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RESEARCH ARTICLE

Dust Characteristics and Its Effect on Solar PV Efficiency at Different Tilt Angles

Husham M. Ahmed[1*], Noaman M. Noaman [2], Haitham Alqahtani[3], Lina S. Calucag[4], Zeyad M. Ismail[5], Omar A. Alhawi[6]

[1, 2, 3,4,5,6] College of Engineering, University of Technology Bahrain, Kingdom of Bahrain

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***Corresponding Author:**

hmahmed@utb.edu.bh

ABSTRACT

Solar photovoltaic Over the past two decades, advancements in photovoltaic (PV) technologies have significantly increased global electricity generation, particularly in regions with high solar irradiation. However, challenges such as dust accumulation can impede the efficiency of PV panels. This research investigates dust characteristics and compares the effects of tilt angle on dust accumulation and PV performance. The study utilizes one year of measured data collected at the University of Technology Bahrain, evaluating the seasonal performance of four sets of monocrystalline PV panels, each with a capacity of 7.8 kW, installed at tilt angles of 14°, 20°, 26°, and 32°.Dust accumulation is quantified by measuring the dust mass per square meter from each row on a monthly basis, with subsequent cleaning of the panels following dust collection. The data indicate that the highest levels of dust accumulation occurred during the summer months, specifically August, July, September, and June with recorded values of 11.58 g/m^2, 10.55 g/m^2, 7.95 g/m^2, and 5.92 respectively. In contrast, the winter months—December, January, February and November—exhibited the lowest average accumulated dust values, measuring 2.45 g/m^2, 3.75 g/m^2, 4.03 g/m^2, and 4.20 g/m^2 respectively. Analysis of panel tilt angles indicated that the lowest tilt angle of 14^0 resulted in the highest average dust accumulation at 6.70 g/m^2. This was followed by 20^0 with 6.27 g/m^2, 26^0 with 5.48 g/m^2, and the lowest accumulation at 32^0 with 4.37 g/m^2.

INTRODUCTION

The growing global energy demand and the urgent need to address environmental challenges have accelerated the shift toward renewable energy sources. Fossil fuel-based systems significantly contribute to greenhouse gas emissions, driving climate change. This urgency has heightened interest in sustainable alternatives, particularly solar photovoltaic (PV) systems, which offer a cleaner, renewable, and cost-effective energy solution. Solar energy is abundant and can greatly reduce reliance on fossil fuels while meeting rising energy needs. Transitioning to renewables is vital for mitigating climate change, enhancing energy security, and fostering economic growth [1-3]. PV technology converts sunlight into electricity through photoelectric conversion and has become increasingly important due to its scalability and versatility. It can be applied in various settings, from small residential installations to large solar farms, catering to diverse energy needs. Homeowners can lower electricity bills and carbon footprints with rooftop solar panels, while large farms generate significantly clean energy for communities. As sustainability and energy independence gain priority, PV technology plays a crucial role in creating a cleaner, more sustainable future [4,5]. The tilt angle of PV panels indicates their inclination from the horizontal and is influenced by factors such as mounting techniques, land topography, and climate. To optimize energy capture, sun tracking systems adjust the tilt and orientation to follow the sun's movement. These systems are categorized as single-axis, which rotates one axis to track the sun, or dual-axis, which uses two axes for precise alignment. While tracking systems can enhance energy generation, they present challenges such as higher installation and maintenance costs, reduced durability, and potential structural instability in harsh weather. Consequently, larger PV plants often opt for fixed tilt configurations, while smaller installations may utilize tracking devices. [6, 7]. References [8, 9] indicated that employing sun-tracking systems can boost energy generation by as much as 40% with dual-axis trackers and up to 20% with single-axis trackers when compared to fixed PV systems. Ref. [10] conducted a study to investigate the performance of photovoltaic (PV) systems influenced by dust, tilt angles, and orientations, using one year of measured, simulated, and analytically calculated data. Analyzing five PV installations totaling 1280 kWp at Cyprus International University, the research examines the impact of dust and cleaning procedures. The plant with 25° tilt angle achieved 17.3% higher yield than the plants with 6° tilt angle. Results also indicated a 2.5% increase in specific yield post-cleaning. A study by ref. [11] experimentally investigates the impact of natural dust deposition on the performance of three photovoltaic (PV) systems installed on the rooftop of the Faculty of Science and Technology in Mohammedia, Morocco. The analysis reveals that power production decreases by 7.4% to 12.35%, and maximum current drops by 11.6% to 18% due to dust accumulation without cleaning. Additionally, optical transmittance of the glass surfaces is reduced from 75% to 5%. Chemical analysis identifies silica and calcite as the main components of the dust, while thermal properties indicate that dust can store energy with rising temperatures. Ref. [12] conducted an experimental study examining the impact of dust on the performance of photovoltaic (PV) systems across various tilt angles in a semi-arid environment. Eight PV modules were installed on a building's roof at tilt angles of 0°, 15°, 30°, and 45°, all oriented with an azimuth angle of 0°. Each pair of modules was set at the same tilt angle, with one module cleaned every two weeks while the other was left exposed to outdoor conditions. To evaluate PV performance, the output power of the modules and relevant climate parameters were measured every minute. The results indicated that the reduction in PV performance due to dust accumulation is significantly influenced by the tilt angle. Ref. [13] Reference conducted a study in the continental climate of northern Poland to assess the degradation of electrical parameters in photovoltaic (PV) modules caused by dust deposition. The findings indicated that dust accumulation was affected by both the angle of inclination and the duration of exposure, resulting in a recorded annual decrease in power output between 3% and 12.35%. Ref. [14] studied the effect of season and inclination angle on dust accumulation in two locations in Perth in Austrillia and in Nusa Tenggara Timur, Indonesia. The study concludes that dust accumulation on glass surfaces varies by season and tilt angle. In Indonesia, the highest dust density occurs at the end of summer, while in Perth experiences greater accumulation at the end of the dry season. Less rainfall correlates with increased dust deposition. The analysis reveals that lower tilt angles lead to higher dust accumulation, with ROTA's modules accumulating less dust due to their higher tilt angle and shorter summer duration. Additionally, higher humidity at Perth contributes to greater cementation of dust on surfaces. Ref. [15] conducts a study using a two-way fluid–structure interaction analysis to evaluate the wind-induced vibration response of flexible cantilever solar panel systems at various tilt angles. The analysis establishes a methodology for determining wind-induced vibration coefficients, including model creation and solution settings. Modal analysis is performed for different tilt angles, followed by an evaluation of the transient response and wind field variations. Results indicate that tilt angle significantly affects wind-induced vibration coefficients, particularly internal forces, with displacement variations being notably greater than those in internal forces. Ref. [16] presented a year-long analysis of tilted global solar irradiance data from fixed and moving photovoltaic panels at Bahrain Polytechnic. The moving panel, utilizing a two-axis solar tracker, achieved a 33% higher annual energy gain and a 54.7% increase in June, demonstrating superior efficiency during peak demand. The findings underscore the potential for solar investments in Bahrain, particularly given the fluctuating energy needs throughout the year. Ref. [17] conducted experimental investigation in Malaysia examined the variation in photovoltaic (PV) performance and electrical parameters at different tilt angles under both indoor and outdoor conditions. Two experimental setups were used: one with constant irradiation at 750 W/m^2 and another varying irradiation intensity with a single-axis tracker. Results indicated that a 5° increase in tilt angle led to a power drop of 2.09 W indoors and 3.45 W outdoors, with corresponding efficiency decreases of 0.54% and 0.76%. The study concluded that the optimal tilt angle for maximizing PV performance in Malaysian conditions is 15°. Ref. [18] carried out a study focused on optimizing tilt angles for solar panels using solar radiation data collected from eight major provinces in Turkey. By analyzing tilted surfaces at angles ranging from 0° to 90° in 1° increments, the research aimed to identify the angle that maximizes daily total solar radiation over specific periods. The findings revealed that the optimum tilt angle varied between 0° and 65° throughout the year. Notably, the minimum optimum tilt angle of 0° occurred in June and July, corresponding to maximum monthly average daily total radiation. Conversely, the optimum tilt angle increased during the winter months, peaking in December across all provinces. Ref. [19] developed a model for optimizing the photovoltaic (PV) tilt angle in Lahore, Pakistan, and other cities. They recommended four annual tilt adjustments to enhance yearly energy generation by about 6.6% compared to a fixed tilt. Additionally, the study estimates soiling losses, revealing that lightly soiled panels can lose up to 10% of power, while heavily soiled ones may lose 40%. Their results revealed that dust on horizontal panels leads to a 26.2% energy loss over 100 days, compared to a 13.5% loss on vertical panels. Ref. [20] conducted a study focused on optimizing the tilt angles of photovoltaic (PV) panels to maximize energy capture throughout the year. They reported that by adjusting the tilt to optimal angles with seasonal and monthly modifications, solar energy capture can increase by 7.59%, 7.60%, and 9.19%, respectively, compared to a fixed tilt.

The primary aim of this study is to investigate dust accumulation characteristics and evaluate the impact of various tilt angles on the seasonal performance of photovoltaic (PV) systems in Bahrain. Accumulated dust creates a layer that absorbs light and reduces the glass's transmission, negatively affecting energy production. By analyzing dust composition and its accumulation at different angles throughout the year, the research aims to identify the optimal fixed angle for maximizing energy output. This evaluation is crucial for ensuring the optimal performance of PV systems both before and after installation. The findings will offer valuable insights into small-scale PV installations, where fixed angles are often preferred due to cost and space constraints, ultimately enhancing energy generation and improving overall system efficiency while proposing effective solutions and mitigation strategies.

II. METHODOLOGY

The photovoltaic (PV) system consists of 76 monocrystalline solar panels organized into four groups of 19 panels each, with each group having a generation capacity of 7.8 kW, resulting in a total system capacity of 31.2 kW. These panels are mounted on an adjustable structure that allows tilt angles ranging from 14° to 32° with horizontal. Installed on the rooftop of the University of Technology Bahrain, the system is oriented southward. To determine the optimal fixed angle for Bahrain's environment and assess dust characteristics and accumulation at different angles, the panels are set at angles of 14°, 20°, 26°, and 32°, as shown in Figure. 1. Dust accumulation is monitored by collecting dust mass per square meter from each row monthly, followed by routine cleaning of the panels. The system captures the direct current (DC) generated by the PV cells and employs a Maximum Power Point Tracking (MPPT) controller to optimize power output. This DC power is then converted to alternating current (AC) via a controlled three-phase inverter connected to the utility grid for efficient energy distribution. Additionally, a weather station near the PV panels gathers essential data on solar radiation, humidity, surface temperature of the PV panels, ambient temperature, and wind speed. This information is crucial for analyzing and enhancing the PV system's performance under varying environmental conditions. This investigation utilizes the PV panel system to evaluate seasonal performance at different angles to identify the dust accumulation effect and optimal angle for maximum efficiency, providing recommendations for future installations in Bahrain.

Fig. 1. Solar PV panels setup

II. RESULTS AND DISCUSSIONS

The current analysis aimed to examine dust characteristics and evaluate the effect of title angles on the seasonal performance of a photovoltaic (PV) panel system. The research was conducted over 12-

month periods from Oct 2023 to Sept 2024. At the rooftop of the university of technology Bahrain. Dust was collected from the four rows of panels tilted at angles of 14°, 20°, 26°, and 32° at the end of each month. This process was administered for eight months (October 2023 and March to September 2024) when no rainfall was recorded, allowing for a full month of dust accumulation to be collected. However, during the winter season (November 2023 to February 2024), collections were made only on sets of days without rain. For these months, dust samples were taken over a specified number of days (ranging from 7 to 10 days) and then extrapolated by multiplying the results to estimate the total monthly accumulation.

The Kingdom of Bahrain, located in the dust belt of the Arabian Peninsula, is known for its desert climate, characterized by extremely low annual rainfall. It is particularly prone to significant dust events during the summer months. The combination of minimal precipitation and frequent dust storms creates challenging environmental conditions that affect the performance and installation of photovoltaic (PV) solar panels.

The current analysis aimed to examine dust characteristics and evaluate the effect of tilt angles on the seasonal performance of a photovoltaic (PV) panel system. The research was conducted over a 12-month period, from October 2023 to September 2024, at the rooftop of the University of Technology Bahrain. Dust was collected from four rows of panels tilted at angles of 14°, 20°, 26°, and 32° at the end of each month. This process was carried out for eight months (October 2023 and March to September 2024), when no rainfall was recorded, allowing for a full month of dust accumulation. During the winter season (November 2023 to February 2024), collections were made only on sets of days without rain. For these months, dust samples were collected over specified periods ranging from 7 to 10 days. The results were then extrapolated by multiplying the findings to estimate the total monthly accumulation. The data analysis revealed that the highest levels of dust accumulation on all four rows of panels occurred during the summer months, specifically June, July, August, and September, with recorded values of 5.92 g/m², 10.55 g/m², 11.58 g/m², and 7.95 g/m², respectively. In contrast, the winter months—November, December, January, and February—showed the lowest average dust accumulation values, measuring 4.20 g/m², 2.45 g/m², 3.75 g/m², and 4.03 g/m², respectively, as shown in Figure 2.

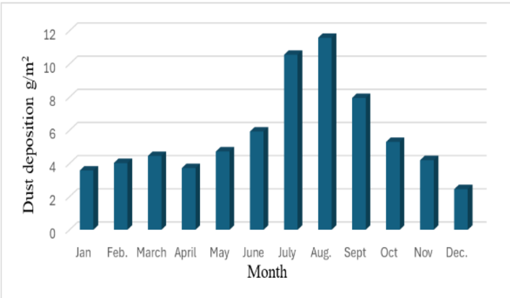

Fig. 2 Monthly Variations in Dust Accumulation

A comparison of the four sets of panels indicates that those set at a tilt angle of 14° accumulated the highest annual dust total, measuring 80.4 g/m². This was followed by panels at 20° with 75.2 g/m², then 26° with 65.8 g/m², and finally, panels at 32° with an accumulation of 52.4 g/m², as illustrated in Figure 3.

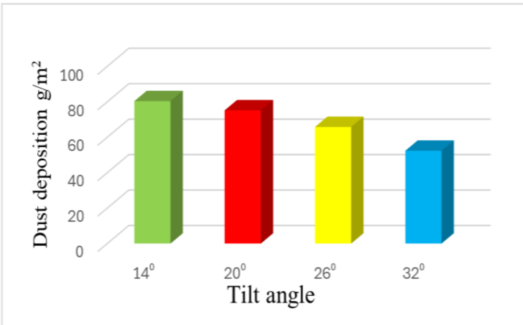

Fig. 3. Impact of Tilt Angle on annual Dust deposition

A three-dimensional plot depicted in Figure 4 represents dust deposition across the four tilt angles throughout the annual period.

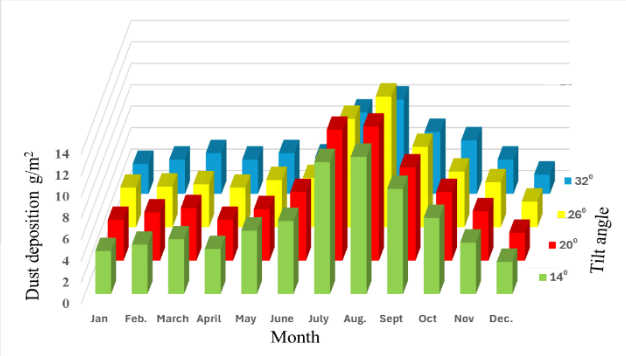

Fig. 4 Annual dust deposition across tilt angles

Wind speed plays a significant role in influencing the amount of dust deposited on photovoltaic (PV) panels, acting as both a source and mechanism for transporting dust from urban areas and deserts to the panel surfaces. Additionally, higher wind speeds can facilitate the removal of dust accumulation from the panels, thereby enhancing their efficiency. In the current experiment, it was observed that the average measured wind speeds remained relatively stable throughout the year, averaging 1.39 m/s. The lowest recorded average value was in December at 1.09 m/s, followed by April at 1.14 m/s. Conversely, the highest average occurred in February at 1.79 m/s, followed by July at 1.62 m/s. These results suggest that wind speeds in Bahrain are generally low, which limits their impact on both dust deposition and removal processes. This is illustrated in Figure 5.

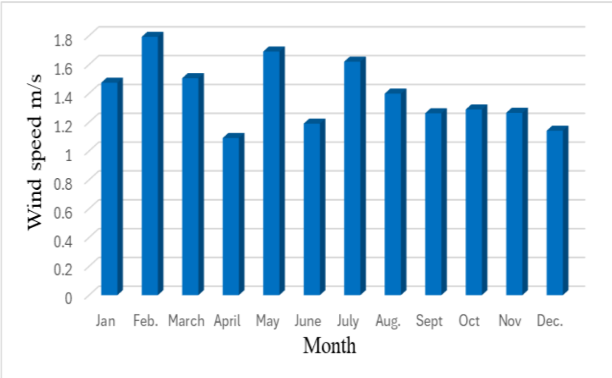

Fig. 5 Annual Variation in Average Wind Speed

Dust samples were sent to a specialized laboratory in Bahrain for analysis. The composition of dust, detailed in Table 1, reveals that silicon dioxide (SiO2) constitutes 18.0% of the total dust, while calcium oxide (CaO) accounts for 26.7%. Other components include aluminum oxide (Al2O3) at 5.4%, iron oxide (Fe2O3) at 5.8%, sulfur trioxide (SO3) at 6.1%, and magnesium oxide (MgO) at 5.8%. Together, these materials represent 67.5% of the collected dust composition. Notably, these components also comprise approximately 90% to 95% of cement composition , which correlates with the proximity of a concrete ready-mix factory situated about 400 meters from the university. Furthermore, loss on ignition makes up 27% of the dust composition, indicating the presence of moisture and organic materials incorporated into the dust layer.

Table 1. Analysis of Dust Composition

No	Parameter	Results %
1	Silicon Dioxide (SiO_2)	18
2	Aluminum Oxide (Al_2O_3)	5.4
3	Iron Oxide (Fe_2O_3)	5.8
4	Calcium Oxide (CaO)	26.7

5	Magnesium Oxide (MgO)	5.3
6	Sulphur Trioxide (SO3)	6.1
7	Loss on ignition @ 950^0 C	27.2
8	Chloride (Cl)	1.4
9	Sodium Oxide (Na_2O)	1.4
10	Potassium Oxide (K_2O)	0.36
11	Nickel Oxide (NiO)	<0.01
12	Zink Oxide (ZnO)	0.05
13	Chromium Oxide (Cr_2O_3)	<0.01
14	Manganese Oxide (Mn_2O_3)	0.06
15	Copper Oxide (CuO)	0.06

When the total output of each panel angle compared with each other through out of the year compared with each other, it was found that the panel raw with tilt angle of 26^0 gave highest yield and can be recommended for fixed angle for the kingdom of Bahrain when fixed angle panels installed, this can be clearly seen in Fig. 7. The total annual energy generation of panels with a 26° tilt angle is 1.1% higher than that of panels set at a 32° angle, 2.89% higher than panels with a 20° tilt angle, and 5.22% greater than panels set at a 14° angle. Furthermore, Statistical analysis, based on selecting the optimal performance angle for each month, indicates that adjusting the tilt of photovoltaic (PV) panels seasonally to align with the sun's zenith angle can increase energy output by 7.26%. This adjustment ensures that the panels are positioned to capture the maximum sunlight throughout the year, enhancing overall energy efficiency. A 3D plot illustrating the seasonal power generation comparison for the four different angle sets is presented in Fig. 6.

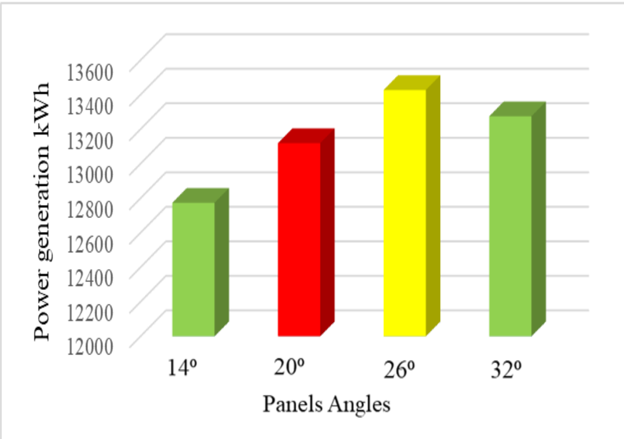

Figure 6. Analysis of energy generation at different tilt angles

V. CONCLUSIONS

The analysis conducted in the Kingdom of Bahrain highlights the significant impact of dust accumulation on photovoltaic (PV) panel performance, particularly within the context of the region's desert climate and low annual rainfall. Key conclusions drawn from the study include:

1. **Seasonal Dust Accumulation Patterns**: The data indicate that dust accumulation is markedly higher during the summer months, with peak values recorded in June, July, August, and September. This trend is attributed to the increased frequency of dust storms and minimal precipitation during this period, which creates challenging conditions for PV systems.

2. **Effect of Tilt Angles**: The study reveals that PV **panels** tilted at 14° accumulated the most dust over the year, followed by those at 20°, 26°, and 32° angles. This suggests that tilt angle plays a crucial role in dust deposition, which can affect energy efficiency and overall system performance.

3. **Wind Speed Influence**: Although wind speed is known to influence dust deposition and removal, the average wind speeds observed in Bahrain were relatively low throughout the year. This limitation suggests that wind may not significantly mitigate dust accumulation on PV panels, further emphasizing the need for effective cleaning strategies.

4. **Dust Composition Insights**: Analysis of collected dust samples indicates a composition rich in materials such as silicon dioxide and calcium oxide, which are common in cement production. The proximity of a concrete factory to the study site likely contributes to this dust composition, reinforcing the need for targeted cleaning measures

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