

Review on Performance improvement of Solar PV Panels with alignment of different Environmental Parameters

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ABSTRACT

This study examines the critical environmental parameters that influence photovoltaic performance, including solar irradiance, temperature, wind speed, humidity, and dust deposition, to elucidate the complex links between ambient conditions and panel efficiency. Specifically, research indicates that efficiency is directly proportional to solar irradiance and wind speed and is inversely proportional to temperature, humidity, and dew point temperature. To quantify these relationships, linear regression analysis is often employed to model efficiency as a dependent variable against independent meteorological factors, thereby allowing for the prediction of power generation under varying weather scenarios. Field studies have demonstrated that energy losses ranging from 21.4% to 37.5% can occur due to the absence of rainfall over extended periods, highlighting the severity of environmental stressors on photovoltaic systems. Furthermore, specific environmental parameters such as wind velocity, ambient temperature, and dust concentration have been shown to influence power output continuously, with lower humidity levels between 69% and 75% correlating with increased power generation.

Keywords: Energy Loss, Performance loss, Dust impact

Parameters influencing Solar PV

The growing global demand for renewable energy has positioned photovoltaic panels as a primary technology for solar energy harvesting, yet their operational efficiency remains inextricably linked to prevailing environmental conditions [1]. While solar irradiance serves as the fundamental driver of energy generation, ambient variables such as temperature, humidity, wind speed, and dust deposition introduce complex non-linear effects that can significantly alter the actual power output relative to theoretical performance [1], [2].

Conversely, the accumulation of airborne dust and other atmospheric contaminants presents a significant physical barrier to energy conversion, as these particles obstruct sunlight from reaching the photovoltaic cells and can reduce power output to as low as 50% of maximum levels without regular maintenance [1]. Beyond physical obstruction, high relative humidity contributes to efficiency losses by promoting the formation of water droplets and sticky dust layers that scatter incident radiation and prevent direct sunlight from reaching the solar cells [1]. This phenomenon is further exacerbated by elevated dew point temperatures, which indicate higher atmospheric moisture levels and have been statistically correlated with a decline in photovoltaic efficiency through a negative linear relationship [3].

Background on Solar Photovoltaic Technology

Solar photovoltaic technology functions on the fundamental principle of converting incident sunlight directly into electrical energy through the photovoltaic effect; this process relies on semiconductor materials to absorb photons and dislodge electrons, creating a flow of current.

However, the exposure of these systems to the open atmosphere subjects them to various environmental phenomena that can induce performance degradation, system deterioration, and energy loss, particularly in regions characterized by high humidity, frequent rainfall, and significant temperature swings [4].

Principles of Photovoltaic Conversion

The photovoltaic effect occurs when photons with sufficient energy strike the semiconductor material, typically silicon, causing electrons to be excited from the valence band to the conduction band and thereby generating electron-hole pairs that are separated by the internal electric field of the p-n junction to produce direct current electricity[5].

External circuitry subsequently harnesses this generated voltage to power electrical loads, though the magnitude of the output is highly sensitive to the spectral distribution of the incident light and the operating temperature of the semiconductor material[6], [7].

As the operating temperature rises, the semiconductor's bandgap narrows slightly, which increases the intrinsic carrier concentration and leads to a reduction in the open-circuit voltage, ultimately diminishing the overall conversion efficiency of the photovoltaic device[8], [9].

Types of Solar Panels

The theoretical performance of photovoltaic systems is governed by the Standard Test Conditions, which specify an irradiance of 1000 W/m², a cell temperature of 25°C, and an air mass of 1.5, yet real-world deployment exposes modules to a dynamic range of meteorological variables that deviate significantly from these idealized parameters.

These environmental stressors include ambient temperature fluctuations, solar irradiance variability, wind velocity, humidity levels, and particulate accumulation, all of which interact to modify the actual energy yield compared to laboratory-rated capacities [10], [11].

This discrepancy arises because the remaining incident solar radiation that is not converted into electricity is transformed into heat, which raises the temperature of the PV module and reduces its efficiency [9].

High relative humidity further compounds these thermal losses by introducing moisture that can corrode electrical contacts and promote the adhesion of dust particles, which scatter incoming light and reduce the effective irradiance reaching the active cell area [3], [12]. Additionally, the angle of incidence of solar irradiation and the intensity of the incident light are critical determinants of the maximum power value obtainable from a solar panel [13].

The spectral content of the sunlight also plays a crucial role, as the semiconductor material's bandgap energy determines the specific range of photon wavelengths that can be effectively absorbed to generate electron-hole pairs [14]. Elevated temperatures alter the dynamics of charge carriers, hindering their contribution to electrical current generation [14].

Environmental Parameters Affecting Solar Panel Efficiency

Temperature Effects exerts a profound influence on the electrical characteristics of photovoltaic modules, as the performance of semiconductor materials is intrinsically sensitive to thermal variations that alter the efficiency of the photovoltaic conversion process[15].

Specifically, as the cell temperature increases beyond the standard test conditions, the open-circuit voltage decreases at a rate of approximately 0.3% to 0.5% per degree Celsius[16], resulting in a net reduction of power output despite a marginal increase in short-circuit current[15]. Consequently, for most crystalline silicon technologies, the maximum power output typically declines at a rate of 0.4% to 0.5% per degree Celsius increase in cell temperature, creating a significant performance gap in hot climates where module temperatures frequently exceed 25°C. This thermal sensitivity necessitates careful consideration of installation methods and site selection to minimize heat accumulation and ensure that the operating temperature remains as close as possible to standard test conditions for optimal energy yield.

Electrical Losses.

Electrical losses within photovoltaic systems arise primarily from internal resistances, including series resistance in the cell's bulk material and contacts as well as shunt resistance across the p-n junction, all of which impede the flow of generated current and reduce the fill factor.

These resistive losses are further compounded by the temperature dependence of the semiconductor material, where increased thermal energy leads to higher intrinsic carrier concentration and a reduction in the open-circuit voltage, thereby diminishing the overall power output [17], [18].

The temperature coefficient quantifies this reduction in voltage, which typically indicates a power loss of approximately 0.4% per degree Celsius rise above standard test conditions of 25°C [19], [20].

Material Degradation

Impact Assessment and Case Studies. Evaluating the real-world consequences of environmental stressors requires a comprehensive analysis of empirical data gathered from diverse geographical installations to quantify the magnitude of efficiency losses.

By examining performance data across distinct climatic zones, researchers can identify specific environmental stressors that disproportionately affect energy yield, such as the severe efficiency penalties observed in arid regions due to dust accumulation or the thermal losses prevalent in tropical areas with high ambient temperatures.

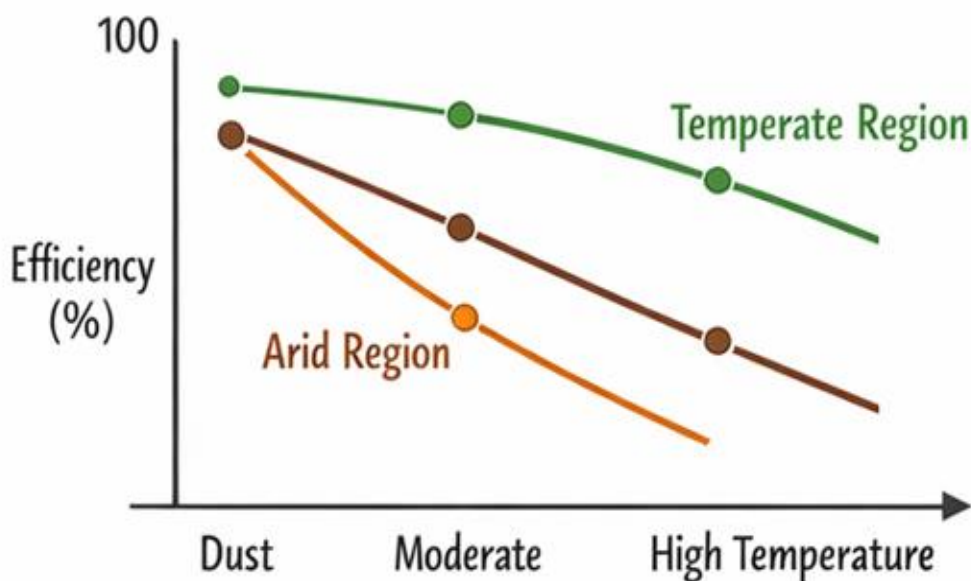


Fig 1.1. Effect of temperature on Efficiency

These findings underscore the necessity for region-specific performance modelling to accurately predict energy yields and optimize system configurations for local environmental conditions.

Regional Variations in Performance Loss

Geographical location plays a decisive role in determining the magnitude and nature of efficiency losses, as distinct climatic zones impose unique combinations of thermal stress, soiling rates, and meteorological conditions on photovoltaic arrays.

For instance, installations in arid desert environments frequently experience substantial energy yield reductions primarily due to high soiling rates and extreme ambient heat, whereas coastal deployments must contend with corrosive salt mist accumulation and persistent humidity that accelerates material degradation.

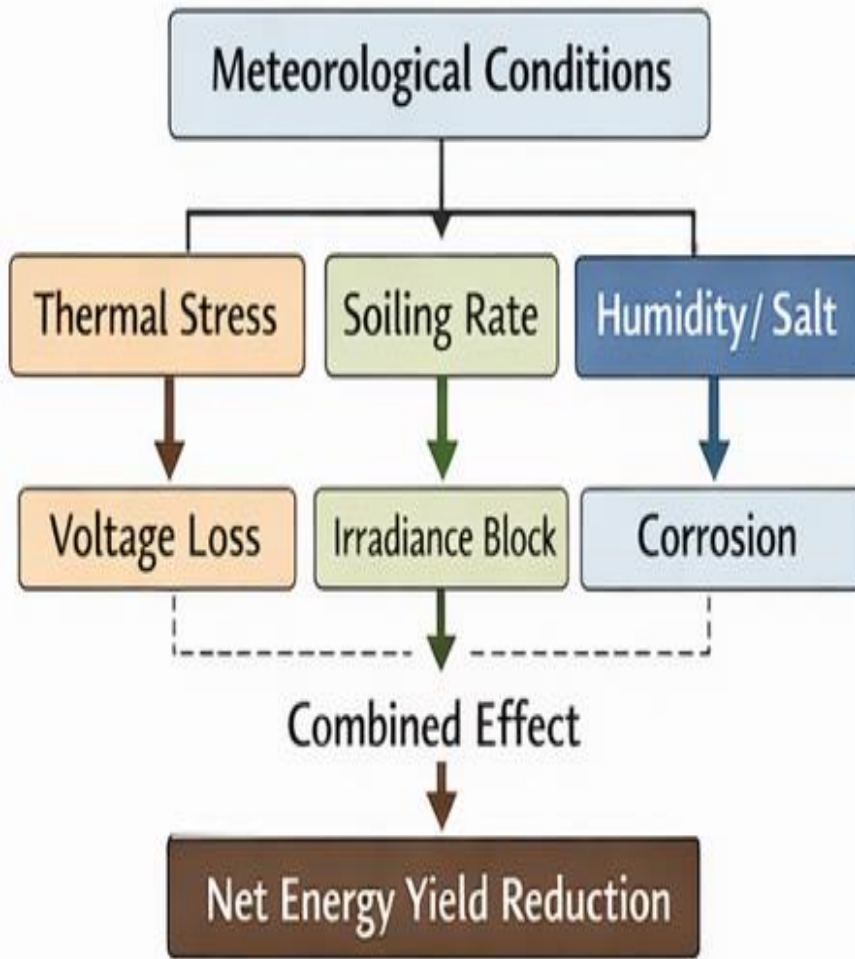


Fig 1.2. Environmental Stressor model

Conversely, systems situated in high-altitude or temperate regions often benefit from increased irradiance levels and lower ambient temperatures, which can enhance voltage output and overall system efficiency, provided that other meteorological factors such as cloud cover and wind patterns remain favourable.

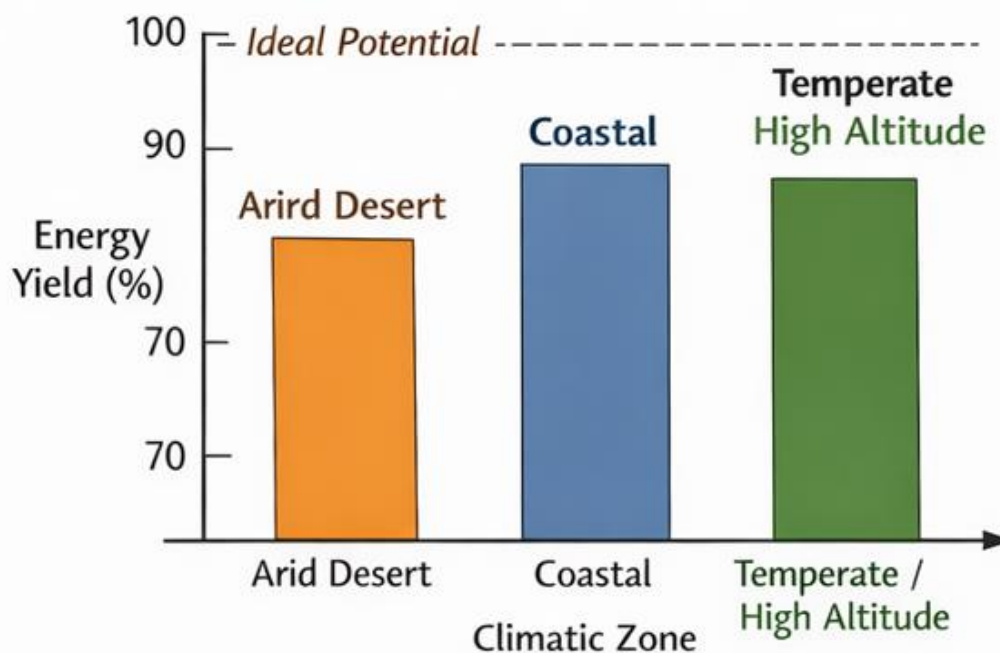


Fig 1.3. Energy Yeild Vs Region

Economic Implications of Decreased Efficiency

The financial viability of solar energy projects is directly compromised by environmental factors that reduce energy yield, as even minor efficiency declines can significantly extend the payback period and lower the levelized cost of electricity. Furthermore, the unpredictability of environmental degradation introduces additional risk premiums that can deter potential investors and complicate the financing models required for large-scale solar infrastructure development.

Geographical location plays a decisive role in determining the magnitude and nature of efficiency losses, as distinct climatic zones impose unique combinations of thermal stress, soiling rates, and meteorological conditions on photovoltaic arrays [2], [21]. For instance, installations in arid desert environments frequently experience substantial energy yield reductions primarily due to high soiling rates and extreme ambient heat, whereas coastal deployments must contend with corrosive salt mist accumulation and persistent humidity that accelerates material degradation [2], [14]. Conversely, systems situated in high-altitude or temperate regions often benefit from increased irradiance levels and lower ambient temperatures, which can enhance voltage output and overall system efficiency, provided that other meteorological factors such as cloud cover and wind patterns remain favorable [2], [22].

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Extreme weather events and shifting climatic patterns further exacerbate these risks, potentially accelerating material degradation rates and necessitating more robust system designs to ensure long-term reliability [2], [24]. Empirical studies indicate that combined environmental stressors can result in performance losses reaching up to 60–70% [23], with specific factors such as dust accumulation capable of reducing output by as much as 60% in desert regions [2]. These substantial losses highlight the critical need for proactive maintenance and environmental adaptation strategies to preserve the economic and operational integrity of photovoltaic installations [2], [23]. Optimizing PV systems for diverse climates and mitigating environmental impacts on productivity is crucial for the continued success of solar photovoltaics [2], [23].

Mitigation Strategies and Optimization Techniques

To counteract the detrimental effects of environmental stressors on photovoltaic performance, a multifaceted approach encompassing proactive maintenance, thermal management, and technological adaptation is essential for maximizing energy yield and ensuring long-term system reliability [2]. Effective cleaning regimes are fundamental to mitigating soiling losses, particularly in arid regions where dust accumulation can severely obstruct incident sunlight and significantly reduce power output [24]. Studies indicate that particulate matter accumulation can degrade efficiency by up to 64%, with specific dust types like coal dust causing the most severe reductions [25], [26]. Consequently, implementing routine cleaning schedules and automated cleaning systems is critical for maintaining optimal transmittance and minimizing the financial impact of soiling-related energy losses [23]. Beyond particulate removal, thermal management strategies are crucial for counteracting the efficiency losses associated with elevated cell temperatures, which can significantly degrade voltage output and accelerate material aging [27]. Active and passive cooling techniques, such as forced air ventilation, water spraying, or the integration of phase change materials, are employed to dissipate excess heat and maintain cell temperatures within optimal ranges for photovoltaic conversion [2], [28]. These thermal regulation mechanisms are particularly vital in high-temperature climates where efficiency penalties are most pronounced, ensuring that the operating temperature remains as close as possible to standard test conditions to maintain the levelized cost of electricity [28], [29].

Panel Design Modifications

Innovations in photovoltaic architecture and material selection play a pivotal role in enhancing resilience against environmental stressors, with advanced encapsulation materials and anti-reflective coatings specifically engineered to minimize optical losses and protect against moisture ingress or UV-induced degradation. Additionally, bifacial cell designs have emerged as a significant advancement, allowing for the capture of reflected light from the rear surface to increase overall energy generation while simultaneously reducing sensitivity to specific angle-of-incidence losses. Solar tracking systems further enhance energy capture by dynamically adjusting the orientation of photovoltaic modules to follow the sun's trajectory throughout the day, thereby maximizing the angle of incidence and increasing total irradiance exposure compared to fixed-tilt installations. These tracking mechanisms are categorized into single-axis systems, which rotate around one axis to follow the sun's east-to-west path, and dual-axis systems, which adjust both azimuth and elevation angles to maintain optimal perpendicularity to the sun's rays throughout the year. While these tracking systems significantly increase energy yield, they introduce additional mechanical complexity and maintenance requirements that must be weighed against the gains in efficiency.

Tracking Systems

Solar tracking systems function by dynamically orienting photovoltaic modules to follow the sun's daily trajectory, thereby maximizing the angle of incidence and increasing total irradiance exposure compared to fixed-tilt installations [30]. These mechanisms are categorized into single-axis systems, which rotate around one axis to follow the sun's east-to-west path, and dual-axis systems, which adjust both azimuth and elevation angles to maintain optimal perpendicularity to the sun's rays throughout the year [30]. Research indicates that the implementation of tracking technologies can significantly enhance energy generation, with the magnitude of improvement dependent on variables such as geographical location, climate conditions, and the specific type of tracking mechanism employed [31]. For instance, a case study in Incheon, South Korea, demonstrated that a tracking photovoltaic system installed on a commercial building generated 26.8% to 35.5% more electricity annually than a fixed system, while also showing promising life-cycle cost savings with a payback period of approximately 8 years [32].

Further empirical evidence from studies in Turkey and Jordan reveals that dual-axis tracking systems can increase power generation by 29.3% to 45.0% on specific days compared to fixed modules [33]. However, the selection between single-axis and dual-axis configurations involves trade-offs between cost-effectiveness and energy yield optimization, as dual-axis systems offer superior performance through precise alignment in both horizontal and vertical planes but entail higher initial costs and increased maintenance complexity due to the additional moving parts [34], [35]. Despite the higher capital outlay, single-axis tracking systems frequently present a more favorable balance between cost and performance for utility-scale applications, offering yield improvements of 15% to over 37.5% relative to fixed-mounted installations depending on the location and solar resource [36]. Floating photovoltaic systems represent another innovative design approach, particularly advantageous in regions where land availability is constrained, as these installations leverage the cooling properties of water bodies to enhance module efficiency while conserving terrestrial space [31].

While these floating systems mitigate land-use conflicts and benefit from evaporative cooling, they must be engineered to withstand unique environmental challenges such as wave action, humidity-induced corrosion, and biofouling, which can potentially offset the efficiency gains if not properly managed through specialized materials and maintenance protocols [35], [37]. Techno-economic assessments further highlight that while dual-axis trackers provide the maximum boost in power generation, they often result in extended payback periods compared to fixed-tilt systems, whereas monthly manual tilt adjustments offer a practical compromise by reducing payback times by approximately 8 months while increasing electricity generation by 3.6% to 5% [36]. Consequently, the selection of an optimal tracking strategy requires a comprehensive evaluation of site-specific meteorological conditions, financial constraints, and long-term maintenance projections to ensure that the chosen technology delivers the most favorable return on investment over the system's operational lifespan [35], [36]. However, the decision to implement tracking systems must also account for potential drawbacks, as the dynamic movement of modules may introduce additional thermal stress on solar cells, particularly when the tracking

mechanism alters the airflow over the module surface or when high irradiance coincides with elevated ambient temperatures [14]. Furthermore, the mechanical complexity inherent in tracking technologies introduces susceptibility to wear and tear, especially in harsh environments where moving parts are prone to degradation and access to skilled technicians for repairs may be limited [38].

Therefore, ongoing research is increasingly focused on developing cost-effective and reliable tracking solutions that optimize the balance between enhanced energy yield and the total cost of ownership, particularly through the design of low-cost dual-axis systems that have demonstrated efficiency improvements of up to 44.89% in experimental settings [39]. Despite these promising experimental results, the widespread adoption of tracking technologies remains contingent upon overcoming challenges related to mechanical reliability, energy consumption for operation, and the economic feasibility of implementation in diverse geographical regions [33], [40]. To address these operational challenges, recent advancements have integrated artificial intelligence and machine learning techniques into tracking system designs, which are critical for enhancing the accuracy and reliability of solar tracking while facilitating predictive maintenance and real-time monitoring to improve overall system performance and reduce operating costs [33]. These intelligent systems utilize sophisticated sensors and predictive algorithms to dynamically adjust panel orientation with high precision, thereby mitigating the efficiency losses associated with suboptimal sun alignment and ensuring that photovoltaic arrays operate at peak

CONCLUSION

The comprehensive analysis of environmental parameters underscores the profound influence that factors such as temperature, irradiance, soiling, and humidity exert on the operational efficiency of solar photovoltaic systems, necessitating a holistic approach to system design and site selection. Future research must prioritize the development of advanced materials and predictive maintenance technologies that can mitigate these environmental stressors, thereby ensuring the long-term reliability and economic viability of solar energy infrastructure in an increasingly variable global climate.

Specifically, the integration of artificial intelligence and machine learning algorithms offers a promising pathway to optimize performance forecasting and operational resilience, as these technologies enable the recognition of complex environmental patterns and facilitate predictive maintenance strategies that reduce long-term costs [42], [43]. By leveraging intelligent algorithms for real-time monitoring and adaptive control, these advanced systems can significantly enhance energy yield while simultaneously addressing scalability concerns and minimizing the environmental footprint associated with operational inefficiencies [23], [44]. Ultimately, the successful deployment of next-generation photovoltaic infrastructure will depend on the synergistic application of smart materials and data-driven analytics to create resilient energy systems capable of withstanding diverse environmental stressors [45], [46]. This synergy is essential for minimizing the levelized cost of electricity and ensuring the sustainability of solar power as a dominant component of the global renewable energy mix [42], [46]. As the demand for clean energy accelerates, addressing the environmental vulnerabilities of photovoltaic technology through continuous innovation and adaptive management strategies remains paramount to securing a sustainable energy future [29], [47]. Policymakers and industry stakeholders must therefore support the implementation of favorable regulatory frameworks and financial incentives, such as tax credits and feed-in tariffs, to accelerate the adoption of these advanced technologies and foster a robust renewable energy ecosystem [14].

Collaborative efforts among researchers, industry executives, and policymakers are considered crucial for addressing the increasing difficulties presented by climate change and ensuring the long-term sustainability, efficiency, and efficacy of solar energy systems in a swiftly changing climate [28]. This comprehensive strategy is essential for ensuring the future of renewable energy amid global environmental challenges [28]. Such collaborative frameworks are vital for translating technological advancements into practical solutions that enhance the resilience and cost-effectiveness of solar infrastructure worldwide [46], [48]. These limitations, which include suboptimal energy conversion efficiency, fluctuating energy supply, and thermal degradation, highlight the necessity for continued innovation in adaptive photovoltaics and smart materials to enhance system robustness and long-term sustainability [46]. By addressing these persistent challenges through interdisciplinary research and strategic investment, the solar energy sector can overcome current barriers to efficiency and

reliability, thereby solidifying its role as a cornerstone of the global transition toward a sustainable energy future [39], [46].

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