Heliyon 10 (2024) e30944

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Effects of climatic conditions of Al Seeb in Oman on the performance of solar photovoltaic panels

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ARTICLE INFO

Keywords:
Solar photovoltaic
Wind speed
Humidity
Ambient temperature
Dust
Performance

ABSTRACT

Human activities and climatic elements, including temperature, humidity, and wind speed, have an impact on natural dust deposition. Therefore, this study aims to investigate the effects of wind speed, relative humidity, and ambient temperature on the performance of soiled photovoltaic panels in Al Seeb, Oman. The study was conducted by exposing the solar PV panels to outdoor sunlight for a duration of two months. Parameters such as solar radiation, voltage, current, solar panel temperature, wind speed, relative humidity, and ambient temperature were collected in a short time interval. It was observed that the dust densities of 20.7 g/m^2, 27 g/m^2, and 41.3 g/m^2 resulted in electrical power reductions of 18 %, 33 %, and 40 % for the panels uncleaned for one week, two weeks, and three weeks, respectively. The effect of daily dust resulted in an energy reduction of 14 %. Moreover, dust deposition decreases when the wind speed increases, resulting in a higher power output and vice versa. The higher the humidity, the stronger the dust's adhesion to the surface, resulting in more deposition and reduced power output. The maximum power output of 82.3 W was achieved at the wind speed of 10 m/s, 34.9 % relative humidity, and ambient temperature of 38.5 °C.

1. Introduction

The increasing affordability of renewable energy sources like solar and wind power has led to their widespread adoption [1]. This shift away from fossil fuels is driven not only by economic factors but also by growing concerns about the environmental consequences of burning coal, oil, and natural gas [2]. As renewable energy technologies become more cost-effective, they offer a viable alternative to traditional energy sources. The transition to cleaner energy sources is essential for mitigating the negative impact of fossil fuels on the environment and combating climate change [3,4]. It is currently thought that solar energy would soon replace other energy sources as the primary technology for producing electricity from solar radiation, principally due to the attractive prices of photovoltaic energy [5,6]. This contribution is expected to be between 25 % and 31 % [7]. Environmental factors, including temperature, wind, and the amount of airborne dust, affect PV systems [8–10]. Using a geographic information system (GIS), Charabi and Gastli [11] studied how weather affects a solar power panel. According to the study, when temperature and dust limits were in place, the PV power system drastically decreased by 81 %.

As solar cell efficiency drops by 0.248 %/°C, ambient temperature is one of the weather variations that influence photovoltaic

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https://doi.org/10.1016/j.heliyon.2024.e30944
Received 20 February 2024; Received in revised form 4 April 2024; Accepted 8 May 2024
Available online 9 May 2024
2405-8440/

energy production [12]. Under constant sun radiation, Radziemsk et al. [13] conducted an experiment with a single-crystalline silicon solar cell with the temperature of the solar cell stabilised up to 80 °C. They found that the solar cell's output energy decreased by more than 0.65 %/K. Narvaez et al. [14], who investigated the effects climate change on the performance of PV systems, reported that air temperature was the second main variable affecting PV performance, with a predicated drop in PV efficiency of up to 2.5 %. Other meteorological variables that impact the effectiveness of the solar photovoltaic system include wind speed and humidity [15,16]. Lu et al. [17] examined how wind speed affected the deposition of particles of different sizes. They established that similar results might be observed at varying wind speeds and that the rate of deposition increased with dust diameter. At a wind speed of 1.3 m/s, the maximum dust deposition diameter was 100 mm, and it was 150 mm at a wind speed of 2.6 m/s. This was the case because of the interaction between the different wind speeds and particle masses. In a study by Ahmed et al. [18], the wind speed exhibited minimal impact on the performance of PV cells, mainly when compared with water cooling process and dust depositions. The PV efficiencies were 14.7 %, 15.8 %, and 16.8 % at wind speeds of 0 m/s, 3.5 m/s and 7.2 m/s, respectively.

Kazem and Chaichan [19] observed the greatest impact of relative humidity when compared to other environmental factors, for which there was an inverse relationship between electrical parameters and humidity. Additionally, as the humidity increased during the day, clay accumulated on the PV roof, creating a solid structure that was very difficult to remove even with high wind speeds. This would partially shade the PV panels. Moreover, dust accumulation reduces solar irradiation, and consequently, this reduces the electrical power generated [20]. The surrounding environment, air pollution, humidity, and severe weather like sandstorms all significantly affect the type and amount of dust present. Organic dust particles (pollen, bird droppings, leaves, etc.) and occasionally soil, for example, are commonly found in agricultural regions [21].

The impacts of dust types on photovoltaic performance were examined by Darwish et al. [22], who discovered 17 different varieties of dust. Sand, ash, red soil, limestone, calcium carbonate, and silica were the most prevalent types of dust that had the largest effects on PV performance. By experimentally modelling dust formation, Kaldellis et al. [23] investigated the impact of three air pollutants—red soil, limestone, and carbonaceous fly ash particles—on the electrical performance of PV panels. The performance of PV panels was observed to have significantly decreased, with the source and composition of the particles playing a major role. Over several months of outside exposure, Syed et al. [24] evaluated the performance of solar panels and discovered that the average rate of efficiency decrease was 7 % each month. In a different investigation [25], they discovered that after five weeks of outside exposure, the solar module's output power was reduced by 6 % without cleaning. After 45 days of exposure to the outdoors, the glass cover's transmittance was 20 % in the absence of cleaning.

The impact of dust deposition on reducing PV power output has been studied globally. For example, in Saudi Arabia, the transmittance decreased by 20 %, and the dust density on the PV modules reached 5 g/m^2 after 45 days of placement at an angle of 26° [26]. In Indonesia, a two-week dust deposition was observed to decrease solar electricity production by 10.8 % [27]. In a far longer duration of observation in Tehran that lasted for 70 days without rain, the acquired dust density was 6.1 g/m^2 leading to a 21.5 % decrease in electrical power generation [28]. In Cairo, when the installed inclination angle was extreme at 45° the output power was reduced by approximately 17.4 % monthly [29]. In Belgium, which usually enjoys a good Air Quality Index, dust accumulation resulted in only 4 % of power reduction after five weeks [30]. Kazem et al. [31] developed a model to observe the influence of dust on the grid-connected photovoltaic system of 1.4 kW in northern Oman. The impact of dust was found to be significant, with a PV efficiency of 10.8 %. In another study, Kazeem et al. [32] investigated the effects of each dust component on the PV performance for both monocrystalline and polycrystalline modules, from which an optimal cleaning period was also proposed for different places in Oman. It was observed that polycrystalline modules are more affected by dust than monocrystalline, with a maximum power loss of 54 % observed for polycrystalline and 47 % maximum for monocrystalline modules. In a study by Mustafa et al. [33], the impacts of dust, a quarter shading, and bird fouling were reported to reduce the output power of the PV panels by 8.8 %, 33.7 %, and 7.4 %, respectively. Though there have been studies on the effects of weather conditions on the performance of PV panels, there are limited studies available on the effects of wind speed, humidity, and atmospheric temperature on the performance of soiled PV systems, particularly in Oman. Therefore, the objective of this study was to investigate the effects of wind speed, humidity and ambient temperature on the performance of PV cells in Al Seeb, Oman. This would help analyze the impacts of weather conditions to enhance the performance of PV modules exposed to dust for a different duration. It would also highlight the corrective measures to be taken to enhance power production from the photovoltaic panels exposed to dust and different weather conditions. Additionally, the findings from this article would also be useful in the development of a robust model that predicts the dust effect and environmental factors for the optimal power generation.

2. Experimental setup and techniques

2.1. Climatic condition of the PV systems

The experiment was carried out from March to May 2023 in Al Seeb, Muscat, Sultanate of Oman. The interior is usually hot and dry in Oman, whereas the sea is hot and humid. In the summer, Muscat, the country's capital, the ambient temperature would reach a sweltering 43 °C. Winters are mild, with low temperatures hovering around 17 °C on average. At higher elevations, indoor temperatures are similar but a little milder. The average annual rainfall is only about 100 mm across the country; however, it is higher in the mountains [34].

2.2. PV systems

The geographical location of the photovoltaic panels was at 23°34′34"N 58°18′07″ E and the panels were installed at a height of 1.2 m from the ground facing south. The inclination angle of the PV modules was 20°. Four monocrystalline half-cut photovoltaic panels were used to study the effects of weather conditions on the performance of photovoltaic panels. Fig. 1 depicts the experimental setup used for this study. The rated power (P_{max}) of each panel at standard test conditions was 100 W. In addition, four control panels were installed parallel to the photovoltaic panels to measure solar radiation. The photovoltaic panels were connected to a power meter to measure the panels' power output, and the solar radiance was measured under the control panels (glass panel) using an Arduino microcontroller (solar energy meter). Each solar panel had multiple thermal sensors to measure the panel temperatures at different points. An anemometer was installed to measure the wind speed. To measure the relative humidity and ambient temperature of the surrounding air a thermo hygrometer was utilised. The mass of the dust was measured using a stable and precise dual screen electronic analytical balance with an accuracy of ±0.001 g.

The solar PV panels and measuring devices were connected to the data logger, a paperless recorder, with 26 channels to measure the output of the solar panels and standard parameters such as open circuit voltage (V_{OC}), short circuit current (I_{sc}), solar panel temperature, ambient temperature, wind speed, relative humidity, and solar radiation. The data were collected in 1-s intervals via the PC. The panels were exposed to dust and climatic conditions for an extended period of time. The electrical power output (P_{out}) is calculated by:

$$P_{out} = V \times I \tag{1}$$

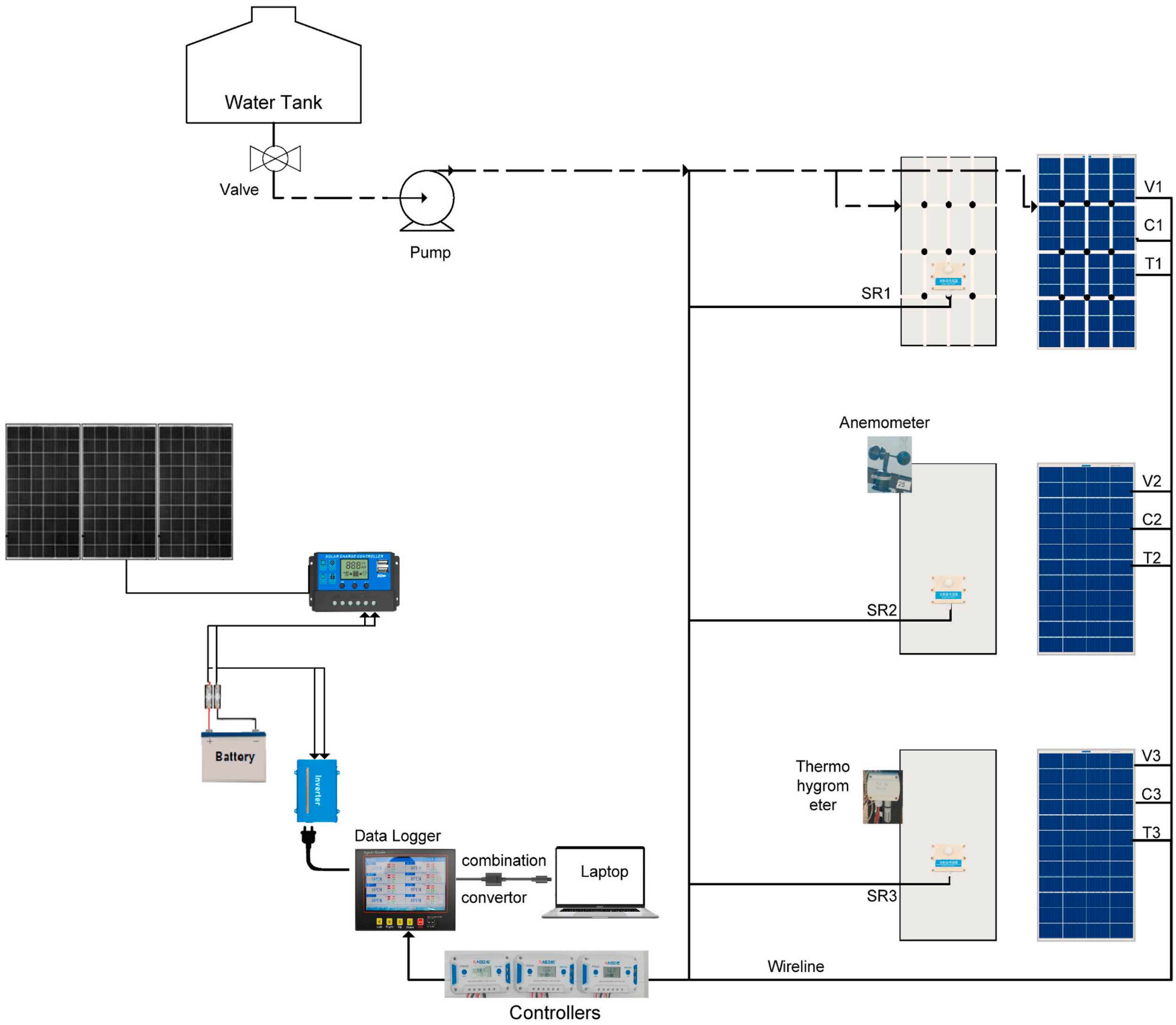


Fig. 1. Experimental setup.

The input solar radiation power (P_{in}) is determined by:

$$P_{in} = G \times A_{PV} \tag{2}$$

where G is the solar irradiation (W/m^2), A_{PV} is the area of the solar panel (m^2). The efficiency of the solar panel is given by:

$$\eta = \frac{VI}{GA_{PV}} \times 100\% \tag{3}$$

The power and efficiency reductions were calculated as follows:

$$\text{Power reduction} = \frac{P_{TPV} - P_{RPV}}{P_{RPV}} \times 100\% \tag{4}$$

$$\text{Efficiency reduction} = \frac{\eta_{TPV} - \eta_{RPV}}{\eta_{RPV}} \times 100\% \tag{5}$$

where P_{TPV} and η_{TPV} are the power and efficiency of a tested photovoltaic panel, P_{RPV} and η_{RPV} are the power and efficiency of a reference photovoltaic panel.

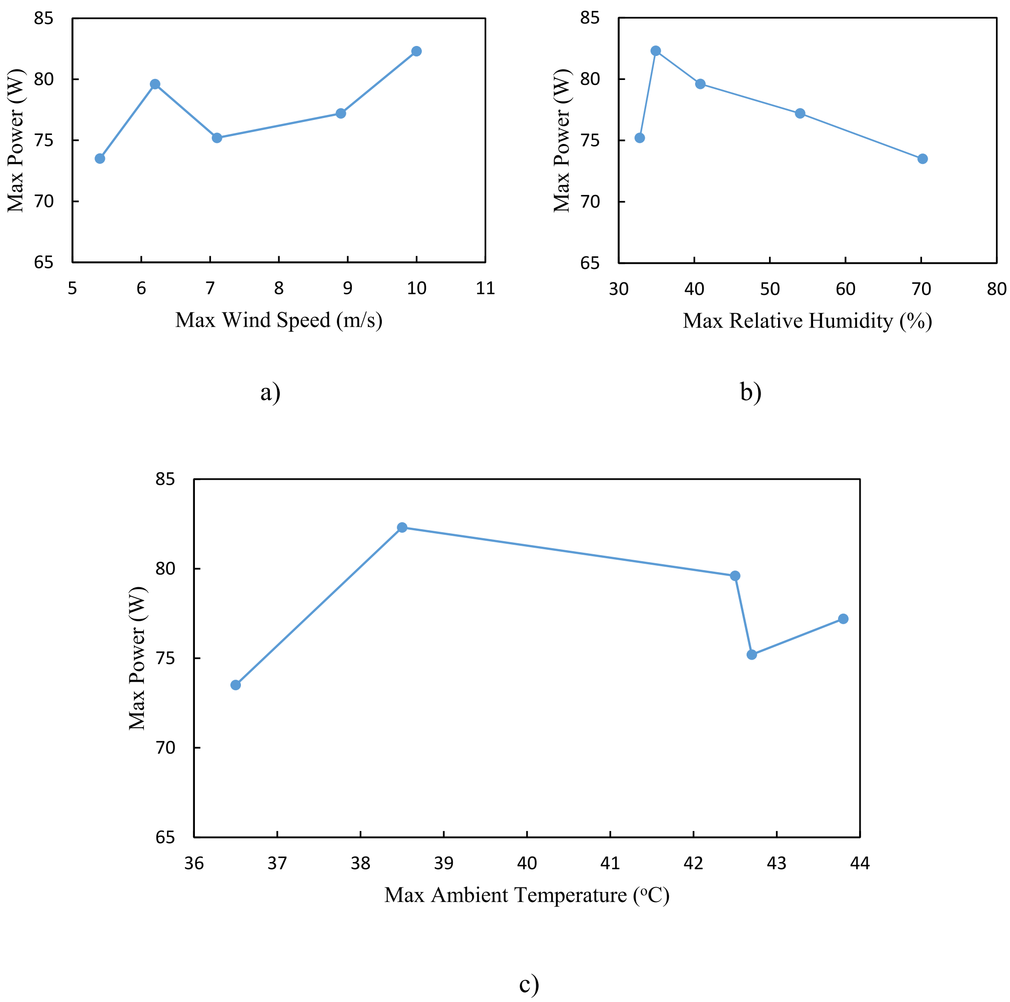


Fig. 2. Maximum power profiles: a) wind speed, b) relative humidity, and c) ambient temperature.

3. Results and discussion

3.1. Effects of environmental factors on the performance of photovoltaic solar panels

3.1.1. Weekly observations

The photovoltaic panels were exposed to dust and climatic conditions for five days without cleaning at a tilt angle of 20°. A comparison was made between a PV panel at an angle of 20° that was exposed to dust for five days and a PV panel that was exposed to dust for a longer period of time. Fig. 2a shows the maximum output power at different wind speeds. As the wind speed increases, dust deposition decreases, increasing power generation, and vice versa. The effects of wind were minimal at lower speeds. However, there was an increase in power output for higher wind speeds.

Fig. 2b shows the maximum output power for different relative humidity. A higher humidity level causes dust to adhere to surfaces more strongly, causing more deposition and reduced energy output. The results reported by Kazem et al. [19] also showed a significant impact of humidity in Sohar, about 190 km to the northwest of the present study's site; they reported a significant reduction in power when there was an increase in relative humidity. The ambient temperature, shown in Fig. 2c, was always lower than the surface temperature of the PV panels. The highest output power of 82.3 W was achieved at the wind of 10 m/s, relative humidity of 34.9 %, and ambient temperature of 38.5 °C.

The surface temperature of the photovoltaic panels is shown in Fig. 3. The results show that the temperature decreases when dust is deposited on the photovoltaic panel. As can be seen, the temperature of the surface of the panel decreases with time. The maximum temperature of the panel after being exposed to dust for five days was 38.3 °C. It was 39.8 °C for the continuously uncleaned panel. The hourly variation of the surface temperature of the PV panel, on the other hand, shows insignificant variation and thus would require cooling for enhanced power output.

The maximum current and voltage over days and daily profiles are shown in Figs. 4 and 5, respectively. As the dust deposition increases, the values of voltage and current decrease. The maximum voltage and current of the panel after being exposed to dust for five days reached 20.3 V and 5.1 A, respectively. The voltage and current values were 14.8 V and 4.4 A, respectively, for the continuously uncleaned panel. A similar drop in current was observed for the daily current profile, as depicted in Fig. 4b.

Fig. 6a–b shows daily and hourly solar radiation variations. It is shown that solar irradiance decreases with dust deposition, and thus reducing the energy transfer onto the solar panels. The maximum solar radiation for the panel exposed to dust for five days was 813.7 W/m^2, which was higher in comparison to the continuously uncleaned panel (726.8 W/m^2). Similar profiles could be seen from the hourly variation showing the influence of dust deposition on the solar irradiance.

Figs. 7 and 8 show the time variation of power and efficiency of the PV panels, respectively. The maximum power and efficiency of the panel after being exposed to dust for five days reached 73.5 W and 15.2 %, respectively. Comparatively, power and efficiency reduced to 60.2 W and 14.02 % for the continuously uncleaned panel. In this case, the power decreased by 18 % due to dust depositing on the photovoltaic panels for five days. It was also measured that the dust accumulated at the end of the week was 20.6 g/m^2, showing a significant dust deposition.

3.1.2. Fortnightly observations

The photovoltaic panel was exposed to dust and climatic conditions for 12 days without cleaning at an angle of 20°. A comparison was made between a PV panel exposed to dust and a PV panel exposed to dust for a long time at a similar angle. The three most important factors affecting the amount of dust deposited on solar PV panels were found to be wind, humidity, and ambient temperature. Fig. 9a-b-c show that at low winds, it can lead to the deposition of dust, and consequently reducing the output power. On the other hand, at high wind speeds, it leads to dust removal, which is a form of natural cleaning of the PV modules that hinders drop in the output power. Dahham et al. [35] observed that high wind velocity had an influence on the removal of fine particles from the surface of the PV panels, with an improvement in PV performance of 10.9 % for natural dust. However, the effects were minimal for large particle

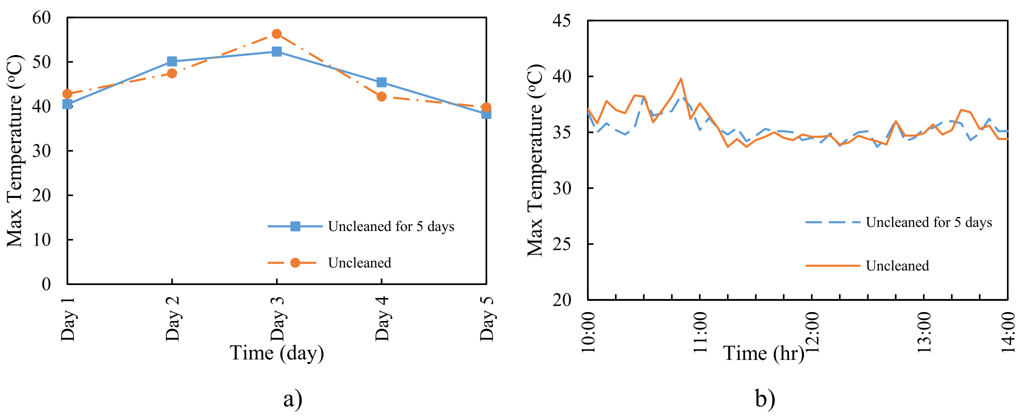


Fig. 3. Variation of temperature over time: a) daily and b) hourly (Day 5).

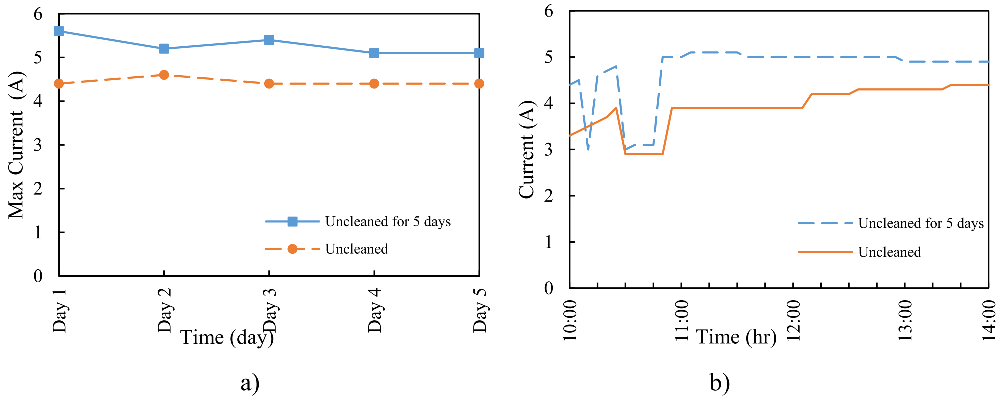


Fig. 4. Variation of current with time: a) daily and b) hourly (Day 5).

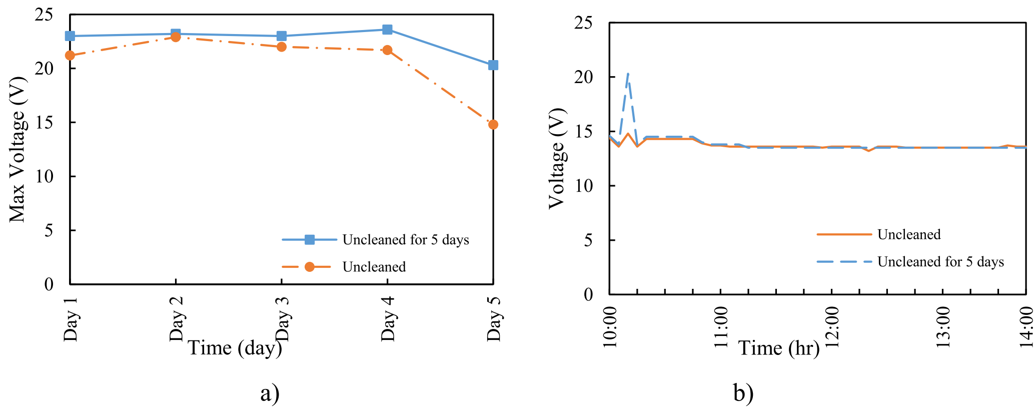


Fig. 5. Variation of voltage with time: a) daily and b) hourly (Day 5).

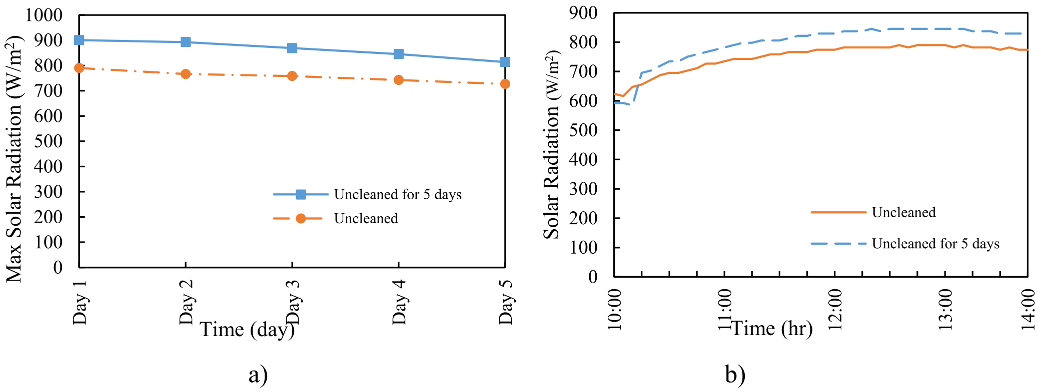


Fig. 6. Solar radiation over time: a) daily and b) hourly (Day 5).

size. They also reported a greater dust deposition rate with increasing airborne dust concentration.

Furthermore, the ambient temperature plays a role in dust deposition. The ambient temperature is always lower than the PV panel's surface temperature; however, it affects the amount of dust deposited and the efficiency of photovoltaic panels. At low ambient temperatures, the output power is less than when the ambient temperatures are high. In addition to humidity, when the humidity increases, the adhesion force between dust and the PV module surface increases, and dust precipitation increases. Mekhilef et al. discussed that an increase in adhesion of approximately 80 % occurs when the relative humidity increases from 40 % to 80 %. High relative humidity also promotes the growth of sticky and dusty coatings on the surface of the PV module [36]; a similar result was also

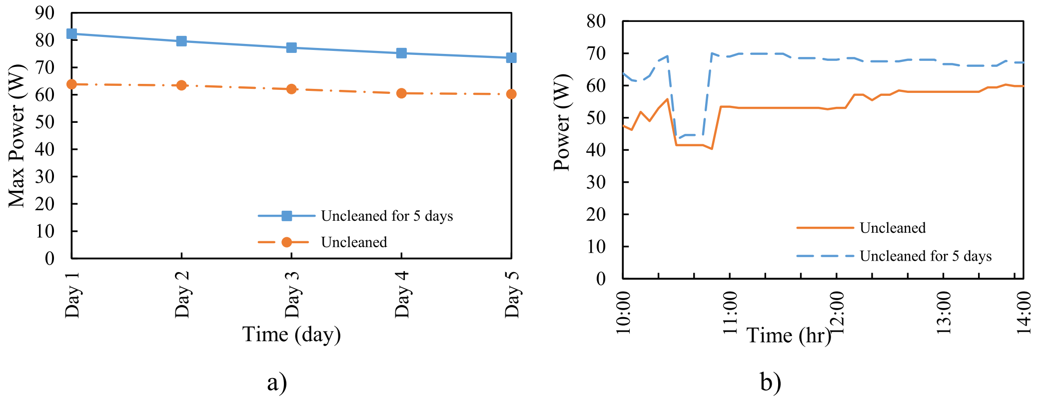


Fig. 7. Variation of power with time: a) daily and b) hourly (Day 5).

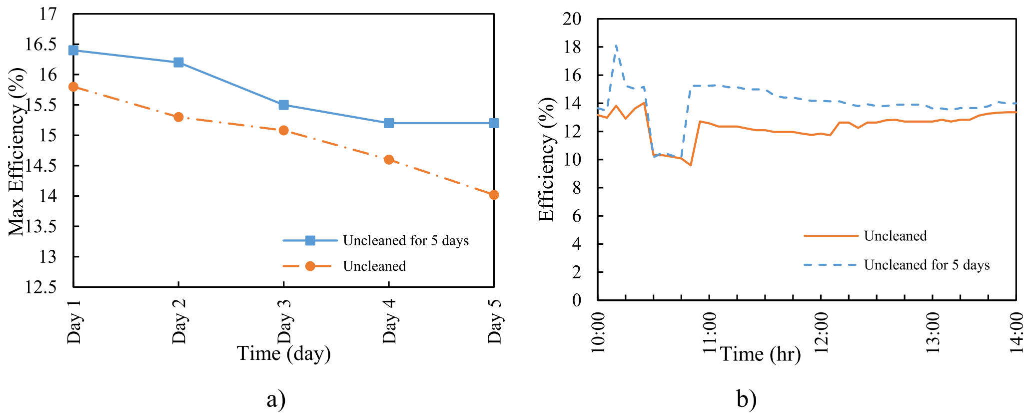


Fig. 8. Efficiency over time: a) daily and b) hourly (Day 5).

reported by Ali et al. [37].

Fig. 10a–b and 11a-b show the output current and voltage profiles, respectively. In comparison to the continuously uncleaned PV panel, which reached 14 V and 2.9 A, the cleaned panel (after 12-day exposure to dust) reached maximum values of 14.2 V and 4.3 A.

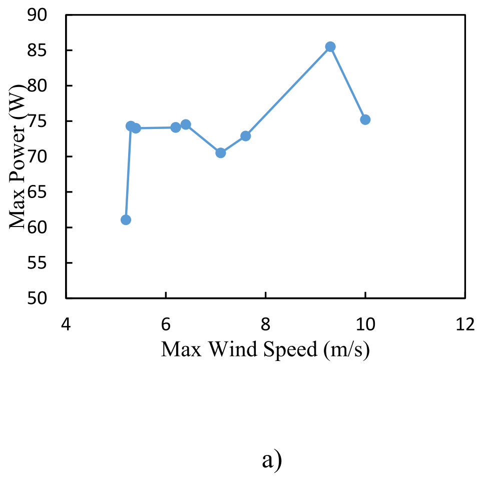
As for solar radiation, the more dust deposition the less would be solar irradiation, and consequently, the less energy transfer onto the solar panels. The maximum value of the cleaned PV panel after being exposed to dust for 12 days reached 600.4 W/m^2, which is far higher as compared to the uncleaned one at 474 W/m^2 (Fig. 12).

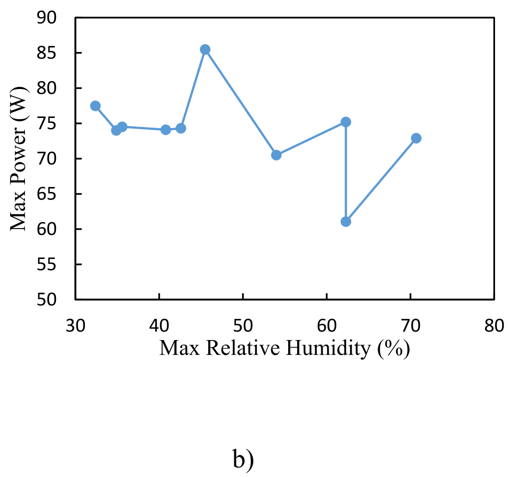
The temporal variation of power and efficiency for the cleaned and uncleaned PV panels are shown in Figs. 13 and 14, respectively. The maximum power and efficiency of the cleaned panel (after being exposed to dust for 12 days) reached 61.06 W and 17.8 %, respectively. For the uncleaned panel, the power and efficiency were lower at 40.3 W and 15.9 %, respectively. In this line, the power decreased by 34 % due to dust depositing on the photovoltaic panels for 12 days. At the end of the duration, the panel was cleaned, and the accumulated dust was found to be 20.7 g/m^2. In a study after 11 weeks of exposure to the weather outside, Ali et al. [38] observed that the solar modules' average output capacity decreased by 20 %. They found that the dust's density on the surface of the modules was 9.867 g/m^2.

3.1.3. Three-weeks observations

In this part of the study, the photovoltaic panel was exposed to dust and climatic conditions for 19 days without cleaning, with the angle set at 20°. A comparison was made between a cleaned PV panel (after exposure to dust for 19 days) and an uncleaned PV panel. Fig. 15 shows the effects of environmental factors on the maximum output produced from the PV panels. It is shown in the figure that the effects of wind speed became insignificant for wind speeds less than 5 m/s. However, the maximum power was shown to be increased at a higher wind speed of more than 10 m/s. The high humidity reaching more than 80 % led to a reduction in the maximum power to less than 50 W, as depicted in Fig. 15b. The high ambient temperature of above 40 °C led to a higher surface temperature of the PV panels, thus requiring cooling as this would lead to a significant power reduction.

Figs. 16 and 17 show the variation of output current and voltage with time, respectively. As the panels were uncleaned for a longer period, the influence of dust deposition was shown to increase, and this resulted in a reduction in the output current and voltage of the





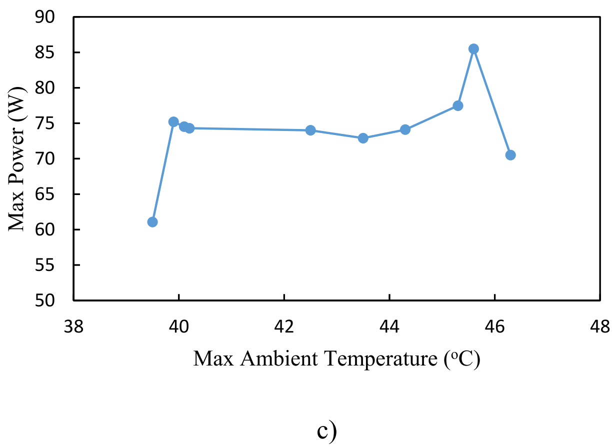
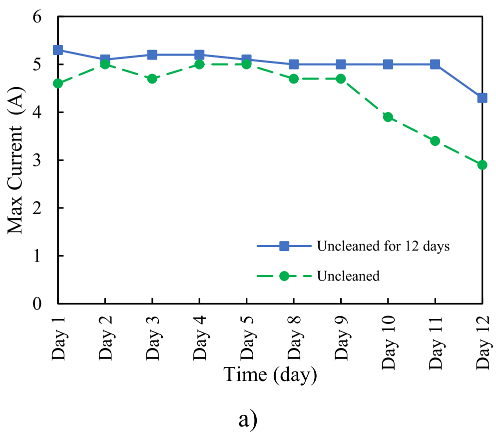


Fig. 9. Effects of environmental factors on the maximum power: a) wind speed, b) relative humidity and c) surrounding temperature.



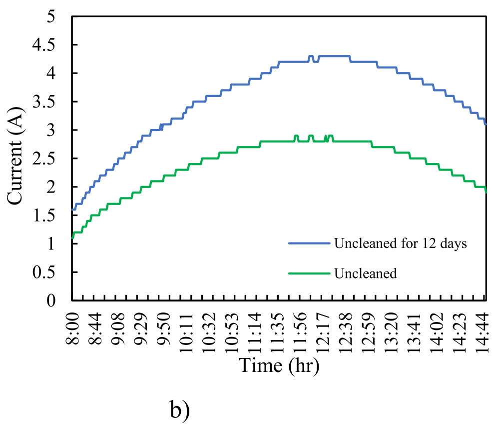


Fig. 10. Current profiles over time: a) day and b) hourly (Day 12).

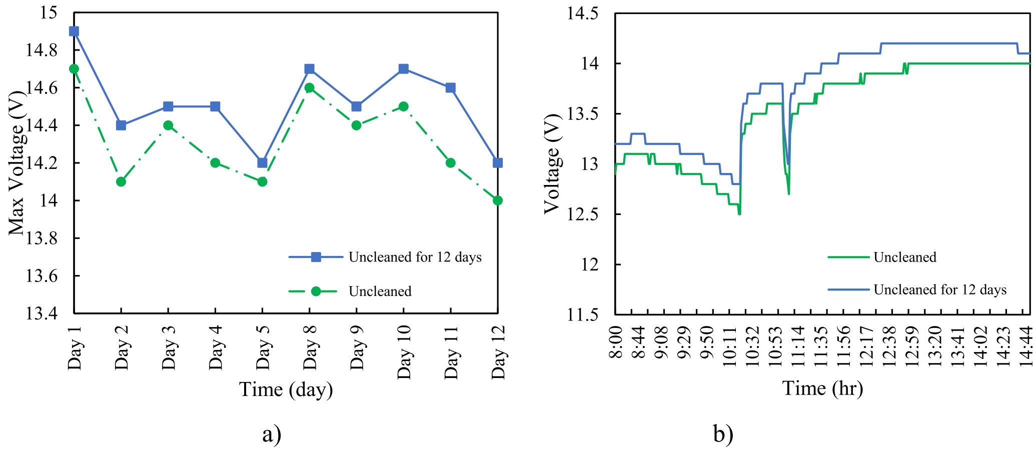


Fig. 11. Variation of voltage with time: a) day and b) hourly (Day 12).

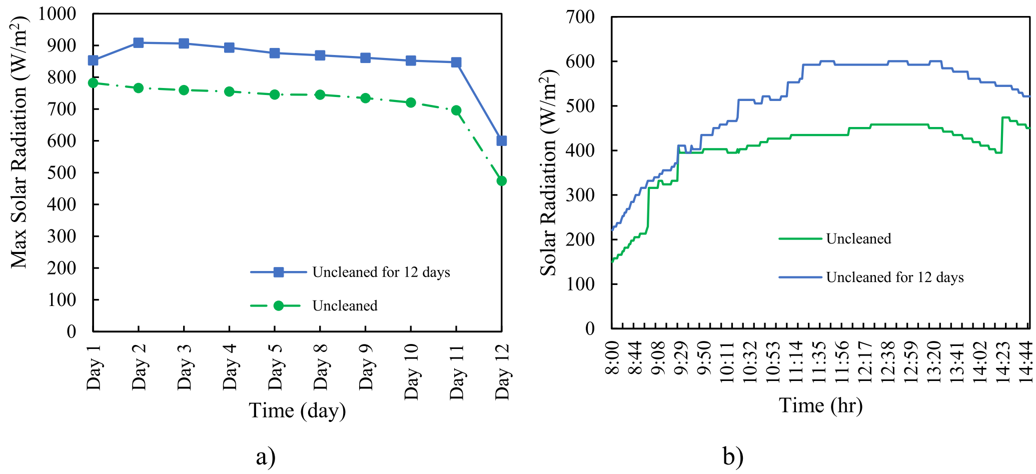


Fig. 12. Variation of solar radiation with time: a) day and b) hourly (Day 12).

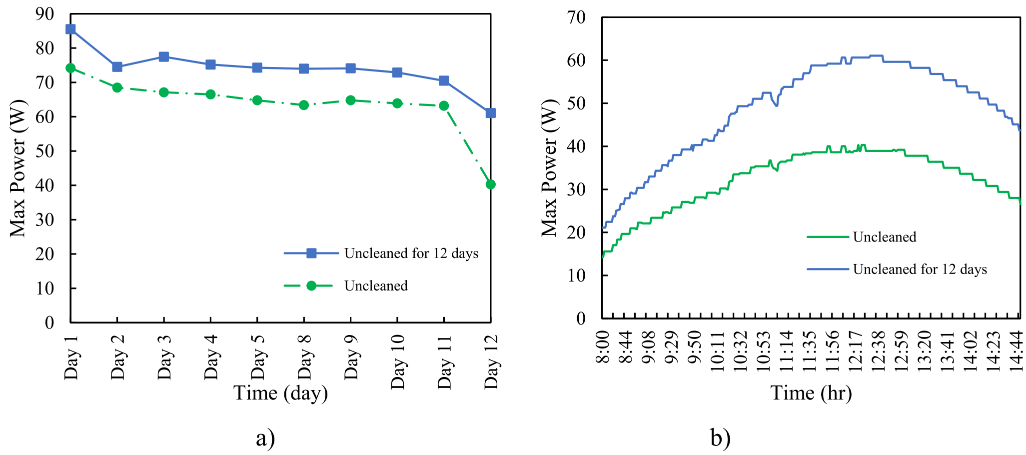


Fig. 13. Variation of power with time: a) day and b) hourly (Day 12).

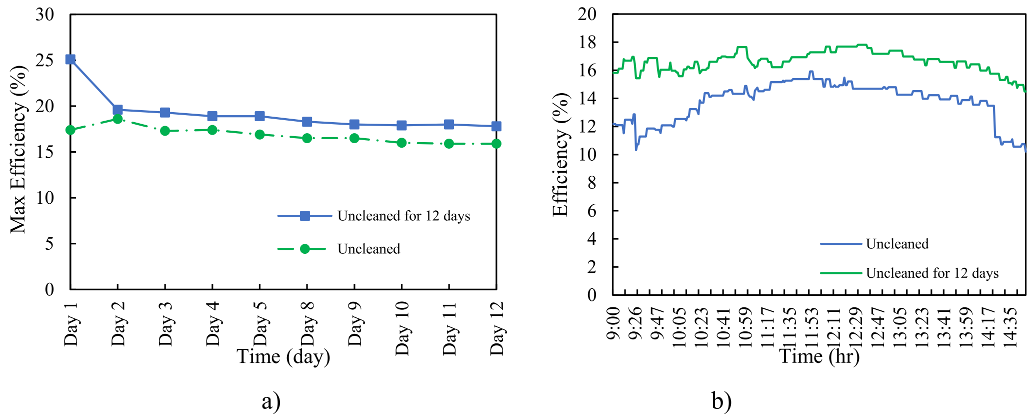


Fig. 14. Efficiency over time: a) day and b) hourly (Day 12).

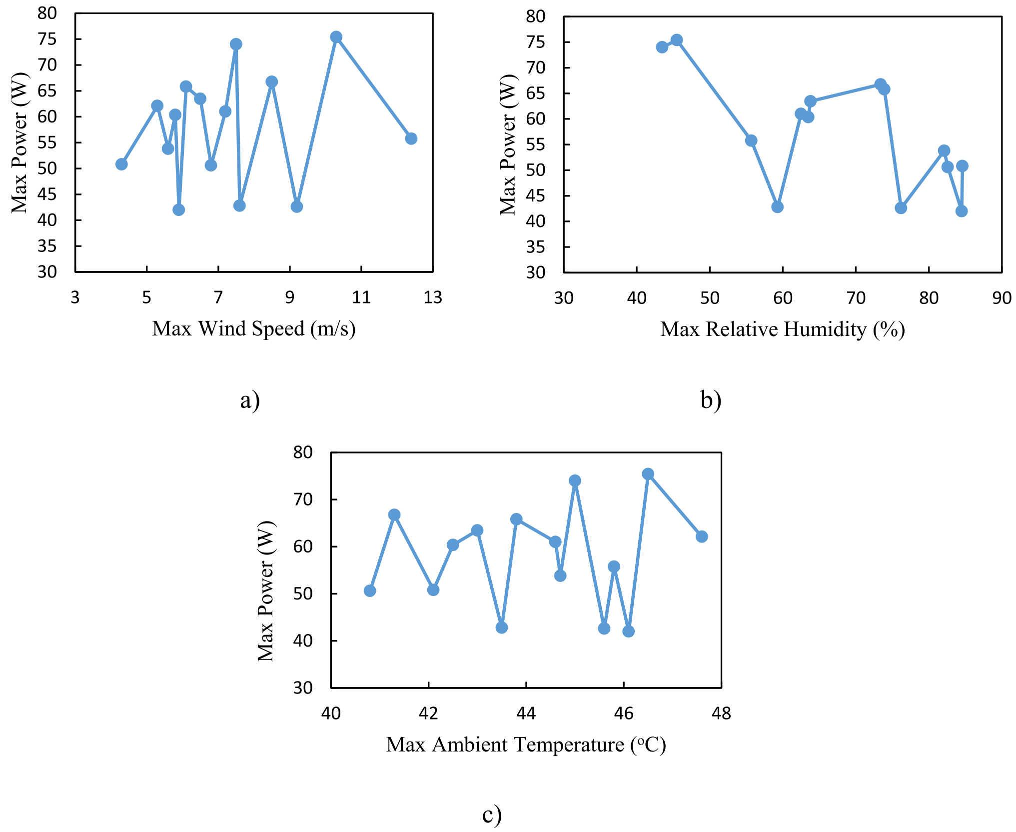


Fig. 15. Maximum power for different environmental factor: a) wind speed, b) relative humidity, and c) ambient temperature.

PV panels. The maximum values of output current and voltage of the cleaned panel (after being exposed to dust for 19 days) reached 3.4 A and 14.2 V, respectively. As for the uncleaned panel, the output reached 2.9 A and 13.9 V. The difference in current was smaller when the panels remained uncleaned for a longer duration.

The variation of solar irradiation for the uncleaned panels for 19 days are depicted in Fig. 18. The hourly solar irradiation on Day 19 is shown in Fig. 18b. It is shown in the figure that as the dust deposition increases, the resulting solar irradiation decreases, and consequently the energy transfer onto the solar panels decreases. The maximum solar radiation of the uncleaned panel (after exposure to dust for 19 days) reached 521.4 W/m^2, as opposed to 513.5 W/m^2 for the uncleaned panel.

Figs. 19 and 20 depict the temporal variations of power and efficiency of the PV panels, respectively. The maximum values of the output of the cleaned PV panel (after being exposed to dust for 19 days) reached 41.9 W and 17.7 %, which are higher as opposed to the

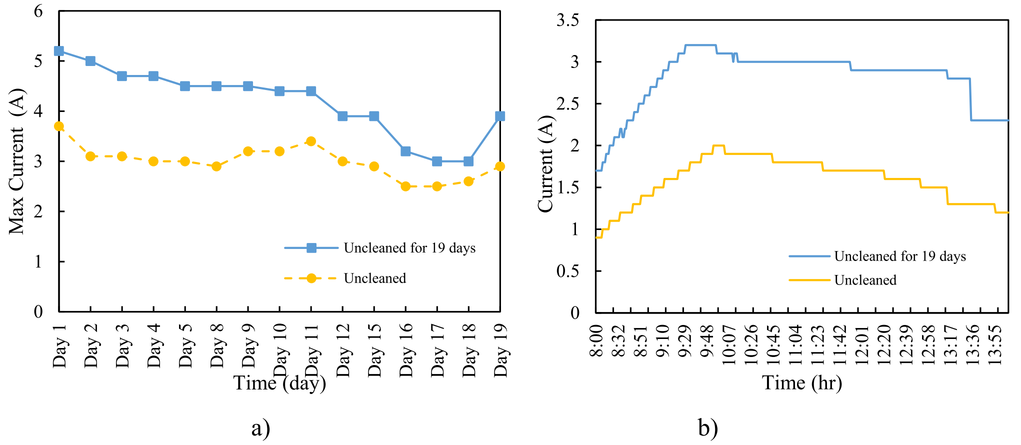


Fig. 16. Variation of current over time: a) day and b) hourly (Day 19).

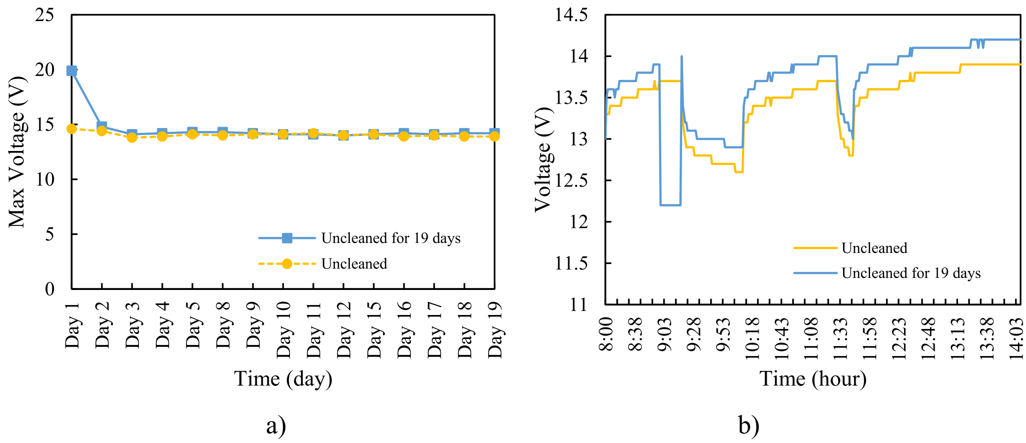


Fig. 17. Variation of voltage with time: a) day and b) hourly (Day 19).

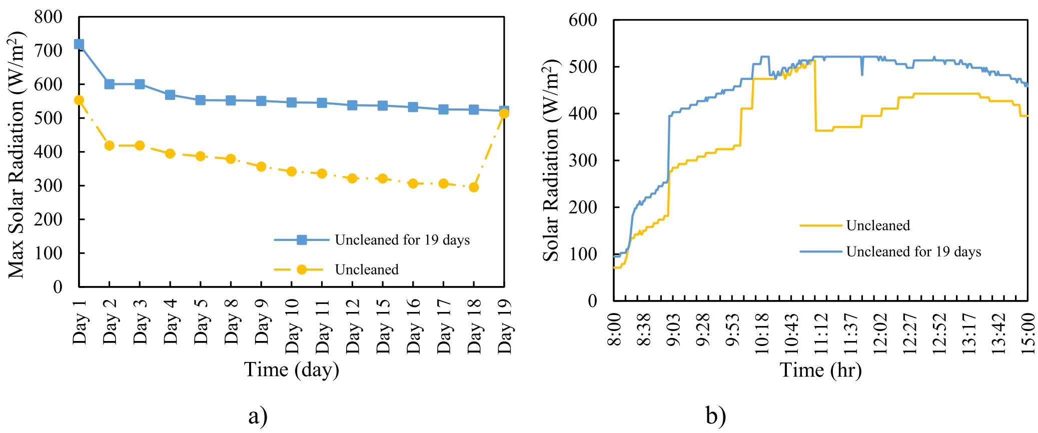


Fig. 18. Solar radiation versus time: a) day and b) hourly (Day 19).

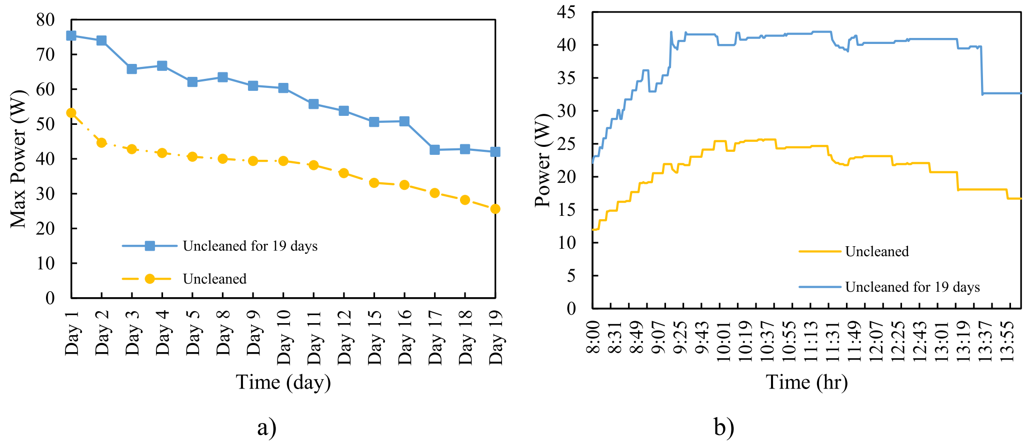


Fig. 19. Power profiles over time: a) daily and b) hourly (Day 19).

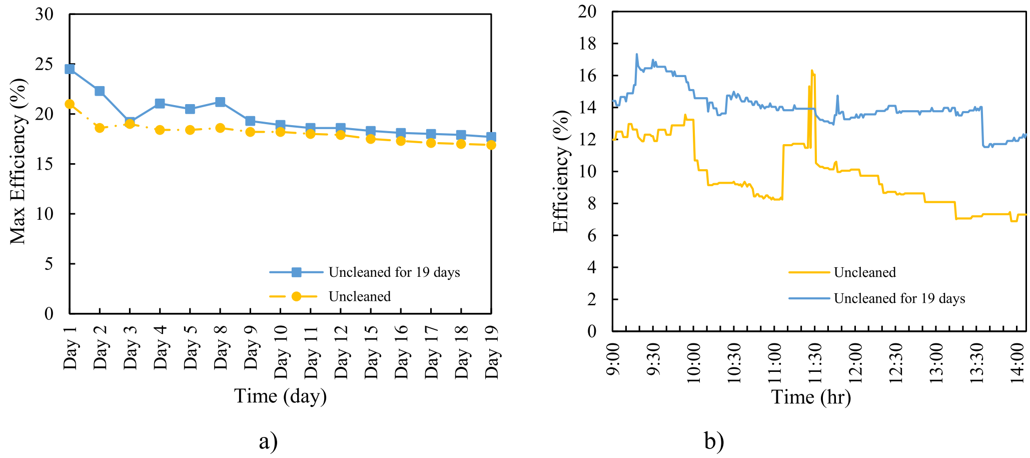


Fig. 20. Efficiency over time: a) day and b) hourly (Day 19).

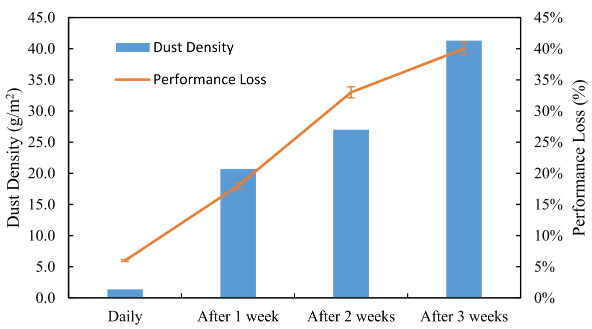


Fig. 21. Cumulative dust density and power loss over durations.

uncleaned panel at 25.3 W and 16.9 %. Subsequently, the power decreased by 40 % due to dust deposition on the PV panels for 19 days. The panel was cleaned, and the dust accumulated was found to be 23.8 g (41 g/m^2).

3.2. Comparison of the performance of photovoltaic panels between daily and weekly

The dust density of the PV panels was determined on a daily and weekly basis. Fig. 21 shows cumulative dust density and power loss over durations. It can be seen that the greater the deposition and dust density, the greater the energy loss, and vice versa. The dust densities were found to be 20.7 g/m^2, 27 g/m^2, and 41.3 g/m^2 for the panels uncleaned for one week, two weeks, and three weeks, respectively. The corresponding electrical power generated was reduced by 18 %, 33 %, and 40 % for the panels left uncleaned for one week, two weeks, and three weeks, respectively. It was found that the uncertainty of the power output is less than 3 %, which is within the acceptable range. Salamah et al. [39] discussed that little dust particles negatively affect solar module efficiency more than bigger dust particles. In a study by Chen et al. [40] a dust density of 10 g/m^2 reduced the maximum power by 34 %. Rashid et al. [41] also observed a significant loss in the efficiency of solar PV with a dust density of 6.388 g/m^2, resulting in an efficiency loss of 15.08 %. In comparison, a dust density of 10.254 g/m^2 reduced the efficiency by 25.42 %. After 45 days of exposure to the outdoors, a study conducted in Saudi Arabia also found that the transmittance reduction was 35 % for the dust deposition of 5 g/m^2 [42].

4. Conclusions

One of the most promising future energy sources is the photovoltaic power system. The buildup of dust on solar panels, known as soiling, lowers the optical efficiency of PV systems. Photovoltaic systems' performance significantly drops when dust accumulates on clear surfaces. This study investigated the effects of wind speed, humidity, and ambient temperature on the performance of photovoltaic panels in Al Seeb, Oman. Solar radiation, voltage, current, solar panel surface temperature, humidity, wind speed, and ambient temperature were measured through the photovoltaic operational parameter acquisition system. The experiment was conducted for a period of two months. It was observed that the dust densities of 20.7 g/m^2, 27 g/m^2, and 41.3 g/m^2 resulted in electrical power reductions of 18 %, 33 %, and 40 % for the panels uncleaned for one week, two weeks, and three weeks, respectively. The effect of daily dust resulted in power reduction of up to 14 %. Moreover, dust deposition decreases when the wind speed increases, so the resulting power generated increases, and vice versa. The PV panels' surface temperature is always higher than the surrounding air temperature, necessitating optimal cooling to produce more power. The higher humidity was found to strengthen the dust's adhesion to the surface, resulting in more deposition and reduced output power. The findings in this article could also be useful in the development of a robust model that predicts the dust effect and environmental factors, emphasizing the optimal cleaning and cooling of PV panels to maximise the performance of PV systems for greener energy sources in the future.

CRediT authorship contribution statement

Girma T. Chala: Conceptualization, Methodology, Investigation, Writing – original draft, Writing - review & editing, Resources. **Shaharin A. Sulaiman:** Writing - review & editing, Resources. **Shamsa M. Al Alshaikh:** Methodology, Writing - original draft.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgement

The authors would like to thank the Ministry of Higher Education, Research and Innovation (MoHERI) Oman for funding this research through the grant reference code of MoHERI/BFP/ICEM/01/21.

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