International Journal of Electrical Engineering and Sustainability (IJEES)
ISSN (online): 2959-9229
https://ijees.org/index.php/ijees/index
ISI 2023-2024: (0.557) Arab Impact Factor: 1.51 SJIF 2024 = 5.274
Volume 3| Number 4 | October-December 2025 | Pages 70-84

Impact of Dust, Sandstorms, and Air Pollution on Solar Energy Conversion Efficiency

Alaebad Alkhair[1]
[1]Department of Hospitality and Tourism, College of Tourism and Archaeology Technology - Garma, Libya

*Corresponding author: **makrswalabdbdalslam@gmail.com**

Received: September 09, 2025 Accepted: December 20, 2025 Published: December 27, 2025

Abstract: This article examines the impact of dust deposition, sandstorms, and air pollution on solar energy conversion efficiency, with particular focus on photovoltaic and solar thermal systems operating in harsh environments. The analysis shows that dust accumulation on solar panel surfaces reduces optical transmittance, lowers power output, and decreases overall conversion efficiency, with the severity of losses depending on particle density, size, composition, humidity, tilt angle, and exposure duration. Sandstorms were found to cause both immediate and long-term performance degradation through atmospheric reduction of solar irradiance, post-storm soiling, and mechanical abrasion of exposed surfaces. In addition, air pollution, including particulate matter, aerosols, and industrial emissions, attenuates solar radiation through scattering and absorption processes, thereby reducing the amount of usable solar energy reaching solar conversion devices and increasing uncertainty in energy yield prediction. The study further highlights that mitigation strategies such as regular cleaning, anti-soiling coatings, optimized tilt angles, real-time monitoring, and predictive maintenance are essential for limiting performance losses and improving system reliability. Overall, the findings confirm that environmental degradation mechanisms must be systematically integrated into solar energy planning, design, and operation to enhance energy yield, reduce maintenance costs, and ensure the long-term technical and economic viability of solar systems in dusty and polluted regions.

Keywords: Dust deposition, Sandstorms, Air pollution, Solar energy conversion efficiency.

1. Introduction

Solar energy has emerged as one of the most promising pathways for achieving a sustainable and low-carbon energy future [1,2]. With the global increase in electricity demand and the urgent need to reduce greenhouse gas emissions, photovoltaic and solar thermal technologies have gained considerable attention as clean and renewable alternatives to fossil-fuel-based power generation. Their deployment has expanded rapidly in arid, semi-arid, and urban regions where solar irradiance is abundant and large-scale installations are technically feasible [3,4]. However, despite the significant potential of solar systems, their actual energy conversion efficiency is strongly influenced by environmental conditions that affect the transmission, absorption, and utilization of solar radiation [5,6]. Among these conditions, dust deposition, sandstorms, and atmospheric pollution represent critical challenges that can substantially reduce system performance and economic viability.

Dust accumulation on the surface of solar collectors and photovoltaic modules is one of the most widely recognized factors responsible for efficiency degradation. In many dry and desert climates, airborne dust particles settle on panel surfaces, forming a layer that blocks or scatters incident sunlight before it reaches the active solar cells [7-10]. This phenomenon, often referred to as soiling, reduces optical transmittance and lowers the electrical output of the system. The severity of this impact depends on several variables, including particle size, dust composition, deposition density, panel tilt angle, humidity, and exposure duration [11-13]. As a result, even regions with high solar potential may experience considerable energy losses if soiling effects are not properly monitored and mitigated through regular maintenance or advanced surface protection techniques.

In addition to gradual dust deposition, sandstorms pose a more intense and sudden environmental threat to solar energy systems, particularly in desert and coastal regions. Sandstorms can dramatically reduce solar irradiance by increasing atmospheric turbidity and limiting the penetration of sunlight through the atmosphere [14-16]. At the same time, they may cause rapid accumulation of sand and abrasive particles on solar panel surfaces, which not only decreases power generation but may also damage protective glass layers and shorten system lifespan. The recurring occurrence of sandstorms in many solar-rich regions makes them an important subject of investigation, especially for countries seeking to expand solar energy infrastructure under harsh climatic conditions. Understanding the direct and indirect effects of sandstorms is therefore essential for improving system resilience and maintaining reliable electricity generation [17-19].

Air pollution further complicates the relationship between solar resource availability and solar energy conversion efficiency. Pollutants such as aerosols, particulate matter, black carbon, sulfur dioxide, nitrogen oxides, and other industrial emissions can alter atmospheric transparency by absorbing and scattering incoming solar radiation [20-23]. This attenuation reduces the quantity and quality of sunlight reaching solar conversion devices, thereby affecting both photovoltaic electricity generation and solar thermal heat collection. In urban and industrial areas, where air pollution levels are often elevated, the combined influence of polluted atmospheres and surface contamination may lead to a significant reduction in system productivity [24,25]. Moreover, the interaction between air pollutants and meteorological variables such as wind speed, temperature, and humidity can create complex environmental conditions that require detailed analysis for accurate performance assessment [26-30]. Several studies have examined the impact of dust deposition, sandstorms, and air pollution on solar energy conversion efficiency, as presented below.

In [31], this study investigated how dust composition, relative humidity, and air quality collectively affect the performance of photovoltaic (PV) systems in Jubail, Saudi Arabia, which represents a typical arid coastal environment. Four dust categories, montmorillonite, kaolinite, bentonite, and natural dust were deliberately deposited on polycrystalline PV modules at surface loadings ranging from 1.0 to 7.0 g/m^2 under controlled outdoor conditions during September 2025. At the same time, key atmospheric variables, including relative humidity, air quality index (AQI), and module surface temperature, were continuously monitored to evaluate their interaction with dust-induced performance degradation. Scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) identified clear differences in mineralogical composition, showing that natural dust contained high proportions of silica (25.37%) and calcium oxide (30.52%), whereas montmorillonite exhibited a notably high iron content (62.67%), which affected both light transmittance and thermal behavior.

The study [32] indicated that photovoltaic conversion efficiency remains nearly constant at specific particle loading levels, suggesting a nonlinear relationship between particulate deposition density and conversion efficiency. Overall, dust accumulation was found to reduce solar PV panel efficiency within a range of 7.8% to 19.2%, depending on the degree of surface contamination. At the same time, the experimental findings showed an efficiency recovery of about 6.8% to 7.9%, reflecting the beneficial effect of partial dust removal or cleaning. Natural environmental factors, particularly wind and rainfall, were also observed to improve PV performance because they help remove deposited dust from the panel surface and restore light transmittance.

This research [33] aimed to improve solar energy forecasting in dust-prone regions such as the United Arab Emirates, where frequent dust storms reduce photovoltaic (PV) performance through the scattering and absorption of incoming solar radiation. Many conventional forecasting models do not adequately account for dust events, which often leads to reduced prediction accuracy under such atmospheric conditions. To overcome this limitation, the study develops and compares several machine learning approaches, including long short-term memory (LSTM), gated recurrent unit (GRU), and hybrid LSTM-GRU models, using a combination of solar, meteorological, and dust-related input variables. The models were tested over multiple forecasting horizons of 1, 6, 12, and 24 hours, and the results showed that incorporating dust-related features significantly improves forecasting accuracy, particularly for short-term prediction intervals. Temporal and seasonal analyses further revealed that dust events occur most frequently during the late afternoon and early spring, and are strongly associated with noticeable reductions in solar power generation.

This article contributes to the solar energy literature by providing an integrated assessment of how dust deposition, sandstorms, and air pollution jointly affect solar energy conversion efficiency under real environmental conditions. It clarifies the mechanisms through which surface soiling, atmospheric attenuation, and abrasive storm events reduce optical transmittance, solar irradiance availability, power output, and long-term system reliability in photovoltaic and solar thermal applications. The article also advances practical understanding by linking environmental degradation factors with mitigation strategies such as cleaning technologies, anti-soiling coatings, optimized tilt angles, monitoring systems, and predictive maintenance approaches. In doing so, it offers a comprehensive framework that supports more accurate performance evaluation, improved maintenance planning, and more resilient design of solar energy systems in dusty, polluted, and harsh climatic regions.

2. Assessment of Dust Deposition Effects on Photovoltaic Performance

Dust deposition is one of the most critical environmental factors affecting the operational performance of photovoltaic (PV) systems, particularly in arid, semi-arid, and industrial regions [33-35]. As dust particles accumulate on the surface of solar panels, they form a layer that reduces the transmission of solar radiation to the photovoltaic cells. This reduction in light transmittance directly decreases the amount of absorbed energy, resulting in lower current generation, reduced power output, and diminished overall conversion efficiency. The severity of this effect depends on several interacting factors, including dust density, particle size, chemical composition, panel tilt angle, surface roughness, and local climatic conditions such as wind speed, humidity, and rainfall [36-38]. Consequently, even in locations with high solar irradiance, dust accumulation can significantly compromise the technical and economic effectiveness of PV installations if not properly managed. Figure 1 illustrates criteria for evaluating the impact of dust deposition on photovoltaic efficiency.

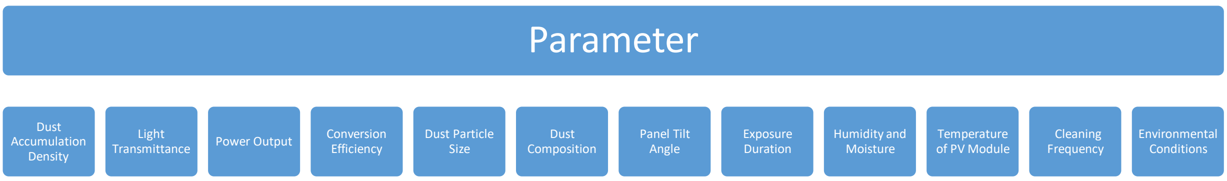

Figure 1. Criteria for evaluating the impact of dust deposition on photovoltaic efficiency.

Assessing the effects of dust deposition on photovoltaic performance is therefore essential for understanding real-world efficiency losses and improving system reliability. Such an assessment helps quantify the relationship between soiling intensity and electrical performance parameters, including short-circuit current, open-circuit voltage, maximum power output, and energy yield. It also supports the development of suitable mitigation strategies, such as optimized cleaning schedules, anti-soiling coatings, automated washing systems, and improved panel design configurations [39-41]. Furthermore, evaluating dust-related losses under different environmental conditions provides valuable insights for site selection, maintenance planning, and long-term performance forecasting of solar energy systems. For this reason, the study of dust deposition effects has become a major research focus in photovoltaic engineering, especially in regions where airborne particles are a persistent challenge to sustainable solar power generation [42,43]. Table 1 summarizes the main variables associated with dust deposition on photovoltaic modules and highlights their influence on light transmittance, power output, and overall conversion efficiency under different environmental conditions.

Table 1. Assessment of dust deposition effects on photovoltaic performance [44-48].

Parameter	Description	Effect of Dust Deposition on PV Performance
Dust Accumulation Density	Amount of dust deposited on the solar panel surface over time.	Higher dust density blocks more sunlight, leading to a significant reduction in energy output.
Light Transmittance	Ability of solar radiation to pass through the panel glass and reach the solar cells.	Dust layers reduce light transmittance, decreasing the amount of usable solar irradiance.
Power Output	Electrical power generated by the photovoltaic module.	Dust deposition lowers the generated current and overall power output.
Conversion Efficiency	Ratio of electrical energy produced to the incident solar energy received.	Reduced light penetration causes a decline in photovoltaic conversion efficiency.
Dust Particle Size	Physical size of deposited dust particles.	Smaller particles may form compact layers, while larger particles may cause partial shading; both negatively affect performance.
Dust Composition	Chemical and mineralogical characteristics of dust, such as sand, clay, salts, or industrial particles.	Certain dust types adhere more strongly and cause greater optical losses than others.
Panel Tilt Angle	Inclination angle of the solar panel relative to the horizontal surface.	Lower tilt angles often promote greater dust accumulation, while steeper angles may allow partial self-cleaning.
Exposure Duration	Length of time the panel remains uncleaned under dusty conditions.	Longer exposure increases dust buildup and intensifies efficiency degradation.
Humidity and Moisture	Presence of atmospheric humidity or dew on panel surfaces.	Moisture can cause dust to stick more firmly, making cleaning more difficult and increasing losses.
Temperature of PV Module	Operating temperature of the solar panel during dust exposure.	Dust may indirectly increase module temperature by reducing heat dissipation, further lowering efficiency.
Cleaning Frequency	Number of cleaning cycles performed during operation.	Frequent cleaning helps restore transmittance, power generation, and system efficiency.
Environmental Conditions	Local climate factors such as wind speed, rainfall, and atmospheric dryness.	Wind may increase dust transport, while rainfall can naturally remove some deposited particles.

Dust deposition has a pronounced negative influence on photovoltaic performance because it creates a physical barrier between incoming solar radiation and the active surface of the module. As the level of accumulated particles increases, optical transmittance declines, which limits the amount of sunlight reaching the solar cells. This reduction leads directly to lower photocurrent generation and a noticeable drop in output power. In practical operation, even a thin layer of deposited material can cause measurable efficiency losses, especially under high-irradiance conditions where the energy potential of the system would otherwise be at its maximum.

The severity of performance degradation also depends on the physical and chemical characteristics of the deposited material. Fine particles often form a compact and uniform layer over the glass surface, which can significantly restrict light penetration. Larger particles may produce partial shading and non-uniform coverage, creating localized performance losses across the module. In addition, dust composition plays an important role, since sticky or hygroscopic materials such as salts, clay, and industrial residues tend to adhere more strongly to the panel surface and are harder to remove. Such conditions can prolong soiling effects and intensify the reduction in energy yield over time.

Environmental and design-related factors further shape the magnitude of dust-related losses. Panel tilt angle is one of the most influential parameters, since low-angle installations generally retain more dust, while steeper configurations may allow partial self-cleaning through gravity and wind action. Humidity can worsen the situation because moisture helps particles attach more firmly to the surface, forming crusted layers that are difficult to clean. Longer exposure periods without maintenance also increase deposition density and cause cumulative efficiency decline. Under dusty climates, a lack of regular cleaning can therefore result in substantial reductions in annual electricity production and economic return.

Maintenance strategies are essential for limiting such losses and restoring photovoltaic performance. Frequent cleaning helps recover light transmittance, output power, and conversion efficiency, particularly in regions exposed to persistent airborne particles. Effective mitigation may also include anti-soiling coatings, optimized tilt design, and monitoring systems capable of identifying performance drops linked to surface contamination. A clear understanding of the relationship between dust accumulation and photovoltaic behavior is therefore necessary for improving system reliability, reducing operational losses, and enhancing the long-term viability of solar energy projects in challenging environments.

3. Influence of Sandstorms on Solar Irradiance and Energy Generation

Sandstorms are among the most significant environmental challenges affecting the performance and reliability of solar energy systems, particularly in arid and semi-arid regions where photovoltaic deployment is rapidly expanding as outlined in Figure 2. During sandstorm events, large concentrations of suspended dust and sand particles alter atmospheric transparency through scattering and absorption processes, which substantially reduce the amount of solar radiation reaching photovoltaic and solar thermal collectors [49,50]. This reduction is especially critical for direct normal irradiance, which may decline much more sharply than global horizontal irradiance, thereby causing immediate fluctuations in power generation and limiting the stability of solar electricity supply. In addition to atmospheric attenuation, sandstorms often leave considerable amounts of deposited particles on module surfaces, forming a soiling layer that continues to degrade optical transmittance and energy conversion efficiency even after the storm has ended [51,52].

Figure 2. The Effect of Sandstorms on Solar Irradiance and Energy Production.

Beyond temporary irradiance losses, repeated exposure to sandstorms may also lead to long-term physical degradation of solar system components. High-velocity sand particles can produce abrasion on front glass, anti-reflective coatings, and exposed structural materials, gradually reducing optical quality and shortening operational lifetime. Such conditions increase maintenance frequency, cleaning requirements, and operational costs, while also complicating energy forecasting and system planning. Therefore, understanding both the short-term and cumulative impacts of sandstorms on solar irradiance and energy generation is essential for improving the technical resilience, economic viability, and long-term sustainability of solar installations in dust-prone environments [53-58].

A. Severe reduction in solar irradiance during sandstorm events

Sandstorms can cause a major decline in the solar resource available to photovoltaic (PV) and concentrating solar power (CSP) systems because airborne mineral dust increases atmospheric extinction through scattering and absorption. Quantitative studies have reported an average reduction of about 11% in global horizontal irradiance (GHI) and about 41% in direct normal irradiance (DNI) during strong dust events, while other observations showed solar radiation intensity deterioration of up to 54.5% relative to pre-storm conditions. In Kuwait, prolonged dust-haze or sandstorm-like events lasting more than 12 hours were associated with irradiance reductions reaching 60%, which demonstrates how strongly suspended particles can suppress solar input in desert climates.

B. Rapid short-term decline and instability in power generation

Because PV output is closely linked to incident irradiance, sandstorms often trigger abrupt reductions in voltage, current, and instantaneous power. Recent assessments indicate that sandstorms can reduce PV efficiency by around 20% within minutes, while large-scale grid analyses have shown even stronger effects during extreme events. For example, during the March 2022 Saharan dust episode over Spain, the national PV capacity factor dropped by 50%, and PV contribution to electricity demand fell from an expected 11% to only 7% during the event. Such short-term variability is particularly important for grid operators because sudden irradiance collapse can increase forecast error, reduce dispatch reliability, and require faster balancing reserves.

C. Persistent post-storm losses due to deposited dust and sand

The impact of a sandstorm does not end when the storm passes, because a residual layer of deposited particles often remains on the module surface and continues to block light transmission. Experimental evidence shows that a dust loading of 10 g/m^2 can reduce peak PV output power by approximately 34%, while long outdoor exposure under dry conditions has produced a 21.47% drop in power after 70 days with a measured surface deposition of 6.10 g/m^2. Field-based techno-economic analysis also found that energy losses immediately after sandstorm days reached 7.37 kWh, equivalent to about 1.45% of total production over a 7-day operating period containing two storm days. This confirms that post-storm cleaning strategy is a critical part of energy-yield recovery in dusty regions.

D. Mechanical abrasion and long-term optical degradation of solar surfaces

High-velocity sand particles can erode front glass, damage anti-reflective coatings, and create micro-scratches that reduce optical transmittance and short-circuit current over time. Reliability studies note that abrasion degrades glass transmittance and therefore directly lowers photocurrent generation in long-term desert operation. Sandstorm erosion experiments on solar reflective materials have recorded specular reflectance losses exceeding 40% under severe exposure, while PV durability testing standards often use a 5% transmittance-loss threshold as a meaningful failure criterion for coated glass surfaces. Although reflectors and PV cover glass are not identical components, both sets of findings indicate that repeated sand impact can move solar surfaces from reversible soiling losses toward irreversible material degradation.

E. Long-term consequences for annual yield, maintenance, and plant economics

Repeated sandstorm exposure can significantly reduce annual energy production and increase operation and maintenance requirements, especially in arid and semi-arid zones. A recent synthesis reported that Saharan dust events commonly reduce PV output by about 25–40%, with losses exceeding 50% during extreme episodes. Broader assessments of dust accumulation indicate that annual revenue losses can reach about 35% when solar radiation is reduced by 20% due to soiling, and reported cleaning costs range from USD 0.016 to 0.9 per m^2 depending on technology and site conditions. Field optimization studies further suggest that cleaning immediately after sandstorm days is economically preferable, and in some cases a cleaning interval of around 20 days kept energy reduction near 1.60% under dust-accumulation conditions.

Sandstorms have a substantial and multidimensional impact on solar energy systems, influencing both the availability of solar radiation and the operational condition of system components. Their short-term effects are mainly associated with severe reductions in solar irradiance, sudden fluctuations in photovoltaic output, and temporary instability in energy generation. At the same time, post-storm dust deposition creates persistent soiling losses that continue to suppress module performance until effective cleaning or natural removal occurs. Repeated storm exposure further intensifies the problem through surface abrasion and gradual material degradation, which can reduce optical transmittance and undermine the long-term durability of solar panels and related infrastructure.

Overall, the influence of sandstorms extends beyond a temporary weather disturbance and must be treated as a major design and operational consideration for solar projects in desert and polluted regions. Accurate assessment of irradiance losses, deposited dust effects, and abrasion-related damage is necessary for improving energy yield prediction, optimizing maintenance schedules, and reducing economic losses. Consequently, integrating storm-resilient design features, regular cleaning strategies, anti-soiling technologies, and environmental monitoring systems will be essential for sustaining reliable solar energy conversion under harsh climatic conditions.

4. Impact of Air Pollution on Solar Radiation Attenuation

Air pollution is a major environmental factor that can significantly influence the performance of solar energy systems through its effect on atmospheric transparency and solar radiation transmission. Pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), aerosols, black carbon, sulfur dioxide, nitrogen oxides, and industrial emissions modify the optical properties of the atmosphere by scattering and absorbing incoming sunlight before it reaches the Earth's surface [59-62]. This process, known as solar radiation attenuation, reduces the intensity and quality of available solar energy, thereby lowering the amount of usable irradiance received by photovoltaic and solar thermal systems. The problem is especially pronounced in urban, industrial, and densely populated regions where pollutant concentrations are persistently high and haze formation is frequent.

The attenuation of solar radiation due to air pollution has both technical and economic implications for solar power generation. A reduction in direct normal irradiance affects concentrating solar technologies and tracking photovoltaic systems, while declines in global horizontal irradiance reduce the overall energy input available for electricity and heat production. In addition, atmospheric pollution can alter the spectral distribution of sunlight, which may further influence photovoltaic conversion efficiency depending on the solar-cell technology used [63-65]. For this reason, understanding the relationship between pollutant concentration, atmospheric scattering, and solar energy availability is essential for accurate performance prediction, system design, site selection, and long-term energy planning. Investigating the impact of air pollution on solar radiation attenuation is therefore crucial for improving the reliability and sustainability of solar energy deployment in polluted environments.

Table 2. Assessment of dust deposition effects on photovoltaic performance [66-69].

Parameter	Description	Effect of Dust Deposition on PV Performance
Particulate Matter (PM10 and PM2.5)	Fine and coarse airborne particles suspended in the atmosphere	Scatter and absorb solar radiation, reducing the intensity of sunlight reaching photovoltaic and solar thermal systems
Aerosol Concentration	Amount of liquid or solid particles present in the air	Increases atmospheric turbidity and decreases solar transmittance, leading to lower solar irradiance at ground level
Industrial Emissions	Pollutants released from factories, power plants, and combustion processes	Contribute to atmospheric opacity, reducing the amount of usable solar energy available for conversion
Black Carbon	Light-absorbing carbonaceous particles produced from incomplete combustion	Strongly absorbs incoming solar radiation, causing significant attenuation and reducing surface-level irradiance
Sulfur Dioxide (SO_2)	Gas emitted mainly from industrial activity and fossil fuel combustion	Forms secondary aerosols in the atmosphere, which enhance radiation scattering and reduce solar penetration
Nitrogen Oxides (NO_x)	Pollutant gases generated from vehicles, industry, and thermal power stations	Participate in atmospheric chemical reactions that increase haze formation and diminish solar radiation intensity
Atmospheric Scattering	Deflection of solar rays caused by pollutants and suspended particles	Reduces direct solar radiation and alters the spectral distribution of sunlight reaching solar devices

Atmospheric Absorption	Uptake of solar energy by gases and aerosols before reaching the Earth's surface	Decreases the total available radiation for photovoltaic electricity generation and solar thermal heating
Visibility Reduction	Decline in atmospheric clarity due to pollution and haze	Indicates high pollutant concentration, often associated with lower solar irradiance and unstable energy yield
Direct Normal Irradiance (DNI)	Solar radiation received directly from the sun without scattering	Strongly affected by air pollution, especially in regions with high aerosol loading, reducing CSP and tracking PV performance
Global Horizontal Irradiance (GHI)	Total solar radiation received on a horizontal surface	Declines under polluted atmospheric conditions due to reduced direct and diffused solar components
Photovoltaic Output	Electrical power generated from solar panels	Falls as air pollution lowers irradiance and changes the spectral quality of incoming solar energy
Solar Thermal Efficiency	Ability of solar thermal collectors to convert solar radiation into useful heat	Decreases when atmospheric pollutants reduce the heat-carrying portion of incident solar radiation
Urban and Industrial Pollution Zones	Areas with high concentrations of traffic and industrial emissions	Experience stronger solar attenuation, leading to greater efficiency losses in solar energy systems
Mitigation Measures	Strategies to reduce pollution-related solar losses	Include air quality control, site selection, pollution monitoring, and adaptive design of solar systems

Air pollution exerts a substantial influence on solar radiation attenuation because suspended particles and gaseous pollutants modify the optical behavior of the atmosphere before sunlight reaches solar conversion systems. Particulate matter, especially $PM_{2.5}$ and PM_{10}, plays a dominant role in this process through scattering and absorption mechanisms that reduce atmospheric transmittance. As pollutant concentration rises, a smaller fraction of incident solar radiation reaches the surface, which directly lowers the solar resource available for photovoltaic and solar thermal applications. Aerosols and industrial emissions further intensify atmospheric turbidity, producing hazy conditions that weaken solar penetration and reduce the intensity of usable irradiance.

The reduction in direct and diffuse solar components has important consequences for different solar technologies. Direct normal irradiance is particularly sensitive to polluted atmospheric conditions, which means concentrating solar power systems and tracking photovoltaic units often experience significant performance degradation in industrial or urban areas. Global horizontal irradiance is also adversely affected, resulting in a decline in the total energy input received on solar collection surfaces. In addition, black carbon has a stronger radiative impact than many other pollutants because of its high absorptivity, while sulfur dioxide and nitrogen oxides contribute indirectly through secondary aerosol formation, further enhancing radiation losses.

Another important issue is that pollution does not only reduce the magnitude of solar radiation but can also alter its spectral composition. Changes in the wavelength distribution of incoming sunlight may affect photovoltaic technologies differently depending on their material properties and spectral response. For example, some solar cells may become less effective when shorter wavelengths are scattered more strongly in polluted atmospheres. This means that air pollution can influence not only the total irradiance level but also the conversion behavior of the solar device itself, making performance assessment more complex in heavily contaminated environments.

From an operational perspective, the findings indicate that air pollution must be treated as a critical planning and design parameter in solar energy projects. Urban and industrial zones are more vulnerable to persistent attenuation losses, which can reduce annual electricity production and weaken the economic feasibility of installations if atmospheric effects are ignored. Therefore, mitigation strategies such as pollution monitoring, improved site selection, atmospheric correction modeling, and integration of local air-quality data into solar forecasting tools are essential.

Overall, the impact of air pollution on solar radiation attenuation must be considered an important challenge in solar energy planning and operation. Accurate assessment of pollution-related irradiance losses can support more reliable energy forecasting, improved system sizing, and better selection of suitable sites for solar installations. In addition, integrating air quality monitoring, atmospheric correction models, and mitigation strategies into solar energy studies can help reduce uncertainty and improve the long-term performance of renewable energy systems. Therefore, addressing air pollution is not only beneficial for environmental and public health protection but also essential for maximizing the effectiveness of solar energy technologies.

5. Mitigation Strategies to Improve Solar System Efficiency in Polluted and Dusty Environments

Solar energy systems installed in arid, semi-arid, urban, and industrial regions are frequently exposed to dust deposition, airborne pollutants, and atmospheric contaminants that reduce their operational efficiency and long-term reliability. Dust and pollution affect solar panels through two main pathways: first, deposited particles on the panel surface reduce light transmittance and create soiling losses; second, suspended pollutants in the atmosphere scatter and absorb incoming solar radiation, decreasing the amount of usable energy reaching photovoltaic and solar thermal systems [70,71]. As a result, solar installations in polluted and dusty environments often experience lower power output, reduced conversion efficiency, greater variability in energy generation, and increased maintenance requirements. This challenge is particularly important in regions where solar energy is expected to play a major role in electricity supply, yet environmental conditions continuously threaten stable system performance as demonstrated in Figure 3.

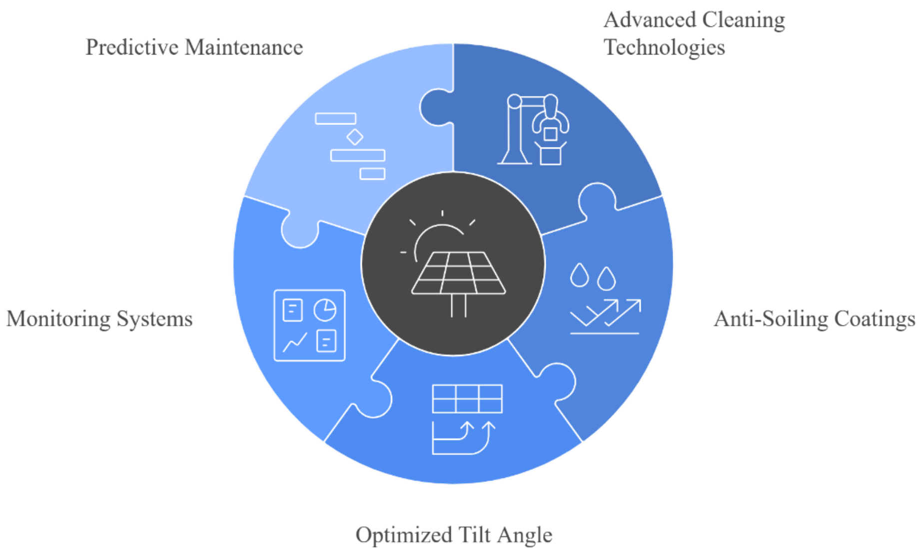

Figure 3. Mitigation Strategies to Improve Solar System Efficiency

To address such losses, a range of mitigation strategies has been developed to improve solar system efficiency and sustain energy yield under harsh environmental conditions. Effective approaches include manual and automated cleaning technologies, anti-soiling and self-cleaning coatings, optimized panel tilt angles, real-time monitoring systems, and predictive maintenance models based on environmental and operational data [72,73]. Each of these strategies contributes to reducing surface contamination, improving light absorption, minimizing unnecessary maintenance, and enhancing the overall reliability of solar installations. Therefore, examining mitigation strategies for polluted and dusty environments is essential for improving the technical performance, economic feasibility, and long-term sustainability of solar energy systems in challenging climates [74-78].

A. Advanced cleaning technologies can recover large fractions of lost power

Dust accumulation can reduce PV efficiency by about 15–20%, and in some field conditions the reduction may approach 30% if cleaning is delayed. Experimental results comparing mitigation methods showed that when dust density increased from 7.5 to 18.15 g/m², the power drop reached 37% for an untreated reference module, compared with 33% for a nano-coated module and 23% for a self-cleaning wiper system. The same study reported payback periods of about 1.07 years for nano-coating and 2.79 years for the wiper-based cleaning system, indicating that cleaning technology selection has both technical and economic consequences.

B. Anti-soiling coatings can reduce adhesion and improve baseline output

Anti-soiling and anti-reflective coatings do not only reduce dust adhesion; they can also improve clean-panel optical performance. Reported results indicate that coated PV modules can show an average 4–8% increase in clean power output because of lower reflection losses, while dust-related fouling can be mitigated by roughly 5% in some textured anti-reflective coating configurations. Reviews published in 2025 also note that passive coatings such as superhydrophobic and anti-fouling thin films are increasingly favored because they reduce adhesion forces without relying on water-intensive cleaning.

C. Optimized tilt angle can lower soiling rates and reduce efficiency loss

Panel inclination has a measurable effect on dust retention, especially in dry regions. One recent study reported efficiency losses of 3.1%, 2.9%, and 2.5% at tilt angles of 14°, 24°, and 34°, respectively, over about one month, showing that steeper mounting can reduce dust-related degradation. Another 2025 study recommended a tilt angle of around 30° in dust-prone or low-rainfall regions to minimize soiling losses, while flatter configurations near 0°–15° should generally be avoided unless frequent cleaning is guaranteed.

D. Monitoring systems can quantify soiling losses with high accuracy

Real-time monitoring has become essential because soiling does not affect all sites or days equally. The IEA PVPS report identifies sensors and measurement techniques as a core part of plant-level mitigation strategy, while newer optical soiling detectors have demonstrated prediction errors below 1.4% for transmittance-loss estimation under outdoor validation conditions. This level of accuracy is important because soiling-related performance losses can otherwise go unnoticed until they produce significant energy and revenue reductions.

E. Predictive maintenance can optimize cleaning intervals and reduce unnecessary O&M

Data-driven maintenance is increasingly replacing fixed cleaning schedules. A 2025 machine-learning study modeled PV performance under soiling levels from 1% to 5%, showing that artificial neural networks and Gaussian process regression can successfully predict power reduction and soiling losses under realistic operating conditions. Another recent study reported that a hybrid LSTM-KNN model achieved about 98.22% accuracy in predicting dust-related energy losses, outperforming standalone LSTM (95.51%) and KNN (61.49%) models.

Overall, improving solar performance in polluted and dusty environments requires an integrated approach that combines preventive design, operational control, and intelligent maintenance planning. No single strategy is sufficient under all site conditions; rather, the most effective solution depends on local climate, pollutant type, dust intensity, water availability, and economic constraints. Therefore, adopting a combination of mitigation measures tailored to environmental conditions will be critical for maximizing the reliability, efficiency, and financial viability of solar energy systems in regions exposed to persistent soiling and atmospheric pollution.

6. Conclusion

The findings of this article confirm that dust, sandstorms, and air pollution are among the most significant environmental factors limiting the real-world efficiency of solar energy systems. Dust deposition on photovoltaic surfaces reduces optical transmittance and restricts the amount of solar radiation reaching the active layers of the module, which leads directly to lower current generation, reduced output power, and declining conversion efficiency. The magnitude of this degradation depends on several factors, including deposition density, particle size, dust composition, panel tilt angle, humidity, and exposure duration. Accordingly, solar installations located in arid and semi-arid regions may suffer considerable technical and economic losses if soiling effects are not properly addressed.

The investigation also shows that sandstorms create both immediate and long-term challenges for solar power generation. During storm events, suspended particles in the atmosphere reduce solar irradiance, especially the direct component, causing sharp fluctuations in photovoltaic output and weakening the stability of electricity generation. After the storm, residual dust and sand remain on panel surfaces, extending performance losses beyond the actual event. Repeated exposure may additionally result in mechanical abrasion, surface scratching, and gradual deterioration of optical materials, which can shorten system lifespan and reduce long-term energy yield. This demonstrates that sandstorms should be considered not only as temporary meteorological disturbances but also as critical operational and design challenges for solar energy systems deployed in exposed environments.

Air pollution further intensifies solar performance degradation through atmospheric attenuation of solar radiation. Pollutants such as particulate matter, aerosols, black carbon, sulfur dioxide, and nitrogen oxides scatter and absorb incoming sunlight, reducing both direct normal irradiance and global horizontal irradiance. This lowers the amount of usable solar energy available for photovoltaic and solar thermal conversion and can also alter the spectral distribution of sunlight, which may affect different solar technologies in different ways. In urban and industrial regions, persistent pollution can therefore reduce annual energy production and increase uncertainty in performance prediction, making air quality an important parameter in solar resource assessment and project planning.

The study further highlights that maintaining solar system efficiency in polluted and dusty environments requires a combination of practical and adaptive mitigation strategies. Regular cleaning, automated washing technologies, anti-soiling coatings, optimized tilt angles, real-time monitoring systems, and predictive maintenance models all contribute to reducing performance losses and improving operational reliability. Their effectiveness depends on local environmental conditions, the type of pollutant or deposited material, water availability, maintenance cost, and system design. For this reason, no single mitigation measure can be considered universally sufficient; instead, integrated site-specific solutions are required to ensure the sustainable operation of solar plants in harsh climates.

Overall, the article concludes that the successful expansion of solar energy in dust-prone and polluted regions depends not only on the availability of strong solar resources but also on the ability to understand, quantify, and manage environmental degradation mechanisms. Accurate assessment of soiling, storm-related irradiance loss, and atmospheric pollution effects is essential for improving energy yield forecasting, reducing operation and maintenance costs, and enhancing system durability. Therefore, future solar energy planning should incorporate environmental risk analysis, advanced material protection, intelligent cleaning management, and continuous monitoring frameworks in order to maximize solar energy conversion efficiency and ensure long-term technical and economic viability.

Author Contributions: Authors have contributed significantly to the development and completion of this article.
Funding: This article received no external funding.
Data Availability Statement: Not applicable.
Acknowledgments: The author would like to express their sincere gratitude to College of Tourism and Archaeology Technology - Garma, Libya for their invaluable support and resources throughout the course of this research.
Conflicts of Interest: The author(s) declare no conflict of interest.

References

[1] S. Zei, M. Rrci, and A. Al-Khalidi, "Advances and challenges in solar energy conversion: Technologies, integration pathways, and future prospect," *ECM*, 2025.

[2] Y. F. Nassar *et al.*, "Carbon footprint and energy life cycle assessment of wind energy industry in Libya," *Energy Convers. Manag.*, vol. 300, no. 117846, p. 117846, 2024.

[3] L. Shen, A. Elshkaki, S. Zhong, X. Hu, X. Wu, and J. Ge, "Global energy transition and low carbon technology pathways," *Energies*, vol. 18, no. 21, p. 5701, 2025.

[4] Y. F. Nassar *et al.*, "Design of reliable standalone utility-scale pumped hydroelectric storage powered by PV/Wind hybrid renewable system," *Energy Convers. Manag.*, vol. 322, no. 119173, p. 119173, 2024.

[5] W. Jiang, T. Jung, H. Dai, P. Xiang, and S. Chen, "Transition pathways for low-carbon steel manufacture in East Asia: The role of renewable energy and technological collaboration," *Sustainability*, vol. 17, no. 10, p. 4280, 2025.

[6] M. Mohamed, Wahab Shah, & Mohamed Amer. (2025). Concentration Dynamics in Solar PV Supply Chains: Lessons for Clean Energy Transitions. *Libyan Journal of Sustainable Development Research*, 1(1), 52-60.

[7] M. Khaleel and Z. Yusupov, “Advancing sustainable energy transitions: Insights on finance, policy, infrastructure, and demand-side integration,” *Unconventional Resources*, vol. 9, no. 100274, p. 100274, 2026.

[8] M. Elmnifi *et al.*, “Solar and wind energy generation systems with pumped hydro energy storage: City of Derna,” in *Environmental Science and Engineering*, Cham: Springer Nature Switzerland, 2025, pp. 209–226.

[9] Y. F. Nassar *et al.*, “Regression model for optimum solar collectors’ tilt angles in Libya,” in *2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES)*, 2023.

[10] M. Khaleel *et al.*, “Evolution of emissions: The role of clean energy in sustainable development,” *Chall. Sustain.*, vol. 12, no. 2, pp. 122–135, 2024.

[11] B. Zheng, Y. Hu, and M. Alkahtani, “Strategies to reduce urban pollution effects on solar panels: A review,” *Solar*, vol. 5, no. 1, p. 11, 2025.

[12] H. Oufettoul, O. Oubraik, I. Ait Abdelmoula, S. Motahhir, and B. EL Majid, “A novel solar panel cleaning system for improved efficiency,” *Unconventional Resources*, vol. 8, no. 100249, p. 100249, 2025.

[13] Y. F. Nassar *et al.*, “Assessing the viability of solar and wind energy technologies in semi-arid and arid regions: A case study of Libya’s climatic conditions,” *Appl. Sol. Energy*, vol. 60, no. 1, pp. 149–170, 2024.

[14] A. Upadhyay and A. P. Dimri, “Evolution of storms: From solar to severe,” in *Severe Storms*, Singapore: Springer Nature Singapore, 2025, pp. 627–645.

[15] S. N. Shorabeh, H. Mahmoodi, K. Choubineh, M. K. Firozjaei, L. Ghahremani, and J. J. Arsanjani, “Assessing environmental vulnerability of renewable energy infrastructure to dust storm hazards in arid regions: A case study of Iran,” *Results Eng.*, no. 109870, p. 109870, 2026.

[16] M. F. Tamimi, F. A. Abanumay, A. G. Hamad, M. I. A. Qamar, and A. A. Alshannaq, “Probabilistic modeling of sandstorm frequency and socioeconomic impacts in arid environments under a high-emission warming scenario,” *Results Eng.*, vol. 28, no. 107313, p. 107313, 2025.

[17] H. El-Khozondar *et al.*, “Economic and environmental implications of solar energy street lighting in urban regions: A case study,” *waujpas*, pp. 142–151, 2025.

[18] A. Alkhazmi *et al.*, “Design and analysis of PV solar street lighting systems in remote areas: A case study,” *waujpas*, pp. 1–14, 2025.

[19] Y. Nassar *et al.*, “Simulating the energy, economic and environmental performance of concentrating solar power technologies using SAM: Libya as a case study,” *jsesd*, vol. 12, no. 2, pp. 4–23, 2023.

[20] K. M. Omemen and M. O. Aldbbah, “Climate change: Key contributors and sustainable solutions,” *ijees*, vol. 3, no. 1, pp. 10–27, 2025.

[21] A. M. Makhzom *et al.*, “Carbon dioxide Life Cycle Assessment of the energy industry sector in Libya: A case study,” *ijees*, vol. 1, no. 3, pp. 145–163, 2023.

[22] A. Alsharif, C. W. Tan, R. Ayop, A. Ali Ahmed, M. Mohamed Khaleel, and A. K. Abobaker, “Power management and sizing optimization for hybrid grid-dependent system considering photovoltaic wind battery electric vehicle,” in *2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2022.

[23] M. M. Khaleel, A. Alsharif, and I. I. K. Imbayah, “Renewable energy technologies: Recent advances and future predictions,” *AJAPAS*, pp. 58–64, 2022.

[24] Y. M. O. Khaleel, M. A. M. Haweel, K. M. Saied, A. A. S. Gheidan, and A. J. Meelad, “Design of A single-cover solar collector to heat water for A typical building,” *ijees*, vol. 2, no. 4, pp. 27–37, 2024.

[25] F. Alasali, A. S. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani, “Assessment of the impact of a 10-MW grid-tied solar system on the Libyan grid in terms of the power-protection system stability,” *Clean Energy*, vol. 7, no. 2, pp. 389–407, 2023.

[26] D. Afonso, O. Mesbahi, A. Bouich, and M. Tlemçani, "Influence of long-term and short-term solar radiation and temperature exposure on the material properties and performance of photovoltaic panels: A comprehensive review," *Energies*, vol. 18, no. 19, p. 5072, 2025.

[27] A.-K. Hamid, M. M. Farag, and M. Hussein, "Enhancing photovoltaic system efficiency through a digital twin framework: A comprehensive modeling approach," *International Journal of Thermofluids*, vol. 26, no. 101078, p. 101078, 2025.

[28] A. Ghayth, Z. Yusupov, A. Hesri, and M. Khaleel, "Performance enhancement of PV array utilizing Perturb & Observe algorithm," *ijees*, vol. 1, no. 2, pp. 29–37, 2023.

[29] M. Andeef, Y. F. Nassar, H. Awad, H. J. El-Khozondar, and M. Khaleel, "Transitioning to solar fuel instead of fossil fuel in the electricity industry," *ijees*, vol. 1, no. 4, pp. 32–46, 2023.

[30] M. Khaleel, Z. Yusupov, and S. Rekik, "Exploring trends and predictions in renewable energy generation," *Energy 360*, vol. 4, no. 100030, p. 100030, 2025.

[31] A. Almarri *et al.*, "Experimental and modeling study of dust composition impact on photovoltaic performance in arid coastal environments," *J. Mater. Res. Technol.*, vol. 39, pp. 5455–5467, 2025.

[32] H. S. Abd *et al.*, "Dust deposition and cleaning effect on PV panel: Experimental approach," *Results Eng.*, vol. 27, no. 106041, p. 106041, 2025.

[33] K. Hayawi, H. Maliakkal, N. Venugopal, T. M. Hussain, and G. B. Rajagopalan, "Machine learning - driven solar forecasting in dust-prone regions for sustainable energy systems," *Solar Energy Advances*, vol. 5, no. 100108, p. 100108, 2025.

[34] Z. Wang, S. Yue, G. Bian, T. Deng, F. Kong, and X. Wang, "Study on the influence of dusty weather natural wind on the dust characteristics of trough concentrator regions in alpine areas," *Energy Convers. Manag.*, vol. 332, no. 119689, p. 119689, 2025.

[35] I. Hamed, A. F. AbdelGawad, and R. Ragab, "Reducing sand deposition on solar-power plants using windbreaks: A numerical study," *J. Sol. Energy Eng.*, pp. 1–27, 2026.

[36] M. Khaleel, N. El-Naily, H. Alzargi, M. Amer, T. Ghandoori, and A. Abulifa, "Recent progress in synchronization approaches to mitigation voltage sag using HESS D-FACTS," in *2022 International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS)*, 2022.

[37] L. Zaghba, M. Khennane Benbitour, A. Fezzani, S. Mekhilef, and A. Borni, "Investigating the theoretical and experimental effects of sand dust and sandstorms on photovoltaic power plants in arid environments," *Energy Sustain. Dev.*, vol. 81, no. 101507, p. 101507, 2024.

[38] M. A. Razig, A. E. Mohammed, and A. G. Khalifa, "Manufacturing of A solar desalination system," *ijees*, vol. 2, no. 4, pp. 19–26, 2024.

[39] M. Khaleel and M. Elbar, "Exploring the rapid growth of solar photovoltaics in the European Union," *ijees*, vol. 2, no. 1, pp. 61–68, 2024.

[40] Y. F. Nassar *et al.*, "Sensitivity of global solar irradiance to transposition models: Assessing risks associated with model discrepancies," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 11, no. 100887, p. 100887, 2025.

[41] M. Khaleel, Z. Yusupov, M. Elmnifi, T. Elmenfy, Z. Rajab, and M. Elbar, "Assessing the financial impact and mitigation methods for voltage sag in power grid," *ijees*, vol. 1, no. 3, pp. 10–26, 2023.

[42] Z. Said, E. Bellos, H. Muhammad Ali, S. Rahman, and C. Tzivanidis, "Nanofluids, turbulators, and novel working fluids for heat transfer processes and energy applications: Current status and prospective," *Appl. Therm. Eng.*, vol. 258, no. 124478, p. 124478, 2025.

[43] M. Elmnifi, M. Khaleel, Z. Yusupov, Y. F. Nassar, and H. J. El-Khozondar, "Economic and environmental benefits of recycling electrical and electronic waste products in north African countries," in *Environmental Science and Engineering*, Cham: Springer Nature Switzerland, 2025, pp. 55–93.

[44] A. J. S. Alrafadi, "Emerging trends in solar water heating technologies," *ijees*, vol. 2, no. 3, pp. 47–59, 2024.

[45] A. Alsharif *et al.*, "Applications of solar energy technologies in north Africa: Current practices and future prospects," *ijees*, vol. 1, no. 3, pp. 164–173, 2023.

[46] M. Khaleel *et al.*, "Emerging issues and challenges in integrating of solar and wind," *ijees*, vol. 2, no. 4, pp. 1–11, 2024.

[47] M. P. Ndeto, D. W. Wekesa, F. Njoka, and R. Kinyua, "Aeolian dust distribution, elemental concentration, characteristics and its effects on the conversion efficiency of crystalline silicon solar cells," *Renew. Energy*, vol. 208, pp. 481–491, 2023.

[48] A. Abudabbous, "Performance simulation of a 100 MW utility-scale solar PV plant in Sirte using Sunny Design Web," *ijees*, vol. 3, no. 3, pp. 19–30, 2025.

[49] K. Dahli and N. Cheggaga, "Novel approach to sandstorm-resilient solar tracking system for optimal energy generation," *Energy Sources Recovery Util. Environ. Eff.*, vol. 46, no. 1, pp. 4029–4050, 2024.

[50] Q. Bao *et al.*, "Influence of the change direction of total solar irradiance at the inclined surface on power generation performance of photovoltaic power station: A focus on output power and photoelectric conversion efficiency," *Energy (Oxf.)*, vol. 324, no. 135975, p. 135975, 2025.

[51] L. Micheli, F. Almonacid, J. G. Bessa, Á. Fernández-Solas, and E. F. Fernández, "The impact of extreme dust storms on the national photovoltaic energy supply," *Sustain. Energy Technol. Assessments*, vol. 62, no. 103607, p. 103607, 2024.

[52] M. Khaleel, E. Yaghoubi, E. Yaghoubi, and M. Z. Jahromi, "The role of mechanical energy storage systems based on artificial intelligence techniques in future sustainable energy systems," *ijees*, vol. 1, no. 4, pp. 01–31, 2023.

[53] M. Almamoori, M. Almaktar, M. Khaleel, F. Mohamed, and A. Elbreki, "Assessing STATCOM-enabled reactive power control in fragile power transmission systems: A case study perspective," *Math. Model. Eng. Probl.*, vol. 11, no. 8, pp. 2019–2028, 2024.

[54] M. Khaleel, I. Imbayah, Y. Nassar, and H. J. El-Khozondar, "Renewable energy transition pathways and net-zero strategies," *ijees*, vol. 3, no. 4, pp. 01–16, 2025.

[55] O. S. Abualoyoun and A. A. Amar, "Advancing the global integration of solar and wind power: Current status and challenges," *ijees*, vol. 3, no. 2, pp. 73–88, 2025.

[56] K. Bi, X. Chen, H. Cui, F. Zhang, Y. Cui, and C. Wang, "Influence of Extreme Climate events on wind and Solar Energy over the Gobi Desert Region of China in the future," *Theor. Appl. Climatol.*, vol. 156, no. 2, 2025.

[57] Muftah Ali, & Mohamed Khaleel. (2025). Decarbonizing Buildings at Scale: Energy Codes, Innovation Pathways, and the Net-Zero Transition. *Libyan Journal of Sustainable Development Research*, *1*(1), 45-51.

[58] N. Wang *et al.*, "Quantifying the influence of dominant factors on the long-term sandstorm weather - A case study in the Yellow River Basin during 2000–2021," *Atmos. Res.*, vol. 311, no. 107717, p. 107717, 2024.

[59] L. Yang, X. Gao, Z. Li, and D. Jia, "Quantitative effects of air pollution on regional daily global and diffuse solar radiation under clear sky conditions," *Energy Rep.*, vol. 8, pp. 1935–1948, 2022.

[60] M. Mardani, S. Hoseinzadeh, and D. A. Garcia, "Developing particle-based models to predict solar energy attenuation using long-term daily remote and local measurements," *J. Clean. Prod.*, vol. 434, no. 139690, p. 139690, 2024.

[61] X. Zhang, M. Zhang, Y. Cui, and Y. He, "Estimation of daily ground-received global solar radiation using air pollutant data," *Front. Public Health*, vol. 10, p. 860107, 2022.

[62] Z. Song, S. Cao, and H. Yang, "Quantifying the air pollution impacts on solar photovoltaic capacity factors and potential benefits of pollution control for the solar sector in China," *Appl. Energy*, vol. 365, no. 123261, p. 123261, 2024.

[63] X. Cheng, D. Ye, Y. Shen, D. Li, and J. Feng, "Studies on the improvement of modelled solar radiation and the attenuation effect of aerosol using the WRF-Solar model with satellite-based AOD data over north China," *Renew. Energy*, vol. 196, pp. 358–365, 2022.

[64] Y. Nassar, R. Elzer, A. Alkhazmi, H. El-Khozondar, M. Essid, and A. Mbaye, “Thermal analysis of air-heating flat-plate thermal solar collectors,” *ijees*, vol. 1, no. 3, pp. 129–144, 2023.

[65] Y. Nassar *et al.*, “Solar and wind atlas for Libya,” *ijees*, vol. 1, no. 3, pp. 27–43, 2023.

[66] M. K. Lodhi, Y. Tan, X. Wang, A. Suprijanto, and M. Imran, “Advancing urban solar assessment: A deep learning and atmospheric modelling framework for quantifying PV yield and carbon reduction,” *Energy Build.*, vol. 338, no. 115717, p. 115717, 2025.

[67] A. Y. Abu-Aeshah, M. A. Alghafoud, and Mustafa M Elsherif, “Performance analyses of solar water heating system with thermal storage using SAM simulation,” *ijees*, vol. 3, no. 1, pp. 01–09, 2025.

[68] M. Khaleel, Z. Yusupov, N. Yasser, H. Elkhozondar, and A. A. Ahmed, “An integrated PV farm to the unified power flow controller for electrical power system stability,” *ijees*, vol. 1, no. 1, pp. 18–30, 2023.

[69] A. Abdessadak, H. Ghennioui, B. El Bhiri, N. Thirion-Moreau, M. Abraim, and S. Merzouk, “Assessing the effects of dust on solar panel performance: A comprehensive review and future directions,” in *ICATH 2025*, 2025, p. 9.

[70] A. Alsharif, “Mitigation of dust impact on solar photovoltaics performance considering Libyan climate zone: A review,” *Engineering Technology Open Access Journal*, vol. 5, no. 3, pp. 22–27, 2023.

[71] M. Khaleel *et al.*, “Battery technologies In electrical power Systems: Pioneering secure energy transitions,” *J. Power Sources*, vol. 653, no. 237709, p. 237709, 2025.

[72] S. S. Alanzi, B. Aldalali, and R. M. Kamel, “Effects of sandstorms on hybrid renewable energy sources and load demand in arid desert climates: A case study,” *Energy Sustain. Dev.*, vol. 81, no. 101473, p. 101473, 2024.

[73] L. Zafar, M. S. Abbasi, A. Rao, Shehryar, and A. Anwar, “Evaluating and mitigating the effects of dust accumulation on photovoltaic panel performance,” *Results Eng.*, vol. 28, no. 107672, p. 107672, 2025.

[74] F. Al-Failkawi and B. Abdulrahman, “Evaluating the role of thermal energy storage in the performance of concentrated solar power plants,” in *Lecture Notes in Electrical Engineering*, Singapore: Springer Nature Singapore, 2025, pp. 47–54.

[75] Mohamed Khaleel, & Ali Hesri. (2025). Improving Power System Reliability Using Hydrogen Fuel Cell–Integrated D-FACTS for Power Quality Enhancement. *Libyan Journal of Sustainable Development Research*, *1*(1), 01-16.

[76] O. S. M. Jomah, N. Mohamed, A. A. Ahmed, A. Alsharif, M. M. Khaleel, and Y. F. Nassar, “Simulating photovoltaic emulator systems for renewable energy analysis,” in *2024 IEEE 4th International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA)*, 2024.

[77] M. Elmnifi *et al.*, “Design of an innovative wastewater treatment system using photovoltaic-hydro system coupled with reverse osmosis technology: Sustainability and continuous improvement,” in *Environmental Science and Engineering*, Cham: Springer Nature Switzerland, 2025, pp. 137–157.