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Review

Review of Strategies to Mitigate Dust Deposition on Solar Photovoltaic Systems

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Abstract: In recent years, there has been an increased focus on developing and utilizing renewable energy resources due to several factors, including environmental concerns, rising fuel costs, and the limited supply of conventional fossil fuels. The most appealing green energy conversion technology is solar energy, and its efficient application can help the world achieve Sustainable Development Goal 7: Access to affordable, clean energy. Irradiance, latitude, longitude, tilt angle, and orientation are a few variables that affect the functioning of a solar photovoltaic (PV) system. Additionally, environmental factors like dust accumulation and soiling of panel surfaces impact the cost of maintaining and producing electricity from a PV system. Dust characteristics (kind, size, shape, and meteorological elements), one of the largest factors affecting PV panel performance, need to be investigated to devise specific solutions for efficiently harnessing solar energy. The essential findings of ongoing investigations on dust deposition on the surface of PV structures and various mitigating measures to tackle soiling issues are presented in this review study. This comprehensive assessment critically evaluates the current research on the soiling effect and PV system performance improvement techniques to determine the academic community's future research priorities.

Keywords: solar energy; photovoltaics (PV); dust; soiling; performance degradation; environmental factors; energy storage systems; productive life; cleaning; control

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1. Introduction

The ensuring energy security and mitigating climate change are two of the current critical energy problems witnessed on a global scale mandating an immediate transition to clean renewable energy sources for powering a safer world [1,2]. Utilizing renewable energy is crucial for sustainably meeting the steadily rising demand for energy. A variety of semiconductor materials are employed in photovoltaic (PV) cells. When a semiconductor is exposed to light, the light's energy (photons) is absorbed and transferred to the semiconductor's negatively charged electrons [3,4]. The additional energy enables the electrons to conduct an electrical current through the material. The PV systems rely heavily on silicon, a semiconductor material. This method of producing electricity has widespread use in commercial and residential applications due to its low environmental impact and power grid independency. PV cells' life expectancy is high, up to 25 years.

Innovations in PV technologies have been successfully used for both domestic and commercial applications. They offer the notable advantages of tapping for clean, reliable, abundantly available, and environmentally friendly energy sources [5,6]. Improvements in PV systems necessitate a thorough understanding of material science, design, and economic practices [7–10]. The long-term impacts of solar PV energy conversion are the focus of many studies undertaken by the research community [11–13]. Technological developments have improved efficiency and have been crucial in bringing down prices of solar PV systems, thereby encouraging their wider use [14–17]. Significant efforts are being taken to ensure optimal performance and reliability of PV systems [18–20]. Internal obstacles that impede technological expansion generally receive less attention and funding than external operational issues [21–23]. In the deployment of most solar PV systems, the accumulation of dust particles from the surroundings on exposed PV surfaces is a natural occurrence. Even though it affects PV panels' performance and energy output, this externality is given minimal attention. Dust adversely affects the intended function at the initial surface/light interaction, substantially reducing conversion efficiency or even shutting it down altogether [24–27]. Considering the need for continued efficient power generation of PV systems and prolonged component life, the effects of dust on performance and mitigation techniques have recently attracted the attention of the research community [28–30].

Dust particles have a diameter of 500 μm or lesser. This is ten times smaller than the diameter of the optical fiber. Dust comprises of bacteria, fungi, plants, hair, human/animal cells, carpet fibers, biological alloy derived from clay and sand, or deteriorated geomorphic fall clastic rock [31–35]. There are numerous sources of dust particles (aerosols) in the environment, such as floating dust components (Aeolian dust), volatile emissions, motor vehicle traffic, and pollution. Dust particle size and structural components differ from one zone to another [36,37]. The weather, topography, and metropolitan region influence the formation of dust on the surface of solar panels. Shape, circulation, weight, width, structure, charge, and chemistry are common features of dust particles that are relevant to the study of their generation [38–40]. Humidity, wind speed, PV panel tilt angle, and time influence dust formation on PV systems [41–43]. Different weather elements like wind, pressure and temperature cause power loss due to the soiling of solar panel surface by dust, dirt and grime [44]. Figure 1 portrays the different reasons for dust formation on solar panels and shows the connection between certain variables. Several Researchers have studied the influence of the formation of dust on PV systems and made many observations for several decades. However, the main problem of energy loss due to dust deposition demands appropriate solutions for sustained efficiency of PV modules [45].

This review presents a comprehensive overview of past and recent research studies on the impact of dust and dirt accumulation on the energy production of solar panels and mitigation initiatives to keep them dust-free. Even though several review articles are present in the literature, this review focuses on the recent developments in the dust impact on PV. It also shares insights into the mechanics of dust build-up mechanics, chemistry, and optics to forecast the effects of soiling on the power output of PV systems. The connection between the technique (hardware), the location of the PV system, and the surrounding conditions is examined. Airborne dust properties that eventually collect on PV surfaces are related. The recent advances in the field are captured in this present review. It highlights recent research studies, relations, observations, remedial actions, and future research scope. Their relation to the collection of airborne dust particles on PV surfaces are related and the properties of dust particles are scrutinized. The recent advances in the solar PV energy generation field are presented and captured in this detailed review. It highlights recent research studies, a correlation between PV panel output and dust accumulation relations, observations, remedial actions, and future research scope.

The current review is structured in a systematic manner and is comprehensively summarized in the following sections. Section 1 provides the background and the distinct needs for the present review. Section 2 elaborates on the aspects of PV module tilting, orientation, glazing surface characteristics, and height of solar panels. Section 3 discusses dust particle properties. Environmental conditions that influence dust deposition on solar panels and the current state-of-the-art solar panel cleaning systems and required remedial actions to tackle problems of performance reduction and power loss due to dust deposition are presented in Section 4. Section 5 summarizes the significant conclusions and scope for extending the study further.

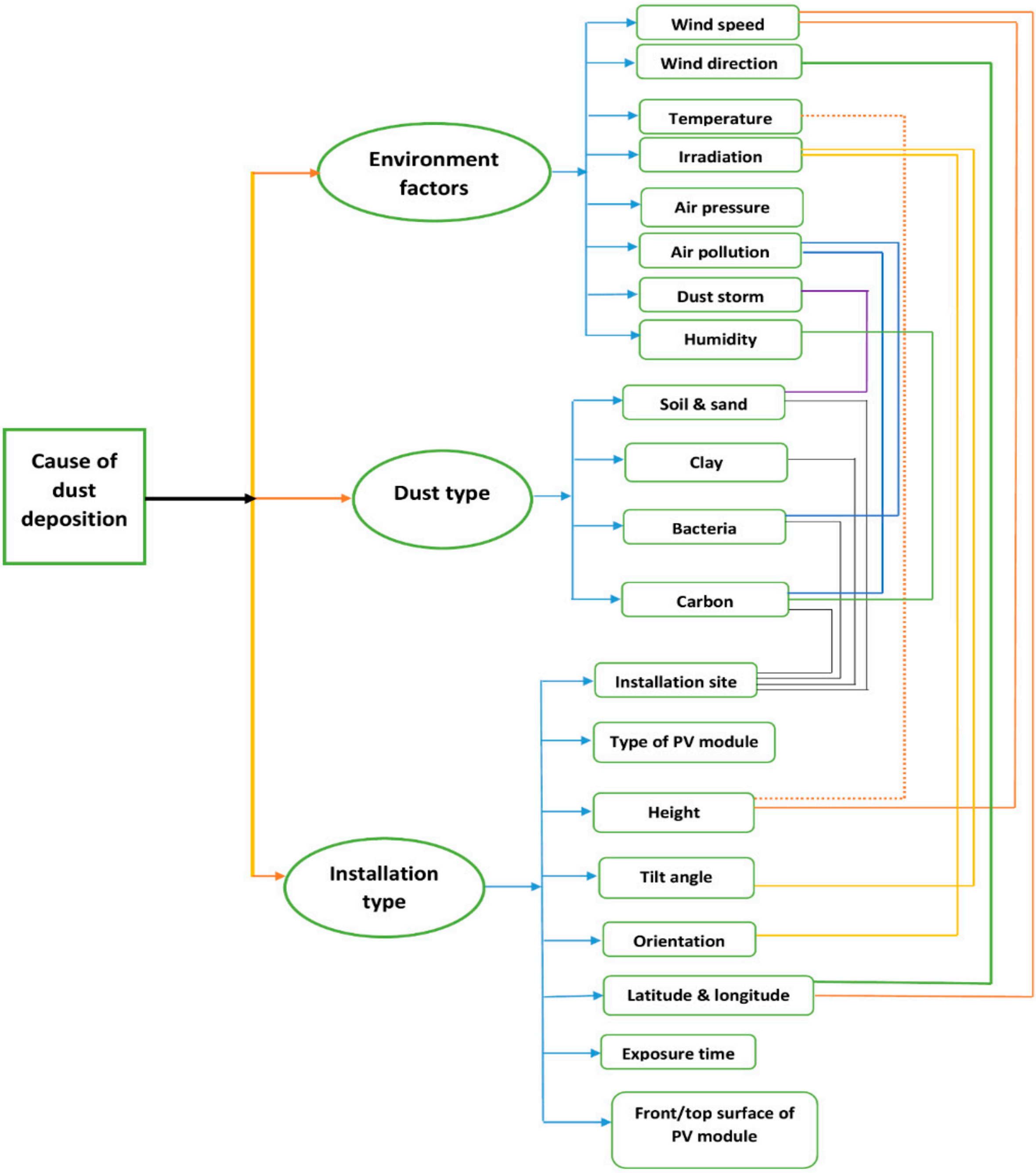

Figure 1. Causes for dust on PV panels [29] (Open access).

2. Features of PV Modules and Systems

Solar systems are designed to maximize energy generation with abundantly available solar energy. As a result, the properties of PV systems are permanent, and some of these qualities may lead to soiling loss, especially if regular cleaning regimes are not meticulously followed.

2.1. Tilt Angle and Orientation

Salim et al. [46] constructed a PV testing system in Saudi Arabia to examine the effects of dust particle accumulation over time on PV power generation. The system's monthly output power reduction was calculated by comparing its performance in the clean range to a tilt angle with a fixed value of 24.6°. After eight months, the reduction in energy production reached 32%. However, this inquiry did not reveal the physical characteristics of the PV system at the test site. The energy obtained from dirty solar panels diminishes over a period leading to a fall in efficiency because dust and dirt block solar radiation affecting output power. The experiment conducted by Hassan et al. [47] demonstrated that power output decreased within the first 30 days of exposure to dust. Without proper PV panel cleaning, the output capacity decreased by 33.5% after one month and by 65.8% after six months. Sayigh et al. [48] found that after 38 days of exposure to the atmosphere with 0°, 15°, 30°, and 45° tilt angles, dust-covered glass panels' transmission had decreased by 64%, 48%, 30%, and 17%, respectively. Figure 2 shows the actual views of dust accumulated solar PV panels [30].

Figure 2. Actual photographic view of dust accumulation density of 13.2 g/m^2 [30].

El-Shobokshy and Hussein [49] examined the PV exteriors that had been tarnished with various sorts of dirt and gauged the power of the PV cells under various conditions. The most important factor to be considered is that all PV surfaces are contaminated at low air velocities [50,51]. Hottel and Woertz [52] performed a three-month performance examination of collectors with tilt angles of 30° exposed to dust from four-track railroads as they were in an industrial area close to the PV power plant. On examining the dust accumulation on the collector, it was noted that the net capacity was significantly lower (4.7%) than expected, while forecasts reported a maximum reduction in glass transmission of 2.7%. They referred to these lower values as indicating a degradation in performance, which was attributed to soiling by snow and rain in Boston, USA, while recommending the use of self-cleaning of solar collectors. Similarly, dust build-up on the surfaces of solar PV panels raises maintenance costs and cleaning expenses [53]. According to Michalsky et al. [54], enough data must be available to develop efficient solar PV systems that consider dust collection and removal measures.

All PV modules should face south for optimal power production in the northern hemisphere. PV modules in the southern hemisphere must be oriented north of the equator. This placement ensures that the PV modules are exposed to intense sunlight for a prolonged duration to maximize solar energy collection. Elminir et al. [55] investigated the relationship between dust accumulation and the orientation and tilt angle of the PV module. They concluded that glass samples in the northeast collected more dust than samples in other directions. This was due to the wind blowing in the study area, bringing in emissions from the nearby manufacturing manufacturers. The analysis showed that dust density and surface orientation significantly impacted the typical solar transmission efficiency of the PV glass and reduced power generation efficiency. The transmission was estimated to be reduced by 52.54 to 12.38 percent when the dust density ranged from 15.84 to 4.48 g/m^2. A decrease in inclination angle and an increase in dust deposition led to a large reduction in solar PV transmittance. A significant decrease in transmittance was seen with an inclination angle of 150 degrees and a 450-degree north orientation. The northeast winds blew in small particles from different sources, primarily from the emissions of cement manufacturing industries, and this particulate matter accumulated on the glass plates.

2.2. Glazing Surface Characteristics

Airborne dust on external surfaces of solar system modules lowers solar cell glazing transmittance and significantly reduces PV module output efficiency. Mustafa et al. [56] experimentally tested the output reduction of several solar modules with component surface impacted by dust deposition from air pollution. The experiments were conducted on a continuous basis under controlled settings. The results of the study revealed that dust contamination had a considerable effect on the output generation of the solar system. As dust density increased from 0 to 22 g^{-2}, PV productivity decreased by up to 26%. The relation between energy capacity reduction and variation in deposition due to PV cell types was unclear.

Semaoui et al. [57] considered the energy production obtained from PV modules connected in series in the desert areas of Algeria. A 32% decrease in PV output was observed due to the deposition of dust over 8 months. The reduced reduction in solar PV performance was noted to be 10% in the sunny season and 6% in the cold season. Dusty panels blocked the solar radiation by 60–70% of its initial value if there was no cleaning of solar PV modules for a year [58]. A one-year experiment was conducted by Hegazy [59] in central Egypt at a desert temperature. The solar panel tilt angle was found to be the most influential factor for dust deposition among the other factors, such as the time of exposure and site climatic conditions. After 10 days of exposure, researchers in Roorkee observed that dust and other pollutants deposited over a glass plate tilted at 45 degrees reduced solar transmittance by 8% [60]. The tilt angles of solar panels and solar coverage rate results were studied by Elminir et al. [55]. With an inclination angle of 0 to 60°, and varied concentrations of dust deposition on PV panels, the equivalent transfer power output was reduced from 52.54% to 12.38%. Figure 3 shows the outdoor dust deposition testing research infrastructure [30]. Figure 4 shows the power output variation of solar PV surfaces with and without dust [30].

Figure 3. Outdoor PV panel testing facility with clean and dusty panels [30].

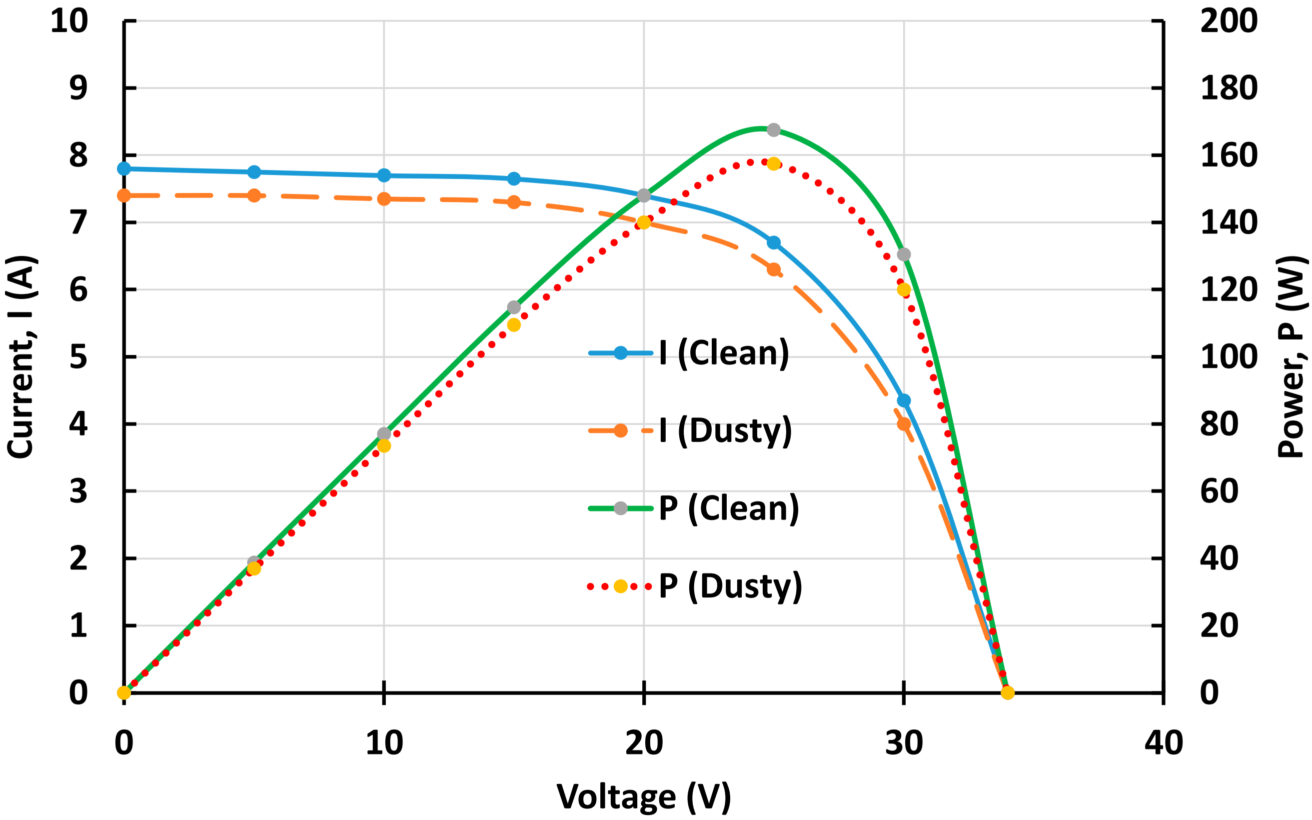

Figure 4. The variation of PV output power for clean and dusty solar panels [30].

The grouping of common outdoor atmospheric dust that accumulates on components of PV systems is shown in detail in Figure 5, based on particle size. The influence of dust on the transmission of different polished materials was investigated in the arid climatic condition of the Thar desert (India) [61]. The glass transmission decrease was noted to be 19.17%, 13.81%, and 5.67% for the respective 0°, 45°, and 90° tilt angles. The decrease in the acrylic light transfer was 23%, 13.98%, and 8.29% for the 0°, 45°, and 90° tilt angles, respectively. According to Mastekbayeva [62], the solar system performance was affected by the glazing's ability to transmit solar radiation. The effect of dust deposition on the solar radiation transmittance of low-density polyethylene glazing with a thickness of 0.2 mm was assessed.

2.3. Height of Solar Panel

The height at which a solar power plant is installed determines the quantity of soiling on its surface. As the panel's installation height is raised, dust deposition may be reduced. Quang et al. [63] investigated the profiles of dust particle density close to the metro lines. Researchers found that the dust concentration was lower for panels located 5 m above the ground because of automobile exhaust pollution. Ambient particulate matter (PM10) dust concentration and dust deposition were reported by McGowan et al. [64]. For panels located under a height of 5 m, PM10 concentrations peaked at around 125 μg/m^3; at about 100 m, they dropped to 95 μg/m^3. The air traveling over deployed PV modules diminishes the dust deposition since wind velocity increases with height [65]. Beattie et al. [66] tested PV modules indoors under controlled conditions. The height of the panel arrangement was altered due to nonlinearity, and it was discovered that as the height increased, the dust deposition on panel surfaces reduced.

Figure 5. Most normal open-air dust molecule sources and their trademark components.

3. Dust Particle Properties

3.1. Particle Size

Cadle [67] noted that a dust particle is an object with a defined physical border in all directions without a limit to its magnitude. Dust, soils, sediments, and associated topological materials comprise of particles that are tens of metres in diameter and much smaller than a micrometer (nanoparticles). Cells themselves can be end-particles or end-particle aggregates. It is important to evaluate the size of individual particles from clay, sediment, or other materials found circulating in the air. Under natural conditions, wind flow exists, even in airless surroundings. Tiny dust particles are naturally circulated in the air and can be transferred to a surface even with little air velocity. Fine particles can transfer at little air velocity. Analysis of dust deposits in the Negev dry area region of southern Israel has consistently indicated that large deposits of dust occur at higher air velocities [68]. The background air speed (storm incident) usually varies from 1–3 ms^{-1} sequence [69]. When the wind is low, it predominantly results in the formation of sedimentary deposits of dust on flat surfaces [70]. The impact of the weight of grain dust and size of coal dust on PV performance was predicted by measuring and accessing the electrical parameters of the PV panels [71].

3.2. Composition of Dust Particles

When dust particles strike a solid surface, ionic alloys in dust can disperse in water and alter the contact forces between surfaces and dust. This can lead to dust build-up. In that case, an increase in the combined forces interacts with the coordinating forces brought on by the dry clay. When compressed water vapor is used to create dust, alkali (NaOH) and alkaline metal ($CaCO_3$) compounds melt, increasing the pH of the water [72]. The dust aggregation on dust shielding surfaces of a PV module and the force of attraction between dust atoms and the separator surface were both investigated by Katarzyna et al. [73]. They discovered that charging a shielding surface produced delayed attractive effects on dust particles but did not affect attachment force. They discovered that the dust shielding surface delayed the adhesion of dust particles but did not affect attachment force. The adherence of dust particles to common indoor surfaces in a cooling environment was studied by Tan et al. [74]. The solar panel's local temperature rises increased due to dust build-up. For epidemiological research, the rules to be followed for quantifying smaller dust particles were stated [75].

Uno et al. [76] reported the accumulation of dust on PV module surfaces globally, including in Asian countries. The budget controls the formation of cirrus clouds and supplies nutrients to marine ecosystems and the open ocean. In the western United States, Neff et al. [77] investigated how human activities affected the deposition of aeolian dust. They saw that higher dust transition prevalent in current times caused the emissions of K, P, Mg, Ca, and N elements to increase fivefold. Hai et al. [78] focused attention on the deposition of airborne dust on solar PV installations. The dust contamination impacted PV performance and reduced PV efficiency. They examined different types of solar cells but did not find any changes in them. The performance of self-cleaning and anti-reflective coated pressed glass of a solar PV module was examined by Verma et al. [79]. They discovered that non-lithographic micro-ordered pressed glass surfaces improved self-cleaning capabilities at the glass/air interface while reducing refraction. Lu et al. [80] evaluated the impact of surface soiling on the performance of a solar panel. The data gathered from the study indicated that a significant factor in reducing the solar transmission of standard glass was the amount of dust collected on its surface. The dust deposition on the glass surface depended on the tilt angle and surface orientation of the PV system.

Mazumder et al. [81] concentrated on determining the efficiency of PV modules exposed to dust from hydrogen generators. The authors found that the dust particles on the thin film PV cell's surface turned out to be electrostatically charged and were scattered by the moving wave generated by the applied electric field. Niknia et al. [82] examined the effect of dust accumulation on the proficiency of a solar collector. They compared the operating performance of a clean solar panel and a dust-laden solar panel to determine the impact of the deposition of dust particles on system efficiency.

Sakhuja et al. [83] investigated the outdoor lifespan of PV glass with intelligent and self-cleaning applications. Over a long period of exposure to the outdoor environment, tests revealed that the nanostructured glass showed better self-cleaning capacity and PV execution. The size of dust particles deposited on PV modules were on par to particle size scales that were described by Blott and Pye [84]. They also evaluated the solar collector performance at various times with dust deposition on module surfaces. Sayyah et al. [85]

concentrated on the drop in energy yield actuated by dust aggregation on solar boards. They aimed to identify the most proficient cleaning methodology for uninterrupted energy created by a solar framework. They compiled an information database covering different kinds of dirt deposited on solar panel surfaces in various places across the world.

Sueto et al. [86] examined the utilization of a photocatalytic coating as a protective covering to limit adherence of dirt, dust and other particulate matter on PV modules. Khonkar et al. [87] discussed the need to clean clusters of solar power stations located in a desert setting. Recognizing the fact that extreme meteorological occurrences are common occasions that can happen in a desert setting, they highlighted the need for periodic cleaning of PV modules to ensure continued effective energy generation by the PV system framework. Appels et al. [88] examined the need for periodic maintenance of solar panels to keep their surfaces free of dust, dirt, and grime. They demonstrated that special coatings on glass could decrease dust formation that causes power reduction in PV modules but reported that the higher cost incurred with such dust-repelling coats was a deterrent.

4. Environmental Effects

Soiling on the top of PV panels is highly dependent on many environmental factors which tend to vary over a period. This section discusses numerous site-specific factors that influence the deposition of dust and dirt on PV module surfaces.

4.1. Wind Velocity and Direction

The effect of wind speed on the temperature of the PV system was studied for a specific test period and was found to be minimal [89]. Increased air temperature resulted in a considerable solar panel voltage drop and a negligible increase in output current. Rounis et al. [90] compared the effectiveness of building-integrated transparent PV systems for new constructions with single and multiple inlets using a numerical model. The researchers analyzed the thermal and electrical performance of PV systems located in warm regions under various wind conditions in summer. Multiple building-integrated transparent PV systems had a 1% greater electrical performance than only one building-integrated transparent PV system. The system could be upgraded to contribute 7% power to a 120-kW solar system's total output and achieve up to a 24% increase in thermal performance. The suggested system was tested to see how variables like sun radiation, air velocity, temperature, and the condensed condensation chamber influenced its functioning. The PV system's overall performance was assessed, and the maximum efficiency was noted to be 57% [91].

The ambient air significantly influences the deposition and removal of dust from the top of a solar module. Dust is moved around by air velocity. Dust can accumulate slowly in the air but can also be cleared quickly. The speed of wind and attention to the movement of airborne dust particles carried by wind determine how much dust is likely to accumulate on PV module surfaces. The settling of dust particles on PV collectors was evaluated in airflow-simulated studies by Goossens and Offer [68] and Goossens et al. [70]. Their research indicates that the wind's direction had a significantly higher impact on dirt settling than the air velocity. In Libya, the lowest wind speed for conveying dust was 6.5 m/s, and increased dirt settling was noted to be mostly caused by an increase in average monthly wind speed [92]. The wind's direction and the orientation of PV surfaces determine the quantum of dust creation [55]. According to Kohli and Mittal [93], the accumulation of fine dust particles on the surface of PV panels resulted in greater performance degradation than bigger dirt elements. They found that as the size of the dust particles decreased below 50 μm, the resistance of the particles to clearance by wind forces increased considerably. No particulates lower than 10 μm were eliminated at wind speeds less than 25 m/s. The most important discovery of their study was that the forces of attraction between the dust molecules and air increased as the size of the particles reduced. In areas prone to strong winds, the practical design, construction, and installation of weather-resilient PV systems become essential to withstand high wind speeds and safeguard against possible damage.

4.2. Moisture, Dew and Rainfall

As with most alloys, corrosion is an unavoidable degradation of a given material brought on by interaction with its environment. Metal objects have traditionally been associated with being subjected to corrosion. Almost all metals are susceptible to corrosive attacks. Corrosion was found to be the primary consequence of the deposition of dirt particles affecting the efficiency of PV systems [94]. Three different soil types were considered in the research. Roadway dirt in Arizona gradually accumulated over panel surfaces and was unaffected by variations in relative moisture. The soot samples exhibited no corrosion-causing properties at the studied humidity levels. When the humidity level rose, sea salt markedly accelerated the rate of glass surface corrosion. Surface pressure increased, current leakage reduced efficiency, and sea salt accumulated on the PV module's top surface [95]. The PV system's performance was investigated at maximum voltages in outdoor settings of extreme temperature and relative humidity. The use of zinc oxide as the conducting electrode instead of tin oxide could help combat the problem of corrosion [96]. As solar panels age, their efficiency decreases due to various reasons, including loss of adhesive adhesion between solar cells, deterioration of packaging materials, deterioration of interface, deterioration of the semiconductor device, and deterioration brought on by moisture leaks. Jorgensen et al. [97] examined the relative efficacy of several combinations of packaging techniques for shielding PV devices against dust. Researchers have found that glass surfaces made of aluminum and glass structures made of ethylene vinyl acetic acid prevent aluminum from disintegrating. Higher rates of moisture entry and the egress of dangerous chemicals are permitted by breathable back sheets of solar panels [98].

The solar panel material's electrical conductivity is impacted by humidity, which results in the breakdown of the metallic intersections of panels and results in poor performance [99,100]. Rainfall has a fundamental impact on soil development. A limited period of light rain may improve the soil's aeration. In a mild downpour, water droplets combine with airborne dust deposited on the surfaces of the module. A PV module's top surface may get washed clean by intense downpours. A minimal 20 mm of rain is required to clean the PV panel face, according to studies by Kimber [101] on the dust deposition on surfaces of solar panels and its removal by rainfall. When the surfaces are very dirty, the dust is difficult to remove and calls for the adoption of a mechanical cleaning method. During extended dry spells in between periods of rainfall, dusty layers could not often be cleaned [102–104]. Caron and Littmann [105] examined the dust formation and precipitation patterns in the Southern Central Valley, California, from November 2010 to March 2012 [104]. The deployment of solar PV and wind turbine hybrid systems in remote places must be actively encouraged to harness solar radiation and wind energy effectively. Such hybrid energy systems can provide almost uninterrupted power generation throughout seasons. On and off-grid operations are feasible, and the improved reliability and economic perspectives are both due to the use of promising technologies [106–108]. Wind-solar electricity resource combinations could help ensure optimal power delivery on a regular basis [109]. Different renewable energy sources with an optimal blending of operations based on the source availability provide more sustainable power generation [110–112]. The impact of dust accumulation and soiling on performance must be considered while optimizing the solar-wind hybrid systems [113–118].

Deposited dust changes the aerofoil streamlines of wind rotors. Different deep learning algorithms help determine the optimal operation of solar-wind hybrid energy systems based on modeling climatic and geographical conditions like dust and soiling on surfaces of renewable energy systems [119–122]. Hybrid deep learning models that combine lengthy short-term memory with data filtering techniques help monitor the air quality indices at industrial locations. To estimate the hybrid power generation accurately, superior machine-learning and metaheuristic models with high accuracy must be created [123–130]. Specific machine-learning methods could be used to maintain adequate voltage and regulate frequency in renewable hybrid and integrated power systems [131–135]. Dust circulating in the ambient air and accumulating on system components affects how well solar and wind energy systems generate electricity. Wind speed is crucial to produce electricity by a turbine. While considering dust in the air, on the panels/wind rotors, and the balance of the systems, technical and financial optimization of solar-wind hybrid energy systems employing computational technologies could produce superior outcomes. The key findings on dust build-up gathered from research studies linked to PV systems and mitigation methods for the removal of dust deposition from surfaces of PV panels are shown in Table 1.

Table 1. Findings of studies on mitigating dust accumulation on PV panels from 2019 to date.

Ref.	Remarks
[136]	The PV panel soiling ratio was predicted using broadband or single–wavelength transmittance. The visible band's average transmittance corresponded to absorbance better than the ultraviolet or near-infrared wavelengths.
[137]	Simulation studies showed how dust collection influences sunlight transmittance and PV performance.
[138]	Different self-cleaning coatings on solar cell cover glass were explored experimentally.
[139]	The PV output under soiling circumstances was estimated by obtaining real-time sensor output from the site location in Sharjah.
[140]	Different dust morphologies affect the PV performance.
[141]	Soiling, raindrops and other global weather factors impacted PV production. A model for calculating hourly PV production using the performance ratio factor was presented for various climatological settings in Chile.
[142]	Using existing solar radiation data from National Renewable Energy Laboratory, the proposed model suggested the best PV tilt angle for Lahore and other locations in Pakistan. The soiling and the tilt angle of PV panels at the sites were studied.
[143]	The dust on a refrigerant-based PV/T system was investigated in Surat, India, for varying dust characteristics.
[144]	Simulation studies were conducted in three different US sites and concluded that $PM_{2.5}$ was over-estimated while PM_{10} was under-estimated.
[145]	Sand, cement, and gypsum were noted to be poorly transported and stored in Iran, resulting in significant amounts flying into the air.
[146]	Soiling rates and the fluctuation in soiling ratio over time were computed for the driest season of the year, with values ranging from 0.07 to 0.14 percent each day, in Southern Europe. The relationship between precipitation, the primary natural cleaning agent, and soiling recovery indicated that light rainfall value of approximately 2.2 mm had a 50% chance of reducing the soiling ratio.
[147]	The PV power losses from soiling on the PV panels in Lahore, Pakistan, were analyzed. The study also provided suggestions for improving the efficiency of the panel performances.
[148]	The effect of dust accumulation on the reflector of a parabolic solar thermal power plant in China was analyzed.
[149]	The surface of PV panels could be easily damaged if / when subjected to harsh mechanical cleaning procedures. To keep the PV panel surface clean and free of dirt, sensitive and electronically regulated self-cleaning processes are required.
[150]	Samples taken from sand and dust collected on 330 solar modules made by 53 manufacturers from various countries were tested.
[151]	When working outside of controlled laboratory conditions, the efficiency of PV modules was found to be significantly decreased. Lower performance and daily energy losses due to dust collection on PV modules were investigated.
[152]	Higher wind speeds lowered the maximum PV temperature and dust deposition drastically.
[153]	The self-cleaning coated panels effectively improved the panel's performance by reducing dust build-up.
[154]	The soiling process in a desert climate was simulated using optical and electrical techniques.
[155]	Dust accumulation severely impacted the visible light transmittance of glass, significantly reducing the PV system's efficiency. Due to micro-nano structures and low surface energy, a superhydrophobic coating could reduce the surface adhesion rate of dust. Most coatings of planar modules had poor durability. The durability of coatings must be enhanced.

Table 1. *Cont.*

Ref.	Remarks
[156]	Industrial materials and urban pollutants, such as sandstone, lime, and dolomite, were found to be the primary sources of dust on PV panels.
[157]	The analysis revealed that the African dust studied was a mixture of various chemical compounds, with SiO_2-type quartz accounting for approximately 73.8% and calcite ($CaCO_3$) 13.6% of the total deposition. Diffuse reflectance spectroscopy demonstrated that these particles reflected more than 70% of the irradiation reaching the PV panels.
[158]	In a climate characterized by arid conditions, dust accumulation was noted to be one of the primary concerns as it caused significant degradation of PV efficiency. Dust deposition decreased the power output of PV systems by 21.57% when compared to clean PV panels.
[159]	The impact of dust samples gathered from Iran's desert region on the power efficiency of the PV system was investigated.
[160]	An indoor laboratory experiment was performed to determine the influence of dust deposition density on PV performance.
[161]	The PV panels' performance and impact of panel soiling were examined using robotic vehicles, Mars landers and rovers.
[162]	A collision-adhesion model was used to examine the interaction between particles and the performance of PV modules.
[163]	Dust collection significantly impacted the efficiency of PV transmittance. With increasing wind speed, dust accumulation was reduced initially but subsequently increased.
[164]	Dust composition and environmental variables influenced soiling loss per unit area of PV surfaces over the years.
[165]	Dust on PV modules reduces the solar radiation received, lowering the efficiency of PV systems.
[166]	A single-diode equivalent electrical circuit was used to simulate and forecast the electrical behavior of a PV system.
[167]	Soiling, or the accumulation of particulate matter on the surfaces of PV modules, reduced the total solar energy harnessed by the system. Because of the impact on energy production and associated maintenance costs, evaluating environmental factors was found to be essential in developing a PV installation.
[168]	The power loss due to soil deposition on PV panel surfaces was estimated using a probabilistic quantification with soiling image analysis.
[169]	Three natural dust samples were analyzed for structural, chemical, and optical attributes, including their undesirable impact on energy transmission from a plant.
[170]	Sudden climate changes, including sandstorms or long spells of rain, were observed to induce alterations in energy output rates of a PV system.
[171]	A luminescence image was utilized to detect and categorize soiling and quantify the losses.
[172]	A hydrophobic nano coating's function in reducing energy losses was investigated. The transmission loss reduced significantly when dust deposition was reduced. The effect of dust composition and accumulation densities on PV power output was examined.
[173]	Solar PV panels were exposed to dust circulating in the external surroundings, which was a serious cause of performance detriment. The selected study location was an area with severe air pollution and low rainfall during the dry winter months due to its unpredictable environmental conditions.
[174]	The electrical characteristics, dust life cycle, and cleaning techniques were found to be associated with the performance of PV systems installed in various climatic zones around the globe.
[175]	In regions with high soiling rates, dust storms, water scarcity, and high solar energy potential, soiling was a significant obstacle to solar power generation. In high humidity conditions, dew condensation on the solar panels significantly affected the cementation of dust particles.
[176]	The impact of dust collection and soiling on the PV panel's performance was investigated in Australia.
[177]	The grid-connected PV system's performance impacted the collection of dust and soiling effects.
[178]	The soiling mitigation of a ground-mounted solar panel soiling was statistically explored. Gravity was seen to influence the behavior of dust particles greatly.

Table 1. *Cont.*

Ref.	Remarks
[179,180]	The effect of dust density on energy efficiency was examined to estimate the influence of dust particle accumulation on PV performance.
[181]	Accumulation of dust on the solar collector was noted to result in a significant reduction in system efficiency. Changes in the thermoelectric and exergy behavior under varying dust levels were analyzed, and the impact of dust density on overall PV system efficiency was evaluated. In the conducted natural dust deposition experiments, the effect of seasonal silt accumulation on the efficiency of a PV system was investigated.
[182]	Soiling on PV modules reduced the solar irradiance of the modules, diminished their performance significantly, and resulted in substantial economic losses. Soiling was noted to be a complex phenomenon that varies with location, time, and measurements.
[183]	Optical losses caused by dust deposits on the mirrors of the solar panels were analyzed.
[184]	The model of a one-diode solar cell is improved by including the study of dust impact in the simulation of solar cell performance to test the suggested model. Three primary components of dust were used in varying proportions.
[185]	The electrical performance of modules with and without anti-soiling coating was analyzed at various incidence angles and soiling layers.

Solar PV systems are electrical generators that use the PV effect to convert sunlight into electricity. A grid of solar cells housed in a protective metal casing makes up a solar PV system. All photons from the sun that strike it are converted into useful energy. Its two main extra attachments are the battery banking system and the solar tracking system, which help improve overall performance (storing the output power). Many people employ solar PV technology because it is flexible and adaptable. A solar PV system's size varies greatly depending on the load and the application. Careful upkeep is necessary to keep solar PV systems operating at their optimal level and to lower the probability of breakdowns. Advanced cleaning methods with high accuracy and minimal energy requirements are essential for large-scale deployments. Due to thermal stress, uncleaned panels are frequently exposed to temperature increases and panel deterioration [186–190]. Water immersion is one method that offers the dual benefits of both cooling and cleaning PV modules [191]. The last two decades have seen much research into different panel cleaning and cooling strategies [192–194]. Phase change material-based cooling of PV and electronics has gained much attention in recent decades due to their contribution to cooling and energy storage [195]. The daily dust density deposited on the surface of the PV module was 0.9867 mg/cm^2 in desert areas [196]. Dust deposition reduced the efficiency of monocrystalline and polycrystalline solar PV modules by 3.55% and 3.01%, respectively.

Cooling and cleaning the PV system by passive, mechanical methods on a periodical basis improves the efficiency of solar cells and maintains the protection offered by selective coatings [197,198]. The temperature distribution plays a significant role in PV power output [199,200]. Drone-based image capture and selective deep learning algorithms with cleaning techniques pave the way to improved performance and prolonged life of PV systems [200–202]. Figure 6 shows the difference in power output for different cleaning frequencies from weekly to annually [200]. Figure 7 shows the effect of dust volume on solar panel power output [192].

The cleaning frequency of PV panels improves the power output from PV panels. Compared to annual cleaning, the monthly cleaning showed 13.1% more power output. A linear piezoelectric actuator-based solar PV cleaning technology that is compact and lightweight is used in industries to increase power generation [203]. The solar cell's surface is cleaned by a wiper attached to an actuator that moves in a linear motion. More machine-learning research must be conducted to forecast the temperature rise caused by ambient changes and their impact on the performance of solar panels. Mechanical, natural, electrostatic, and self-cleaning nanofilms are a few options for removing dust, dirt, soot, and grime from PV panel surfaces [204,205]. PV dust deposition density of 20 g/m^2 reduces short-circuit current, open circuit voltage and efficiency by 15–21%, 2–6%, and 15–35%, respectively [206,207]. Thus, selective and reliable coatings for PV are essential to mitigate dust deposition and its adverse consequences. Many researchers have been figuring out how to lower the cost of cleaning solar modules [208,209]. The amount and size of dust particles on a PV surface affect efficiency in a direct proportion [210–215]. The power output and module efficiency both decrease as the amount of dust implantation rises [216–218]. Different cleaning techniques are needed in semi-arid environments. The best approach for cleaning PV panels is by using water and a brush. This simple cleaning technique can produce 97.2% cleaning efficiency in dry and 98.8% in wet seasons. Sand removal from the PV surface can be achieved more effectively by applying electrostatic force. About 90% of the sand from the PV surface can be removed using this technique. This innovative technology may be exceptionally helpful in maintaining solar power plants installed in desert regions.

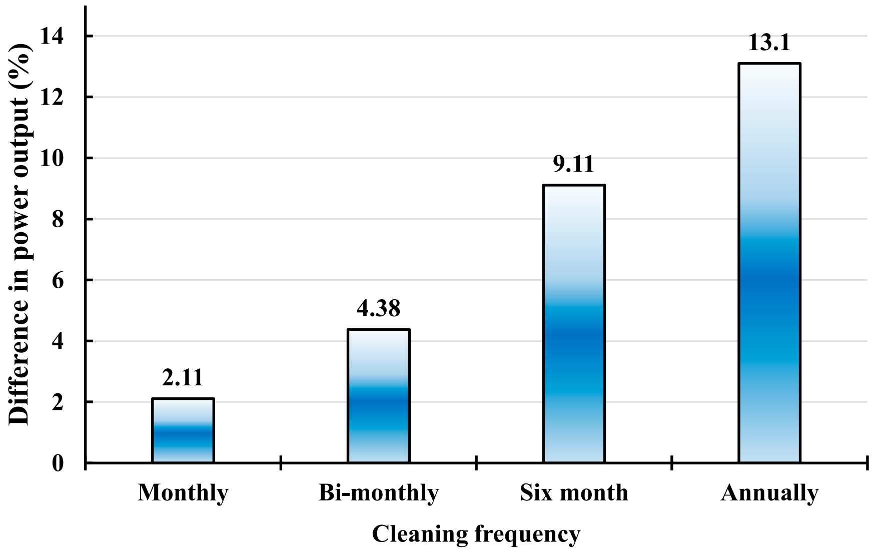

Figure 6. The difference in power output for the weekly cleaned PV panels with monthly, bi-monthly, once in six month, and annual cleaning frequency [200].

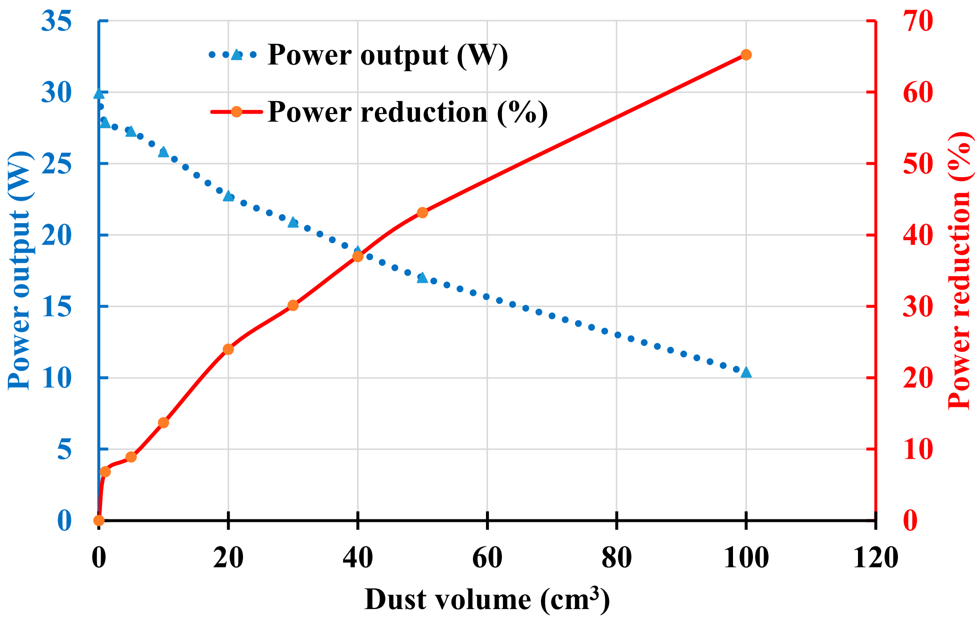

Figure 7. Effect of dust volume on solar panel power output [192].

A robotic arm system with an electromechanical drive can be used effectively to clean the PV module surface. This robot system's effectiveness can be calculated quantitatively. The power generation performance and efficiency of solar panels are mainly affected by the accumulation of dirt, dust, soot, bird droppings and other particulate matter. A few automatic cleaning devices have also been manufactured to tackle the issue of dust particle deposition on PV panel surfaces. Figure 8 shows the energy conversion in hybrid energy systems. Hybrid energy systems benefit from overcoming the non-linearity in power generation by optimally combining power sources and energy storage systems [219,220].

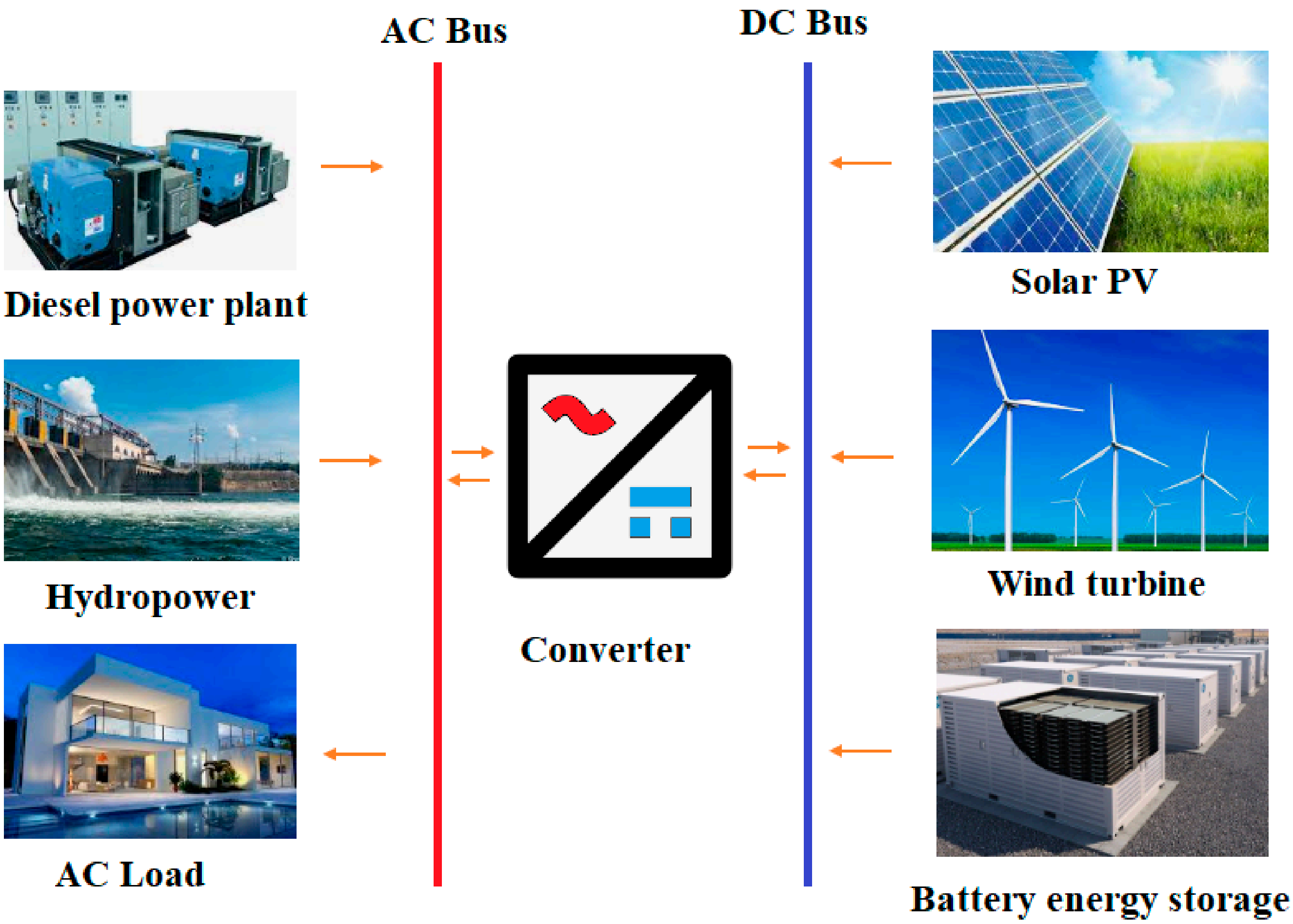

Figure 8. Energy conversion in hybrid energy systems.

Solar power systems are at risk of soiling as they are installed in outdoor environments. "Soiling" is the term used to describe the accumulation of dirt, dust, and other organic and inorganic pollutants on the surfaces of the PV module. These deposits pose a possible risk to photovoltaic systems because they absorb, reflect, and scatter some of the light that strikes the PV panel surface. As a result, less light reaches the PV cell because of the blockage by dust deposition. This lowers the efficiency of PV systems, as they produce less power. Contrarily, anti-soiling measures can counteract the effects of soiling through careful observation and optical measurement techniques, leading to higher productivity and efficiency. Appropriate extraction algorithms should be utilized during process monitoring to gauge the degree of soiling. Suitable measures must be adopted to remove dust deposits on a regular basis to prevent the soiling of PV panel surfaces. Figure 9 shows the life cycle of deposited dust on surfaces of PV panels [193].

Figure 10 outlines various dust and debris cleaning strategies. There are two types of cleaning and mitigation measures. Both natural and synthetic cleaning products are used. Rain, wind, snow, gravity, and dew all contribute to the cleaning process of nature. There are many ways of mechanical cleaning, including manual, semi-automated, and automated methods, as well as electrodynamic screen cleaning and heating of the surface. Preventive measures include setup (tracking system, site adaption, and site selection) and installation of special PV modules (anti-soiling coating, optimized module design).

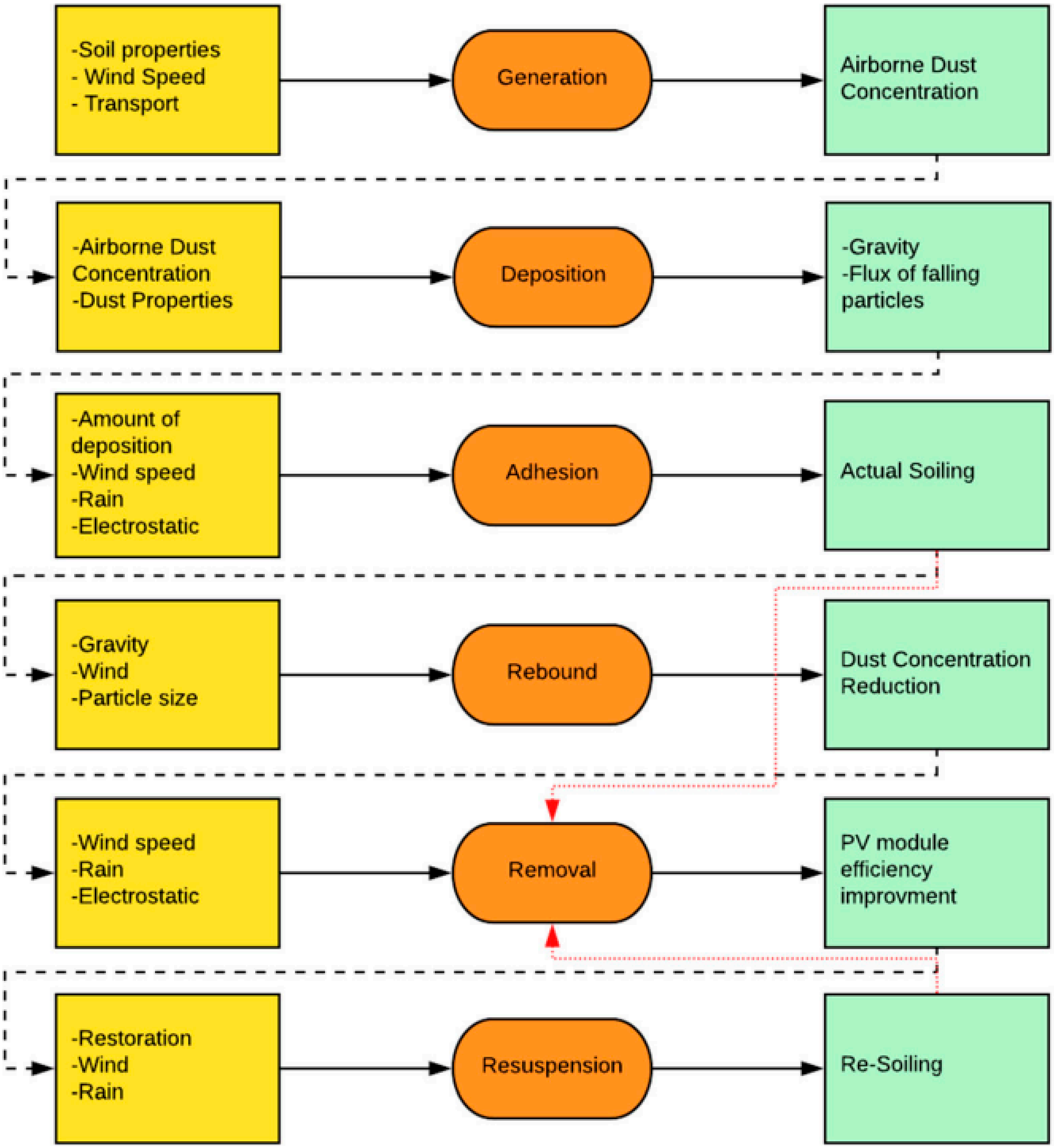

Figure 9. The life cycle of dust accumulation on solar PV panel surfaces [193].

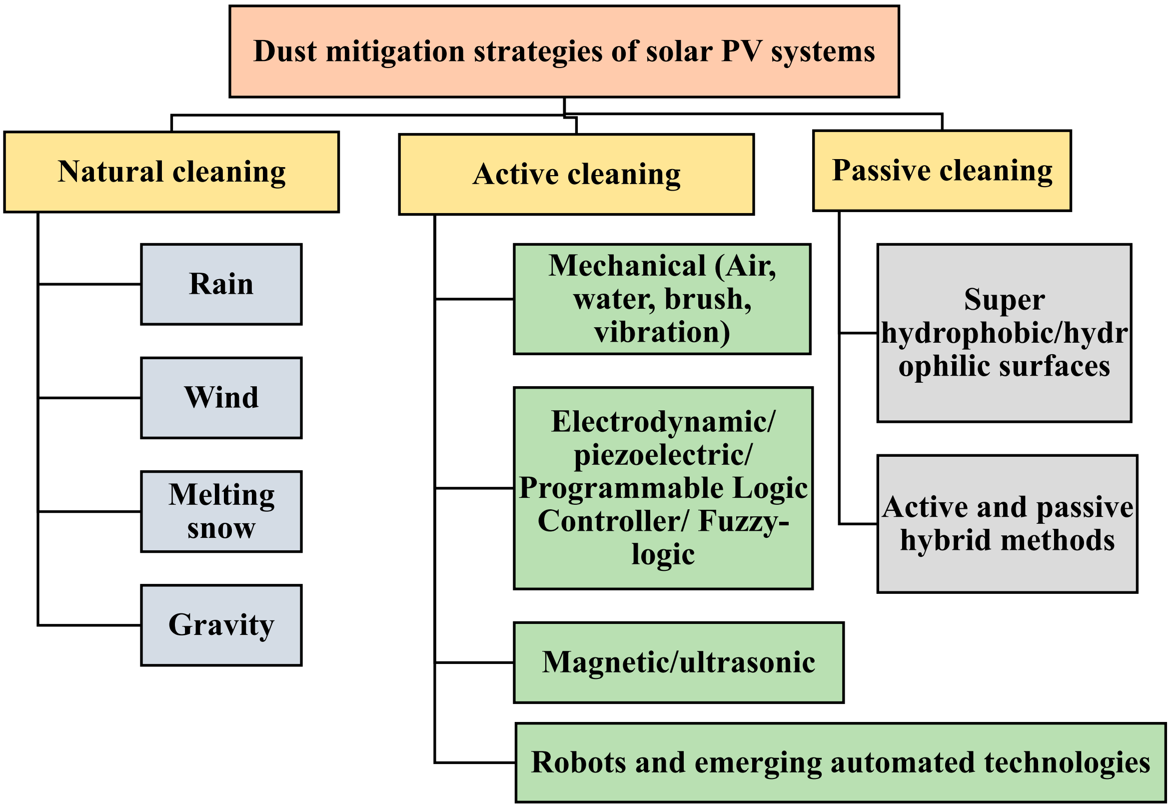

Figure 10. Dust mitigation methods and techniques adopted for solar PV systems.

The electrical output of a PV device with soiled surfaces is measured and compared with that of a clean PV device at soiling stations (requires two PV devices). The cleaning procedure must be carried out based on the desired outcome. Commercial de-soiling facilities are common and readily available. They are a routine monitoring method that can directly measure the influence of the soiling of PV surfaces on power output. It is important to note that soiling stations must be regularly serviced, require human interaction (are not autonomous), and only achieve partial cleanliness. The effectiveness of automatic cleaning is poor. It tends to overlook a few hard-to-access areas, such as the device's sides and corners. Improvements in cleaning efficiency and new automation methods are priorities for the soiling stations to avoid power output losses and maintain the performance and efficiency of PV panels.

The electrical loss is estimated using optical soiling measurement detectors, which characterize the optical characteristics of the soiling build-up on PV glass surfaces. The Dust IQ detector and the Mars soiling sensor are the first devices that became available in the market for sale. The level of soiling on the PV cells is then quantified using image processing techniques in Open Street Maps. These detectors' primary advantages are their affordable price and the encouraging results they show in field validation. Subsequently, soiling losses are estimated using sensors. The soiling losses of full-sized PV modules can be calculated with the help of small glass coupons, which are measured by sensors. Images of the PV module are analyzed using image analysis sensors, which calculate the soiling coverage area. Coverage measurements are used to estimate soiling levels. Sensors for use in image analysis are the subject of ongoing study. Sensors based on image analysis technology can directly quantify soiling on PV modules, detect soiling that is not uniform, and identify various failure and defect types in PV panels. However, the implementation and optimization of sensors are focused on cost, as the technology becomes unworkable if not constantly monitored.

The dust particles are directly deposited on the PV panel when subjected to the physical environment. It is unavoidable, but it would be removed by inducing a new clearing strategy manually or automatically. Dust particle swarm accumulation and power loss reduction of the solar PV cell module using automatic tilt adjustment carried by a flexible, powerful sensor unit [157]. The PV module was automatically tilted by a powerful, flexible sensor unit attached to it. Drones have recently gained traction as a convenient tool for monitoring PV modules through image-processing algorithms. More factors, such as reflection, camera settings, and lighting, affect sensors and must be properly analyzed. Further research is required to improve the prediction and control of smooth power generation from hybrid energy systems using resource-efficient computing models. Figure 11 shows schematic layout of solar PV plant components and connections for PV array performance, cleaning schedules, control, and monitoring [27]. The percentage of power output losses due to the dust over a period is depicted in Figure 12 [30].

Smaller dust particles are better at blocking the radiation from PV modules; hence power output deficits are made worse as they get smaller. Sand, silica, ash, and red soil are a few examples of the various deposits. The energy output of panels exposed to the environment for as little as two months without cleaning can decrease by 6.5% due to contaminated air. The PV cells in the desert receive a lot of dust. To determine electrical performances, dust accumulations are examined using radiation, particle size, mass, and operating circumstances. Since there had been no rain for so long, a significant portion of energy was lost. Depending on the circumstances surrounding their formation, dust particles have various physical and chemical characteristics. Weight and size are further distinguishing characteristics. Beyond merely wind speed and direction, there are other environmental elements that contribute to dust and its accumulation in the PV cell. The output of a PV system is, at best, hardly affected by dust. The PV system cleaning technology helps protect and maximize solar cells' performance. Surface dust can be removed in various ways, including mechanically, naturally, electrostatically, and using self-cleaning mechanisms.

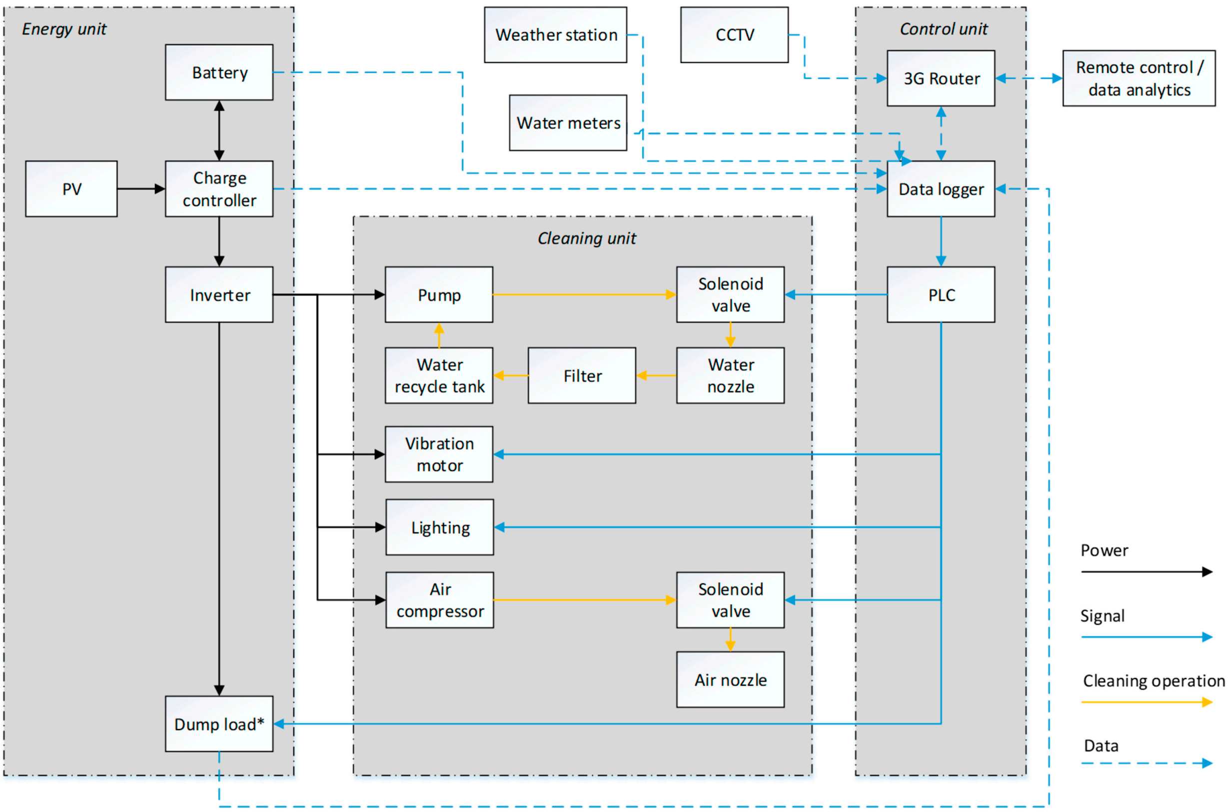

Figure 11. Schematic layout of solar PV plant components and connections for PV array performance, cleaning schedules, control, and monitoring [27].

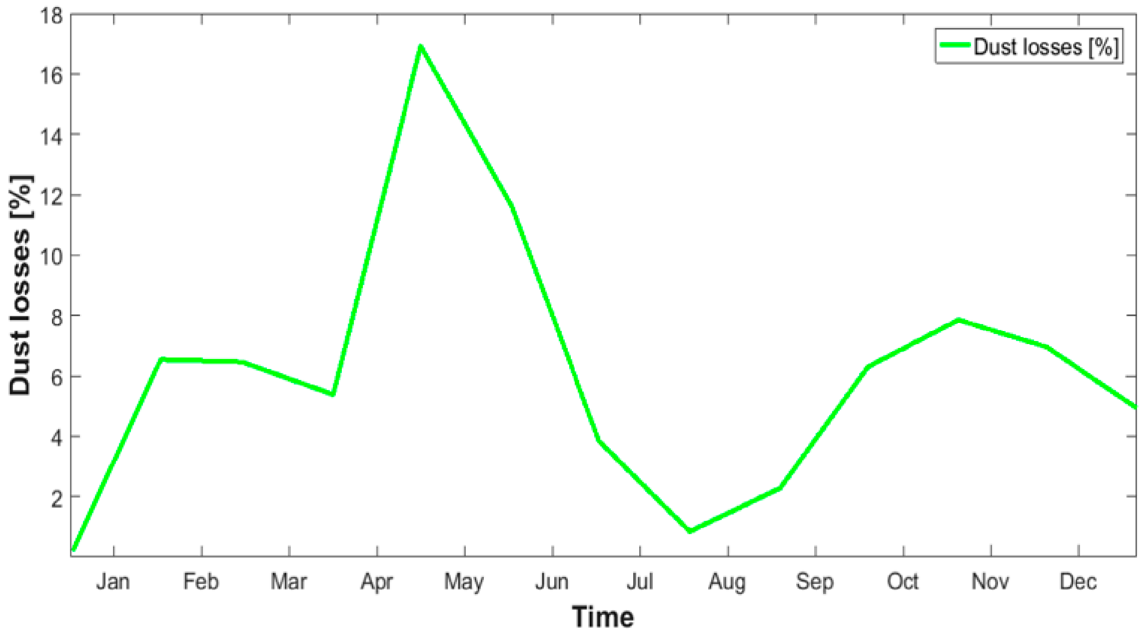

Figure 12. Variation of daily dust losses over the months [30].

Compact and lightweight solar panel cleaning technology based on linear piezoelectric actuators is used in the solar PV industry to increase power generation. A linear actuator with a wiper is used to clean the solar cell's surface. A lot of researchers have been trying to figure out how to lower the cost of cleaning equipment for solar modules. Modified cleaning procedures are required in the semi-desert environment. The most effective means of cleaning is water and a brush. Academics, engineers, and designers continue to evince keen interest in the solar PV system. The use of a cost-effective coating with self-cleaning characteristics must be investigated as it offers the primary benefit of a low bonding force between dust particles and panel surfaces.

5. Conclusions

The capacity of PV panels to produce electricity is significantly impacted by the accumulation of dust and other particulate matter on their surface. Dust from the ambient air collecting on PV panel surfaces lowers the solar radiation that reaches the PV surface. As the dust particles cling to the panel surfaces, they can lead to scratches and corrosion, decreasing the panels' lifespan. Influencing factors such as characteristics of collected dust and ambient conditions must be considered in the design of solar plants. Examining the problems of dust collection on panels, along with its adverse effects and mitigation strategies, can contribute to devising safe and efficient dust-cleaning techniques for solar panels. How dust deposition affects solar panels' performance must be critically analyzed. The key findings of the current review study are outlined below.

- The deposition of dust particles on the surfaces of solar panels affects their performance by reducing the solar radiation reaching the cells and shortening their average lifespan.
- The size and structure of the dust particles deposited on PV panel surfaces and other environmental factors like wind and temperature affect the PV system's efficiency.
- Even though the frequency of dust storms and precipitation are significant natural factors, there is no established schedule for the removal of dust deposited on the surfaces of PV modules.
- Hydrophobic and hydrophilic surfaces are more beneficial passive techniques than traditional power-consuming and water-intensive cleaning technologies.
- Advanced cleaning technologies like electrostatic and ultrasonic methods could provide better benefits than fluid jet cleaning methodologies.

- Automated detection of dust and other contaminants on panel surfaces and deploying appropriate cleaning techniques on time could be very beneficial for sustaining the performance of PV systems.

More research is required to combat dust deposition using drone image-based techniques. Based on the artificial intelligence system, an ideal cleaning method for dirty solar PV panels can be obtained with minimal auxiliary energy consumption. Considering dust in the atmosphere and deposition on the hybrid energy system's components, technical optimization of solar-wind hybrid energy systems employing computational technologies could produce better results. Models of solar irradiance and wind characteristics with effects of dust deposition and soiling on PV panels are required to assess the reliability of the output power generation. Thermally conductive selective coatings are necessary to avoid local hot spot issues while mitigating dust deposition. Thus, strong multi and interdisciplinary approaches regarding the physics of dust formation, impact analysis, panel cleaning and cooling solutions, and machine-learning based controls are essential for providing suitable solutions for dust and soiling issues of PV systems which hamper their power generation capacity and lead to power loss.

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