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Impact of dust and tilt angle on the photovoltaic performance in a desert environment

Mansour Alzahrani [a,b,*], Tasmiat Rahman [b], Muhyaddin Rawa [c,d], Alex Weddell [b]

[a] Department of Information Technology, College of Computers and Information Technology, Taif University, P.O. Box 11099, Taif, 21944, Saudi Arabia
[b] School of Electronics and Computer Science, University of Southampton, Southampton, SO17 1BJ, UK
[c] Smart Grids Research Group, Center of Research Excellence in Renewable Energy and Power Systems, King Abdulaziz University, Jeddah, 21589, Saudi Arabia
[d] Department of Electrical and Computer Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah, 21589, Saudi Arabia

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ABSTRACT

Dust accumulation on photovoltaic (PV) modules significantly reduces their performance, especially in desert environments. Cleaning can be costly or not feasible. This paper presents a comprehensive study of PV modules performance in a desert environment, focusing on the impact of dust on power output reduction at various tilt angles to determine the optimal angle in uncleaned conditions. Seven pairs of PV modules were installed on the roof of the Faculty of Engineering in Jeddah City at angles of 0°, 15°, 25°, 45°, 60°, 70°, and 90°. The output power of both the cleaned and dusty modules was recorded over a 12-month period. The results show that dust accumulation, tilt angle, and rain significantly reduce power. The optimal tilt for maximum average output power varies with the seasonal position of the sun and the amount of dust on the module's surface. After 183 days of dust accumulation without rain, the power reduction for the dusty modules reached 80.4%, 75.6%, and 60.2% at tilt angles of 0°, 15°, and 25°, respectively. In the rainy period, the highest performance of the dusty modules was observed at a 45° tilt angle, with a power reduction of 5.9%. Conversely, during the dry period and throughout the year, the tilt angle that generated the highest power output was 25°, with power reduction of, respectively, 28.7% and 20.7%. These findings provide valuable insights into the impact of dust and tilt on PV module performance and contribute to the development of predictive models and optimization strategies for solar panel systems in harsh desert conditions. This research highlights the importance of strategic tilt selection to enhance the performance and longevity of PV installations in desert environments.

1. Introduction

Photovoltaic (PV) energy output depends enormously on the amount of solar irradiance reaching the surface of the PV module. Currently, most PV modules convert only approximately 20% of the incident solar irradiance into electricity, and the rest is converted into heat [1]. The value of solar radiation for PV modules, whether fixed horizontally or at an angle, varies by both location and time of day throughout the year [2]. A study in Saudi Arabia investigated the influence of regional variations in identifying optimal tilt angles for maximum solar panel performance. The analysis showed that tilt angles of 20°, 25°, and 30° towards south are optimal, depending on the site. The study also defined three distinct solar energy zones: SEZ-A, SEZ-B, and SEZ-C, corresponding to optimal tilt angles of 20°, 25°, and 30°S, respectively [3]. The accumulation of material on the surface of a PV module, commonly referred to as soiling, is an important environmental factor that reduces its power yield. Soiling significantly reduces reflectance or transmission of the cover glass, causing irradiation loss, hence a reduction in PV module power yield [4]. In desert regions, the high irradiance level makes PV ideal to generate solar power. However, in such a climate the power yield can be significantly reduced due to the accumulation of dust on the modules. Soiling can cause a power loss that exceeds 1% per day [5], while a dust storm can decrease output by 20% and long-term exposure by up to 50% [6]. In 2018, the worldwide impact on solar energy yield associated with soiling was estimated to have reduced annual PV energy production by 3 to 5%, resulting in a global economic loss of at least €3 to 5 billion [5]. One key strategy to reduce soiling accumulation and consequent losses is to adjust the tilt of PV modules. The tilt impacts both the effectiveness of rain cleaning and the accumulation of dust. Rain stands out as the most effective natural cleaning mechanism, significantly enhancing modules efficiency by cleaning their surface. However, the water droplets that persist on the PV surface may make it adhesive [7], and a light rain can actually

* Corresponding author.
E-mail address: M.Alzahrani@soton.ac.uk (M. Alzahrani).

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Table 1
The specifications of PV module.

Model type	Poly 10 W
Max output power (P_{max})	10 W ± 3%
Voltage at P_{max} (V_{mp})	18 V
Current at P_{max} (I_{mp})	0.56 A
Open circuit voltage (V_{oc})	21.3 V ± 3%
Short circuit current (I_{sc})	0.64 A ± 3%
Nominal operating cell temperature	45 ± 2 °C

have a negative effect, gathering airborne dust particles and depositing them onto the module, creating a surface cementation layer of dust that may lead to a sudden decline in PV module performance [8]. Although rain has considerable cleaning potential, its effectiveness is influenced by tilt, a steeper angle enhances cleaning more than smaller angles [9]. After six months of soiling, [10] reported a 50% reduction in power output on PV modules tilted at 26° in Eastern Saudi Arabia. Moreover, [11] observed a 28% decrease over two months on modules tilted at 25° in the non-coastal area of western Saudi Arabia. After exposing PV modules to outdoor sunlight in Kuwait for 14 days, their efficiency dropped by 37.6%, 14.1%, and 10.9% for the 0°, 25°, and 45° angles, respectively [12]. This shows that an increased tilt promotes self-cleaning: gravity causes the larger-diameter particles to move towards the lower parts of the module and potentially fall off as the angle increases. Another key strategy to prevent power loss caused by soiling of PV modules is regular cleaning. Several studies have been undertaken, using cleaning methods such as blowing air, spraying water, or an electrostatic design to mitigate soiling [13–15]. However, these solutions are not always feasible, and come at considerable cost. Soiling is highly heterogeneous, necessitating accurate assessment of soiling rates to inform the cleaning schedules. Modeling approaches still need refinement, plus additional data for improvement and validation. This study offers both comprehensive data and insights into the impact of soiling on the performance of fixed, and tilted PV modules at various angles in a desert environment. The primary objective is to determine the optimum tilt to minimize potential irradiance loss while maximizing power generation through reducing the loss from soiling. The findings aim to contribute to the development of a reliable and scalable solar energy optimization model suitable for application in harsh desert conditions.

2. Experimental setup

Seven pairs of 10 W polycrystalline solar panels were installed at tilt angles of 0°, 15°, 25°, 45°, 60°, 75°, and 90°, facing south, on the roof of the Faculty of Engineering at King Abdulaziz University (KAU) in Jeddah City, Saudi Arabia, as shown in Fig. 1. Jeddah is one of the world's worst soiling accumulation zones, namely the MENA (Middle East and North Africa) region and Central Asia [16]. The city is characterized by a desert environment with high temperatures, low precipitation, drought conditions, and winds that cause dust and sandstorms [17]. To achieve a better understanding of the relation between dust accumulation and tilt, each pair consisted of two modules: one was cleaned every day, while the other was allowed to accumulate dust. During the 12-month test period, the PV modules performance was monitored and reported automatically every minute via WiFi into a ThingSpeak cloud-based interface. Additionally, an air quality cloud-based monitoring system was deployed to continuously measure airborne particulate matter (PM), enabling the correlation between dust events and performance variations. Daily weather conditions, including rainfall, cloud cover, and horizontal visibility, were collected from the National Center for Meteorology. The electrical specifications of the polycrystalline silicon (poly-Si) PV modules used in the experiment are in Table 1.

3. Results and discussion

To investigate the influence of tilt angle and dust accumulation on PV modules output, this experimental study investigated various cases, considering both clean and dusty PV modules. During the experiment the dry and rainy periods, together with environmental events such as rain, dust storms, and long-term dust accumulation were highlighted for performance analysis. The duration of the dry and rainy periods was 183 and 182 days, respectively. The output power of both the clean and dusty modules at each tilt angle was recorded every day at one-minute intervals between 09:00 and 16:00. This period was chosen for the power yield and to mitigate any potential shading by nearby objects at the site. The following sections present the specific cases that were investigated. Notably, the 90° angle modules experienced technical issues, leading to partial elimination of the clean 90° angle module from the analysis.

3.1. Impact of dust accumulation and environmental events on PV modules performance

To investigate the impact of dust accumulation on the PV performance, this study used two sets of modules with variations in tilt angle: one was cleaned regularly, while the other was intentionally left uncleaned throughout the study. Fig. 2 presents the daily average output power for (a) the clean and (b) the dusty modules at various tilt angles, alongside the environmental events. To comprehensively understand the influence of such environmental events on the PV performance, the study examined light rain, dust storms, heavy rain, long-term dust accumulation, and cloudy days. Each had a distinct impact on the modules, as detailed below.

Following **light rain** (0.8 mm/day) on March 3rd, an impact on the module performance became apparent. For instance, the performance of the dusty 45° tilt module improved, approaching that of its initial clean state. By contrast it was observed that the modules with a tilt angle of 0° retained a significant quantity of water on their surface. This accumulated water combined with dust caused cementation that resulted in decreased performance, as shown in Fig. 3. Therefore, the recovery of the PV performance after light rain varied with tilt angle, demonstrating the angle effect on rain-induced cleaning. Lower rainfall intensities (<1 mm/day) exacerbated dust accumulation and adhesion, particularly at smaller angles. The adverse consequences of such rainfall conditions are discussed in [8].

A **dust storm** was observed on April 11th, with an average daily PM_{10} value above $230\,\mu g/m^3$ recorded by the air quality monitoring system, significantly exceeding the average Jeddah value of $101\,\mu g/m^3$ on non-dust stormy days [18]. Moreover, horizontal visibility experienced a significant reduction, to 3 km. This event escalated the accumulation of dust on module surfaces, leading to a substantial decline in power yield and an average power reduction of 37.3%, 31.1%, and 21.9% for the 0°, 15°, and 25° tilt angles, respectively.

After 182 days, **extended dust accumulation** became evident because, without rain, every dusty module experienced a significant decline in performance. The module with a 25° tilt angle recorded the highest daily average power output of 1.98 W, while the 0° and 15° tilt angles had outputs of 0.70 W and 1.06 W, corresponding to an average power reduction of 80.4%, 75.6%, and 60.2%.

After **heavy rain** (6 mm/day) on April 28th the performance of all modules improved significantly. This event occurred 16 days after the dust storm. The modules at smaller angles displayed superior performance, possibly due to the effective collision of water droplets on their surfaces. Furthermore, as the study reached 183 days, marking the onset of the rainy period, a significant change in performance was observed. After two **heavy rain** events (7 mm/day on October 28th and 9 mm/day on October 29th), the performance of every dusty module improved significantly. The modules at the 45° and 25° tilt angles yielded the highest power output of all dusty modules and

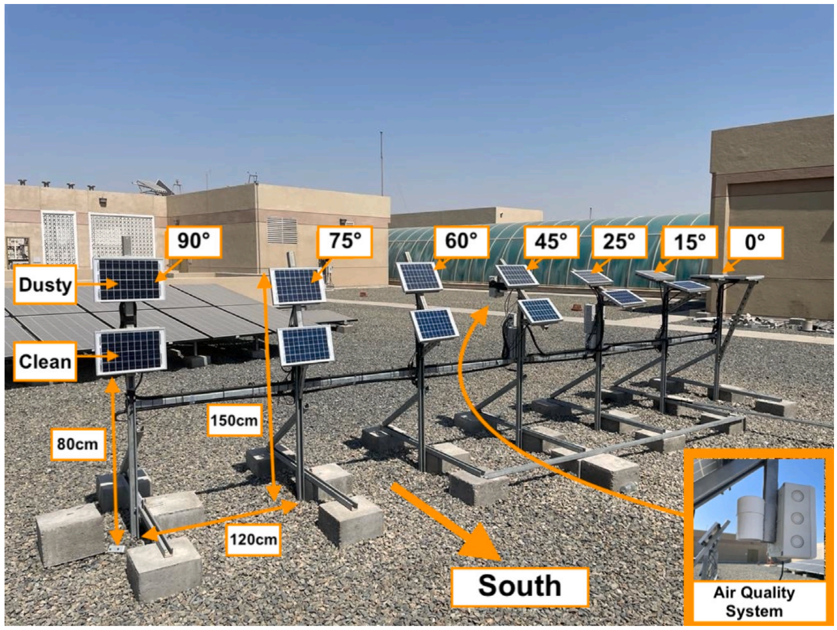

Fig. 1. Experiment setup with different tilt angles.

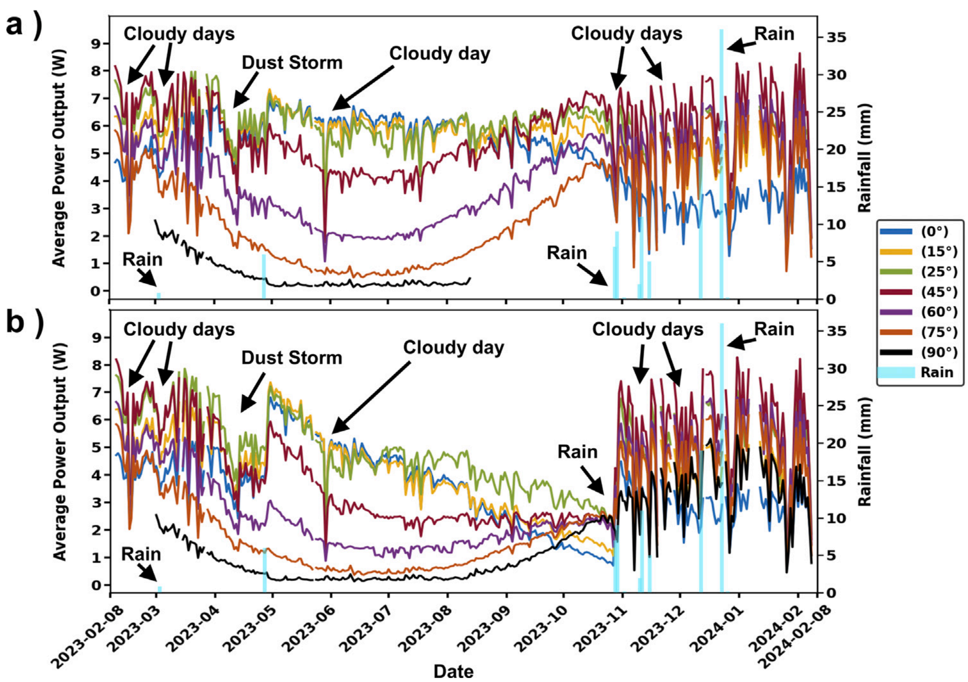

Fig. 2. Daily average power output across different tilt angles under (a) clean condition and (b) dusty condition alongside environmental events.

maintained a consistent power output until the end of the experiment. This highlighted that heavy rainfall mitigates the effect of prolonged dust accumulation, thereby enhancing the overall performance of PV modules.

On **cloudy days** the modules gave varying performances. Cloudy day events with 95 to 100% cloud cover during the experiment had a greater impact on the smaller-angle modules than those at steeper inclinations. Cloud cover diminishes the intensity of direct sunlight, and reduces the modules energy conversion efficiency. Consequently, the power output of these modules saw a notable decline on cloudy days. For example, the cloudy day of May 29th caused a significant decrease in power output, with a reduction of 63.6% for the 0° angle and of 9.4% for the 75° angle compared to the previous sunny day.

The daily average output power analysis revealed the progressive reduction in the performance of dusty modules over time, particularly evident after extended periods of dust accumulation. However, the effectiveness of rain-induced cleaning depended on the tilt and amount of rain, with modules at lower inclinations exhibiting a superior performance after a heavy rainfall.

3.2. *The monthly average output power of the clean and dusty PV modules*

The heatmap in Figs. 4 and 5 provides a comprehensive view of the performance of solar panels at various angles under clean and dusty conditions over the year. Fig. 4 shows the variation in power output across different tilt angles and months under clean conditions. The

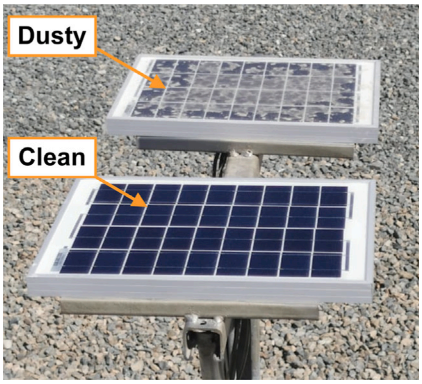

Fig. 3. Surface conditions of PV modules set with 0° tilt after light rain in March.

45° angle had a strong start in February, but tended to fall behind the 25° angle in subsequent months. Given its consistent performance throughout that period, the 25° angle emerged as the optimal tilt angle for solar PV modules in the one-year study time-frame, under clean conditions. It consistently achieved the highest or near-highest average power outputs each month, indicating its effectiveness in maximizing solar energy capture under clean conditions. This finding is aligned with the PV Standard Installation guidelines set by the Saudi Electricity Company [19].

Fig. 5 shows the variation in power output across different tilt angles and months under dusty conditions. Notably, the first half of the year, especially from February to May, displays higher power output across most tilt angles. This period saw two rainfall events that contributed to an increase in performance. Specifically, the heavy rain on April 28th significantly improved the performance of the PV modules at smaller angles, with a relatively lower enhancement observed for those at steeper angles. This may be attributed to the specific direction of that rain, being driven by the wind, and the seasonal shift in the sun's position. From May, a consistent decline in performance was noted across all angles, and this can largely be attributed to increased dust accumulation, lack of rain, and possibly higher temperatures negatively affecting the dusty modules performance. However, during the early summer months (May and June), modules at both 0° and 15° angles began to achieve maximum monthly average power output, despite their smaller angles leading to greater dust accumulation. The solar zenith angle emerged as a significant factor in maximizing solar irradiance capture, thereby enhancing the performance of these lower-inclined modules throughout the summer. However, as the months without rain progressed and dust accumulation increased, those modules at 0° and 15° angles started to exhibit the effect of dust accumulation, namely reduced daily average power output during the subsequent dry months to 1.43 W and 1.98 W, respectively, and by the end of the period (October) they saw a monthly power reduction of 66.9% and 63.1% ; by contrast, the 25° tilt angle showed a lesser effect of dust accumulation, maintaining better performance with an average power output of 3.17 W and a monthly power reduction of 47.9%. Following heavy rain at the end of October, marking the beginning of the rainy period, seven rainfall events contributed to increased performance across all modules. The 45° and 25° angles gave the best performance of the modules during winter months (November to April). These results highlight the monthly variation in power output, influenced by tilt and dust. Initially, during the winter months, the 45° angle proves more effective in capturing energy. As the year transitions into the summer months, the 25° angle becomes more efficient in energy capture. However, the 25° angle demonstrated a remarkable resilience in maintaining performance throughout the entire experimental one-year period, making it a practical choice to mitigate dust effects.

3.3. Impact of seasonal variation (dry and rainy periods) on the PV modules performance

In the experiment, three periods were selected for analysis: the rainy months, the dry months, and a full year. This aimed to understand the performance and reliability of PVs under varying environmental conditions. The comprehensive approach provided a holistic view of the PV performance over time. Figs. 6, 7, and 8 are comparative plots of average power output against tilt under various conditions.

In Jeddah the **dry period** typically has a lack of rain, higher temperatures, and clear skies, providing an opportunity to evaluate the performance of PV modules in optimal sunlight exposure. Although the increased solar exposure raises their power output, the accompanying very high temperatures degrade their efficiency due to heating issues. This happens at a time critical to the modules power loss since, due to dust accumulation, there is no rain to clean them. Hence, the analysis assesses the resilience and performance of PVs under these conditions. Fig. 6 indicates that the reduced performance of the dusty modules at all tilt angles is in accordance with the findings of previous studies [10–12]. The presence of dust affects the optical scenario by increasing light reflectance and scattering. For both the clean and dusty modules the highest PV performance was observed at a 25° angle. The dusty modules produced a median power output of 4.28 W, only a 28.7% reduction. For comparison, the closest counterpart, the 15° angle, achieved a median power output of 3.64 W, in a 39.1% reduction. This suggests that the 25° angle offers the optimal balance to mitigate the impact of dust in the dry season. Further, we found that the power output range for the steeper angles is consistent, whereas the performance of these modules at smaller angles is less stable.

The **rainy period** is characterized by greater cloud coverage, increased precipitation, and possibly lower overall solar irradiance. Analyzing this period helps understand how rain and cloud cover affect the modules performance. Rain removed the dust accumulation from the dusty PV modules by cleaning them; therefore, the highest power output was nearer to that of the clean modules, as shown in Fig. 7. The optimum tilt angle, that with the best performance, differs from that in the rainy season, and a 45° angle for both the clean and dusty modules exhibited a greater power output. The dusty 45° angle median power output was 6.05 W, with a reduction of 5.9%, while the dusty module's 25° angle median power output was 5.53 W, with a reduction of 7.2%. However, the 25° angle was found to be less susceptible to fluctuations in performance. It is worth noting that the 25° angle showed a strong performance in both dry and rainy conditions, with a relatively smaller reduction in power output due to dust accumulation than that at other angles.

Lastly, the inclusion in this study of a full year ensured that the analysis is not limited to extremes of weather conditions but encompasses all transitional periods to characterize the yearly average performance of both types of module. The maximum average power output for both was achieved at an angle of 25° (shown in Fig. 8). Moreover, the clean module at a 25° angle showed a higher median power output of 6.05 W, suggesting that it is optimally positioned to capture solar radiation efficiently in clean conditions. This finding complies with the Saudi Electric Company's recommendations. However, the study by [3] suggested an optimum tilt angle of 20°, identifying Jeddah as falling within the SEZ-A zone, while another study [20] recommended 21.76° as the optimum tilt angle for Jeddah. These differences, compared to present study, can be attributed to the limitations of our experimental setup, particularly the absence of a 20° tilt angle in the design. Therefore, incorporating additional tilt angles between 15° and 25° in future studies could provide further insights. Furthermore, the analysis shows that the dusty 25° angle module had a significantly higher median power output, at 4.76 W, than that at other angles under the same conditions, with reduction of 20.7%. Thus, it can be concluded that the optimal 25° angle effectively achieves a balance between sun exposure and the impact of dust accumulation on the PV consistent performance.

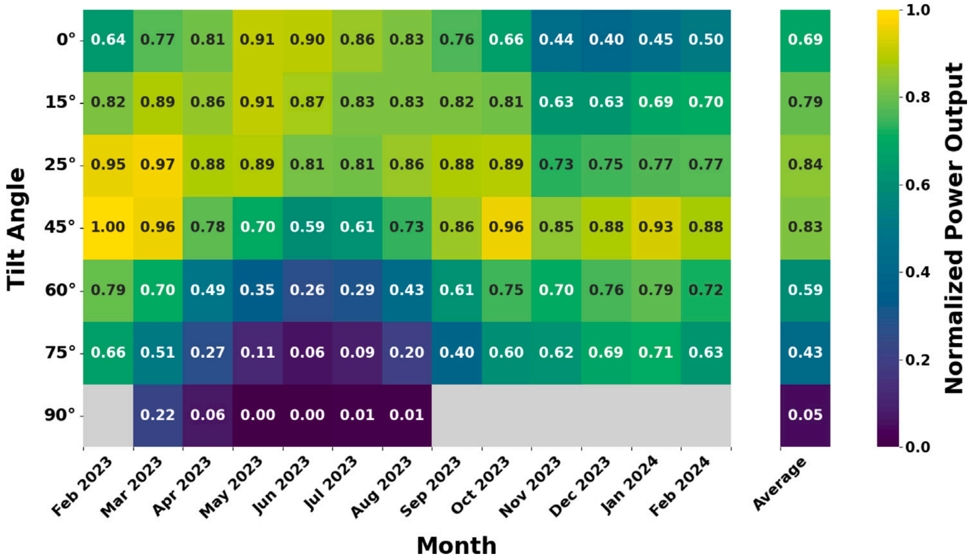

Fig. 4. Normalized monthly average power output across different tilt angles under clean conditions.

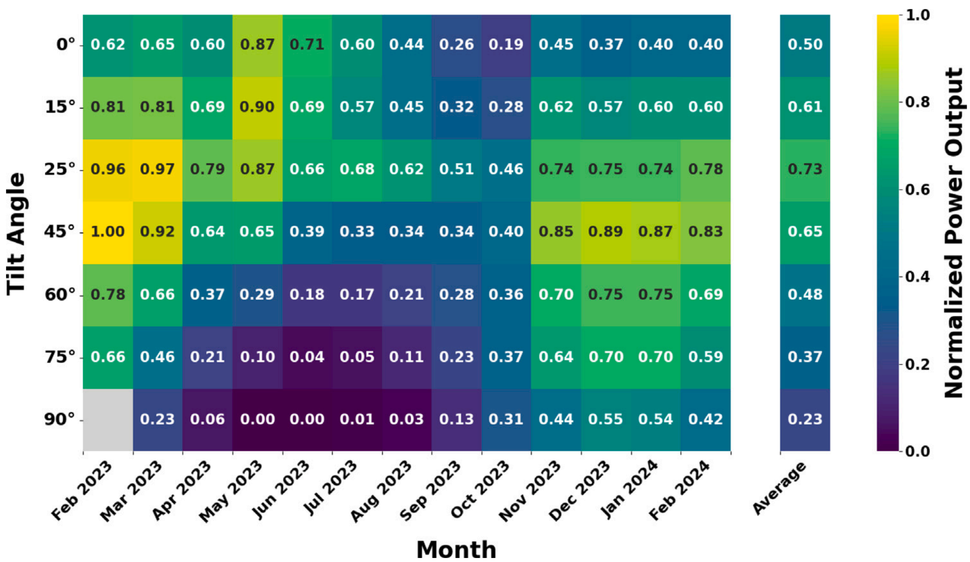

Fig. 5. Normalized monthly average power output across different tilt angles under dusty conditions.

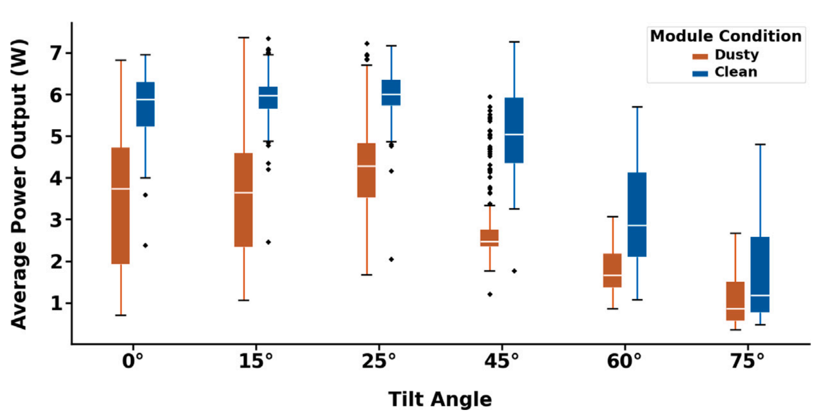

Fig. 6. Average power output distribution for dusty and clean modules at various tilt angles in the dry period.

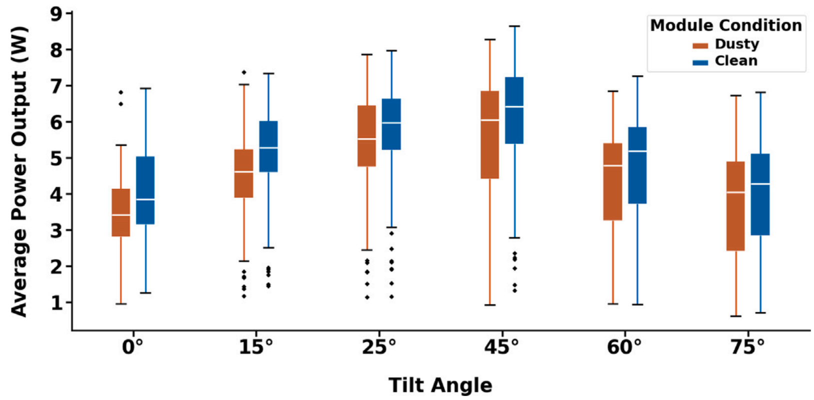

Fig. 7. Average power output distribution for dusty and clean modules at various tilt angles in the rainy period.

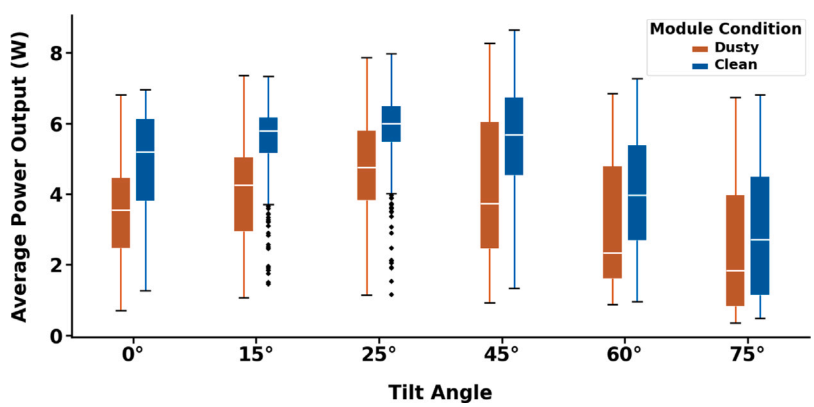

Fig. 8. Average power output distributions for dusty and clean modules at various tilt angles over a year.

4. Summary and conclusions

This study underscored the significant impact of dust accumulation on the performance of PV modules in a desert environment. Through a detailed analysis of the PV modules installed at various angles in Jeddah City, the study identified the optimal tilt to maximize power output under various environmental conditions. The findings revealed that dust accumulation significantly reduces power output, with a reduction of up to 80.4% observed after 183 days without rain for a module at a 0° angle. Rain significantly helped clean the PV modules by removing dirt accumulation naturally, especially on those at steeper angles. However, lower rainfall intensities (<1 mm/day) increased dust buildup and adhesion, causing cementation on the module at 0° angle. A 25° angle demonstrated the best performance during the dry period, balancing effectively the reduction of dust accumulation and maximum capture of the solar irradiance. During the rainy period, the optimal angle shifted to 45°, which enhanced the module performance due to natural cleaning by rain. Over the entire year, modules with a 25° angle consistently performed best, even without regular cleaning. Additionally, the study highlighted the critical role of environmental factors, such as rain intensity, dust, sandstorms, and cloud cover on the PV modules performance. By identifying the optimal tilt and understanding the environmental patterns, this research provided valuable guidelines for enhancing the efficiency and longevity of solar panel installations in desert environments.

CRediT authorship contribution statement

Mansour Alzahrani: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tasmiat Rahman:** Writing – review & editing, Visualization, Validation, Supervision. **Muhyaddin Rawa:** Resources. **Alex Weddell:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data supporting this study can be found at https://doi.org/10.5258/SOTON/D3344.

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