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Experimental measurement of the effects of sand dust accumulation on photovoltaic module performance in an arid climate

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ABSTRACT
Dust accumulation is one of the important factors that degrades the efficiency of photovoltaic (PV) panels. As a result, this research paper experimentally investigates the correlation between sand dust accumulation density and changes in the electrical performance of PV modules. This study is highly significant as it helps predict the behaviour of photovoltaic solar panels under varying densities of sand dust in a desert region where such conditions have not been previously studied. Based on the obtained results, it aims to propose solutions that contribute to enhancing the performance of photovoltaic solar systems in similar regions. For that, numerous practical tests were conducted in southeast Algeria to demonstrate the impact of sand dust accumulation on the power output of PV panels in an arid climate. To achieve this objective, four identical PV panels (TE 500-P, 55 Watts) were installed on the rooftop of the Higher Normal School of Ouargla (southern Algeria). These modules were fixed, tilted at 30°, and oriented due south. Sand dust deposition levels of 0 g/m² (always clean) as a reference, 3.49 g/m², 7.8 g/m², and 12.17 g/m² were applied, respectively. The electrical power output for the different modules was recorded every hour from 09:00 to 17:00 local time on a typical day. The results show an average decrease of 3.34 %, 5.36 %, and 10.92 % in the maximum electrical power produced by the PV panels with sand dust densities of 3.49 g/m², 7.8 g/m², and 12.17 g/m², respectively, compared to the clean one, which makes the regular cleaning of PV solar panels essential to consistently achieve optimal performance.

Section: RESEARCH PAPER

Keywords: PV panel; solar irradiation; sand dust accumulation; power loss; arid climate; southern Algeria

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1. INTRODUCTION

The current surge in electricity usage can be ascribed to the combination of high population density and an increasing demand for electricity. Fossil fuels are the principal and commonly acknowledged source of electricity, playing a crucial role in meeting the global energy needs. Solar energy is an enduring and replenishable energy source that supplies the Earth with substantial volumes of everyday solar radiation. Different systems have the ability to utilize this energy for the purpose of heating and generating electricity.

In addition, there are two different methods to producing electricity from solar energy: solar concentration, which make use of the sun's heat, and photovoltaic (PV) systems, which capture the solar irradiation. PV energy functions as an extremely dependable and environmentally friendly energy source for the production of power. The process involves the direct conversion of sunlight into electrical current utilizing semiconductors such as crystalline silicon. Over the past few years, there has been a substantial reduction in the investment cost of PV systems. As a result, the utilization of PV energy has become increasingly prevalent, both in standalone setups and grid-connected systems [1]-[8]. Thus, the sole limitation linked to PV modules is their efficiency in generating electrical power.

Subsequently, various weather conditions, including sunlight, ambient temperature, wind velocity, humidity, and soiling, extensively effect the performance of solar PV panels used for energy production. The deposition of dust on the surface of a PV system has a significant negative impact on its efficiency. Dust is the main ingredient responsible for the decrease in efficiency.

Over the last decade, there has been extensive research into the effect of dust on PV modules' efficiency. The majority of research is conducted in arid areas, resulting in a significant presence of sand particles in the air and quick accumulation of dust. In addition, the extremely low occurrence of rainfall in these areas hinders the natural cleansing of the panel's surface. This necessitates the implementation of a regular cleaning system and schedule to minimize the inevitable decrease in power output [9]-[21]. Some of them have collected and reviewed various research studies in this area [9], [11]. For example, A. Gholami et al. [9] conducted an exhaustive literature analysis on the parameters that influence dust formation. The study extensively examined the categorization of influential factors and their influence on the deposition of dirt on the surfaces of solar panels. In addition, they provided a thorough and analytical evaluation of the current state of the art, followed by a compilation of obstacles for future study. They verified that the obtained data can serve as a comprehensive point of reference for researchers, designers, and engineers who are involved in working with solar systems in areas that are prone to dust, specifically in the MENA region and Iran.

More recently, Younis et al. [10] conducted a thorough literature analysis, classifying and detailing the experimental processes used in laboratories to study the impact of dust buildup on PV panels. The authors then expertly examined and interpreted the data gathered from these studies. As a result, their findings, which also serve as useful added values, were a generalizable pattern derived from earlier studies in the field. Dust sampling and physiochemical characterization were the first steps in this systematic organization. Again, H. Abuzaid [11] conducted an inclusive assessment of 278 papers on the effect of dust on PV panel performance, as well as other environmental parameters such as wind speed, temperature, and humidity. They emphasized the need of modelling dust accumulation alongside other ecological elements due to their interconnected nature, as well as the disparities in cleaning procedures and schedules' efficiency. Again, M. Nezamisavojbolaghi et al. [9] provides a comprehensive review of recent research on the impact of dust on PV panels across various locations, addressing key areas for future investigation. Additionally, it examines a range of cleaning methods, offering valuable insights for researchers seeking the most effective dust removal techniques. The findings of this paper highlight the significant influence of dust accumulation and pollutants on the energy production of PV panels.

On the other hand, in their study, M. Rashid et al. [13] examined the impact of dust deposition on the energy generation and operating temperature of PV modules in two distinct cities of Pakistan: Bahawalpur and Islamabad. After a period of six weeks of being exposed to air, it was found that modules covered in dust had noticeably reduced efficiency, which was directly related to the density of the dust in the two areas. Similarly, an examination of module temperatures indicated that the presence of dust causes an increase in temperature. This increase in temperature is a contributing factor to the decrease in power output from PV systems, even when the amount of irradiance remains constant.

Using two methods, the quantitative and the qualitative procedures, respectively, and adding a significant parameter, the dust accumulation coefficient ((%)/mg/cm^2), M. Benghanem et al. [14] experimented the impact of dust deposition on the surface of PV panels, which cause losses in their power output. Out of the 60 days of dust accumulation, they found 28 % of the output power losses at Madinah City. Additionally, they suggested an intelligent cleaning system that uses the concept of dust density to begin cleaning as soon as power losses reach an acceptable level. Again, in an experiment conducted in the desert climate of Oman, H. A. Kazem et al. [15] looked at how air pollutants such silica sand, ash, red soil, and calcium carbonate affected the power output of a photovoltaic module. They found that the type of pollutant and the amount of deposition greatly affect the loss in PV power and voltage. Also, out of all the dust pollutants tested, the ash pollutant had the most impact on the voltage of the PV modules. In order to determine what components make up dust on solar cells, Kazem et al. [16] gathered and studied this material. From the Empty Quarter desert, which is next to the Al-Batinah region, they deduced that sand makes up the bulk of the dust in Sohar City, accounting for 65 % of the total. Additionally, this dust has significant amounts of gypsum (4.94 % concentration) and cement (5.25 % concentration), two volatile construction ingredients. Ash concentrations are rather high (4.92 %) due to fuel burning in smelters, power stations, and refineries.

In an Algerian study, M. Mostefaoui et al. [17] examined the electrical performance of photovoltaic modules deployed in the Saharan region of southern Algeria (Adrar) in the context of sandstorms and sand dust deposition. In order to assess the impact of sand dust on the efficacy of these modules, they measured their current-voltage characteristics. It was shown that sandstorms and the accumulation of dust limit the effectiveness of power and energy due to a decrease in transmittance.

In addition, in an experimental study conducted in northeastern Iraq, G. Jendar [18] examined the effects of soiling on photovoltaic modules. The power, energy, current, and voltage curves of two identical modules, one of which was naturally dusty and the other of which was routinely cleaned, were measured over a five-month period. They discovered that soiling accounted for an average of 16 % of the daily energy loss.

In their study, Shariah et al. [19] examined how the presence of shadow and natural dust impacts the efficiency of solar PV modules at the Jordan University of Science and Technology Campus in Irbid, Jordan. The researchers found that the presence of shade and concealing cells in PV modules has the most significant effect on module efficiency. The presence of natural dust has a direct impact on performance, resulting in a reduction in output power by 13 % after a period of three months of accumulation. Subsequently, K. R. C. Lakshmi [20] revealed a comprehensive examination of the performance of solar PV modules in the tropical climate of Chennai, India, where the prevalence of dust particles is extremely high. Data was obtained for four distinct dust samples of varying densities at four solar irradiation levels: 220, 525, 702, and 905 W/m^2. They discovered that the maximal power loss was 73.51 %, 66.29 %, 65.46 %, and 61.42 % for coal, sand, brick powder, and chalk dust, respectively. Additionally, F. Mohammadi [21] examined an Off-grid solar system, taking into account the impact of climate conditions and environmental elements, such as dust, on the efficiency of PV panels. The study presented the efficiency and performance of a PV system utilizing PVsyst software in four regions of Iran (Sanandaj, Rasht, Abadan, and Mashhad) with

Figure 1. Aria study location.

Figure 2. Installation used in the experiments.

varying climatic conditions. The study revealed that the majority of the efficiency loss, amounting to 11.19 %, is observed in Sanandaj due to its chilly and humid climate. However, Abadan experiences an 8.33 % loss in relation to its geographical location near desert areas, which is attributed to its hot and humid climate. Rasht, characterized by a temperate and humid environment, has a 2.27 % decline in yield. In contrast, Mashhad, known for its cold and dry climate, sees a 2.19 % decrease in yield.

Again, R. J. Mustapha et al. [22] investigates the reliability and validity of past studies that look at how various environmental conditions affect the efficiency of PV systems. The study is unique in that it evaluates four particular environmental elements in one analysis: dust deposition, drops of water, bird droppings, and partial shadowing. They obtain that dust, shade, and bird droppings have a substantial impact on the current and voltage of PV systems, affecting the amount of energy harvested. Among these parameters, shading has the greatest impact on PV module efficiency. For example, increasing the shadowed area of a PV module by 25 %, 50 %, or 75 % results in power decreases of 33.7 %, 45.1 %, and 92.6 %, respectively.

So, the principal goal of this research paper is to investigate by experimentation the correlation between sand dust accumulation density and the output power of solar PV panel, by using four identical PV modules with different sand dust densities in Ouargla region, south-east of Algeria. These panels are fixed, tilted at 30° and oriented due south.

For this purpose, the organization of this investigation is as follows: Section 2 outlines the methods utilized in the experimentation. This section commences by examining the environmental conditions in Ouargla city and introduces the measurement devices employed to acquire the results that will be subsequently exposed and discussed in Section 3.

Discussion in the later section present data obtained from experimental tests and analysis of PV module performance, power and current output drop due to dust deposition. In addition, this Section presents and analyses the correlation between the daily electrical energy produced and the dust accumulation density. Section 4 functions as the concluding section, where the main findings of this study are summarized and thoughtful suggestions are given based on the current study.

2. METHOD

2.1. Study aria climate

The Ouargla region, seen in Figure 1, is situated in the southern part of Algeria and covers an area of 163.233 km². Its precise geographical coordinates are 164 m above sea level, 31° 57' N latitude, and 5° 21' E longitude. The region is defined by a desert climate, resulting in extremely hot summers and enjoyable winters. There is relatively little precipitation, and the skies are clear for the most of the year (an average of 135 days) [23], [24]. This city is regarded one of Algeria's warmest regions. Moreover, it is characterized by the frequent prevalence of sandstorms, particularly during the spring season.

2.2. Description of the studied system

The examined system is combined of four identical PV modules (i.e., reference, PV_1, PV_2, and PV_3) (see Figure 2), which have the same electrical properties exposed in Table 1, were used in tests with different dust density for each one of them as shown in Table 2, to evaluate the correlation between these densities and their electrical performances.

The different dust quantities are collected and weighed precisely, as shown in Figure 3.

2.3. Procedure of experiments

The experiment took place in an outdoor setting at Higher Normal School of Ouargla, Ouargla (latitude 31.97 N, longitude 5.42 E). Four panels of maximum power 55 W; were fixed and tilted at 30° facing south (see Figure 3); electrical characteristics are exposed in Table 1. One of them is considered a reference (always clean), while the others have varying amounts of dust on their surfaces, as shown in Figure 2.

The purpose of the experiment was to ascertain how dust accumulation over the PV module affected it. Three modules were covered with dust (see Table 2) while the reference one was left clean for the purpose of comparing output power.

The day chosen for the trials had favourable conditions, including cloudless skies, gentle breezes, typical temperatures for the season, and minimal humidity, as indicated in Table 3 [25].

Table 1. The used PV panel electrical characteristics.

Parameter	Specification
Type	TE 500-P
Maximum power, P_{max}	55 W
Voltage at maximum power, V_{mp}	17.5 V
Current at maximum power, I_{mp}	3.14 A
Open-circuit voltage, V_{oc}	22.2 V
Short-circuit current, I_{sc}	3.5 A

Table 2. Both quantities & densities of dust used in the experiments.

Parameter	PV_1	PV_2	PV_3
Dust quantity in g	1.6	3.6	5.6
Dust density in g/m²	3.49	7.8	12.17

Table 3. Climatic conditions of the day of tests [25].

Time (h)	Wind speed (m/s)	Relative humidity (%)
09:00	0.9	23.2
10:00	2.4	19.2
11:00	2.3	16.0
12:00	1.4	14.2
13:00	2.4	14.0
14:00	1.9	12.0
15:00	1.8	11.0
16:00	0.7	11.0
17:00	1.9	11.0

These conditions made it an optimal day for carrying out the experiments.

Under outdoor climate conditions on March 13, 2024, from 09:00 to 17:00 local time, the collected data pertains to the operational electrical characteristics, including power, current, and voltage. It encompasses both dirty and clean modules, which are outputted simultaneously.

Experimental measurement described in Figure 4, each panel was attached to digital ammeter and voltmeter, maximum power was also examined. Module current and voltage were measured by supplying power to a variable rheostat (see Figure 4).

3. OBTAINED RESULTS AND DISCUSSIONS

Figure 5 depicts the daily ambient temperature and sun irradiation as a function of local time on March 18, 2024, from 9:00 to 17:00. The day was extremely sunny, with an average ambient temperature of 27.71 °C and a top solar irradiation of 1100 W/m^2 recorded at 13:00 local time.

3.1. Impact of dust deposition on power and current output

This section compares three structures (PV_1, PV_2, and PV_3) covered with different dust densities to the conventional one (see Figure 3), in terms of short-circuit current and output power.

Figure 6 exposes the daily variation of short-circuit current as a function of local time. A digital ammeter measured these currents when we short-circuited the PV modules. The clean panel (reference) consistently outperforms the others during the whole testing day, followed by PV_1, PV_2, and PV_3, respectively. At solar noon, all structures produced their maximum current: 3.3 A, 3.11 A, 2.98 A, and 2.94 A for the reference, PV_1, PV_2, and PV_3, respectively. In this case, the variable factor among the four panels is the density of dust on their surfaces, which prevents some sunlight from reaching the cells. As a result, the current produced decreases, explaining the graphs in Figure 6.

As a result of variations in dust collection on the four modules' receiving surfaces (see Figure 3), their power output loss percentage increase with the density of dust (i.e. 2.53 %, 5.35 %, and 12.27 % for PV_1, PV_2, and PV_3, respectively, compared to the clean panel), as shown in Figure 7.

3.2. Effect of dust accumulation density on the electrical energy produced

Figure 8 exposes the daily variation of the electrical energy produced by PV modules in the day of tests as a function of dust deposition density. The figure illustrates the inverse relationship between the daily electrical power produced and the density of dust deposition on the solar panels. A downward-sloping straight line that does not pass through the origin can represent this relationship. Its mathematical equation is as follows [26]:

Figure 3. Images of the process of weighing quantities of dust used in the experiment.

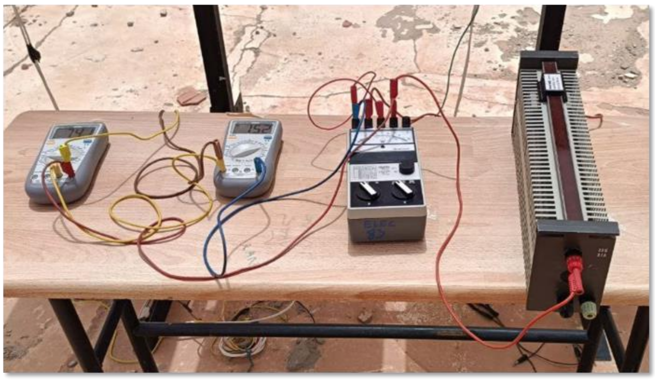

Figure 4. Electrical circuit measurements.

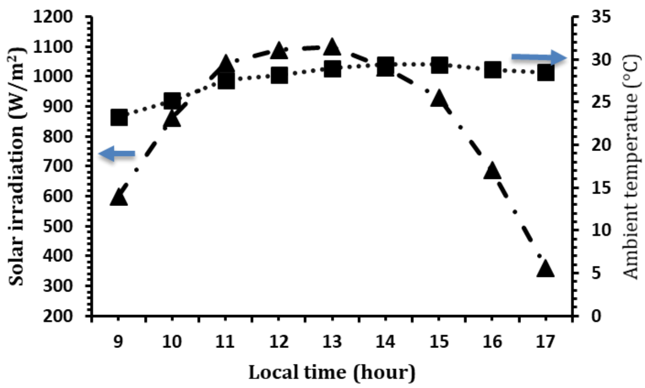

Figure 5. Ambient temperature & solar irradiation of the test day.

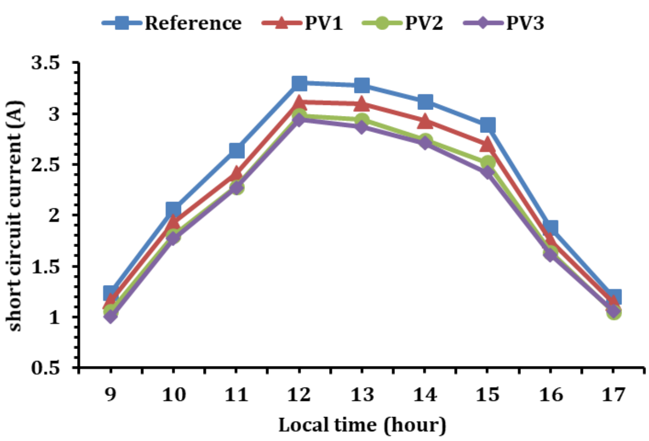

Figure 6. Short-circuit current of PV modules.

$$E = -0.0846 \cdot D + 2.5257\,; \qquad (1)$$

where D is the dust accumulation density on the PV module's surface in g/m², and E is the daily electrical energy the PV panel produces in kW·h.

4. CONCLUSION

This paper investigates experimentally the effect of sand dust accumulation on the performance of PV panel under Ouargla climatic conditions (southern Algeria). Additionally, the correlation between the daily electrical energy produced and the dust deposition density was also examined in this study. The most attained results are listed as follows:

1. Dust deposition significantly impacts the efficiency of P) modules, making the implementation of effective cleaning strategies essential to sustain optimal energy production,
2. Both power output percentage and short-circuit current of dirty PV modules decreases as dust density increases,
3. The daily electrical power produced and the density of dust accumulated on the surface of the solar panels have an inverse relationship between them, which can be represented by a downward-sloping straight line that does not pass through the origin.

Finally, this paper recommends that users of photovoltaic solar energy systems in desert regions regularly clean their panels using economical methods. It emphasizes the importance of performing this maintenance promptly after each sandstorm to ensure optimal performance. Additionally, the authors of this work emphasize the need for further research to develop innovative cleaning technologies and techniques aimed at improving the efficiency of dust removal from PV panels.

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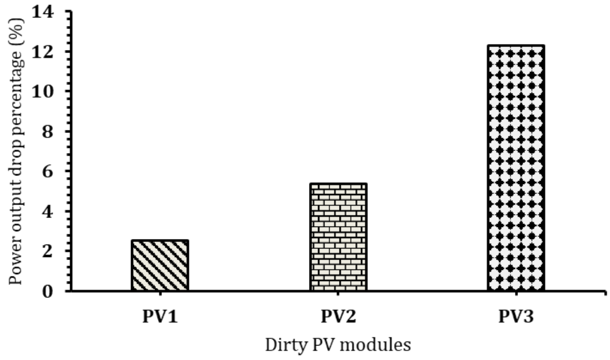

Figure 7. Power output drop percentages of dirty modules.

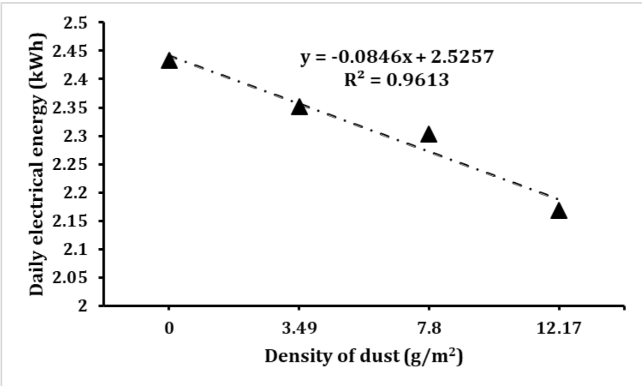

Figure 8. Correlation between the daily electrical energy produced & the density of dust.

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