent environmental, design, and operational factors that evolve over both short and long-time scales. Solar irradiance variability and spectral effects define the fundamental energy input to PV systems, yet real-world atmospheric conditions, cloud dynamics, and air mass variations frequently lead to deviations from rated performance. These spectral and irradiance-related effects are highly technology-dependent, underscoring the importance of climate- and location-specific PV technology selection to minimize spectral mismatch losses and improve energy yield predictability. However, thermal behavior emerges as a persistent and unavoidable constraint on PV efficiency, particularly in hot climates where elevated ambient and cell temperatures lead to voltage degradation, reduced conversion efficiency, and accelerated material aging. When combined with soiling and surface contamination, thermal effects can compound performance losses, as dust layers not only attenuate incident radiation but also alter heat dissipation characteristics. The cumulative impact of dust deposition, pollution, organic residues, and surface degradation emphasizes that optical losses are neither uniform nor transient, but rather strongly site-dependent phenomena that require adaptive, data-informed mitigation strategies such as optimized cleaning schedules, anti-soiling coatings, and self-cleaning technologies.

System design considerations related to shading, orientation, and configuration play a decisive role in determining how effectively PV systems convert available solar resources into usable electrical energy. Partial and dynamic shading can cause disproportionate mismatch losses and complex power–voltage behavior, while suboptimal tilt angles and azimuth orientations reduce annual energy yield and increase sensitivity to shading and soiling. Conversely, well-optimized array layouts, informed orientation strategies, and the integration of module-level power electronics, such as power optimizers and microinverters, can significantly enhance system resilience under non-uniform operating conditions, improving both energy harvest and operational stability. Beyond environmental exposure and system design, long-term operational practices and degradation mechanisms ultimately govern PV system reliability and lifetime energy production. Inverter efficiency, load matching, grid interaction, and maintenance quality directly influence day-to-day performance, while aging processes such as potential-induced degradation, delamination, ultraviolet exposure, and thermal cycling progressively erode system output. The increasing availability of high-resolution monitoring data and advanced fault detection techniques enables a shift from reactive to predictive maintenance, allowing early identification of performance degradation and targeted intervention before irreversible damage occurs.

Overall, the manuscript collectively demonstrates that maximizing PV system performance and durability requires a holistic, systems-oriented approach that integrates environmental awareness, robust system design, and intelligent operation and maintenance. Performance optimization can no longer rely on isolated considerations of individual factors but must instead address their combined and cumulative effects across the system lifecycle. Such an integrated framework is essential for reducing performance uncertainty, extending system lifetime, and ensuring that PV technologies deliver reliable, cost-effective, and sustainable energy across diverse climatic and deployment contexts.

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