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Experimental study of the impact of dust on azimuth tracking solar PV in Sharjah

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ABSTRACT

Dust is one of the significant constraints in utilizing solar photovoltaic systems under harsh weather conditions in the desert regions due to creating a shadow that blocks solar irradiance from reaching solar cells and consequently, significantly reducing their efficiency. In this research, experimental study was performed to comprehend the nature of dust particles and their impact on the electrical power output that is generated from azimuth tracking solar PV modules under Sharjah environmental conditions in winter season. According to laboratory experiments, the power losses are linearly related to the dust accumulated density on the surface of the solar panel with a slope of 1.27% per g/m2. The conducted Outdoor studies revealed that the absolute reduction in output power increased by 8.46% after 41 continuous days with one low-intensity rainy day. The linear relationship obtained from indoor experiments was applied later to estimate the dust deposited density on the outdoor setup. The results showed that a regular cleaning process every two weeks is recommended to maintain the performance and to avoid the soiling loss. This work will help engineers in the solar PV plants to forecast the dust impact and figure out the regularity of the cleaning process in case of single axis tracking systems.

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1. INTRODUCTION

Recently, environmental impacts and rapid growth in energy demand have raised concerns in utilizing solar power as a clean and renewable source for energy production around the globe [1]. The United Arab Emirates, in addition to other Middle Eastern and North African countries, has a bright future for solar energy deployment because of its strategical location in the global Sun Belt region. This location gave the country high global irradiance in the range of 1900 to 2300 kWh/m2 [2]. The population growth, quick industrialization, and rapid increase in water need from desalination plants have led to high energy demands that require various solutions. As claimed by Business Monitor International, a significant rise is predicted in the yearly power demand of the nation during the time interval from 2012 to 2021, parallel to this prediction, the annual power consumption is expected to increase by 5.6% [3]. United Arab Emirates receives a high exposure to solar irradiance since there are 350 sunny days out of 365 annually. The total energy obtained from the sun is approximately 6.5 kWh/m2 per day and this amount is varying with respect to the location and season.

Nevertheless, PV performance in the arid area such as the gulf region is affected by several parameters like temperature, humidity ratio, average wind speed, and dust. Many previous studies investigated the impact of these parameters in the region, especially in UAE [4], [5]. Mohandes *et al.* investigated the effect of environmental factors using 500 W copper indium diselenide PVs in United Arab Emirates. It was revealed that due to low temperature at night in the dry areas, the dew could quickly be generated on the surface of solar panels and catch the dust particles accumulated in the atmosphere. Later on, when the temperature rose during daytime, dew evaporated and left behind a layer of dust. Moreover, it was concluded that the output power would decrease rigorously as the humidity increases. Due to the deposition of dust, the degradation in output power will reach 10% in 5 weeks [6]. Nonetheless, dust accumulation was already reported to be the major constrain in desert climates. Consequently, a 50% drop in the power has been reported in 6 months if the system is left without cleaning [7], [8].

The existence of dust in the surrounding environment forms a shading effect that limits the arrival of irradiance to the solar module and scatters it [9], the deposition of dust particles also tends to increase the effect of shading and stops the irradiance from touching the PV panel, leading to increased solar PV temperature which affects the efficiency of the cell and decreases its output electrical power [10]. Various research works in this area proved that the deposition of the dust particles on the PV modules leads to a remarkable drop in their performance [11]. The dust deposition rate on the solar panels relies on different factors, these factors are the inclination of the panel, the speed of the wind, humidity ratio, and the environmental conditions [12].

Dust-linked photovoltaics' efficiency degradation is significantly affected by the properties of the deposited dust. Enormous research work proved that the effect of the soil on PV power output mainly relies on the particles' physicochemical characteristics [13]-[20]. These research investigations introduced 15 types of dust in the atmosphere, six of these types, which are ash, limestone, red soil, CaCo3, Sio2, and sand, are confirmed that they significantly affect the Photovoltaics' efficiency when compared to other types of dust [21]. Chemical composition of dust affects interaction with the transparent glass, this interaction influences the performance of solar panel dust removal techniques [22]-[24]. Several theories suggested that it is highly possible to mitigate soiling by coating the Photovoltaic panel surface with a hydrophilic or hydrophobic substance. Nevertheless, it was demonstrated that the strong adhesive energy between the soil particles and the transparent glass surface is a complicated event and not uniquely dependable on the glass specifications. Other factors are also considered such as particle properties and weather conditions. The mentioned theories indicate the essential role of investigating the properties of accumulated pollutants [25].

The performance degradation that is mainly related to dust deposition is affected also by the shape and size of the accumulated particles [26], [27]. Particle size is the main factor that causes solar irradiance distribution and scattering, therefore, it deteriorates Photovoltaics' efficiency. The considerable propensity for large dust particles allow deposition of small particles due to low wind velocity [28]. Finer particles may also lead to more deterioration of solar panels' performance than larger particles for equal dust weight. Tiny particles, which have bigger surface volume, can be scattered homogenously when compared to the coarser and big dust particles. In general, there are few studies on the size and shape of dust deposited over solar modules in the arid environment.

Hachicha *et al.* inspected the influence of the dust particles on the output power of solar modules experimentally. The gathered dust from the experiments was variable in shape and size (between 1.61 to 38.40 μm). Controlled lab tests showed that the electric power that is generated from the solar panels is directly proportional to the dust density, indoor experiments showed that the system performance decreased by a rate of 1.7 per g/m2 of the particles accumulated on the transparent surface [29].

Javed *et al.* checked the properties of the dust particles and the settlement rate with different periods of exposure in Doha, Qatar. The authors examined the rate of accumulation of dust and the size of the distributed particles. This work proved that the rate of accumulation increased proportionally with the duration of the exposure until the point of relatively consistent values at steady exposure is reached for long duration of time [8].

Adıgüzel *et al.* gathered several shapes and sizes of coal pollutants and investigated their influence on the output power of the PV panels. The experimental work proved that higher weights of deposited coal particles decreased the efficiency of the system, which proportionally increased the energy loss. The deposited dust with smaller diameter but constant weight increased the energy loss as it do not let more radiation reach the surface of the PV cells unlike larger particles [30].

Gholami *et al.* performed a long experiment for 70 days to examine the influence of dust settlement on the power deterioration of the PV panels. The experimental work revealed that 21.47% from the total output power decreased due to the accumulation of 6.0986 gram per meter square after 10 weeks on the transparent glass of the solar panel with a total absence of rain [31]. Chang studied the efficiency of solar modules by utilizing an azimuth tracking system. Results from the experimental work revealed that the azimuthal tracking performance is better than the fixed mounted solar panels by 18.7% [32]. Al Mohamad designed and studied the output power of one-axis tracking system. His experimental results showed a remarkable improvement of 20% in the performance of the tracking system compared to normal solar panels [33].

The paper is organized as follows: The introduction that shows the previous studies and research work of dust impact, the experimental setup which is categorized into three parts, the outdoor experiments, the indoor experiments, and the dust characterization experiments, and the PV performance and dust characteristics.

2. RESEARCH METHOD

The experimental setup in the current study was installed on the rooftop of the W-12 building of the University of Sharjah campus in Sharjah, UAE. Its location is defined by the geographical coordinates of latitude: 25° 34′ N and longitude: 55° 42′ E. The study was conducted within 6 weeks starting from 29th of January 2020 to 10^{th} of March 2020. Two strings consist of six typical polycrystalline silicon solar panels where three series panels are on each string, each panel has a rating of 320 W and each string has a rating of 960 Wp per string as shown in Figure 1. Table 1 show the electrical specifications of the solar panels. The tilt angle was fixed at 20 degrees during the investigation. The PV System has a tracking mechanism using one-axis mobility and azimuthal tracking strategy in the east-west direction. Initially, both strings are cleaned thoroughly by water and a complete day profile is recorded to determine the initial power difference between the reference and experiment strings. Afterwards, the reference string is cleaned each time before recording the data and the other string is left without cleaning to determine the impact of dust on its glass surface. Equipment and devices from solar photovoltaics energy lab at the University of Sharjah were used to log the output power from the system. A small calibrated monocrystalline silicon solar module from Fronius was used as a solar irradiance sensor with an annual average tolerance of ±5%. Regarding the ambient temperature and module temperature sensor, PT1000 sensors with an accuracy of ±0.8 ℃ were utilized. To complete the private weather station, a cup anemometer with reed contact was employed to measure the exact wind velocity with a tolerance of ±5%. all sensors were installed with a data logger to collect the data. The Profitest PV analyzer device from Gossen Metrawatt with a resolution of ±5% and reproducibility of ±2% was used to measure and record the current-voltage and power voltage curves from both strings. The data was collected each week from 9:00 am to 3:00 pm with a resolution of five minutes and sent directly to the computer to analyze it.

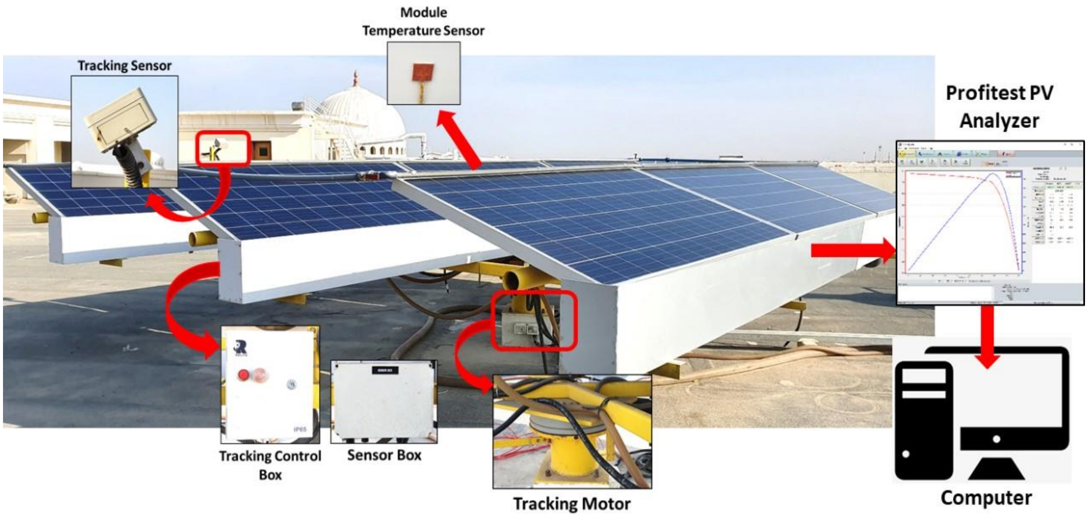


Figure 1. Outdoor experimental setup

For the controlled environment experiment, a clean energy trainer experimental setup from Heliocentris was used. A small polycrystalline based solar panel of 1.2 W was utilized. A graded and calibrated lamp that would provide the 1000 W/m2 at a distance of 30 cm simulated the sun. The dust was carefully weighted using a sensitive balance from RAD WAG with an uncertainty of ±0.001 g and distributed homogenously on the small PV panel utilizing a manual procedure. The tests were initiated by measuring the reference I-V and P-V curves with a clean panel. 2 g/m2 of dust was added each time to reach cumulatively up to 14 g/m2. In our scenario, the small photovoltaic panel was fixed at a 20-degree tilt to be consistent with the outdoor experiments.

Table 1. Electrical specifications of the solar panels

Parameter	Value
Type	Polycrystalline
Maximum Power	320 W
Maximum Voltage	37.1 V
Maximum Current	8.63 A
Open Circuit Voltage	45.7 V
Short Circuit Current	9.04 A
Weight	23 kg
Dimensions	1956*992*50 mm

The dust characterization was conducted by utilizing the real dust samples which are picked from the dusty string in the system. The gathered dust was initially sent to the Advanced Materials Laboratory to be analyzed. By checking an electron beam that is connected with the particles, Tescan VEGA3 operated at 20 kV was utilized to perform the scanning electron microscopy (SEM) test. This test aims to receive a clear visualization of the particles and their size. Maintaining the same SEM working voltage, X- Max 50 from Oxford Instruments was used to achieve the energy dispersive X-ray spectroscopy analysis. The purpose of the EDS test was to grant the discovery of the particles at the atomic level while exposing the sample to an X-ray source. Due to the importance of analyzing the chemical composition of the dust particles, the X-ray Fluorescence experiment was executed using the Horiba Microscope by determining the fluorescent radiated from the particles after being exposed to a primary X-ray.

3. RESULTS AND DISCUSSION

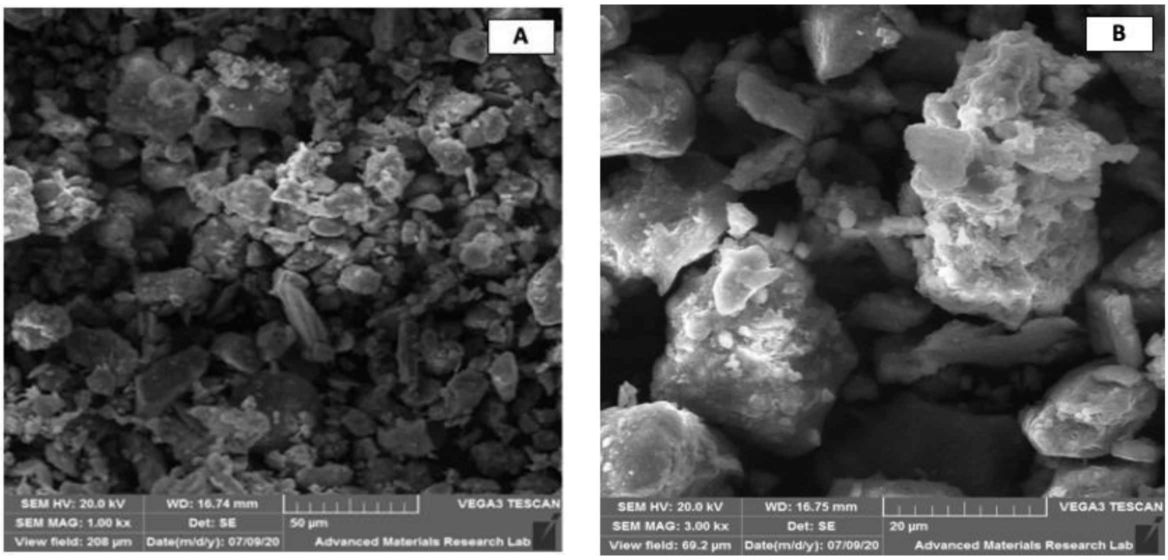
The quantity of the dust settled on the transparent glass of the PV panels is mainly affected by various influencers. For example, to optimize the solar irradiance that is received by the panel, the tilt angle must be close or equal to the latitude of the location. Additionally, solar panels are usually adjusted to the south direction in the northern part of the earth. Rainfall quantities and wind forces are influenced by the weather status of the location and are difficult to be controlled.

Regarding this research work, results from the experiment work can be categorized into three major categories. Initially, a dust sample, which is collected from the solar system, is sent to the X-ray lab to be analyzed by its chemical composition and relative elemental concentrations. A controlled study in the lab is then performed to determine the impact of dust on the PV power output and to find a correlation that relates the dust density (g/m2) and power degradation. Finally, an outdoor study is conducted to investigate the power deterioration that occurred due to accumulated dust under Sharjah weather conditions.

Gathered dust from the dusty string during the experiment was subjected to the X-ray analysis to obtain the chemical composition and morphology of the particles. The size of the particles and their arrangement on the transparent surface of the panel play an important role in creating shadow and consequently decrease the power output from the panel. Finer and smaller dust particles show a tendency to obstacle the irradiance beam with a few amount of gaps and thus significantly affects the PV performance degradation [34]. The mentioned phenomena could easily be explained by assuming that tiny and soft dust particles are homogenously dispersed when compared to the rough particles [35] and consequently lead to diffusing the incident irradiation [34]. Under severe humidity weather conditions, the power drop could be remarkably high and this occurs when finer particles stuck on the PV panel and form a sticky surface that is difficult to clean using wind and air energies [36].

The SEM test in the advanced material lab showed that the settled dust particles on the solar string are heterogeneous and not equal in the shape or size of the particles. Figure 2 represents the results received from the SEM analysis at different magnification values. The size of the dust particles can be obtained by using the scales on the bottom of the pictures, Figure 2(b) indicates that the average particle size can be estimated to be 18 um.

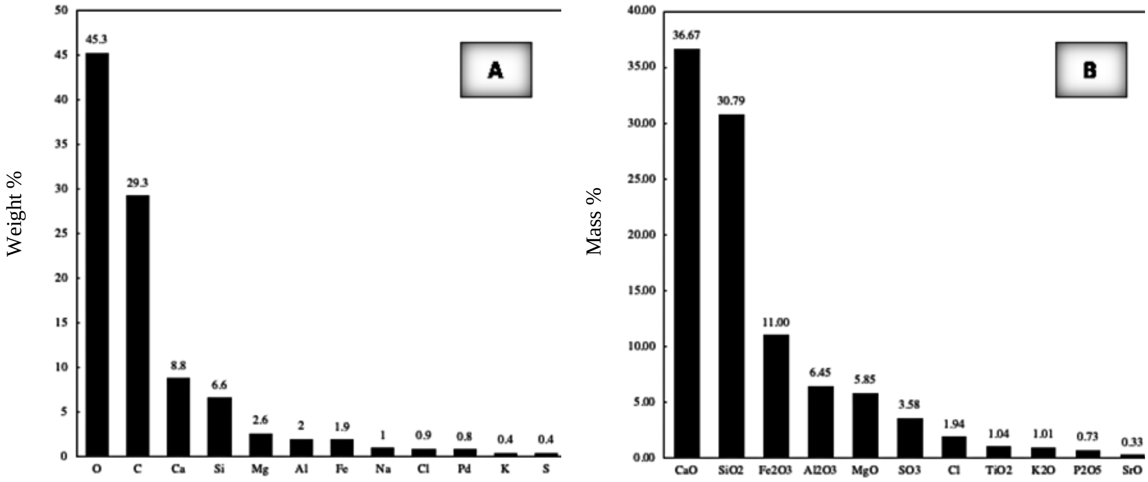
The chemical composition analysis of the dust sample is a crucial test to understand the cohesion of the particles on the surface of the solar panel and could help predicting the suitable cleaning technique. The elemental composition of the dust sample was studied. EDS method was utilized to obtain the chemical composition of the dust particles. The results from the test in Figure 3(a) show a high dominancy of the oxygen with a value of 45.3% followed by 29.3%, 8.8%, and 6.6% for carbon, calcium, and silicon respectively.



(a) (b)

Figure 2. SEM test for the dust sample, (a) At 1000x magnification, (b) At 3000x magnification

Furthermore, XRF analysis was implemented to determine the relative masses of the minerals in the dust sample. The obtained data from the analysis in Figure 3(b) showed that the calcium oxide has major mass when compared to other minerals with a value of 36.67% followed by silicon oxide or silica with an amount of 30.79 and iron III oxide with an average of 11%. Although the elemental content of the particles is mainly affected by the industrial activities in the surrounding environment, the received data from the morphological tests proved that the dust is significantly rich with calcium oxide that is consistent with other research works in the same geographical location [29], [31]. The dominancy of calcium and silicon oxide minerals in the dust sample shows the high donation from CaCo3 and Sio2 sands in the United Arab Emirates which normally transfers by the dusty wind that emerges from the gulf area [8], [29], [31].



(a) (b)

Figure 3. Dust sample analysis tests, (a) EDS, (b) XRF

The chemical content of particles reveals a form of organic materials and inorganic materials that have strong and weak solubility in water. During extreme weather conditions and elevated levels of humidity, minerals which have high solubility generate droplets that contain the low solubility substances. After losing the moisture, the droplets generate a dry and adhesive layer on the glass surface of the solar panel which contains only the low solubility minerals. The chemical properties among the morphological characteristics of the dust are a key factor that affect the ability of adhesive energy for the particles. Moreover, applying the new coating techniques such as anti-reflective layers may help in decreasing the strength of the adhesive layer of the dust particles on the module and consequently facilitate the soiling cleaning process [37].

In a controlled experiment, the impact of dust on the power degradation (ΔP) has been studied. The collected dust from the outdoor experiment is weighted and homogeneously distributed on the examined panel. The experiment starts with 2 g/m2 initially and then the weighted amount of dust is added to reach 14 g/m2 dust deposition. Three trails are conducted and the average values of theses trails are plotted in Figure 4. A linear curve fitting is applied to get the relationship of power loss with respect to dust density. This controlled experiment aims to find a relationship between dust settlement on the transparent surface and the weight of the dust. An average power degradation of 1.27% per gram was observed with 17.77% at 14 g/m2. Thus, the dust deposition caused significant power degradation for the solar panel. The impact of dust on the power degradation can be represented as (1):

$$\%\Delta P = 1.269 \times Dust\ Density\ (g/m^2) \quad (1)$$

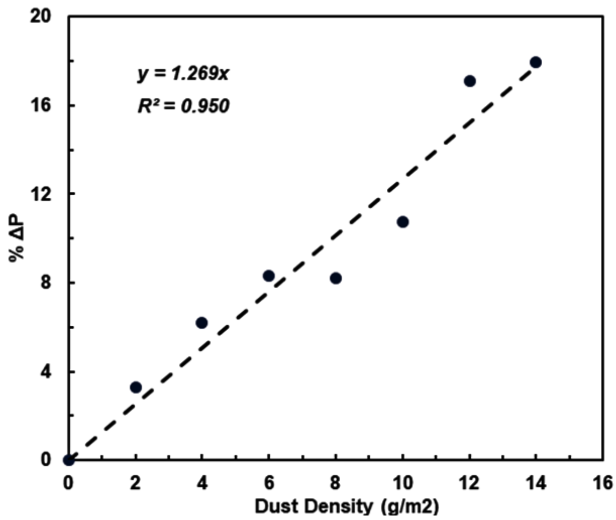


Figure 4. Power loss as a function of dust density

Besides the controlled experiment, an outdoor experiment has been set up to study the impact of naturally deposited dust on the performance of single-axis tracking solar system. The desert climatic conditions of Sharjah are extreme, so it is feasible to study it under real climatic conditions. Initially, both strings are cleaned with water to remove any previous dust accumulation and record the power production from both strings over a period of one day as shown in Figure 5. This is required to determine any discrepancy in output power between both strings due to manufacturing or systematic error. Figure 6 illustrates that both strings follow the irradiance profile and it was observed that there is a difference of 1.46% in output power.

A set of data was collected on 3rd of Feb., 13th of Feb., 18th of Feb., 24th of Feb., 3rd March, and 10th March. On 3rd of Feb., initially, the first half of the day was densely clouded with mild clouds during the afternoon. The 13th and 24th of February had weather conditions with mild clouds in the first half and partially clouded in the afternoon. The 18th of February had partial clouds throughout the day passing from the test site. The 3rd and 10th of March were clear sunny days.

The comparison between the output power and the corresponding irradiance profiles are shown in Figure 7. Initially, at the beginning of the experiment, the difference in the power production between the two strings is 1.46%. This difference is deducted from the observed power difference to get the absolute power difference as (2):

$$\%\Delta P = \left(\frac{P_{Clean} - P_{Dusty}}{P_{Clean}}\right) \times 100 \tag{2}$$

where P_{clean} represents the output power from the daily cleaned reference string and P_{dusty} exhibits the output power in the dusty string. It is noteworthy that all measurements in this experiment for the two strings were obtained during the same time and exact weather conditions and consequently, the impact of other environmental influencers like ambient temperature, wind speed, and humidity are canceled out which makes the quantity of the dust settled on the string's surface to be the only effective factor in the comparison.

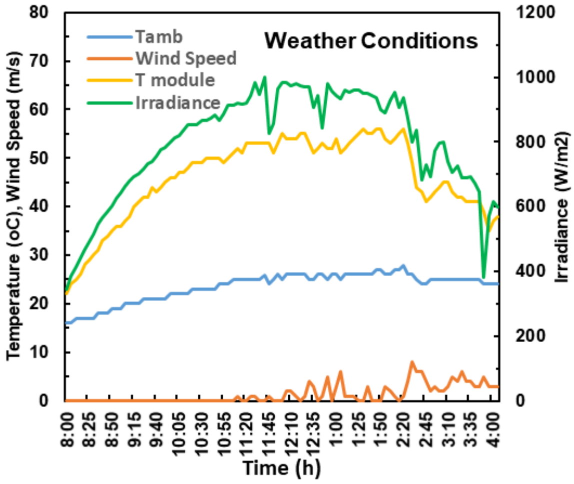


Figure 5. Weather conditions before starting the experiment

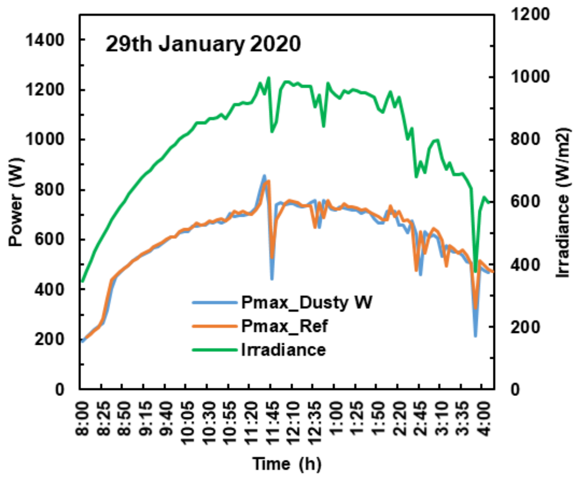


Figure 6. Irradiance and output power from the outdoor setup as a function of time before starting the experiment

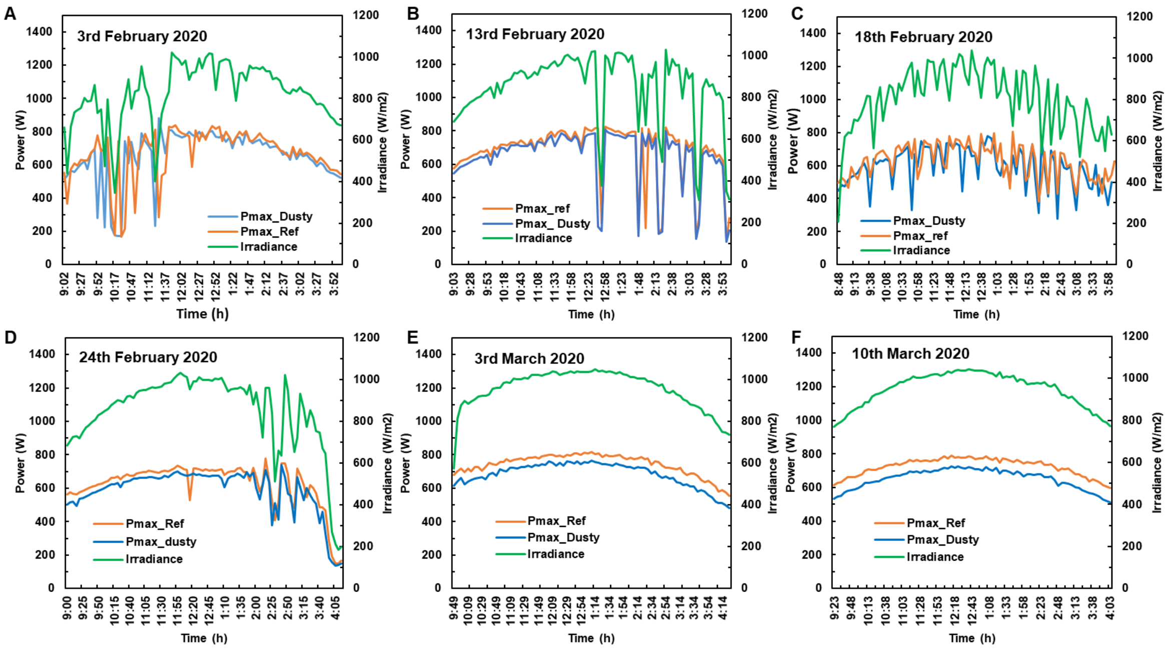


Figure 7. Irradiance and output power generated from the outdoor setup as a function of time for different days

After five days, the absolute power difference is measured to be 1.08% followed by 2.59% after 15 days. The difference in the output power (3.94%) was observed at the end of 20 days followed by 4.67% after

26 days. It is worth mentioning that a mild rain hit the site during the experiment period and as a result, power degradation was less than expectations at that stage. After 34 days, the power degradation was 6.48% while it was 8.47% after 41 days. The summary of the results is presented in Table 2 and Figure 8.

Table 2. Experimental results for the effect of dust study

Day Units	Irradiance W/m^2	Temp. amb ℃	Wind Speed m/s	Temp.Panel ℃	Pmax_Ref W	Pmax_Dusty W	ΔP %	Total no. of Days
29 Jan.	796.14	23.50	1.32	45.97	617.00	607.98	0	0
03 Feb.	822.54	23.73	8.82	40.79	672.10	655.04	1.08	5
13 Feb.	851.12	22.77	4.58	43.31	675.01	647.69	2.59	15
18 Feb.	802.24	29.78	1.91	50.79	625.43	591.65	3.94	20
24 Feb.	848.96	32.63	1.65	56.01	625.17	586.85	4.67	26
03 Mar.	956.16	27.37	7.61	47.46	743.03	684.02	6.48	34
10 Mar.	948.72	28.54	3.88	51.90	725.13	653.16	8.47	41

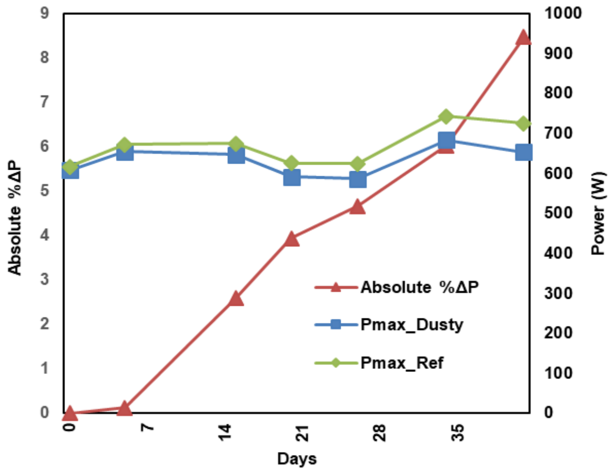


Figure 8. Summary of dust effect

The main aim behind performing the indoor experiment is to come up with a mathematical relationship that connects the dust quantity to the deterioration of electrical power production which leads indirectly to estimating the amount of dust on the outdoor setup. By utilizing the extracted formula from the controlled experiment, the amount of dust on the real system after 15 days was 2.04 g/m2 approximately followed by 3.10 g/m2 after 20 days of exposure. The dust quantity after 26 days, 34 days, and 41 days was estimated to be 3.68 g/m2, 4.75 g/m2, and 6.67 g/m2 respectively. It is worthy to indicate that after 15 days, the absolute power drop was equal to 2.59% and in order to avoid this loss in the electrical power, a periodic cleaning for the system every two weeks is recommended due to the significant issues that the lack of cleaning can lead to such as increasing the module temperature and the sticky dirt accumulation which is hard to clean.

In Saudi Arabia, Said and Walwil investigated the effect of dust fouling on the transmittance of the PV module glass cover. The PV modules were tilted by 26 degrees and exposed for 45 days. The results showed the average output power drop after five weeks without any cleaning process or raining event was approximately equal to 6% [38]. Touati *et al.* investigated the impact of environmental conditions on solar PV efficiency in Qatar's environment. The experimental studies revealed that the performance of the PV panels reduced by around 10% after 100 days due to dust deposition on the surface of the PV panels [4]. In Upper Egypt, Abdeen *et al.* measured the reduction in output power at various tilt angles compared to dust accumulation which is represented as the number of days [39]. The results showed that the degradation of the power output increased for low tilt angle and was equal 9.2% when the tilt angle was 15 degrees. Utilizing high tilt angles such as 45 degrees reduced the dust deposition on the surface and consequently decreased the reduction in output power to 4%. In Athens, the capital city of Greece, Kaldellis, and Kokala examined the impact of dust on a fixed system with a tilt of 30 degrees. The key finding of the research work was that the output power reduced by 6.5% in a period of eight weeks [40]. The comparison of the current study with other research work is represnted in Table 3.

Table 3. Comparison with other research works

Paper	Location	Orientation	Duration	Results
[38]	Saudi Arabia	Fixed, 26	Five weeks	The average output power drop without any cleaning process was approximately equal to 6%.
[4]	Qatar	Fixed	100 days	The efficiency of the PVs reduced by around 10% due to dust deposition.
[39]	Egypt	Fixed,15,45	63 days	9.2% decrease in the power output when the tilt angle is 15. 4% decrease on the power output when the tilt angle is 45
[6]	UAE	Fixed,30	Five weeks	The power drop after 5 weeks was approximately equal 10%
[8]	UAE	Fixed 25	Five months	The experimental study proved that the reduction in output power is increased by the rate of 12.7% and the dust density increased by 5.44 g/m^2
[40]	Greece	Fixed, 30	Eight weeks	6.5% power output reduction
Current Study	UAE	Azimuth Tracking, 20	41 days	8.47 % power degradation for 41 days

4. CONCLUSION

Dust settlement on the glass cover of the solar panels is one of the crucial obstacles in utilizing Solar Photovoltaics systems under harsh weather conditions in desert regions such as United Arab Emirates. The productivity of solar energy technologies is mainly reduced by dust accumulation within the daily exposure periods. In this research study, an experimental examination was performed to measure the dust particles' ability to settle on the surface of the PV modules in Sharjah and to study the nature of these pollutants by performing a series of outdoor and indoor experiments. According to the dust characterization data, the deposited dust on the solar panels has heterogeneous size and shape which was approximately less than or equal to 18 um. That led to significant impact on power degradation. Dust deposition is the key factor that influences the electrical properties of the Solar panels combined with other factors such as wind speed, temperature, and rain that happened during the testing days. The controlled laboratory experiments showed a linear relationship between the absolute difference in generated power and the deposited dust on the panel surface with a slope of 1.269% per g/m2. This relationship was used to estimate the dust density on the outdoor setup under Sharjah's real weather conditions. After 41 days of exposure, the power drop of the solar panel increased by 8.46% which is equal to 0.21% per day. Rainfall played an essential role to increase the generated electric power from the solar panels by reducing dust accumulation. Nevertheless, few dust particles show a tendency to form a sticky layer on the panel surface and may not be easily cleaned. In order to avoid output power degradation, solar panels should be cleaned every two weeks. This experimental study is an essential contribution in illustrating the nature of the dust particles and its impact on PV output power on tracking systems in Sharjah city and other arid areas. The work can be used to predict the efficiency of solar panels under harsh weather conditions. Furthermore, it may be utilized as a resource to design and conceive strong soiling mitigation technologies and dust cleaning techniques.

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