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Impact of dust accumulation on solar photovoltaic panel performance and the efficacy of cleaning methods: A review of technological innovations and regional considerations

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Abstract

Dust accumulation on solar photovoltaic (PV) panels significantly impairs their performance by blocking sunlight, leading to a reduction in energy output. This study investigates various factors influencing PV efficiency and explores the impact of cleaning methods, such as manual, automated, and natural (rainfall), with a particular focus on rural regions like Nansana, Kampala, where dust deposition fluctuates due to seasonal and environmental variations. The findings reveal that dust accumulation contributes to a significant portion of the loss in PV performance. The study reviews recent advancements in PV cleaning technologies, such as robotic cleaning systems and dust-repellent coatings, and assesses the trade-offs between initial investment costs and long-term improvements in system efficiency and energy yield. The analysis emphasizes the need for tailored cleaning schedules, the selection of appropriate cleaning methods, and the incorporation of innovations like AI-powered robotic cleaners to optimize PV system performance. The study concludes that a comprehensive understanding of the dynamics of dust accumulation, coupled with effective, context-specific cleaning strategies, is essential for maintaining peak PV efficiency. Such strategies not only enhance energy output but also improve the economic feasibility of solar energy, making it a more reliable and sustainable energy source in regions impacted by dust-related performance degradation.

1.0 Introduction

The global transition to renewable energy sources has emphasized the significance of solar photovoltaic (PV) technology as a clean, accessible, and sustainable energy solution (Izam, *et al*., 2022). Given Uganda's advantageous equatorial position, characterized by abundant sunshine and conducive climatic conditions, solar PV systems are particularly well-suited for addressing both urban and rural energy needs. However, the actual performance of these systems is heavily influenced by environmental factors, especially dust accumulation, which is a prevalent issue in urban and semi-urban regions. In areas like Nansana, Kampala, where atmospheric dust is abundant due to rapid urbanization, construction activities, and unpaved road networks, understanding and mitigating the impact of dust on PV system performance becomes crucial to ensure optimal power output and efficiency (Eze, et al., 2023a).

When dust builds up on solar panels, it forms a barrier that blocks sunlight from reaching PV cells, which hinders the production of energy. According to studies, even tiny dust layers can cause large power losses because they change how solar radiation is transmitted and absorbed across the PV surface (Eze et al., 2023a). Dust properties, including particle size, colour, density, and composition, which are affected by both seasonal fluctuations and local environmental conditions, determine how much of an impact this has. Dust-related energy losses are frequently ignored, which lowers overall system efficiency, especially in areas like Uganda, where regular maintenance may be limited. The effects of dust on solar PV performance have been the subject of several experimental investigations, especially in arid and semi-arid countries like the Middle East and North Africa (MENA) where dust levels are high (Salamah et al., 2022). According to this research, dust deposition can, in extreme circumstances, cut power output by up to 50%; however, the exact effects vary depending on the ambient circumstances (Azouzoute et al., 2021). Although these results shed light on the mechanics of dust-photovoltaic interactions, more research is needed to fully comprehend how dust affects PV systems locally in tropical and equatorial areas. The features of dust buildup and its effect on PV performance are anticipated to be different from those seen in arid locations due to Uganda's climate and environmental circumstances. In order to offer context-specific insights and solutions, this calls for a localised approach to researching dust effects (Zarei et al., 2022).

Therefore, reviewing and analysing how dust deposition affects solar PV system performance is the focus of this work. This study attempts to estimate the energy losses related to varying degrees of dust deposition on PV modules by field tests carried out in real-world settings. Additionally, this study aims to determine the key factors affecting dust-induced deterioration and evaluate the long-term effects of cleaning procedures, or lack thereof, on system performance. This investigation will contribute valuable data to the body of knowledge on PV performance in tropical urban settings, providing key insights that could support stakeholders in developing strategies for maintaining system efficiency. Through its findings, this study aims to inform PV installation guidelines, cleaning protocols, and maintenance schedules, potentially enhancing the reliability and sustainability of solar power in Uganda. Furthermore, the results can help optimize the deployment of solar PV systems across similar environments, where dust remains an overlooked yet impactful factor in energy generation

2.0 Methodology

With an emphasis on areas with varying dust levels, such as Nansana, Kampala, this study attempts to present a thorough examination of the effects of dust deposition on solar photovoltaic panel performance and the effectiveness of different cleaning techniques. A comprehensive literature search, a feasibility analysis, and a critical evaluation of research on dust accumulation and cleaning methods are all part of the process used. Using databases including IEEE, Scopus, Web of Science, ResearchGate, and Google Scholar, a thorough literature search was carried out. To find pertinent papers published in peer-reviewed journals, keywords such as "dust accumulation on solar PV," "cleaning methods for solar panels," "PV efficiency and dust," "automated cleaning systems," and "solar panel performance in dusty environments" were used in different combinations. A total of 95 articles were found and examined.

Furthermore, industry case studies, field observations from areas with different dust conditions, and reports from solar energy organisations provided information that was essential to the study. To assess the advantages and disadvantages of the current research, pinpoint knowledge gaps, and talk about the implications for enhancing cleaning procedures in various contexts, a critical evaluation of the combined results from the literature search was carried out. The results were reviewed in terms of their applicability for maximising PV performance, cutting maintenance costs, and guiding future research on sustainable PV maintenance techniques. They were also interpreted in light of recent technical developments, such as AI-driven robotic cleaning systems. This methodology allows for a comprehensive assessment of both theoretical and practical aspects, ultimately providing recommendations on optimal cleaning strategies and technologies for different environmental conditions.

3.0 Effects of Dust on Solar Photovoltaic Performance

Solar PV has emerged as a critical component in renewable energy technology, transforming sunlight directly into electricity through semiconductor materials (Zarei, *et al.,* 2022; Uche, *et al.,* 2023). Solar PV systems have garnered global attention for their role in clean energy generation, low carbon footprint, and sustainability. This clean energy solution harnesses solar radiation as a free and inexhaustible source of energy, addressing global energy demand while reducing dependency on fossil fuels, thereby mitigating climate change. The solar PV sector has experienced rapid technological advancements, driven by the need for efficient, cost-effective, and scalable solutions. This evolution, coupled with supportive policy frameworks and incentives, has led to a steady decrease in PV module costs, making solar PV systems increasingly accessible to both industrial and residential sectors (Living, *et al*., 2024; Eze, *et al*., 2023b). A key contributor to grid-tied and off-grid applications, solar PV technology is a linchpin in achieving energy security and resilience, especially in remote and rural areas where conventional grid extension is not viable.

3.1 Solar PV Cells

The fundamental unit of a solar photovoltaic system is the solar cell, which is a semiconductor device primarily composed of silicon (Reinders, et al., 2017). This material is chosen for its favorable electronic properties and abundance, enabling efficient light absorption and energy conversion. Solar cells operate based on the photovoltaic effect, a phenomenon where incoming photons from sunlight transfer their energy to electrons, freeing them and allowing them to move through the material, thereby generating an electric current. When sunlight strikes a solar cell, if a photon possesses energy equal to or greater than the band gap energy (Eg) of the material, it excites an electron, lifting it from the valence band to the conduction band (Eze, *et al*., 2023c: Ukagwu, *et al*., 2024). This process creates an electron-hole pair, where the electron can move freely, contributing to current generation. Structurally, a typical solar cell functions similarly to a photodiode with a p-n junction, but with modifications tailored to optimize light absorption and charge carrier collection.

In conventional PV cells, the n-type layer is designed to be thin and heavily doped, meaning it has a high concentration of donor atoms, creating free electrons (Sio, & MacDonald, 2016). In contrast, the p-type layer is thicker and lightly doped, meaning it has fewer acceptor atoms. This doping arrangement results in a wider depletion region between the p-type and n-type layers, where electric field formation occurs. The width of this region is advantageous, as it increases the area available for photon absorption and subsequent electron-hole pair generation. Additionally, the thin n-layer allows more light to penetrate deeper into the cell, reaching the depletion region effectively, where the electric field can readily separate and drive the electron-hole pairs, minimizing recombination losses as illustrated in Figure 1. When a load is connected to a solar cell, the electric field within the depletion region exerts a force on the free carriers (electrons and holes), causing current to flow (Conceptar, *et al*., 2024; Schleuning, *et al.,* 2022). This electric field directs the electrons toward the n-side and the holes toward the p-side, creating a flow of current across the external circuit connected to the load. This efficient movement of charge carriers from the depletion region, where they are generated by light energy, is fundamental to achieving maximum current output and power generation in a PV system (Malik, *et al*., 2013).

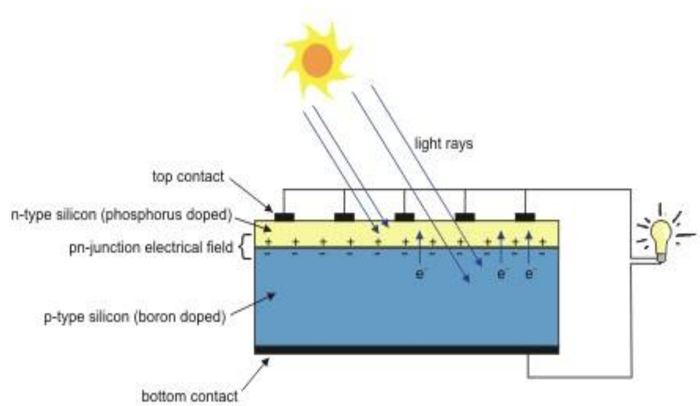

Figure 1: Cross section of a PV cell (Marias Gonzalez, 2020**)**

The equivalent circuit of a PV cell is a simplified electrical model used to represent the key processes and inherent electrical characteristics of the solar cell under illumination. This model enables a better understanding of the interactions between light-generated current and various resistive and diode-related losses within the cell (Eze, *et al*., 2017).

3.1.1 Components of the Equivalent Circuit Diagram

1. Current Source: The light-generated current, also known as photocurrent (IL), which results from incident sunlight, is represented by the current source in the circuit diagram. The p-n junction's internal electric field separates the electron-hole pairs created when photons from sunlight excite the semiconductor's electrons. For a given illumination level, the strength of IL is relatively constant and is directly proportional to the intensity of the incoming light. In the analogous circuit concept, IL is frequently thought of as the ideal current source and is the main current that contributes to the cell's power output.

2. Diode: A diode is connected in parallel to the current source, representing the p-n junction of the PV cell. This diode models the cell’s nonlinear response to voltage and allows for an accurate representation of the recombination losses that occur within the junction, especially at higher forward-bias voltages. The diode current (I_D) follows the Shockley diode equation (1)

$$I_D = I_o\left(e^{\left(\frac{q(V+IR_s)}{nKT}\right)-1}\right) \quad (1)$$

Where; I_o = Reverse saturation current of the diode, V = Voltage across the cell, I = Net output current, R_s = series resistance, q = Electron charge, K = Boltzmann's constant, T = Absolute temperature, n = Ideality factor (which typically ranges from 1 to 2 and depends on the recombination mechanisms within the junction).

This diode component is crucial for modeling the dark characteristics of the cell when it is not illuminated and for understanding how the cell behaves under various levels of external load.

3. Shunt Resistance (R_{sh}): The shunt resistance is connected in parallel with both the diode and the current source, representing leakage paths within the PV cell. These leakage currents arise from imperfections and defects in the semiconductor material, such as grain boundaries or other structural irregularities. Ideally, R_{sh} should be high to minimize leakage losses, however, due to manufacturing imperfections, some current bypasses the ideal path, reducing the overall efficiency. A lower R_{sh} value increases power loss through unwanted current paths, adversely affecting cell performance cell (Eze, *et al*., 2017). The shunt circuit current is given as in equation (2).

$$I_{sh} = \frac{V+IR_s}{R_{sh}} \quad (2)$$

4. Series Resistance (R_s): The total resistance that the current encounters while passing through the cell's material, contacts, and connections is known as the series resistance. The resistance of the semiconductor material, the contacts on the cell surface, and the connections between cells within a module are some of the factors that affect Rs. Because Rs directly affects the cell's fill factor (FF) and maximum power output, minimising it is essential. As the current passes through the cell, higher Rs values result in a voltage drop, which lowers the voltage at the terminals and, consequently, the power output cell (Eze et al., 2017).

5. Output Current (I): The output current of the PV cell, considering the contributions of the light-generated current (I_L), diode current (I_D), and shunt current (I_{sh}), is expressed as in equation (3).

$$I = I_L - I_D - I_{sh} \quad (3)$$

Substituting for I_D and I_{sh}, in equation (2) gives PV characteristic equations as in equation (4)

$$I = I_L - I_o\left(e^{\left(\frac{q(V+IR_s)}{nKT}\right)-1}\right) - \frac{V+IR_s}{R_{sh}} \quad (4)$$

Where: V = Voltage across the PV cell, I = Output current through the external load.

Equation (1) to (4) was modelled by applying Kirchhoff's law in Figure 2, and it illustrates how the equivalent circuit model accounts for the ideal current source (photocurrent) and the parasitic losses associated with the diode (representing recombination), the series resistance, and the shunt resistance.

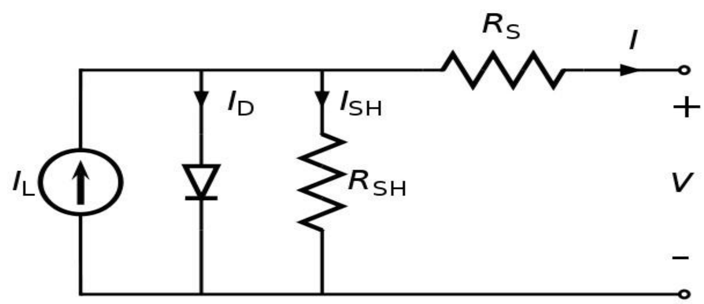

Figure 2: Equivalent Circuit Diagram of PV Cells (Eze, *et al*., 2017; Boyd, *et al*., 2011)

3.1.2 Significance of the Equivalent Circuit Model

As seen in Figure 2, a typical PV cell's equivalent circuit consists of a current source, a diode, and two resistors that stand for series and shunt resistances. Together, these components depict how the cell reacts to external loading circumstances and sunlight. PV cells' performance parameters, including their maximum power point (MPP), fill factor, open-circuit voltage (Voc), and short-circuit current (Ish), can be better understood using the analogous circuit model. Cell design may be enhanced, energy losses can be decreased, and total efficiency can be raised by comprehending and optimising each component, especially Rs and Rsh (Boyd et al., 2011).

3.2. Solar PV Modules

A solar PV module, often referred to as a solar panel, is an assembly of solar cells encapsulated to protect against environmental factors (Ma, *et al.*, 2022). Modules are the primary building blocks of PV systems and are designed to maximize sunlight capture and energy conversion within a confined area. A standard PV module typically consists of the following layers: Solar Cells which are the core energy-generating units, made from silicon or other semiconductor materials. These cells are electrically interconnected and arranged in a grid to collectively produce an appropriate voltage and current level. The Encapsulant Layers, typically made from ethylene-vinyl acetate (EVA), surround the cells, protecting them from moisture and physical damage while maintaining transparency to allow light penetration (Badiee, 2016). The front cover, usually made of tempered glass, the front cover shields the cells from mechanical impact, UV degradation, and other environmental stressors. The

Back Sheet, located at the rear of the module, the back sheet prevents moisture ingress and provides insulation, enhancing module durability. Frame, aluminium or other rigid frame surrounds the module to provide structural support and facilitate mounting, and finally, the junction boxes house electrical connectors and sometimes diodes to prevent reverse current flow, optimizing energy output and safety (Bhowmik, & Amin, 2009).

Solar PV When exposed to sunlight, each solar cell in a module generates a tiny quantity of direct current (DC) electricity. A module that produces a particular voltage and current appropriate for the application is created by connecting the cells in series or parallel (Eze et al., 2016; Ma et al., 20220). Whereas parallel connections increase current, series connections increase voltage. To make system design and interoperability easier, modules are sometimes set up in standardised ratings, such as 60-cell or 72-cell modules. The materials utilised, the quality of the cells, and how well each component layer transmits and converts sunlight into energy all affect a PV module's efficiency. Commercial efficiencies typically fall between 15% and 22%. External variables, including temperature, installation angle, shade, and irradiance levels, also affect module performance. Figure 3 depicts a PV module's typical construction.

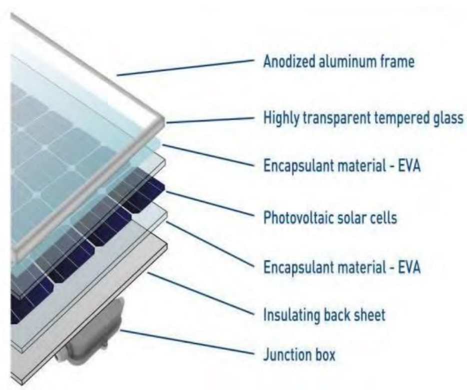

Figure 3: Structure of a PV Module (Sultan, *et al.,* 2019)

3.3. Solar PV Arrays

A solar PV array is an interconnected assembly of PV modules designed to produce a specified power output. Arrays are scalable and can range from small setups for individual homes to large configurations that supply utility-scale power (Zarmai, *et al.,* 2015). A PV array is configured by connecting modules in series and parallel to meet the required voltage and current specifications. The series connections increase the total voltage, while parallel connections increase the current, enabling customization to meet the power requirements of the system's load or grid interface. Furthermore, arrays can also be configured with optimizers or microinverters for module-level power management, allowing each module to operate at its maximum power point and thus enhancing overall array efficiency (Eze, *et al.*, 2016; Zarmai, *et al.,* 2015).

3.3.1 Types of PV Arrays

Photovoltaic arrays can be classified into different types based on their design and intended application. The primary categories are:

1. Fixed Arrays: These PV modules are installed at a precise angle that is tailored to the installation's particular geographic location. Since fixed arrays are the most straightforward and widely used design, they are appropriate for locations that receive a fair amount of sunshine all year round (Eze et al., 2021).

2. Tracking Arrays: In order to maximise energy capture, tracking arrays use a device that modifies the solar panels' orientation to follow the sun's path throughout the day. There are two primary varieties: Dual-Axis Trackers, which offer more accurate tracking by adjusting the panels both horizontally and vertically, guaranteeing optimal sunlight exposure throughout the day, and Single-Axis Trackers, which move the panels along a horizontal axis, usually from east to west, to track the movement of the sun. Depending on the location and weather, tracking arrays can increase energy capture by 10–25% when compared to fixed arrays (Eze et al., 2022).

3. Building-Integrated PV (BIPV) Arrays: BIPV arrays are integrated directly into the building structure, such as on rooftops or walls. These arrays not only generate electricity but also serve as building materials, replacing traditional construction elements like roofing or facades. This dual-purpose design makes BIPV an attractive solution for sustainable architecture (Mekhilef, *et al.*, 2013).

3.3.2 Array Design Considerations

Designing a PV array involves optimizing several key factors to ensure maximum efficiency and performance:

1. Orientation and Tilt Angle: Proper alignment of the modules with the sun's trajectory is critical for maximizing solar exposure. The optimal tilt angle depends on the geographical location and seasonal variation, ensuring that the panels receive the most sunlight throughout the day and year.

2. Inter-module Spacing: Sufficient spacing between modules is essential to prevent shading and allow for better airflow. Adequate ventilation around the panels helps to cool them, preventing temperature-related efficiency losses and enhancing overall performance.

3. Temperature Management: Effective design ensures there is enough air circulation around the modules, which helps maintain an optimal operating temperature. Overheating can reduce the panels' efficiency, so allowing for proper ventilation is crucial to minimize temperature-related performance degradation.

4. Shading Analysis: Reducing the amount of shade provided by surrounding structures, trees, or other obstacles is crucial. Because even partial shadowing on a single panel can impact the performance of other connected modules, shading can drastically lower the array's overall energy production.

3.4 Types of Solar PV

Solar PV cells are the core components of photovoltaic systems, converting sunlight into electrical energy through the photovoltaic effect. They can be classified into various types based on their material composition and structure, with each type offering distinct benefits and drawbacks. This section explores the primary types of solar PV cells monocrystalline, polycrystalline, and thin-film PV cells and discusses emerging technologies such as bifacial and tandem solar cells, which hold promise for future advancements in efficiency and versatility (Awasthi, et al., 2020).

3.4.1. Monocrystalline PV Cells

Monocrystalline photovoltaic cells are manufactured from high-purity, single-crystal silicon (c-Si), using a process that aligns silicon atoms in a uniform and highly ordered structure. This precise crystalline arrangement enhances electron mobility, resulting in superior electrical performance. Visibly, monocrystalline cells exhibit a consistent dark color, typically black or dark blue, reflecting their uniform composition (Goodrich et al., 2013). Among the various PV technologies, monocrystalline cells are known for delivering the highest energy conversion efficiencies, often exceeding 20% under optimal conditions, making them particularly suitable for installations with limited space, such as urban rooftops or portable solar applications. Additionally, their structural integrity and purity contribute to exceptional durability, with many modules offering warranties of 25 years or more. Another key advantage lies in their thermal performance: monocrystalline cells tend to maintain higher efficiency under elevated temperatures compared to polycrystalline and thin-film alternatives, making them a preferred choice in hot and sunny climates. These characteristics position monocrystalline PV technology as a leading option for high-performance and long-term solar energy solutions.

3.4.2. Polycrystalline PV Cells

Polycrystalline photovoltaic cells are produced by melting raw silicon and allowing it to solidify into a block containing multiple silicon crystals, resulting in a characteristic grainy, bluish appearance caused by the crystal boundaries (Azwar et al., 2021; Bhowmik & Amin, 2009). These multi-crystalline structures contribute to slightly lower energy conversion efficiencies, typically in the range of 15–17%, compared to their monocrystalline counterparts. However, ongoing improvements in manufacturing techniques have narrowed this efficiency gap, making polycrystalline cells a practical and widely used option in the solar energy market. One of their key advantages is cost-effectiveness; the simpler production process reduces material wastage and energy consumption, translating into lower upfront costs and a faster energy payback period. Additionally, polycrystalline PV cells tend to have a smaller environmental footprint compared to monocrystalline cells, aligning well with global efforts to promote sustainable energy solutions. These features make polycrystalline technology especially suitable for residential, commercial, and utility-scale applications where budget and environmental considerations are paramount.

3.4.3. Thin-Film PV Cells

Using materials like amorphous silicon (a-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe), thin-film photovoltaic cells provide an alternative to conventional crystalline silicon solar technology. The lightweight, flexible structure created by these materials' ultra-thin layer deposition onto substrates expands the possible applications (Eze et al., 2021; Bosio et al., 2018). One of the key advantages of thin-film PV technology is its adaptability; the flexibility and reduced weight of these modules make them particularly suitable for non-traditional surfaces such as curved rooftops, building facades, vehicles, and even wearable electronics areas where rigid silicon panels are unsuitable. Moreover, thin-film cells exhibit superior performance under diffuse light and partial shading conditions, offering a reliable solution for regions with frequent cloud cover or complex installation geometries. However, this technology typically exhibits lower energy conversion efficiencies, approximately 10–12% compared to crystalline silicon cells, necessitating a larger installation area to generate equivalent power output. Despite this limitation, ongoing research and development are steadily improving thin-film performance, positioning it as a viable option for specialized or space-constrained applications in the broader landscape of solar energy technologies.

3.4.4. Emerging Solar PV Technologies

Emerging technologies like bifacial and tandem solar cells offer significant potential for improving efficiency and expanding application possibilities (Guerrero-Lemus, *et al.*, 2016; Ogundipe, *et al.*, 2024)

3.4.4.1 Bifacial Solar Cells

Bifacial solar cells are advanced photovoltaic devices engineered to absorb sunlight on both their front and rear surfaces, enabling them to utilize not only direct sunlight but also reflected irradiance from the ground or nearby surfaces. This dual-sided configuration can enhance overall power generation by approximately 10–20% compared to conventional monofacial modules (Guerrero-Lemus et al., 2016). A key advantage of bifacial solar cells is their ability to produce a higher energy yield from the same installation footprint, as they effectively harness both direct and albedo-reflected light. Additionally, these modules offer increased versatility in mounting options. They perform exceptionally well in environments with high reflectivity, such as areas with sand, snow, or white rooftops, where the additional rear-side illumination significantly boosts overall system efficiency. As a result, bifacial technology is particularly advantageous for large-scale solar farms and rooftop installations in regions with suitable surface reflectance characteristics.

3.4.4.2 Tandem Solar Cells

Tandem solar cells represent a cutting-edge advancement in photovoltaic technology, characterized by their multi-layered architecture in which each cell layer is composed of materials with distinct band gaps. This configuration enables the absorption of different segments of the solar spectrum across the layers, thereby optimizing spectral utilization and significantly boosting overall energy conversion. By strategically stacking these layers, tandem solar cells can achieve conversion efficiencies exceeding 30%, far surpassing the theoretical limits of conventional single-junction cells (Martinho, 2021). One of the most notable benefits of tandem solar cells is their ability to enhance spectral efficiency by directing specific wavelengths of light to the layers best suited to absorb them. This makes them ideal for high-performance applications in next-generation photovoltaic systems, where maximizing energy output within limited surface areas is crucial. Their potential for ultra-high efficiency positions tandem cells as a transformative solution for both residential and utility-scale solar energy deployment.

Table 1: Comparative Summary of the solar PV types

Monocrystalline	20% or higher	High efficiency, longevity	Residential rooftops, space-constrained areas
Polycrystalline	15-17%	Cost-effective, moderate efficiency	Utility-scale, commercial installations
Thin-Film	10-12%	Lightweight, flexible, good in low light	BIPV, portable solar, off-grid
Bifacial	10-20% increase over mono	Dual-surface light capture	Solar farms, tracking systems
Tandem	>30%	High efficiency, full spectrum capture	High-tech applications, space, and future rooftops

Table 1 shows that each type of solar PV cell offers unique advantages, making them suited for specific applications and environments. Monocrystalline cells remain the most efficient and are optimal for high-density energy applications where space is limited. Polycrystalline cells provide a cost-effective alternative with moderate efficiency, ideal for large installations where cost is a primary consideration. Thin-film cells are versatile, lightweight, and perform well in low-light conditions, broadening their utility to portable and building-integrated systems. Meanwhile, bifacial and tandem cells are emerging as promising technologies that could drive the next generation of solar efficiency and application flexibility.

3.5 Classifications of Solar PV

Solar photovoltaic systems can be classified by application, deployment type, and power supply strategy, each tailored to specific energy needs and infrastructure conditions. These classifications optimize the use and management of solar power across diverse settings, whether integrated with the grid, completely independent, or supplemented with alternative energy sources. The primary classifications are grid-connected (on-grid) and off-grid systems, and standalone and hybrid PV systems (Herez, *et al.,* 2023).

3.5.1. Grid-Connected PV Systems

Grid-connected photovoltaic (PV) systems, also referred to as on-grid systems, are directly integrated with the utility power grid, enabling a two-way flow of electricity. These systems generate electricity from solar energy to meet immediate local consumption, while any excess energy produced is fed back into the grid. Conversely, during periods of insufficient solar generation, such as at night or during overcast conditions, the system draws electricity from the grid to ensure a continuous supply (Eltawil & Zhao, 2010). A key advantage of grid-connected systems is their ability to reduce electricity costs through energy offset and participation in net metering programs, where users are credited for surplus electricity contributed to the grid. Unlike off-grid systems, grid-tied configurations typically do not require battery storage, as the utility grid functions as a virtual backup, enhancing system simplicity and reducing associated costs. Furthermore, these systems are highly scalable and relatively easy to maintain, making them suitable for a wide range of applications from small residential rooftops to large-scale commercial and utility installations.

3.5.2. Off-Grid PV Systems

Off-grid photovoltaic (PV) systems are self-contained units that operate independently from the utility grid, making them particularly suitable for remote or rural areas where reliable grid access is unavailable. These systems rely on battery storage to ensure a continuous power supply, capturing excess energy generated during daylight hours for use when solar energy is insufficient, such as during the night or on cloudy days (Veldhuis & Reinders, 2015). One of the primary benefits of off-grid systems is energy independence, as they are not reliant on external power sources, providing a reliable solution for locations without grid access or for those seeking self-sufficiency. These systems typically incorporate battery banks that are sized to store enough energy to meet consumption needs during periods of low solar generation. While the initial cost of off-grid systems can be higher due to the need for batteries and other components, they offer long-term resilience and reliability, especially in areas where grid infrastructure is either unavailable or unstable. This makes them a valuable option for ensuring energy access in remote and underserved regions

3.5.3. Standalone PV Systems

Standalone photovoltaic (PV) systems are a specific type of off-grid system designed to meet the energy needs of particular loads without relying on backup power sources. These systems are typically installed for dedicated applications where continuous energy availability is not critical, and energy consumption is generally lower (Bataineh & Dalalah, 2012). Unlike hybrid systems, standalone PV systems are often used for simpler, isolated applications, such as powering water pumps, streetlights, or remote monitoring stations. A key advantage of standalone systems is their cost-effectiveness, as they are typically sized to power specific devices or small-scale applications, which makes them less expensive to install and operate. Additionally, the simplicity of these systems, with fewer components than hybrid systems, leads to lower maintenance requirements. However, the main limitation of standalone systems is their reliance solely on solar energy availability, meaning that their power output may be insufficient during periods of low sunlight, such as on cloudy days or at night. Despite this, standalone systems remain a practical and affordable solution for low-demand applications in off-grid areas.

3.5.4. Hybrid PV Systems

Standalone photovoltaic (PV) systems are a specialized subset of off-grid systems designed to meet the energy demands of specific loads without relying on backup power sources. These systems are primarily used for dedicated applications where continuous energy availability is not critical, and the energy consumption is relatively low (Bataineh & Dalalah, 2012). Unlike hybrid systems, standalone PV systems are typically deployed for simpler, isolated applications, such as powering water pumps, streetlights, or remote monitoring stations. One of the key advantages of standalone systems is their cost-effectiveness. They are often sized to power specific devices or small-scale applications, making them more affordable to install and maintain. Additionally, their simplicity, which involves fewer components than hybrid systems, results in reduced complexity and lower maintenance costs. However, a significant limitation of standalone systems is their sole dependence on solar energy availability. This reliance can lead to insufficient power output during periods of low sunlight, such as on cloudy days or at night. Despite this drawback, standalone PV systems offer a practical, low-cost solution for low-demand applications in remote, off-grid locations.

Table 2: Comparative Summary of Solar PV System Classifications

Classification Type	Connection Type	Energy Storage	Backup Power	Typical Applications
Grid-Connected	On-grid	No	Grid	Urban areas, residential/commercial rooftops, solar farms
Off-Grid	Independent	Yes	No	Rural areas, remote communities, and telecommunication towers
Standalone	Off-grid	Yes	No	Water pumps, streetlights, and environmental monitoring
Hybrid	Off-grid	Yes	Yes	Hospitals, data centres, the military, and island communities

Table 2 shows the classification of solar PV systems based on grid-connected, off-grid, standalone, and hybrid which provides unique advantages suited to different geographic, economic, and operational requirements. Grid-connected systems are the most cost-effective for users with reliable access to a utility grid, offering an efficient way to offset electricity costs and reduce dependence on grid energy. Off-grid systems, meanwhile, provide a lifeline for remote or isolated communities, enabling clean energy independence in locations without reliable grid access. Standalone systems are streamlined solutions for specific, low-power applications, whereas hybrid systems deliver continuous, high-reliability power, integrating multiple energy sources to enhance resilience in critical infrastructures.

3.5.4 Solar Technology, Best Solar PV Type and Classification

Solar PV technology has evolved to offer various configurations and applications tailored to environmental conditions and energy requirements (Eze, *et al*., 2021). Broadly, PV technology encompasses two main types: crystalline silicon and thin-film solar cells. Crystalline silicon technology, including monocrystalline and polycrystalline PV cells, dominates the market due to its higher efficiency and long-term stability. Conversely, thin-film technology, which includes cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) cells, is lauded for its lightweight and flexible applications, particularly in areas where weight constraints and unique form factors are necessary (Eze, *et al*., 2022). Technological innovations, such as bifacial panels and concentrated photovoltaic (CPV) systems, have further enhanced the versatility of PV solutions, enabling higher energy yields in diverse geographic and climatic conditions (Mekhilef, *et al*., 2013). For optimal performance, monocrystalline PV modules are typically the preferred choice due to their high efficiency, longevity, and reliability in both high and low sunlight conditions. Their superior efficiency allows for substantial power generation within a smaller installation area, which is particularly advantageous in space-constrained or urban applications. Additionally, grid-connected systems with net metering capabilities are often the optimal classification for urban or semi-urban areas where grid infrastructure exists, as they enable consumers to feed excess electricity back to the grid, enhancing economic feasibility. However, in rural or remote areas without reliable grid access, a hybrid solar PV system with battery storage is preferable, providing both reliability and energy independence. This classification supports continuous power availability, meeting the needs of communities and applications in off-grid settings (Karakaya, & Sriwannawit, 2015)

3.6 Factors Affecting Solar PV Performance

Solar PV technology is pivotal in renewable energy generation, offering a clean and sustainable alternative to fossil fuels. However, various environmental and physical factors influence solar PV systems' efficiency and output. The major determinants of PV performance include solar irradiance, temperature, panel tilt angle, wind speed, and dust accumulation. Each of these factors impacts the ability of PV panels to capture sunlight and convert it into electricity, affecting both short-term energy yield and long-term operational efficiency. Understanding these influences is essential for optimizing PV systems, especially in diverse climatic conditions, to enhance energy output and maximize the economic and environmental benefits of solar technology (Hasan, *et al.*, 2022)

3.6.1 Effect of Irradiance on Solar PV Panel

The performance of a solar PV panel is primarily driven by the irradiance level, which refers to the solar power received per unit area. Higher irradiance directly increases the electrical output of PV panels, as photovoltaic cells rely on incident sunlight photons to produce electricity through the photovoltaic effect. Research highlights a proportional relationship between irradiance levels and power output, though efficiency is influenced by irradiance intensity, spectral distribution, and solar cell technology. Low irradiance, typically occurring during early morning, evening hours, or cloudy days, results in reduced electron excitation within the cells, leading to a decrease in power generation. Additionally, irradiance fluctuations can lead to mismatched energy output among series-connected cells, a phenomenon that leads to shading losses and requires optimization techniques such as Maximum Power Point Tracking (MPPT) to maximize panel efficiency under variable irradiance. New materials, such as perovskites, are being explored for enhanced performance under diverse irradiance conditions, providing potential advances in solar technology (Ibrahim, *et al.,* 2019).

3.6.2. Effect of Temperature on Solar PV Panel

Temperature is a critical parameter in solar PV efficiency due to its impact on the semiconductor materials within PV cells. While increased temperatures may lead to higher electron mobility, they also reduce the bandgap of semiconductor materials, which in turn decreases the open-circuit voltage (Voc) and ultimately reduces efficiency. The relationship between temperature and PV performance is non-linear; most crystalline silicon cells experience a performance decline of approximately 0.3–0.5% per degree Celsius above 25°C. Advanced research has focused on cooling techniques, such as passive cooling methods using fins or heat sinks and active cooling using fluids, to mitigate thermal effects on solar panels. For PV systems deployed in hot climates, heat-resistant materials and thermally conductive coatings are increasingly being incorporated to maintain high performance. Investigating thermal coefficients for different PV technologies, including amorphous silicon and thin-film, has become a focal point, as these technologies show different sensitivities to temperature changes (Zaini, *et al.,* 2015).

3.6.3. Effect of Tilt Angle or Angle of Inclination of Solar PV Panel

The angle of inclination significantly influences the amount of solar irradiance captured by the PV panel, thereby impacting energy production. Optimal tilt angles vary depending on the geographic location, seasonal changes, and latitude, as these factors determine the sun's path and angle of incidence on the panel surface. For maximum power generation, PV panels should ideally be aligned perpendicularly to incoming solar rays; however, fixed installations must compromise for an annual average optimal angle. Research indicates that sub-optimal tilt angles can result in losses of up to 10–20%, especially in high-latitude regions where the sun's angle shifts considerably throughout the year. Modern solar tracking systems have shown to improve PV efficiency by dynamically adjusting the panel's tilt angle to follow the sun's path, thus maximizing irradiance capture. Fixed systems, however, rely on precise initial angle calculations to ensure substantial energy yield across seasons, making angle optimization a vital consideration in PV panel installation (Babatunde, *et al.,* 2018).

3.6.4. Effect of Wind Speed on Solar PV Panel

Wind speed indirectly affects solar PV performance by impacting the panel temperature. Wind acts as a natural cooling agent, dissipating heat from the panel's surface and lowering its operating temperature, thus countering some of the efficiency losses associated with temperature rise. Research indicates a positive correlation between moderate wind speeds and PV efficiency, particularly in areas where high irradiance leads to significant heating of PV modules. However, excessive wind speeds can introduce mechanical stress on PV installations, posing structural risks and potentially misaligning or damaging panels. For rooftop and ground-mounted installations, wind load considerations are integral to design specifications to ensure durability under varying wind conditions. Computational Fluid Dynamics (CFD) simulations are increasingly utilized to model wind interactions with PV panels, aiding in the optimization of panel layout for both cooling efficiency and structural integrity (Al-Bashir, *et al.,* 2020).

3.6.5. Effect of Dust on Solar PV Panel

Dust accumulation on PV panel surfaces is a significant factor in performance degradation, particularly in arid and semi-arid regions where dust density is elevated. Dust particles on PV panels obstruct sunlight, diminishing irradiance and reducing energy conversion efficiency (Mejia, *et al.,* 2014). Studies estimate that dust can reduce panel efficiency by as much as 20–30% in heavily dust-laden areas. The extent of this loss depends on multiple factors, including particle size, shape, density, composition, and environmental conditions. Dust on PV panels creates a barrier between the solar cell and sunlight, scattering photons and limiting their penetration to the PV cells. This obstruction leads to an exponential reduction in irradiance as photon transmission is hindered (Ahmed, *et al.,* 2013). Larger dust particles generally have a less pronounced impact on PV performance than finer particles, as finer particles can cover a greater surface area and more effectively block sunlight. The shape, composition, and color of dust particles further influence their light-blocking properties, with darker and irregularly shaped particles typically absorbing more sunlight and exacerbating performance loss. Moreover, studies indicate that the negative effect of dust can diminish slightly under higher irradiance conditions, as more photons are available to penetrate through the dust layer (Zorrilla-Casanova, *et al.*, 2011).

Furthermore, dust particles contribute to localized heating on the module surface. This thermal buildup elevates the module's temperature, which negatively affects PV performance by altering the semiconductor's band gap, leading to photon energy dissipation. Zdanowicz, *et al.*, (2011) highlight that this temperature rise intensifies performance losses as photon energies above the band gap threshold are more readily dissipated as heat rather than converted to electricity. Dust can also create partial shading effects when it forms patches on the PV surface, disproportionately affecting certain cells. This non-uniform shading not only reduces energy output but can induce hotspots, further degrading PV cells over time. The economic impact of dust accumulation has prompted extensive research into cost-effective cleaning techniques and surface treatments. Hydrophobic and self-cleaning coatings are under development to minimize dust adhesion by altering the surface energy of PV glass, allowing rain or wind to more effectively clean the panel. Robotic cleaning solutions have also gained traction, especially for large-scale installations, offering automated and consistent maintenance to sustain optimal energy output (Zdanowicz, *et al.*, 2011).

Quantitative analysis of dust impact is essential for accurate long-term performance predictions of PV systems in dusty environments. By modeling the influence of dust based on regional dust characteristics and environmental conditions, PV system designers can anticipate maintenance needs and optimize the deployment of PV systems for specific landscapes.

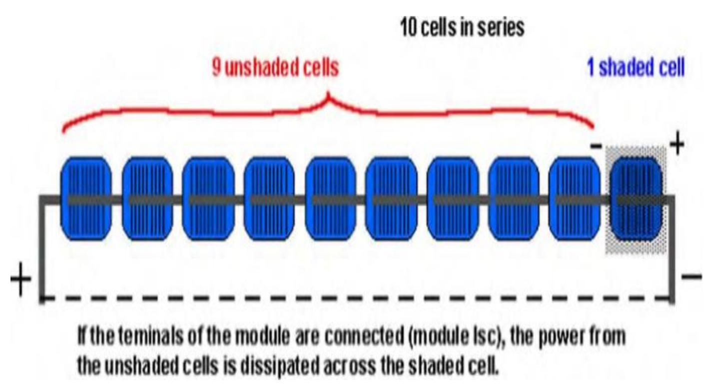

Figure 4: Current flow through shaded cells (Zdanowicz, *et al.*, 2011**)**

A PV module with ten cells is depicted in Figure 4, one of which is shaded and unable to generate any electricity. The shaded cell's state serves as a barrier against the current that the other cells produce. As a result, a hot spot forms in the shaded cell, which may potentially cause damage to the module (Ngan & Tan, 2011; Sheraz & Abido, 2012).

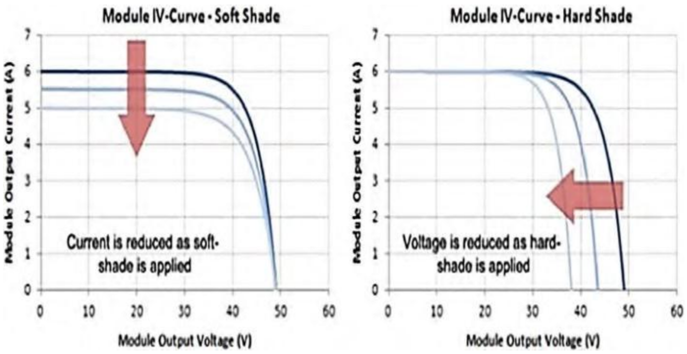

Figure 5: Effect of soft shading and hard shading on module performance (Sheraz, & Abido, 2012)

Figure 5 illustrates the two primary types of shading affecting PV modules: hard shading and soft shading. Hard shading occurs when solid objects, such as accumulated dust, partially or fully block sunlight in a clearly defined shape on the PV module's surface. This type of shading directly impacts specific cells and can cause substantial reductions in power output, depending on the extent of shading. In contrast, soft shading results from diffuse particles, such as atmospheric smog or surface dust, which reduce the intensity of solar irradiance uniformly across the module. While soft shading reduces overall irradiance, it primarily affects the current generated by the PV module, leaving the voltage relatively unchanged. Each shading type influences PV module performance differently. Soft shading typically causes a uniform reduction in current without a corresponding drop in voltage. For hard shading, however, the impact varies based on the distribution of shaded cells. If only a subset of cells is shaded, the unshaded cells can continue to generate current, albeit at a reduced power output. However, if all cells are shaded, the module output drops significantly, potentially halting current flow. Figure 5 demonstrates these effects on the current-voltage (I-V) characteristics of a PV module (Ngan, & Tan, 2011).

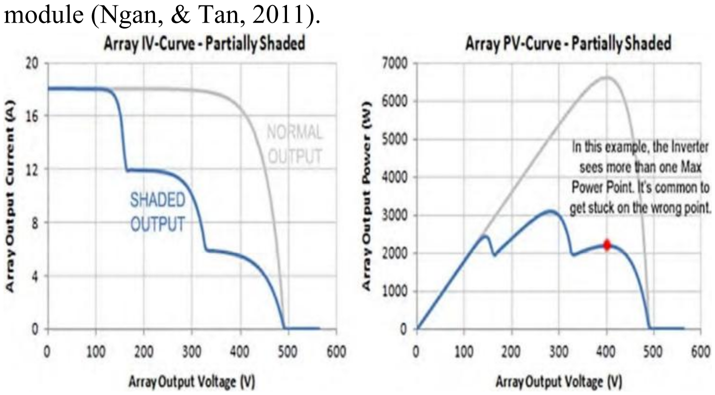

Figure 6: The effect of soft shading and hard shading on array performance (Sheraz & Abido, 2012)

Figure 6 presents the I-V and power-voltage (P-V) curves of a PV array under partial shading conditions, highlighting the challenge of achieving optimal power delivery with voltage mismatches (Sheraz & Abido, 2012)**.** In PV arrays with multiple strings, shading of one string can create current imbalances, especially in parallel configurations where strings share a common inverter. Hard shading on one string affects its voltage output, and the inverter detects and compensates for this change to maintain the required output power. However, partial shading, where different strings are unevenly affected by shading, leads to a mismatch in voltage across the parallel strings. This condition, known as partial shading, presents a unique challenge for inverters because each string delivers a different voltage to the inverter. The inverter then struggles to locate the maximum power point (MPP), compromising the efficiency of the entire array. In such cases, advanced power electronics, such as MPPT algorithms and bypass diodes, are often used to mitigate the effects of partial shading. These components help in optimizing the array's output by isolating shaded cells or adjusting the voltage-current characteristics to match the array's overall MPP (Eze, et al., 2021a; Eze, et al., 2022a; Eze, et al., 2023c). Figure 7 is the diagrammatic representation of the factors influencing dust accumulation in Solar PV panels.

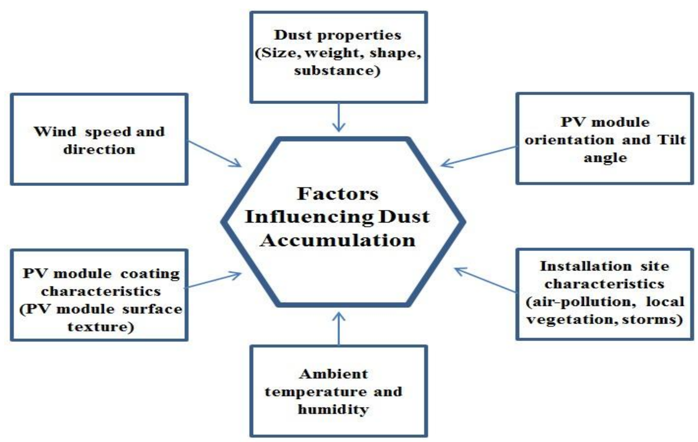

Figure 7: Summary of the factors affecting Dust Accumulation (Zaihidee, *et al.,* 2016**)**

3.7. Cause of Dust Accumulation on Solar PV Panel Surface

The type, size, shape, and weight of dust particles are some of the variables that affect dust collection on solar PV panels. Dust collection on the surface of solar PV panels is also significantly influenced by their tilt angle. Pioneers in the research of dust's effects on solar systems were Hottel and Woertz (1942). Their three-month 1940 experiment on solar collectors revealed that dust buildup on a glass plate angled at a 30° angle in an American industrial area reduced solar PV effectiveness by 1%. In Roorkee, India, Garg and Gupta (1978) compared glass plates and plastic sheets to examine the impact of dirt on solar transmission.

According to the study's findings, grime gathered more on horizontal glass surfaces than on vertical ones. When Sayigh et al. (1985) investigated dust formation on tilted glass plates in Kuwait, they discovered that after 38 days of exposure, transmittance dropped from 64% to 17% for tilt angles ranging from 0° to 60°. They also found that after three days of dust collection, a horizontal collector's useful energy gain decreased by 30%.

The effect of inclination angle on dust settlement was also examined by Gupta et al. (2019), who came to the conclusion that dust accumulation decreases as tilt increases from horizontal. They found that tilt inclinations of 8°, 45°, and 90° reduced transmittance by 19.17%, 13.81%, and 5.67%, respectively. Haeberlin and Graf (1998) examined the buildup of iron dust and other particles around the margins of framed solar cell modules in Burgdorf. They found that dust made of silicon, organic compounds, and iron oxide reduced output power by 8–10%.

Dust adhesion, surface electric fields, and dust movement were the main topics of Stubbs et al. (2017). They came to the conclusion that dust stuck to surfaces mechanically, aided by electrostatic forces and the barbed forms of the dust grains. Dust collection on PV solar modules in the Sahara was examined by Mohamed and Hasan (2012), who came to the conclusion that collected dirt has a major effect on system performance and output power. While Michalsky et al. (1988) tested two pairs of solar PV collectors in Albany, New York, Zarem & Erway (1963) showed that dust reduced solar radiation by 5% on horizontally orientated PV panels. Less than 1% less electricity was produced by the uncleaned panels when one pair was cleaned every day and the other was left unclean for two months (Piliougine et al., 2018).

3.7.1 Effect of Dust Accumulation on the Electrical Performance of Solar PV Panels

One well-known problem affecting solar PV panels' electrical performance is dust collection, especially in areas with high dust levels. Dust, a heterogeneous combination of small particles, can seriously inhibit solar panels' ability to function at their best when exposed to sunlight. Dust collection on the PV surface has been repeatedly shown to reduce the power output of solar modules because dust particles scatter and absorb light, lowering the amount of sunlight that actually reaches the panel cells (Katoch et al., 2021).

1 Mechanism of Dust-Induced Degradation

The mechanism by which dust impairs PV panel performance largely centers on the reduction of irradiance on the cell surface. Dust particles of varying sizes and compositions create a diffuse layer, often resulting in an uneven shading effect. This shading can result in hot spots on PV cells due to the mismatch between illuminated and shaded cell areas, further aggravating the performance decline. The electrical mismatch introduced by partial shading also lowers the system's fill factor and open-circuit voltage, leading to an overall reduction in energy yield (Landis, 1994).

2 Quantitative Impact on PV Performance

Empirical studies have quantified the effects of dust accumulation, revealing losses ranging from 5% to over 40% depending on environmental factors and dust accumulation rates. For instance, in arid or semi-arid regions where dust particles are abundant, losses are often on the higher end. Dust-related losses are exacerbated by meteorological conditions such as low wind speeds, high levels of airborne particulate matter, and minimal rainfall, which prevent natural cleaning (Katoch*, et al.*, 2021).

3 Long-Term Implications

Dust accumulation not only affects the daily performance of PV systems but also has long-term implications for maintenance and operational efficiency. As dust gradually accumulates, the need for regular maintenance becomes critical to sustain energy production levels. Long-term exposure to dust also accelerates panel degradation through abrasive interactions, which can erode the protective layers on the panel surfaces, reducing the panels' lifespan (Katoch*, et al.*, 2021).

3.7.3 Performance Effect of Dust Accumulation on Solar Panels

In Nansana, Kampala, the issue of dust accumulation on solar panels is particularly relevant due to the area's high population density, significant vehicular traffic, and unpaved roads, which contribute to increased levels of airborne dust. This review investigates localized studies and data on the impact of dust in urban Ugandan settings, focusing on how these specific environmental factors influence solar panel efficiency (Nwokolo, *et al.,* 2023).

1. Regional Dust Characteristics and Impact on Solar PV Performance

The composition and density of dust particles in Nansana are influenced by the area's geographical and socioeconomic characteristics. Dust in urban areas like Nansana often includes soil particles, vehicular emissions, and construction debris. These particles are not only abundant but also tend to be sticky due to the high humidity levels, making them adhere more strongly to PV surfaces. This unique dust profile has been shown to cause a higher degree of shading per unit of dust mass compared to less adhesive, dry dust particles (Nwokolo, *et al.,* 2023).

2. Performance Losses Specific to Nansana's Environment

Studies conducted in urban East African settings reveal that dust accumulation can lead to performance drops ranging from 10% to 35%. In Nansana, seasonal variations play a role; during the dry season, dust accumulation tends to be more intense and persistent, exacerbating performance losses. Conversely, the rainy season provides natural cleaning to an extent, temporarily mitigating dust-related losses. However, as urbanization increases, so does the intensity of particulate matter in the air, emphasizing the need for region-specific maintenance strategies.

1. Challenges in Mitigating Dust Accumulation

Dust accumulation on PV panels is a well-documented global challenge, known to significantly reduce energy conversion efficiency and increase operational costs. In response, various mitigation strategies have been developed worldwide, including automated cleaning systems, hydrophobic coatings, and structured maintenance schedules. However, these solutions are typically suited to large-scale or well-resourced PV installations and may not be directly applicable in low-income or rapidly urbanizing contexts. Consequently, it is essential to localize the discourse by examining how such global technical and economic challenges are manifested in specific settings, such as urban Uganda. In Nansana Municipality, the implementation of effective cleaning and maintenance practices for PV systems is constrained by several contextual factors. These include limited access to advanced cleaning technologies, chronic water scarcity, and financial constraints, particularly for residential and small commercial system owners. Many installations operate on minimal maintenance budgets, leading to suboptimal system performance over time. Addressing these challenges is critical for enhancing the long-term viability and energy yield of solar PV systems in urban Ugandan environments, where adoption continues to grow as part of broader renewable energy access efforts.

3.7.4 Solar Panel Cleaning Procedures

Owing to the significant impact of dust on solar PV performance, a systematic approach to panel cleaning is essential. However, cleaning procedures must be designed to balance effectiveness with considerations of resource use, cost, and potential damage to the PV surface (Derakhshandeh *et al.,* 2021).

3.7.4.1 Types of Cleaning Methods

Various solar PV cleaning methods are available, each with its own advantages and limitations. Common methods include manual cleaning, automated cleaning systems, and natural cleaning (e.g., rain). Manual cleaning involves the physical removal of dust using brushes, cloths, or sponges with water or mild detergent. Although effective, this method is labor-intensive and poses a risk of scratching the PV surface if not performed carefully. Automated cleaning systems, such as robotic cleaners, provide a non-intrusive way to remove dust without scratching but are often more expensive and require a stable power source. Natural cleaning, primarily via rainfall, is effective in certain climates but unreliable in arid or heavily polluted areas. In humid environments, rainfall may remove dust particles but could leave behind residues, particularly if the rain itself carries pollutants or acidic compounds. Therefore, reliance solely on natural cleaning is often insufficient in maintaining optimal panel performance (Kazem, *et al.,* 2020).

1. Frequency and Timing of Cleaning

The frequency of cleaning depends on the dust accumulation rate and the performance sensitivity of the PV system. In high-dust environments, weekly or biweekly cleaning may be necessary, while less frequent cleaning may suffice in areas with lower dust levels. Optimal cleaning schedules consider both the cost of cleaning and the economic benefits of performance restoration. In Nansana, Kampala, and similar settings, it has been recommended to time cleaning operations during off-peak sunlight hours to avoid thermal shock, which can occur when water or cleaning agents come into contact with hot panel surfaces. Additionally, it's important to use cleaning methods and agents that do not degrade the anti-reflective coatings of the panels.

2. Advancements in Cleaning Technology

Recent advancements in PV cleaning technology include electrostatic and hydrophobic coatings, which prevent dust particles from adhering to the PV surface, reducing the need for frequent cleaning. These coatings, however, add to the upfront cost and may require periodic reapplication. Robotic cleaning systems, now equipped with AI-driven scheduling and detection mechanisms, are another technological advancement, providing cost-effective and resource-efficient solutions for large PV installations (Wu, *et al.,* 2022).

3.8. Review of Related Work

Historically, the impact of soiling on the power output of solar panels received limited attention. However, recent studies have extensively investigated the effects of dust accumulation, particularly for solar panels installed in arid and semi-arid regions (Kumar, & Chaurasia, 2014). Soiling, defined as the accumulation of dust particles on PV module surfaces, has emerged as one of the most persistent environmental challenges, affecting performance year-round. Dust particles typically consist of substances such as sand, ash, and other materials specific to the surrounding environment (Adinoyi, & Said, 2013).

The research experiments and analyze the effect of Dust on solar PV and conclude that there is a significant reduction in solar irradiance penetration due to dust accumulation on the surface of the solar PV panel.

Rajput, & Sudhakar (2013) experimentally analyzed the effects of dust particles on PV modules, focusing on factors like radiation availability, optimal operating strategies, and system design. Their study concluded that dust significantly reduces the efficiency of solar PV modules. This phenomenon was further investigated and found an average annual energy loss of around 4.4% due to dust accumulation on PV surfaces (Darwish, *et al.,* 2013). During extended dry spells, this loss can exceed 20%. Dust particles vary in chemical composition, physical properties, and phase depending on environmental factors, including air humidity, temperature, and wind speed, all of which influence dust accumulation on PV modules.

Mani, & Pillai, (2010) reviewed the current research on dust's effect on PV performance, identifying gaps and challenges in the field. The researcher further investigated how dust accumulation on the transparent covers of solar collectors reduces normal glass transmittance. They observed that this reduction is highly dependent on dust density, tilt angle, and the orientation of the surface relative to the prevailing wind direction (Elminir, *et al.,* 2006). Kaldellis, & Kokala, (2010) found that a solar panel inclined at 45° facing south experienced a monthly power reduction of approximately 17.4% due to dust.

Said, & Walwil, (2014) focused on dust fouling on PV glass covers. They found a 35% reduction in spectral transmittance, with an overall transmittance loss of around 20%, noting that dust particles were predominantly spherical in shape. Kazem, *et al.*, (2014) studied dust effects on multi-crystalline PV modules and observed significant degradation due to dust and other pollutants. Kazem, *et al*., (2014) correlated dust thickness with reduced efficiency in composite climates, observing output losses of 10–20% when heavy dust layers accumulated. Interestingly, they noted that light dust layers have minimal effect on sunlight transmission to PV modules.

Sulaiman, *et al.,* (2014), reported that external resistance could reduce PV performance by as much as 85%. This study also found that rainwater droplets minimally affect PV module performance. Panjwani, & Narejo, (2014) reported that around 30% of solar energy is reflected or absorbed by clouds, oceans, and land masses. They noted further losses in energy transmission due to reflection and absorption, ranging from 15% to 30%. Additionally, they explored a passive solar tracker activated by bimetallic aluminum and steel strips, achieving efficiency improvements of up to 23% compared to fixed panels, with results aligning well with computer models.

Furthermore, Panjwani, & Narejo, (2014) conducted an experimental study on amorphous and polycrystalline PV modules, analyzing thermal, electrical, and exergy performance, and considering factors like module temperature, heat loss, voltage, current, and fill factor. Shukla, *et al.,* (2015) further analyzed annual performance metrics, comparing power losses and performance ratios using PV-SYST and PV-GIS software tools. They also designed an isolated rooftop PV system for a hostel, simulating its performance and estimating costs for cabling, maintenance, controllers, and manpower (Shukla, *et al.*, 2016).

Caron, *et al.,* (2016) monitored seasonal variations in soiling levels at a solar park in California. They observed low soiling levels during the rainy season but significantly higher soiling during dry months, resulting in a 2.8% peak absolute energy loss due to reduced transmittance. Using theoretical modeling in TRNSYS, Kalogirou, *et al*., (2013) examined how surface cleanliness affects PV module performance, finding that energy absorbed by PV modules is directly proportional to the transmittance-absorptance product and available solar radiation on the surface. Table 3 is a summary of the related reviewed work.

Table 3. Summary of the Reviewed Literature

Authors	Methodology	Findings	Research Gaps/Limitations
Elminir et al. (2006)	Experimental study	Dust reduces glass transmittance, affecting PV performance based on dust density and surface orientation	Limited consideration of alternative cleaning solutions or coatings to mitigate dust accumulation
Kaldellis & Kokala (2010)	Experimental study	A monthly power reduction of 17.4% observed with a 45° south-facing panel due to dust	Lack of studies on the impact of cleaning frequency and environmental factors like weather patterns
Mani & Pillai (2010)	Review study	Identified research gaps on dust's impact on PV performance.	Absence of comprehensive data on the relationship between dust density and PV panel material types.
Mekhilef et al. (2012)	Experimental analysis	Observed 10–20% output loss from heavy dust layers in composite climates.	Insufficient data on how dust accumulation affects different types of PV modules.
Rajput & Sudhakar (2013)	Experimental analysis	Dust significantly reduces PV efficiency; optimal operating strategies and design	Limited focus on specific cleaning techniques or automation technologies in varying climates.

		considerations are crucial	
Darwish et al. (2013)	Experimental study	Average annual energy loss due to dust is 4.4%, with up to 20% loss during dry spells	Lack of detailed investigation into seasonal variability and long-term effectiveness of cleaning methods in dry and wet periods
Caron & Littmann (2013)	Long-term monitoring	Seasonal soiling peaks during dry months, leading to a 2.8% energy loss due to reduced transmittance	Focuses only on seasonal trends, without considering year-round cleaning needs.
Kalogirou et al. (2013)	Experimental study	Energy absorbed by PV modules depends directly on cleanliness and the transmittance-absorptance product.	Insufficient exploration of environmental factors like dust composition and moisture content.
Said & Walwil (2014)	Field observation	Dust fouling reduces spectral transmittance by 35%; overall transmittance loss is 20%.	Limited understanding of the economic trade-offs involved in cleaning PV systems.
Kumar & Chaurasia, (2014)	Experimental study	Experimental study on the effect of dust deposition on solar photovoltaic panels in Jaipur (Rajasthan)	Lacks in-depth qualitative analysis regarding the specific chemical and physical properties of the dust particles and how they affect the PV module.
Shukla et al. (2015)	Experimental study	Amorphous and polycrystalline PV modules show varied performance loss with dust accumulation	Lacks exploration of advanced cleaning techniques for different PV module types.
Azouzoute, et al., (2021).	Experimental study	An increase in dust density from 0 to 1.1 g/m² resulted in a 14.2% reduction in power for a fixed PV system. Over eight months without cleaning, efficiency declined by 27%.	Lacks data on regional variations in dust composition or its impact. There is no analysis of specific cleaning strategies to mitigate transmittance loss, and no long-term assessment of PV performance recovery following cleaning.
Zarei, et al., (2022)	Comprehensive review	Dust settlement on PV surfaces is affected by humidity, rainfall, and gravity.	The absence of standardized field study methods across regions results in inconsistent quantifications of dust impact on PV performance.
Nwokolo, et al., (2023).	Dataset analysis and theoretical model	Showed a Clean Gain Index (CGI) of 0.4737% versus a Soiled Loss Index (SLI) of -0.4708%.	Current empirical models show reduced accuracy in low-latitude locations, highlighting the need for region-specific adjustments.
Ogundipe, et al., (2024)	Review study	High-efficiency PV cells, including multi-junction, PERC, and bifacial cells, significantly improve energy output. BIPV and advanced energy storage, enabling more resilient PV applications.	Challenges in scalability and durability for new materials; high initial costs in BIPV; further R&D needed for cost-effective and long-lasting storage solutions.

4.0 Research Findings

Dust accumulation on PV panels poses a considerable challenge, as it drastically reduces energy output by blocking sunlight. Studies have demonstrated that dust can cause energy losses of up to 50% over prolonged periods in regions with heavy dust levels. This performance loss is closely linked to factors like dust density, particle size, and composition, as well as environmental conditions. When particles settle on PV surfaces, they limit the amount of sunlight reaching the cells, lowering efficiency and leading to significant economic losses, especially in large-scale solar installations. The effectiveness of cleaning methods varies widely, with each approach presenting distinct advantages and drawbacks. Manual cleaning, while simple and cost-effective, carries risks of panel surface damage if not performed correctly. Abrasive particles or improper cleaning techniques can scratch the PV glass, which impacts its light-transmitting efficiency. Automated systems, such as robotic cleaners, offer a solution that minimizes these risks, as they are designed to clean thoroughly without physically impacting the PV surface. However, the high initial investment and energy requirements for these systems can be limiting factors, especially in remote locations where power availability is inconsistent. Natural cleaning, primarily through rainfall, can effectively wash away dust in certain climates, but its reliability is compromised in arid or polluted regions, where rainfall is either sparse or infrequent.

Recent technological innovations in PV maintenance have introduced advanced cleaning solutions that aim to prevent dust accumulation. Electrostatic and hydrophobic coatings are two notable developments, designed to repel dust from adhering to PV surfaces. These coatings reduce the need for frequent cleaning but require substantial initial installation costs and periodic reapplication to maintain their effectiveness. For larger installations, robotic cleaning systems integrated with artificial intelligence (AI) have become an increasingly viable option. These AI-driven systems can detect dust buildup and autonomously determine optimal cleaning schedules, thus conserving resources and maximizing efficiency over time. Regional and climatic factors are essential considerations in determining the frequency and type of cleaning needed. Studies show that high-dust areas may benefit from weekly or biweekly cleaning, whereas lower-dust environments may only require monthly maintenance. The optimal cleaning schedule depends on local weather patterns, dust sources, and the specific design of the PV system. For instance, regions with seasonal variations in dust levels may need more frequent cleaning during dry periods, when dust accumulation rates are higher, compared to wet seasons. Economic trade-offs also play a crucial role in designing effective cleaning strategies. Balancing the cost of cleaning operations with the performance gains achieved is essential to maintain the financial viability of PV systems. Regular maintenance prevents efficiency losses due to dust, thus optimizing the return on investment. While advanced cleaning solutions may demand higher upfront costs, their long-term benefits in sustaining PV performance can justify the investment, especially in large-scale solar parks or areas where dust accumulation is a persistent issue.

5.0 Conclusion

This study highlights the vital role of effective cleaning strategies in sustaining PV panel efficiency, especially in high-dust and heavily polluted environments. Dust accumulation significantly decreases energy yield, with dry and urban areas experiencing the most pronounced performance drops. The choice of cleaning method is essential and should be tailored to specific site conditions, including dust levels, local climate, and resource availability. While manual cleaning is accessible and often economical, automated solutions offer consistent, low-risk maintenance options, though they require a larger initial investment and stable energy supply. Technological innovations, such as dust-repellent coatings and AI-enabled robotic cleaners, hold significant promise for improving PV system performance while reducing maintenance costs, especially in large installations. These advancements help minimize the frequency and intensity of cleaning required, thereby enhancing system longevity and overall energy output. However, they also introduce additional considerations, such as initial costs and the need for periodic reapplication or calibration. Future research should focus on fine-tuning cleaning schedules that balance cost and energy restoration for different environments. Investigations into the long-term durability and effectiveness of emerging cleaning technologies under varied environmental conditions are also crucial. By refining these strategies, the solar industry can maximize PV performance, optimize economic returns, and further advance the sustainability of solar energy solutions across diverse regions.

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Conflict of interest

Every author disclosed that they had no conflicts of interest.

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