

# Environmental Impact on Solar Panel Efficiency

Piyush Bhise, Sahil Singh

G H Raisoni University, Amravati, Maharashtra, India

## Abstract

Long-term environmental and economic development can be supported by solar energy, which has become a very promising and sustainable renewable energy source. However, a number of environmental factors have a substantial impact on the conversion efficiency and operating performance of photovoltaic (PV) systems. This study examines how environmental factors such as temperature fluctuations, dust accumulation, humidity, shade, air pollution, and seasonal variations affect solar panel output characteristics. Because of higher internal resistance and lower open-circuit voltage, elevated temperatures have been shown to impair PV efficiency [1]. Similarly, the deposition of dust and particle matter on the panel surface lowers the effective solar irradiance that reaches the photovoltaic cells by reducing light transmittance and producing partial shading effects [2]. Irradiance intensity is further impacted by humidity and cloud cover, which causes variations in the production of electricity. Prolonged exposure to the environment causes long-term degradation mechanisms, such as material corrosion, optical losses, and decreased electrical stability [3], in addition to short-term performance fluctuations. In order to improve prediction accuracy and operating efficiency, the study highlights how crucial it is to incorporate environmental effect assessment into PV system design and performance modelling. The findings demonstrate that the best tilt angle placement, frequent cleaning, thermal management systems, and ongoing environmental monitoring are essential tactics for increasing system reliability and energy production. This work fosters the development of high-performance, environmentally friendly photovoltaic systems and advances solar energy harvesting technologies. In order to reduce efficiency losses under various climatic situations, this study also highlights the necessity of combining predictive performance modelling with real-time environmental monitoring. The findings demonstrate how better system optimisation and more precise energy yield forecasts are made possible by a thorough understanding of environmental stresses. The operational lifespan and financial feasibility of PV systems can be greatly increased by integrating mitigation techniques with climate-adaptive design methodologies. All things considered; this study fortifies the groundwork for creating robust, highly effective solar energy systems that can produce steady, sustainable electricity in a variety of environmental conditions.

**KEYWORDS:** Photovoltaic (PV) systems, solar energy, solar panel efficiency, environmental impact, temperature effects [4], soiling losses, variations in solar irradiance, shading and mismatch losses, PV system reliability [5], power conversion efficiency, performance degradation, potential-induced degradation (PID), and renewable energy technologies.

## 1. Introduction

Due to the urgent need to prevent climate change, rapid urbanisation, industrial expansion, and population growth, the demand for clean and green energy is rising at a rate never seen before in history [6]. Fossil fuel overuse has had detrimental effects on the ecosystem, including air pollution, global warming, and ecological imbalance. Governments, businesses, and academic institutions are so concentrating on renewable energy technology in order to guarantee low-carbon and sustainable power generation. Of all the renewable resources on the planet, solar energy is thought to be one of the most plentiful and limitless. Photovoltaic (PV) panels use semiconductor materials to directly convert sunlight into power through the photovoltaic effect, providing a clean, quiet, and eco-friendly alternative. Residential rooftops, commercial buildings, and large-scale solar farms have seen a significant increase in PV deployment worldwide due to the falling cost of PV modules, advancements in manufacturing techniques, grid integration technologies, and supportive policies like feed-in tariffs and net metering. PV systems frequently operate differently in outdoor settings than their quoted capacity, despite these benefits and their quick uptake. The ratio of electrical power produced to the total amount of incoming solar radiation received on the module surface is known as solar panel efficiency. Standard Test Conditions (STC) include testing modules at a cell temperature of 25°C, an irradiance of 1000 W/m<sup>2</sup> [7], and a standard spectral distribution. These ideal criteria are rarely matched by actual working conditions, though.

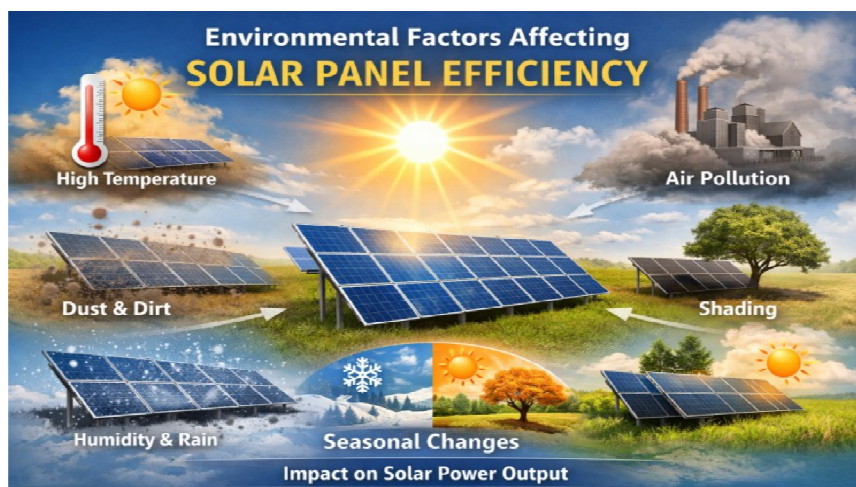
The energy conversion capacity of PV systems is influenced by a number of environmental factors, including temperature, wind speed, variance in solar irradiation, angle of incidence, seasonal variations, humidity, dust deposition, frequency of rainfall, and air pollution. These elements contribute to long-term deterioration mechanisms that shorten system lifespan and reliability in addition to causing transient variations in power output. It is often acknowledged that temperature is one of the most important factors influencing PV performance. A large amount of incident energy is transformed into heat rather than electricity as solar cells absorb sunlight, which raises the module's temperature far above room temperature. A negative temperature coefficient of power results from an increase in intrinsic carrier concentration in semiconductor materials, which lowers the open-circuit voltage at elevated temperatures [8]. Module temperatures in hot climates can rise above 60 to 70°C, which results in considerable efficiency losses during periods of high irradiance. Ageing processes like solder joint failure, encapsulant discolouration, and the spread of microcracks in silicon cells are also accelerated by ongoing heat stress. Thus, better ventilation, heat sinks, phase change materials, or water-based cooling systems are examples of effective thermal management techniques that are necessary to sustain peak

performance. Surface soiling and dust deposition are two more significant environmental issues [9], especially in urban, semi-arid, and dry areas. The accumulation of airborne particles on the glass surface of panels creates a coating that absorbs and disperses incoming solar light, lowering transmittance. The distribution of particle sizes, the module's tilt angle, wind patterns, humidity, and cleaning frequency are some of the variables that affect soiling. Significant drops in energy yield have been seen in extreme situations when panels are left uncleaned for prolonged periods of time. Moreover, dust and moisture can combine to create sticky coatings that are challenging to remove, making maintenance more complicated and raising operating expenses. To reduce these optical losses, the creation of hydrophobic and self-cleaning coatings has shown promise. The performance and longevity of PV modules are also impacted by humidity, precipitation, and moisture intrusion. Because of the thin water layers on the surface, high relative humidity can lead to light reflection losses and encourage corrosion of the busbars and metallic connections inside the module structure. Delamination, insulation failure, and potential-induced degradation (PID) can result from moisture seeping into encapsulation layers, especially in high-voltage systems.

The electrical properties of various PV technologies are also impacted by cloud cover, which lowers direct solar irradiance and modifies the spectrum of sunlight. Particularly in heavily populated industrial locations, air pollution and atmospheric particles scatter and absorb radiation before it reaches the module surface, reducing solar transmittance. Mismatch losses are introduced in series-connected cells when there is partial shadowing from surrounding trees, buildings, utility poles, or passing clouds. Even a tiny area of shade can restrict the string's overall current flow, resulting in disproportionate energy loss and the development of hotspots [10], which are localised heating areas. Such localised heat stress can shorten the lifespan of a module and cause irreversible cell damage over time. Bypass diodes, microinverters, and module-level power electronics are examples of advanced technologies that have been introduced to improve energy harvesting under non-uniform irradiation situations and reduce shading effects. Environmental stressors cause PV modules to gradually deteriorate over the course of their 20–25 year service life, in addition to the initial efficiency losses. Structural and electrical damage can result from a number of factors, including exposure to UV radiation, heat cycling

between day and night, mechanical loads from wind and snow, and chemical reactions brought on by contaminants. Therefore, real-time monitoring systems and performance ratio analysis are crucial for identifying irregularities and guaranteeing optimal system performance.

It is essential to perform thorough evaluations of PV system performance under various climatic circumstances due to the combined and interconnected influence of these environmental elements. Reliable long-term energy yield forecasts, enhanced maintenance planning, optimised tilt and orientation design, and better site selection are all made possible by accurate modelling of environmental implications. Thus, the purpose of this study is to comprehensively examine the environmental factors that influence the efficiency of solar panels, assess the immediate and long-term impacts on performance, and provide practical mitigation techniques to reduce efficiency deterioration. The study helps to maximise the potential of solar energy systems and supports the global shift toward sustainable and low-carbon energy infrastructure by improving operational reliability, durability, and economic feasibility. In conclusion, closing the gap between laboratory-rated performance and actual energy generation requires an understanding of how the environment affects solar panel efficiency. The long-term performance and dependability of photovoltaic systems depend on how well environmental stressors like temperature rise, dust deposition, humidity, air pollution, and shade are handled because these systems work in constantly shifting climatic conditions. More precise performance forecasting, enhanced system architecture, and better maintenance plans are made possible by a thorough assessment of these interrelated variables. In order to address the effects of the environment on photovoltaic performance, standardisation frameworks and governmental support are just as important as technology advancements. PV modules are better adapted to local climatic circumstances because of the creation of climate-specific installation guidelines, performance testing standards, and durability certificates. By offering incentives for high-efficiency modules, cutting-edge monitoring systems, and environmentally friendly maintenance procedures, governments and regulatory agencies can promote the use of resilient solar technologies. The long-term efficiency of solar energy systems can be greatly increased by such concerted efforts by legislators, researchers, and industry players.



**Fig.1 Impact of the Environment on the Production of Photovoltaic Energy**

## 2. Literature Review

The rapid global deployment of solar energy systems based on Photovoltaic (PV) systems has led to extensive research on their real-world performance, revealing that field efficiency is often significantly lower than laboratory-rated values due to environmental stresses. Laboratory measurements are typically conducted under Standard Test Conditions (STC), which assume a cell temperature of 25°C, irradiance of 1000 W/m<sup>2</sup>, and controlled spectral conditions; however, outdoor installations are continuously exposed to dynamic climatic variations. Among these, temperature has been identified as one of the most critical factors influencing PV performance. Numerous studies report that PV module efficiency decreases as operating temperature rises, primarily due to the negative temperature coefficient of voltage. For crystalline silicon modules, power output typically declines by approximately 0.4–0.5% per °C increase above 25°C [11]. Elevated temperatures reduce the open-circuit voltage (Voc) and slightly increase the short-circuit current (Isc), but the net effect is a decline in maximum power output (Pmax). Prolonged thermal stress also accelerates encapsulant browning, solder bond fatigue, and material degradation, thereby shortening module lifespan.

Dust deposition and soiling are widely recognized as major contributors to performance degradation, particularly in arid and semi-arid regions. Accumulated dust particles scatter and absorb incident solar radiation, thereby reducing effective irradiance reaching the cell surface. Empirical studies indicate that energy losses due to soiling can range from 5% to over 30% under moderate conditions and may exceed 50–60% in extreme cases without regular cleaning [12]. The severity of soiling losses depends on particle size distribution, tilt angle, wind patterns, and local environmental conditions. Furthermore, early-stage performance losses have been observed even in newly installed panels operating under suboptimal environmental exposure. Humidity and moisture also play a significant role in determining PV system reliability and efficiency. High relative humidity can form a thin water film over the module surface, leading to reflection and refraction losses that reduce effective solar irradiance. In addition, moisture ingress into the module structure can promote corrosion of metallic contacts, delamination, and potential-induced degradation (PID) [13], especially under high system voltage conditions. Several studies highlight that the combined effect of humidity and dust results in adhesive soiling layers that are difficult to remove, thereby increasing maintenance frequency and operational costs. Over time, persistent moisture exposure contributes to insulation degradation and long-term reliability issues. Shading and partial obstruction represent another critical environmental constraint affecting PV output.

Even minimal shading from nearby trees, buildings, utility poles, or other structures can cause disproportionate power losses due to the series connection of solar cells within a module. Shaded cells limit the current of the entire string, potentially leading to hotspot formation and thermal stress. Research demonstrates that partial shading not only reduces instantaneous energy generation but may also induce localized overheating, thereby accelerating material degradation. This issue is particularly significant in densely populated urban environments where variable shading patterns occur throughout the day. Air pollution and atmospheric particulate matter further compound environmental losses in PV systems. Pollutants such as PM2.5, industrial emissions, and vehicular exhaust reduce solar transmittance by scattering and absorbing sunlight before it reaches the panel surface. In heavily polluted urban regions, studies have reported measurable reductions in annual energy yield directly correlated with increased aerosol concentration. Additionally, pollutant deposition forms surface films that enhance soiling effects and reduce optical transparency. Collectively, the literature indicates that PV performance degradation in real-world environments results from the combined and interrelated effects of temperature rise, dust accumulation, humidity exposure, shading, and air pollution rather than isolated parameters. Modules installed in hot, dusty, humid, or polluted climates consistently demonstrate lower energy yield compared to their rated capacity under controlled conditions. Moreover, prolonged exposure to these environmental stresses accelerates physical and electrical degradation mechanisms, ultimately impacting system reliability, economic returns, and long-term sustainability. Therefore, understanding the synergistic impact of environmental factors is essential for accurate performance prediction, effective maintenance planning, and the development of mitigation strategies aimed at optimizing solar energy generation under diverse climatic conditions.

## 3. Research Methodology

This study uses a combination of experimental and analytical research methods to investigate how environmental factors affect solar panel efficiency. To guarantee maximum annual solar exposure, a photovoltaic (PV) module with a known rated capacity was put at a fixed tilt angle that was optimised based on the research location's geographic latitude. Major environmental factors include ambient and module temperature, solar irradiance, dust accumulation (soiling), humidity, partial shade, air pollution levels, and seasonal fluctuations are the main focus of the experimental inquiry. These factors were chosen because they have a direct impact on the photovoltaic systems' electrical properties, energy yield, rate of deterioration, and long-term operational dependability.

A PV panel was connected to electrical measurement devices, such as a data logger for continuous voltage and current recording and a calibrated digital multi-meter, as part of the experimental setup. Temperature sensors based on thermocouples were used to detect the ambient and module surface temperatures, and a pyranometer was used to record incident solar energy in W/m<sup>2</sup>. A humidity sensor placed close to the panel installation location was used to measure the relative humidity levels. Open-circuit voltage (Voc), short-circuit current (Isc), maximum power voltage (Vmp), maximum power current (Imp), and load conditions were among the electrical performance metrics that were measured at predetermined intervals during the day. Accurate computation of the instantaneous output power and performance fluctuation under varying environmental circumstances was made possible by these data. Readings were taken at various periods of the day when natural temperature swings occurred in order to assess the impacts of temperature. To measure thermal losses and calculate the temperature coefficient of power, the relationship between the voltage output and the module surface temperature was examined.

To replicate actual environmental conditions, a regulated amount of fine dust was evenly applied to the panel surface for the soiling analysis. To ascertain the efficiency loss resulting from optical losses, performance under filthy conditions was

contrasted with that of a clean reference panel functioning under comparable irradiance. Sections of the module were partially covered to imitate blockage from surrounding objects in order to study shading effects, and reductions in string current and overall power output were used to analyse mismatch losses. While seasonal performance variations were evaluated by gathering and comparing data across many months to measure climatic influence on annual energy yield, the effects of humidity and cloud cover were investigated by comparing system output on clear, partially cloudy, and overcast days. The traditional formula  $\eta = (P_{out} / P_{in}) \times 100$  was used to determine the solar panel's efficiency. In this calculation,  $P_{out}$  stands for electrical output power (Voltage  $\times$  Current) and  $P_{in}$  for input solar power (Solar Irradiance  $\times$  Effective Panel Area). For comparative analysis, percentage power loss under various environmental stress scenarios was calculated in addition to instantaneous efficiency.

In order to give a more thorough evaluation of the effectiveness of real-world systems, the performance ratio (PR) and capacity utilisation factor (CUF) were also taken into consideration [14]. Comparative performance evaluation, statistical correlation methods, and graphical representation were used to analyse the gathered data. To determine operational trends, graphs were created showing the relationship between temperature and voltage, irradiance and output power, dust level and efficiency reduction, and humidity and power variance. To ascertain the degree of association between output characteristics and ambient variables, correlation coefficients were computed. Predictive models for evaluating performance under various climatic circumstances were developed using regression analysis. Key performance metrics included seasonal yield variations, power degradation percentage, efficiency fluctuation, and voltage loss from thermal stress. In order to increase the dependability of experimental outcomes, measurement error estimation and uncertainty analysis were also included. Prior to data collection, sensors were calibrated to guarantee accuracy, and repeated tests were carried out to confirm consistency. By tracking performance deterioration trends over prolonged exposure periods, the study also takes the long-term degradation rate into account. Based on the analytical results, suggestions are made for things like real-time monitoring systems, periodic cleaning schedules, thermal management strategies, and optimal tilt angle adjustment.

To ensure comparability with recognised photovoltaic performance evaluation processes [15], standardised testing methodologies were adhered to in addition to the aforementioned procedures. In order to reduce external electrical disturbances, measurements were conducted under stable load circumstances. Accurate temporal correlation was ensured by synchronising ambient data with electrical output values. For the purpose of assessing variations brought on by environmental stressors, a control dataset with almost ideal conditions was created. The accuracy of estimating efficiency loss under various operating conditions was increased by this baseline comparison. Additionally, to improve analytical accuracy, data preparation methods such irradiance value normalisation, repeated measurement averaging, and outlier filtering were used. While seasonal data aggregation allowed evaluation of long-term climate trends, time-series analysis was used to track daily performance cycles and pinpoint peak generation periods. By examining the progressive decreases in maximum power output over time, the degradation rate was calculated [16], offering information on maintenance needs and reliability performance. Lastly, the methodological framework was created to be flexible and expandable for various installation capacities and climate zones. A thorough grasp of how environmental stressors affect solar efficiency is ensured by the systematic fusion of controlled testing, ongoing environmental monitoring, and statistical modelling.

All things considered, this thorough methodological approach guarantees that the study catches both short-term performance changes and long-term deterioration behaviour of solar systems under actual environmental conditions. This study provides a solid cause-and-effect link between solar panel efficiency and climatic stresses by combining controlled experimental procedures with ongoing environmental monitoring and sophisticated statistical modelling. Regression modelling, uncertainty analysis, baseline comparisons, and time-series evaluation all work together to improve the findings' validity and reproducibility. The research's scientific accuracy is reinforced by this methodical methodology, which also offers useful advice for enhancing the design of solar systems, site selection, maintenance scheduling, and operational optimisation. As a result, the approach provides a flexible and scalable basis for further studies that aim to improve the sustainability and dependability of solar energy systems' performance in a variety of environmental settings.

Along with the aforementioned steps, the approach was created to guarantee that the results could be replicated, scaled up, and used practically in a variety of climatic conditions. To determine the primary loss drivers under particular circumstances, sensitivity analysis was used to assess the relative contributions of each environmental parameter to total efficiency change. Long-term energy yield estimation forecasting accuracy is increased by the integrated experimental-analytical framework, which also makes it easier to validate predicted performance models against measured field data. The study creates a thorough and reliable basis for evaluating environmental effects on solar panel efficiency by integrating controlled experimentation, standardised measuring procedures, environmental monitoring, and statistical validation methodologies.

All things considered, the methodological framework used in this study guarantees a thorough and methodical evaluation of how environmental elements affect solar panel efficiency under actual working settings. Accurate measurement of short-term performance changes and long-term degradation trends is made possible by the approach's integration of controlled experimentation, precision instrumentation, ongoing environmental monitoring, and sophisticated statistical analysis.

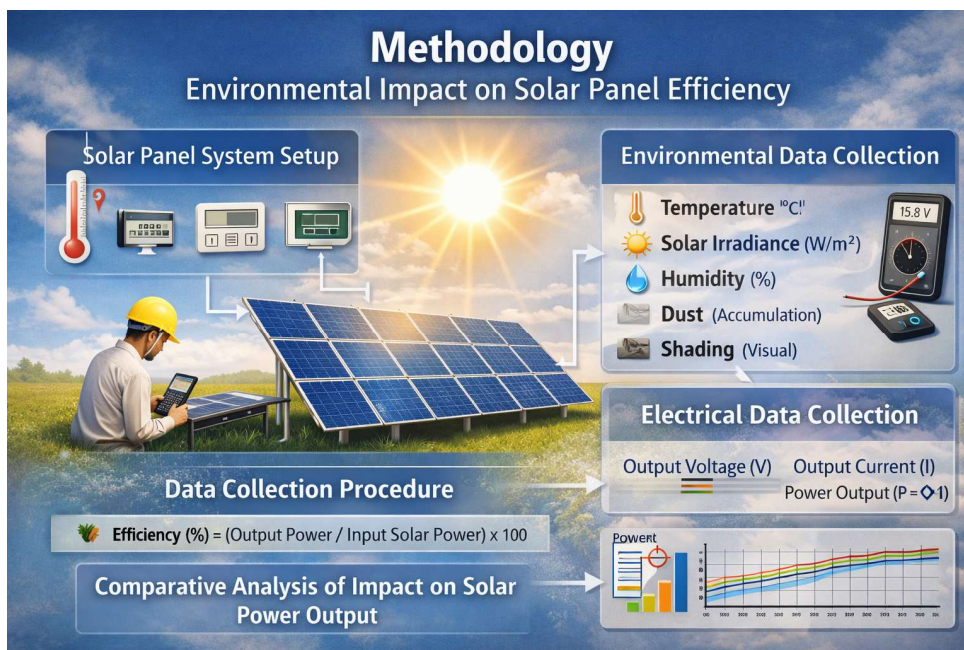


Fig.2 Experimental Design for Assessing Environmental Effects on Solar Panels

4. Result

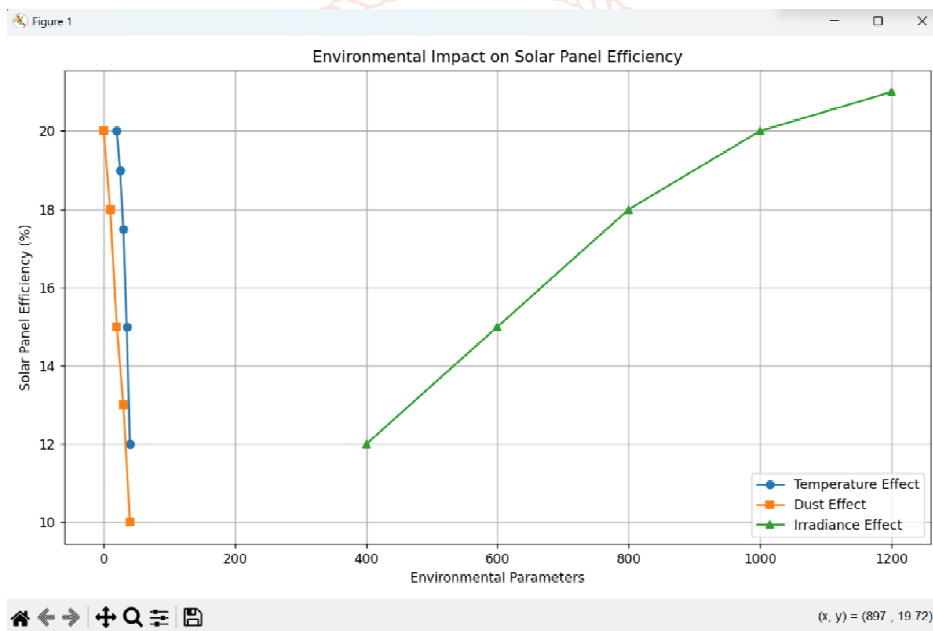


Fig.3 Environmental Parameter vs Solar Panel Efficiency Graph

5. Conclusion

The effects of several important environmental factors on solar panel efficiency were methodically examined in this study. These factors included temperature, dust deposition, sun irradiance, humidity, and shadowing. Because higher irradiance increases photocurrent generation and overall energy yield, the experimental and graphical results show that solar irradiance and photovoltaic (PV) output power are directly proportional. On the other hand, high temperatures have a detrimental effect on panel efficiency because they lower open-circuit voltage (Voc) and increase internal resistive losses, which lower conversion efficiency [17]. By creating a physical barrier on the panel surface, dust deposition was shown to drastically limit effective irradiance, which in turn decreased short-circuit current (Isc) and total power output [18]. Furthermore, optical losses and long-term degradation processes like corrosion

and potential-induced deterioration (PID) are exacerbated by humidity and air pollution. In addition to causing mismatch losses within PV modules, shading effects also result in disproportionate output power reductions. The results show that environmental factors need to be carefully taken into account while designing, installing, and maintaining systems. The mitigation of environmental losses can be achieved by the implementation of heat management systems, anti-soiling coatings, periodic cleaning schedules, and optimised site selection. Consequently, the incorporation of environmental effect evaluation into PV system modelling improves energy yield optimisation, long-term system reliability, and the accuracy of performance forecast. Moreover, this study's results highlight the fact that environmental factors interact in intricate and cumulative ways rather than acting alone. Dust collection and humidity, for example, can hasten corrosion and surface deterioration,

while high temperatures and intense sun radiation can exacerbate heat losses. Seasonal variations also affect ambient temperature, atmospheric conditions, and irradiance levels at the same time, resulting in performance variations all year long. For the purpose of precisely forecasting the behaviour of photovoltaic (PV) systems in the real world under various climatic circumstances, integrated environmental modelling methodologies are therefore crucial.

Furthermore, over the course of PV modules' operational lifespan, cumulative performance loss is largely caused by prolonged exposure to environmental stresses [19]. Microcracks, delamination, encapsulant discolouration, and electrical insulation failures can be brought on by mechanical loads, UV rays, moisture intrusion, and repeated temperature cycling. Over time, these degradation processes lower the dependability and efficiency of the module. To find early indications of deterioration and stop significant energy losses, it is consequently essential to conduct continuous monitoring utilising performance ratio analysis, environmental sensors, and predictive maintenance techniques. The report also emphasises how crucial technology innovation is to reducing negative environmental effects. Heat, dust, and shade-related efficiency losses can be considerably decreased with the adoption of advanced technologies such module-level power electronics, hydrophobic and self-cleaning coatings, better cooling methods, and superior encapsulation materials. Furthermore, by adjusting system operation to shifting environmental circumstances, intelligent monitoring systems that are combined with data analytics and artificial intelligence can maximise energy output. These advances improve economic viability as well as operational performance. From a wider angle, planning PV systems with environmental effect assessment in mind promotes the development of sustainable energy. Maximising annual energy yield and prolonging system lifespan can be achieved by site-specific climatic studies, optimised tilt and orientation design, and planned maintenance scheduling. These methods not only increase return on investment but also bolster solar energy's contribution to national and international renewable energy goals.

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