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SOLAR POWER: ANALYZING CLIMATE CHANGE IMPACTS AND ENVIRONMENTAL FACTORS ON PHOTOVOLTAIC SYSTEM PERFORMANCE

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ABSTRACT

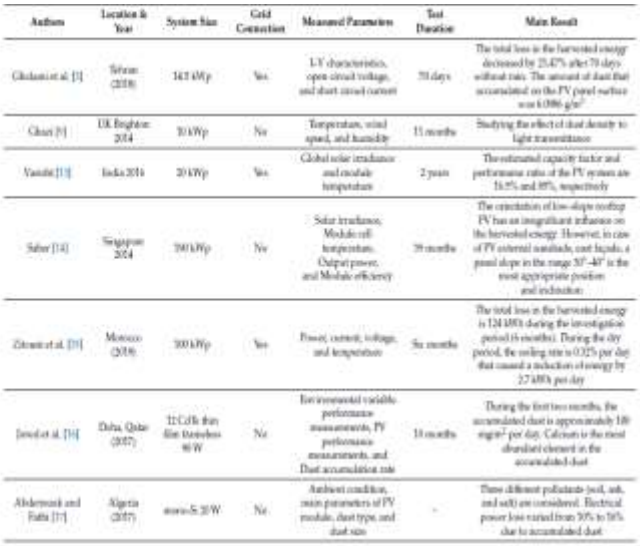
Solar power stands as a pivotal renewable energy source, increasingly vital in the global shift toward low-carbon energy portfolios. The precise understanding of climate conditions is imperative for optimizing solar energy production, regulation, and planning, with climate change effects playing a central role in energy output projections. This study delves into the impact of projected changes in irradiance and temperature on photovoltaic (PV) system performance in Greece. Utilizing data from five regional climate models (RCMs) under the A1B emissions scenario for future periods, the study identifies systematic errors in RCM data, necessitating bias adjustments. By estimating the projected change in PV energy output considering temperature and insolation variations, the analysis reveals a significant increase in mean annual temperature (up to 3.5°C) and mean total radiation (up to 5W/m2) by 2100. Although the performance of PV systems shows a negative linear dependence on projected temperature increases, it is outweighed by the expected rise in total radiation, resulting in up to a 4% increase in energy output. Furthermore, the study investigates the recent applications of solar PV installations in arid climates, highlighting the impact of environmental factors such as weather and dust on PV module performance. By presenting up-to-date experimental results and analyzing the effects of these parameters, the study underscores the critical importance of considering environmental conditions when implementing PV installations in such regions. Additionally, the study evaluates the impact of various environmental factors, including dust accumulation, water droplets, birds' droppings, and partial shading conditions, on PV system performance. Findings reveal that shading exerts the most significant influence on PV module efficiency, with even partial shading resulting in substantial power reductions. Conversely, the impact of water droplets on PV panels leads to improved power output due to decreased panel temperature. Dust accumulation and bird fouling, on the other hand, significantly diminish power output and overall efficiency, underscoring the importance of mitigating these environmental factors for optimal PV system performance.

INDEX TERMS- *Solar power, photovoltaic systems, climate change, irradiance, temperature, regional climate models, bias adjustment, energy output projections, environmental factors, dust accumulation, water droplets, birds' droppings, partial shading, energy efficiency.*

I.INTRODUCTION

The global shift towards renewable energy sources, driven by the diminishing availability of fossil fuels, has propelled the significance of electrical energy. Among renewable energy options, the photovoltaic (PV) industry has experienced rapid growth, with PV systems poised to contribute significantly to global electricity production. By 2018, an additional 100 gigawatts (GW) of PV capacity was installed worldwide, bringing the total installed capacity to 505 GW. Notably, China alone added approximately 45 GW of capacity, reaching a total of 176 GW.

While silicon crystalline PV modules remain prevalent, newer technologies offering lower manufacturing costs, such as amorphous silicon, copper indium selenide (CIS), and cadmium telluride, have emerged. To accommodate these advancements, new standards and testing schemes compatible with these technologies are being developed. With the declining cost of PV systems, they have become increasingly competitive with conventional electricity prices, particularly in regions with high solar irradiation like the solar belt regions.



Authors	Location & Year	System Size	Grid Connection	Measured Parameters	Test Duration	Main Result
Gholami et al. [1]	Tehran (2018)	143 kWp	Yes	I-V characteristics, open circuit voltage, and short circuit current	70 days	The total loss in the harvested energy decreased by 21.47% after 70 days without rain. The amount of dust that accumulated on the PV panel surface was 6.0986 g/m²
Ghazi [9]	UK Brighton 2014	10 kWp	No	Temperature, wind speed, and humidity	11 months	Studying the effect of dust density to light transmittance
Vasisht [13]	India 2016	20 kWp	Yes	Global solar irradiance and module temperature	2 years	The estimated capacity factor and performance ratio of the PV system are 16.5% and 85%, respectively
Saber [14]	Singapore 2014	700 kWp	No	Solar irradiance, Module cell temperature, Output power, and Module efficiency	29 months	The orientation of low-slope rooftop PV has an insignificant influence on the harvested energy. However, in case of PV external sunshade, east façade, a panel slope in the range 30°–40° is the most appropriate position and inclination
Zitouni et al. [15]	Morocco (2019)	300 kWp	Yes	Power, current, voltage, and temperature	Six months	The total loss in the harvested energy is 124 kWh during the investigation period (6 months). During the dry period, the soiling rate is 0.32% per day that caused a reduction of energy by 2.7 kWh per day
Javed et al. [16]	Doha, Qatar (2017)	12 CdTe thin film frameless 90 W	No	Environmental variable performance measurements, PV performance measurements, and Dust accumulation rate	11 months	During the first two months, the accumulated dust is approximately 10 mg/m² per day. Calcium is the most abundant element in the accumulated dust
Abderrezek and Fathi [17]	Algeria (2017)	mono-Si 20 W	No	Ambient condition, main parameters of PV module, dust type, and dust size	-	Three different pollutants (soil, ash, and salt) are considered. Electrical power loss varied from 50% to 58% due to accumulated dust

The performance of PV systems hinges on various factors, including sun position, solar irradiance intensity, temperature, and load demand. Evaluating the dynamic response of PV systems is essential for their integration into utility grids, as interconnecting them may lead to grid instability. Despite progress, uncertainty persists in PV performance modeling, with existing research primarily focusing on module performance rather than system performance.

Dust accumulation on PV systems has garnered significant attention due to its adverse effects on performance. Studies have shown that the rate of dust accumulation varies depending on weather conditions, with substantial differences observed across different locations. For instance, in Colorado, dust deposition rates range from 1 to 50 mg/m^2/day, while in Egypt, rates range from 150 to 300 mg/m^2/day. Experimental studies have demonstrated that prolonged dust exposure can lead to significant reductions in power output, with one study reporting a 21.47% decrease after 70 days without rain.

Various environmental parameters, including temperature, humidity, and airborne pollutants, can impact PV performance. For example, high temperatures decrease PV efficiency, while wind can help cool PV panels, thereby improving their performance. Additionally, soiling from dust and sand deposition can obstruct sunlight, reducing PV efficiency. Mitigation strategies such as mechanical cleaning or water-based solutions have been explored to address this issue. Overall, understanding and mitigating environmental factors are crucial for optimizing PV system performance and promoting sustainable energy production.

II. LITERATURE REVIEW

The literature review encompasses numerous studies evaluating the performance of photovoltaic (PV) systems in various geographical locations and climates. Singh (2013) highlights the importance of factors such as orientation, type, and geographical location in determining PV system performance. Nguyen and Lehman (2006) demonstrate the utility of theoretical and simulation models in assessing power losses in solar cells under different irradiance conditions.

The review focuses on studies conducted in arid or semi-arid regions across the globe, including the Middle East, North America, Australia, Africa, Asia, South America, and even Antarctica and the Arctic. These studies aim to analyze, assess, and evaluate the performance of PV modules in such environments.

In the Middle East, studies conducted in Saudi Arabia, Israel, Yemen, the United Arab Emirates, Iran, Oman, Egypt, Jordan, and Kuwait highlight the impact of high temperatures on PV output, as well as the potential for PV systems to reduce CO2 emissions and provide economically competitive energy solutions for desert communities.

In North America, research in Arizona, USA, and Nevada evaluates the performance of PV systems under arid conditions, emphasizing differences in power degradation between various PV technologies.

Australia-based studies explore the financial and environmental aspects of PV panels, forecasting their performance under future climate changes and analyzing their role in providing renewable energy. Additionally, studies in Western Australia address challenges faced by PV systems in arid remote areas.

African studies in Nigeria, Tunisia, Algeria, Kenya, and Djibouti assess the feasibility and impact of PV grid-connected systems, hybrid energy systems, and remote PV installations under semi-arid conditions.

Research in Asia, particularly in Pakistan, China, and the Gobi Desert, evaluates the potential and competitiveness of solar PV technologies in desert areas.

South American studies in Chile examine the performance of PV technologies in desert climates, highlighting differences between multi-Si and thin-film modules under varying temperature and dust conditions.

European research in Cyprus focuses on testing different PV panels and technologies, while studies in Antarctica and the Arctic assess the feasibility and potential of PV systems in remote and extreme environments.

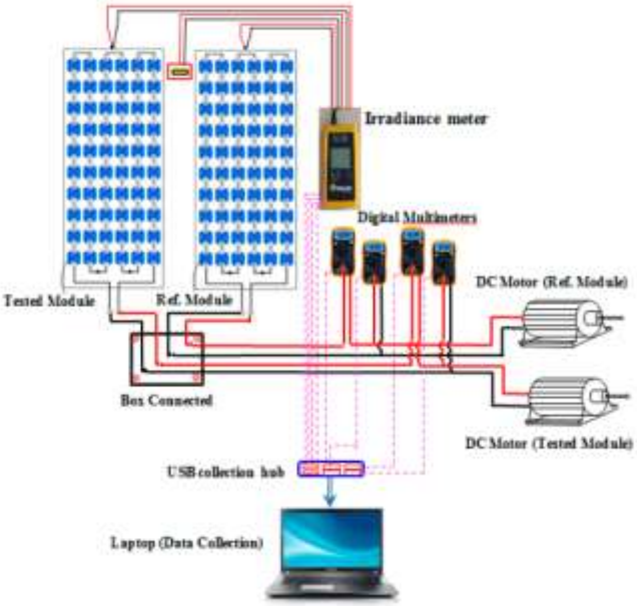
Various methods for enhancing PV system performance are discussed, including predictive modeling based on cloud fractions, monitoring systems to manage dust and weather conditions, cooling systems to improve efficiency, sun-tracking systems, and applications of PV technology in irrigation, desalination, refrigeration, and anti-soiling coatings.

Overall, the literature review provides insights into the performance, challenges, and potential solutions for deploying PV systems in arid and semi-arid regions worldwide.

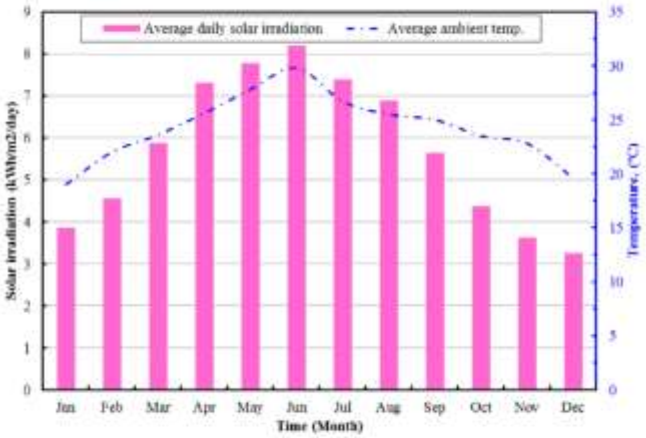
III.METHODOLOGY

PV Module and Load Profile

The experimental setup was positioned on the roof of the Faculty of Engineering at Mutah University. It consisted of two PV modules (Figure 1), each connected to a similar direct current (DC) motor. The characteristics of the photovoltaic modules used in the experiment are detailed in Table 3. While no tracking system was employed, the impact of ambient temperature was considered. The array slope angle was set at 31 degrees, and the array azimuth was directed towards sustainability.



The experimental setup included digital multi-meters for measuring electrical parameters (current and voltage). The specifications of the multi-meters are provided in Table A1 in Appendix A. Short circuit current (Isc) and load current (Iload) were monitored using a multi-meter with an accuracy of ±2% of a 20 A reading, while open circuit voltage (Voc) and load voltage (Vload) were monitored using a multi-meter with an accuracy of ±0.5% of a 200 V reading.



The load profile was simulated by a DC motor, converting electrical energy into mechanical energy. An irradiance meter device, positioned alongside the modules and under the same inclination, measured effective irradiance and ambient temperature. Effective irradiance accounts for global solar irradiance and albedo/reflection fraction from the roofing system. Specifications of the solar irradiance meter are detailed in Table A2 in Appendix A. An infrared thermometer was used to measure PV panel surface temperature, with electronic components providing a temperature reading displayed on the screen, accurate to ±2°C or 2%. Wind velocity and ambient temperature were measured by a thermo anemometer, accurate to 3% (±0.2 m/s).

(a) Reference case (b) Dust module (c) Module with water droplets

(d) Partial shading (e) Birds droppings

Solar Radiation

In the Jordanian southern province of Al Karak, the annual average global solar irradiation is approximately 5.9 kWh/m2/day, with 2600–3500 sunshine hours per year. The site under investigation is situated at 31°9'49.25" N latitude and 35°45'43.34" E longitude. Figure 2 illustrates the solar irradiance per year at the study site, with average solar irradiance ranging from 3.36 kW/m2/day in December to 7.89 kWh/m2/day in June, resulting in a scaled annual average of 5.16 kW/m2/day. The annual average ambient temperature and clearness index were recorded as 24.5°C and 0.57, respectively.

Experimental Procedure

3.The research was conducted from November to February, with data collected over sequential days. Data collection during this period was challenging due to winter conditions, including rainfall and overcast skies. Two Polycrystalline PV modules were utilized, with one serving as a reference PV (RPV) and the other as a tested PV (TPV). The TPV module's surface was subjected to environmentally induced factors such as dust accumulation, water drops, partial shading, and bird droppings. The change in PV power output due to environmental effects was calculated based on measured electrical parameters. Measurements of temperatures, wind speed, humidity, and irradiance were recorded. Real pictures of the system under various environmental conditions are depicted.

PV System Parameters

3.1. Definition of Numerical Performance Parameters

Standard testing conditions (STC) for solar PV modules are defined as a temperature of 25°C and a direct irradiance of 1000 W/m². These conditions serve as the industry benchmark for solar PV modules. However, since STC typically occur indoors, they do not accurately represent PV behavior under realistic outdoor conditions. In this section, we will outline a set of parameters for comparison: energy yield (Yf), outdoor efficiency (η), performance ratio (PR), and capacity factor (CF). Additionally, we will discuss the influence of environmental parameters.

3.1.1. Energy Yield

Energy yield (Yf) is defined as the energy produced by a PV system during a specific period (Edc, kWh) divided by the DC power provided by the manufacturer (P, kWp): $Yf=PEdc$

For a given test period (e.g., one month or one year), Yf represents the theoretical number of hours required under STC to produce the same amount of energy with the same module.

3.1.2. Efficiency

Outdoor efficiency (η) is a dimensionless parameter defined as: $\eta=A\cdot HdcE$

where H is the total irradiance reaching the collector (kWh/m²) and A is the area of the collector (m²).

3.1.3. Performance Ratio

The performance ratio (PR) is the ratio of the actual energy produced (Edc) to the theoretical energy output under standard conditions (ESTC), both measured in kWh: $PR=ESTCEdc$

3.1.4. Capacity Factor

The capacity factor (CF) is the ratio of the actual energy produced (Edc) to the theoretical energy output (P) if the installation were continuously producing at maximum power output, over a given time period (t): $CF=P\cdot tEdc$

3.2. Influence of Environmental Parameters

3.2.1. Solar Irradiance Effects

Global solar radiation is typically higher in arid or semi-arid climates due to less dense cloud cover. This results in lower variability of solar radiation and more predictable power output. Higher solar radiation increases the potential for electricity production.

3.2.2. Spectral Effects

The spectral distribution of light reaching the ground can vary based on atmospheric composition. Factors such as gases, humidity, particles, and atmospheric pressure influence spectral distribution. Variations in spectral irradiance can impact the competitiveness of different PV technologies.

3.2.3. Effect of Dust

Dust accumulation on PV panels, known as soiling, obstructs solar light and reduces system efficiency. Soiling losses can range from 15 to 30% in dusty and dry areas. Cleaning methods such as surface treatments or regular washing can mitigate these losses.

3.2.4. PV Degradation

Long-term reliability of PV modules is affected by various factors including climatic conditions, humidity, temperature, and ultraviolet spectrum. Degradation rates can range from 1.7% to 2.34% per year depending on technology and environmental conditions. Careful monitoring and assessment are necessary to manage degradation effects in arid climates.

Bias Correction

To correct for biases in mean and standard deviation of temperature and irradiance outputs from Regional Climate Models (RCMs), a methodology similar to that presented in Haerter et al. [14] was employed. The bias in mean is adjusted by subtracting the differences between observed and modeled values, and then the model data is corrected to match the variability of historical data. This correction process ensures that the sequence of anomalies is scaled consistently with observed historical variability. The linear transfer function used when data follow a normal distribution is expressed as follows:

corsc=(scmod−conmod)×(conobsconmod)+conobsχcorsc =(χscmod−χconmod)×(σconmodσconobs)+χconobs

where corscχcorsc is the final adjusted time series, scmodχscmod is the raw model predictions for the scenario period, conobsχconobs and conmodχconmod are the mean of observed and modeled data for the control period, respectively, and conobsσconobs and conmodσconmod are the standard deviations of observed and modeled data for the control period, respectively. This correction ensures that the final adjusted model time series maintains the appropriate baseline mean and standard deviation with respect to the observed data.

Estimation of PV Energy Output under Variable Conditions of Temperature and Irradiance

To estimate the potential percentage change in photovoltaic (PV) output, the fractional change ΔPV/PVΔ*P*PV/*P*PV is calculated based on equations (2) and (3) from Crook et al. [10]:

ΔPV/ref=−Δtotc2+Δtot(1−c1+Tref−2c3−c2)−Δtotc3−ΔtotΔc2+Δtotlog10(tot+Δtot)+totlog10(tot+Δtottot)Δ*P*PV/*η*ref =−Δ*TG*tot*β*c2+Δ*G*tot(1−*β*c1+*β*Tref−2*β*c3−*Tβ*c2)−Δ*G*tot*β*c3 −Δ*G*totΔ*Tβ*c2+Δ*G*tot*γ*log10(*G*tot+Δ*G*tot)+*G*tot*γ*log10(*G*tot*G*tot +Δ*G*tot)

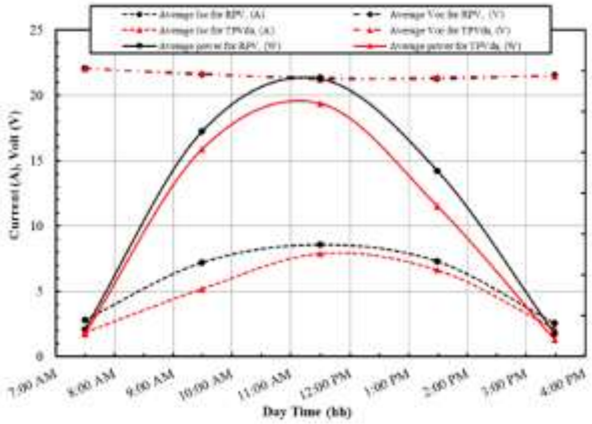
PV/ref=tot(1−(c1+c2+c3tot−ref)+log10(tot))*P*PV/*η*ref=*G*tot (1−*β*(*β*c1+*β*c2*T*+*β*c3*G*tot−*T*ref)+*γ*log10(*G*tot))

where ΔPVΔ*P*PV is the change in PV power output, ref*η*ref is the reference PV efficiency, ΔΔ*T* is the change in temperature between the baseline and scenario period, ΔΔ*G* is the change in irradiance between the baseline and scenario period, *T* is the daytime temperature for the baseline period, tot *G*tot is the irradiance over daylight for the actual cloud cover for the baseline period, ref*T*ref is the reference temperature for which the PV cell performance is estimated by the manufacturer,*β* is the temperature coefficient, *γ* is the irradiance coefficient, and c1*β*c1, c2*β*c2, and c3*β*c3 are coefficients dependent on module and mounting details affecting heat transfer from the cell. The daytime temperature *T* for the baseline period is estimated based on the diurnal range of temperature (*DTR*) and the monthly average temperature, while tot*G*tot is calculated from the monthly average irradiance and the time of daylight for all latitudes of the study site.

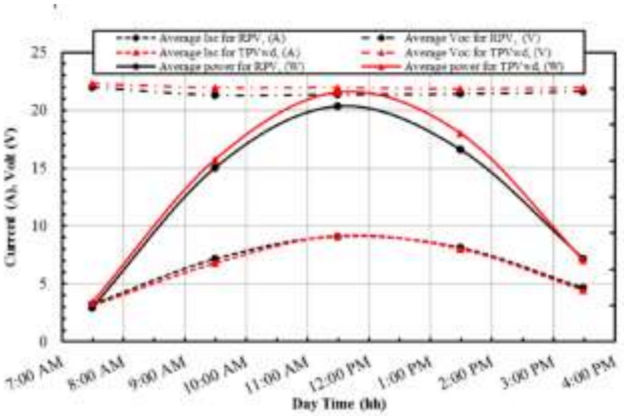
RESULTS

Dust Accumulation

Two polycrystalline PV modules underwent outdoor testing over several weeks, with daily monitoring of power output at two-hour intervals. One module (RPV) was cleaned before data collection, while the other (TPV) was exposed to dust accumulation conditions.



The daily power output, short-circuit current, and open-circuit voltage for each module are depicted in Figure 4. Dust accumulation on the TPV module obstructed solar irradiance, impacting its current and power output. Consequently, RPV exhibited higher power output compared to the dust-affected TPV.



The reduction in power and efficiency of PV modules can be quantified as follows:

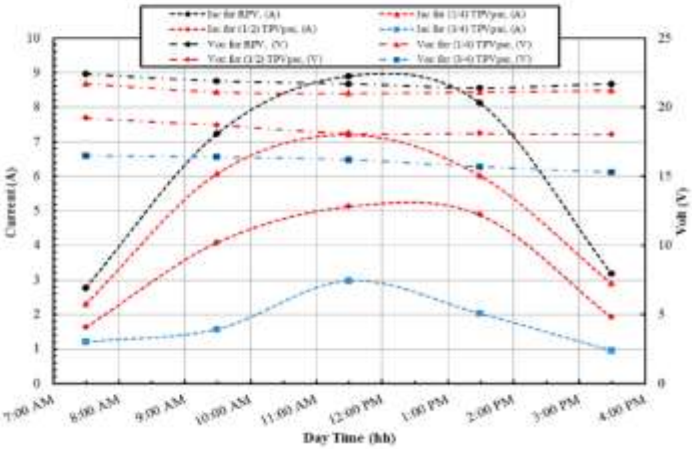
Reduction in power=RPV−TPVRPV×100%Reduction in power=*P*RPV*P*RPV−*P*TPV×100%

Reduction in efficiency=RPV−TPVRPV×100%Reduction in efficiency=*η*RPV*η*RPV−*η*TPV×100%

At 11:30, RPV's output power was 136.1 W, whereas TPV's was 119.12 W, resulting in a 12.47% reduction in output power. RPV's efficiency was 13.86%, while TPV's was 11.7%, indicating an 11.86% reduction in efficiency. These reductions were primarily due to decreased short-circuit current caused by dust accumulation, which dispersed incident sunlight, thus reducing power output. Similar studies have reported even higher reductions in efficiency due to dust accumulation.

Water Drops

Temperature significantly influences electrical flow in PV systems. Cooling systems utilizing water have been explored to enhance PV efficiency under non-optimal temperature conditions. Figure 5 depicts the daily power output, short-circuit current, and open-circuit voltage of PV modules exposed to water drops.



Water droplets on the module surface decrease temperature, increasing potential difference and thus improving power output. The temperature coefficient defines this relationship, indicating that a decrease in temperature by one degree Celsius corresponds to a 0.33% increase in voltage. Water sprinkling cooling systems enhance module efficiency, especially during summer, by reducing surface temperature and increasing power output.

Partial Shading

Partial shading can significantly impact PV module performance due to the interdependent nature of module strings. Figure 6 illustrates the effect of partial shading on PV short-circuit current and open-circuit voltage. Shading reduces current and voltage, resulting in a dramatic decrease in power output, as depicted in Figure 7. Even a small shaded area can lead to substantial power loss, emphasizing the importance of avoiding partial shading whenever possible.

Birds Droppings

Bird droppings, like other forms of dirt, reduce PV panel performance by obstructing sunlight. Figure 8 shows the impact of bird droppings on power output. Although the effect is relatively small compared to other forms of shading, it still affects PV efficiency. Further research is needed to mitigate the impact of bird droppings on PV systems.

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