Experimental Study of Ambient Dusts and Installment Orientations Effects on Solar Panel Efficiency

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Abstract

Most solar panels are stationary without cleaning systems. However, solar panels' power-generating efficiency can be significantly impacted by sunlight intensity and dusts. To remedy this, one method is to maximize the panel's light-catching ability and the other is to keep the panel clean. We systematically studied solar panel efficiency with a panel aligned in different directions relative to the sunlight. We also investigated the dusts' effects by measuring the power output under controlled dust coverages. The results showed that solar panel efficiency can increase by 40% if the panel can follow the sun. Dust deposition can reduce efficiency by 75%. Information on ambient dust concentrations was collected at different locations in southern California, including a house roof, an agriculture field, a highway side, and a cattle ranch. The correlation between the solar panel efficiency and dust coverage was developed to estimate the solar farm performance under various dust coverages.

Keywords: solar panel, dust coverage, installation angle

1. Introduction

The escalating threat of global warming has emerged as a paramount concern for our planet. Governments worldwide are united in their concerted efforts to decelerate the pace of this phenomenon, striving to bequeath a verdant and sustainable earth to future generations. A crucial step in this endeavor lies in transitioning away from our reliance on fossil fuels as the primary energy source and embracing renewable and clean alternatives. These alternatives encompass a diverse array of options, including solar, wind, hydroelectric, geothermal, ocean, and bioenergy sources, each offering a promising path toward a greener and more sustainable future (Aberle et al., 2011; Ang et al., 2022; Jamalabadi and Xi 2023; Paraschiv and Paraschiv 2023).

The key milestone in the exponential growth of solar and wind energy is illustrated in Fig. 1a (Jaeger 2021). In 2000, Germany established renewable energy legislation, and in 2009, the U.S. and China made major stimulus investments in renewable energy (Zhang et al., 2014). After that, new solar and wind energy annual installations matched fossil fuels for the first time. Solar PV became cost-competitive with fossil fuel power and the Paris Agreement was established in 2015 (Skjærseth et al., 2021). In 2021, renewable energy become cheaper than existing coal power for the first time. Figure 1b shows the growth of the renewable energy share, which grew from around 20% in 2001 to 82% in 2020 (Benny 2024). Among the renewable energy sources, wind power and solar PV wave are the two main ones that have been applied. The U.S. has a goal that the renewable generation will reach 44%–45% of U.S. electricity by 2050. In 2008, solar energy was only a very small portion of the total renewable energy. Since then, solar energy has been gradually growing, with the goal that by 2050, 44%–45% of the renewable energy will be solar power (Jones-Albertus 2021).

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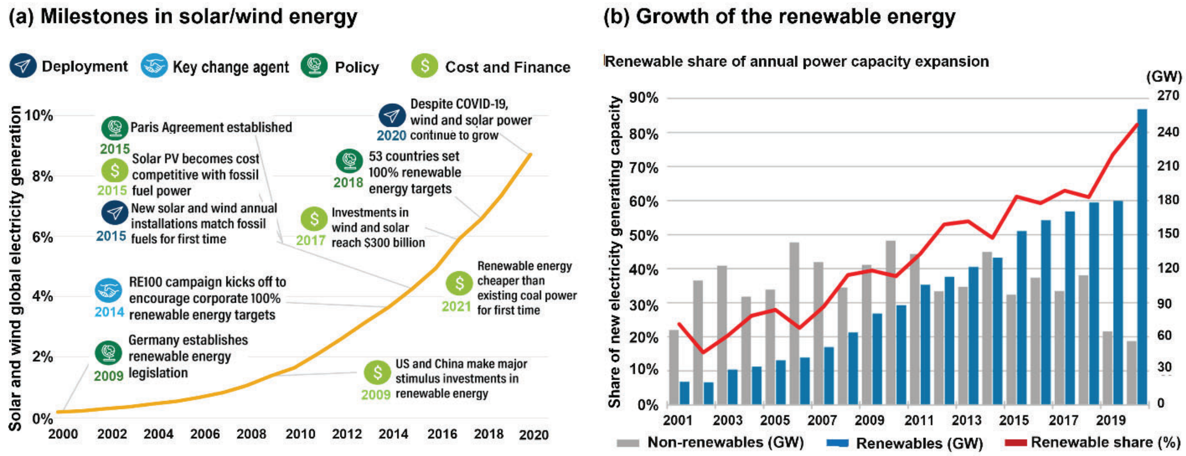

Fig. 1. (a) Key milestones in the exponential growth of solar and wind energy (adapted from Jaeger (2021)) and (b) Renewable share of annual power capacity expansion (adapted from Benny (2024)).

Solar power becomes an important player in future power supply. Different factors can affect solar panel power generation efficiency. The first concern is the degradation of the solar panel with time. However, previous studies showed that solar panel degradation after 25 years was less than 20%, which is small when compared with the degradation rate of other sources of power generation such as the traditional fossil fuel power plant, which needs periodic repair and maintenance (Aghaei et al., 2022; Noman et al., 2022; Olczak 2023; Zhang et al., 2021). Even with this degradation, the same panel after 25 years is still expected to generate 80% of the designed power capacity.

The second factor affecting solar efficiency is the solar panel's orientation relative to the sunshine (Mamun et al., 2022; Prunier et al., 2023; Sharma et al., 2020). Figure 2 shows the simulated energy production of one kilowatt of solar PV capacity in Los Angeles, California.

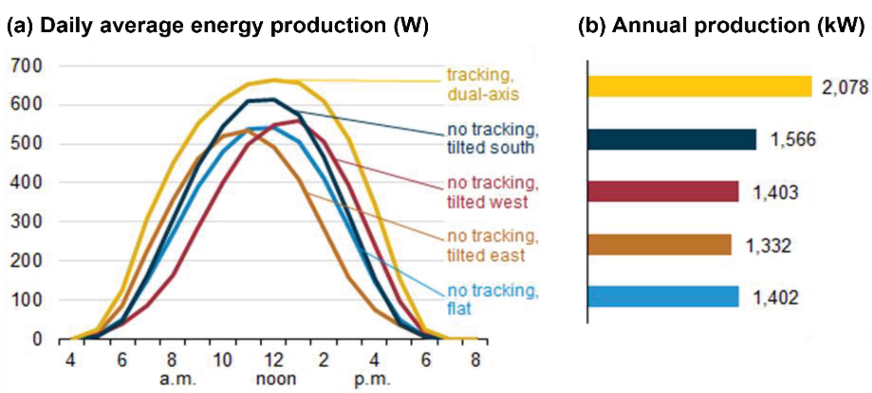

Fig. 2. (a) Average energy production in a day (W) and (b) Annual energy production (KW) (adapted from Zawaydeh 2015).

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In Fig. 2, the solar panel with sunlight tracking generates the highest power, which is about 650 watts (Zawaydeh, 2015). By comparison, a solar panel with no tracking tilted south generates 50 watts less power, whereas a panel with no tracking that is flat generates 150 watts less power. Note that no tracking flat, no tracking tilted east, and no tracking tilted west generate approximately similar amounts of power (Fig. 2b). Within a year, the annual energy production of the same panel tracking sunlight generates 30% or more power than no tracking flat or no tracking tilted south/east/west.

Overall, multiple factors exist affecting solar panel power generation efficiency: wind speed, ambient temperature, solar intensity, dust accumulation, shading, soiling and panel orientation. Among these factors, dust deposition and panel face orientation toward the sunshine can be readily changed. The objective of this study is to better understand the dust deposition and panel orientation effects on solar panel power generation. Specific aims include:

(1) To systematically study the factors affecting the power-generating efficiency of the solar panel with different orientations and dust accumulations
(2) To quantify the effects of ambient dust on solar panel efficiency
(3) To propose strategies to optimize the power-generation efficiency of the solar panel

2. Method and Materials

An HP-866B anemometer (HoldPeak Inc.) was used to measure the wind speed (Fig. 3a). An electric fan was used to simulate wind (Fig. 3b). A VPC300 particle counter from ExTech Instruments was used to mirror the number of particles in the air at different locations (Fig. 3c). The particle counter has six channels, measuring the number of particles with diameters of 0.3, 0.5, 1.0, 2.5, 5.0, and 10.0 μm, respectively. A 2×2-ft solar panel from Dokio made from monocrystalline silicon was used to test the power output under various scenarios (Fig. 3d). Different types of dust particles were considered, including the natural dust deposited on the panel surface, dirt dust, and flour power.

Fig. 3. Experimental methods and instruments: (a) anemometer, (b) electric fan, (c) particle counter, and (d) solar panel. (Photo credit: Xiuhua Si.)

3. Results

3.1 Dust coverage area and dust particle color

Figure 4a shows two dust-covered solar panels. A thick layer of dust particles covered the entire area of the first solar panel. Beside dust particles, there were also kernels, leaves, and other types of debris accumulated on top of the second panel. Figure 4b shows three solar panels with different dust coverages in preparation for experimental tests. Dirt particles were evenly distributed on the first panel. The second panel was covered with flour powders to assess the color effects. The third panel was covered with a flour solution that was applied to the panel surface by a brush. Depending on the test condition, the coverage could be even or scattered, and one layer or multiple layers.

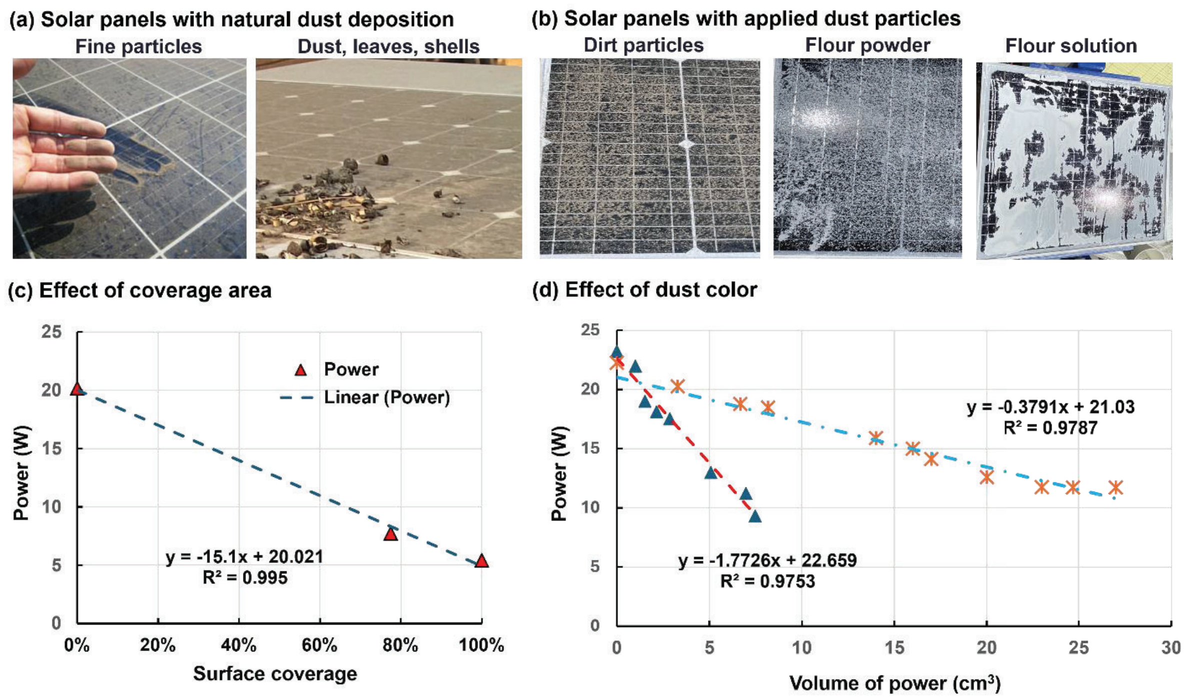

Fig. 4. Experimental results: (a) panels covered by scattered dust particles and fully covered by a thick layer of mud-like dusts, (b) experimental panels covered by different particles, (c) power output effects of surface area coverage, and (d) power output effects of scattered particles and colors of particles. (Photo credit: Xiuhua Si.)

We first compared solar panels fully covered and scatter-covered by dust. Flour powders were used to cover different regions of the solar panel. The power outputs by the solar panel were measured, as shown in Fig. 4c. Clearly, the more area was covered, the less power was generated. Power decreased linearly with increasing coverage. We also scattered different types of dusts on the panel surface. The more powder was scattered, the less power was generated.

The color of the dust was also found to affect the power generation of a solar panel. The lighter the dust color was, the smaller effect it had on the power generation. In Fig. 4d, the blue line (with the brown asterisk) represents the power generated by the panel covered with white powders. The red line (with the blue data symbols) represents the power generated by the panel covered with dirt dust (the brown color). Apparently, the

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white powder has less of a negative effect on the power generation of the solar panel than the brown dust does.

3.2 Coverage Thickness Effect

We also simulated the situation when the solar panel was covered by a thicker layer of material, with different numbers of leaves scattered on the solar panel that was already covered by fine dust particles. It is clearly visible in Figure 5 that the more leaves were on the panel, the less power was generated, as demonstrated by the power output variation from Fig. 5a to Fig. 5c. The relatively large area of leaves and their irregular shapes form shade that can effectively block the sunshine reaching the PV panel.

Figure 5. Coverage with dust and leaves: (a) 30% coverage with leaves, (b) 15% coverage with leaves, and (c) no leaves. (Photo credit: Xiuhua Si.)

When small raindrops fall on the solar panel covered with very fine dust particles, ring-shaped patterns form. More rain droplets or condensates can form liquid streams, leaving furrow-shaped patterns. In both conditions, dust coverages with varying thicknesses can form (Fig. 6a). As alluded to above, the thicker the dust coverage is, the less power will be generated.

For a partially covered solar panel, if the dust particles are more scattered, will it affect the total power generation? Figure 6b shows the power output with different amounts of dust particles. The number of particles did exert a noticeable effect on the power generation, but when compared with a fully covered panel, this effect is much smaller.

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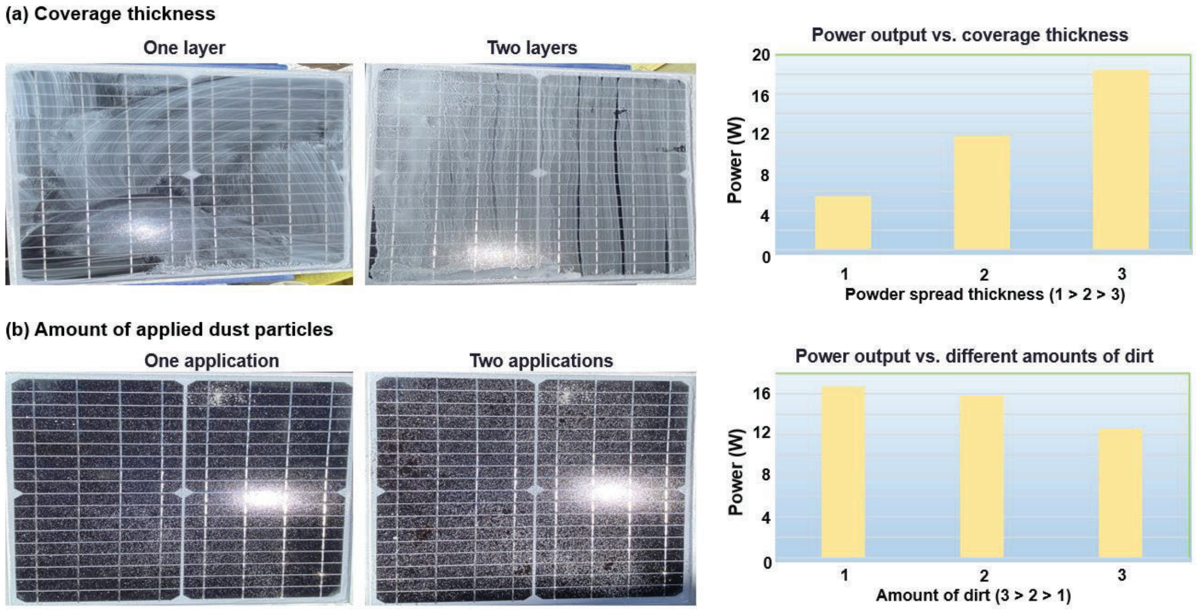

Fig. 6. Coverage layers and amounts of dust: (a) coverage thickness effect due to one layer or two layers of brushed flour solution 30% coverage with leaves, (b) effect of the amount of applied dust particles. (Photo credit: Xiuhua Si.)

3.3 Solar Panel Installation Angle Effect

Figure 7 shows photos of solar panels on top of the engineering building at California Baptist University that were installed in 2018. In the first photo (Fig. 7a), the panels were installed on top of the roof and parallel to the direction of the roof, facing south. Figure 7b shows the panels installed on slant frames, whose angle is almost straight up relative to the roof (Fig. 7b). The rightmost photo is a zoomed view of one of the panels in Fig. 7b. Compared with the panels in Fig. 7a, where there is a much smaller slope angle, far fewer dust particles are on the surface of the nearly straight-up panels in Fig. 7b.

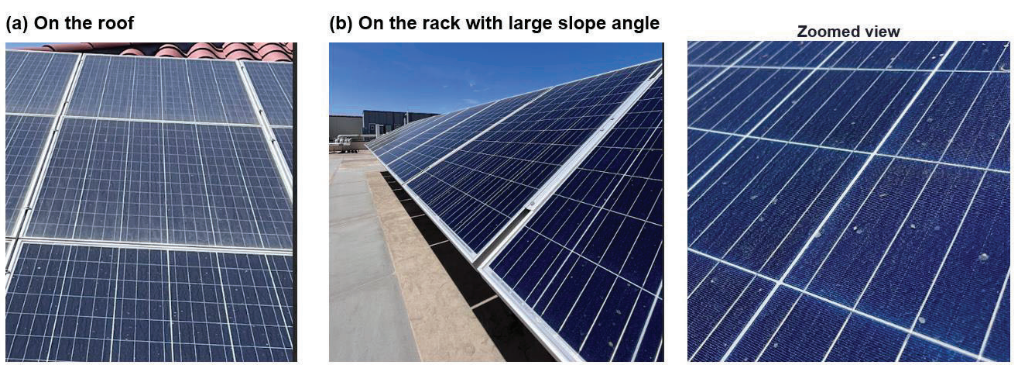

Fig. 7. Panel installation angle: (a) on the roof, and (b) on the rack with a large slope angle (Photo credit: Xiuhua Si.)

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Figure 8 shows photos of the experimental solar panels with different amounts of dust particles on the surface. The power output decreases with increasing dust mass. Furthermore, this relationship is not strictly linear. This might be due to the fact that some particles pile up without spreading.

Fig. 8. Nonlinear panel output vs. applied dust amount (Photo credit: Xiuhua Si.)

3.3 Ambient Dust at Different Locations

It is crucial to know what kinds of dust aerosols are there and how many dust particles will be deposited on the solar panels. To research this question, we visited different solar farms in southern California. The first was in a parking lot in Riverside city suburb. The second was on top of a four-floor parking structure near a highway. The third was in a desert area. The fourth was on a mountainside (Fig. 9a). A particle counter was used to measure the particle-size distribution of the ambient air. Particles smaller than 1.0 μm can easily follow the airflow. If the ambient aerosol has more particles above 1.0 μm, the panels will be likely to collect more particles.

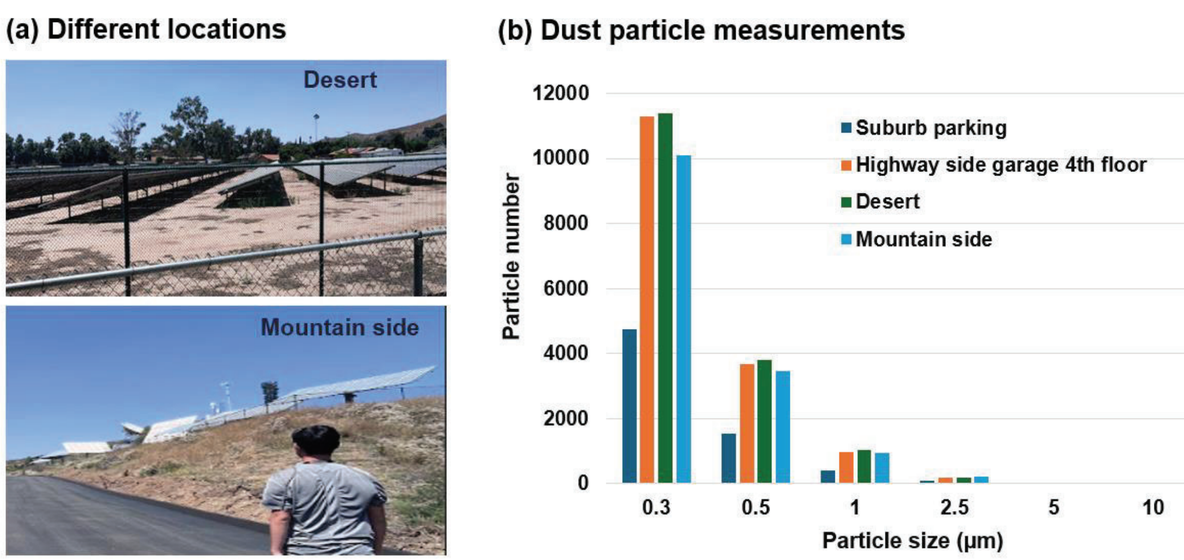

Fig. 9. Ambient dust measurements: (a) different locations, (b) particle count measurement (Photo credit: Xiuhua Si.)

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Table 1. Dust size distribution at different locations

PM (μm)	Suburb parking	Highway side garage 4th floor	Desert	Mountain side
0.3	4765	11290	11386	10096
0.5	1545	3682	3791	3447
1.0	389	979	1031	941
2.5	78	182	197	205
5.0	11	12	19	26
10.0	6	4	11	9

As shown in Table 1 and Fig. 9b, the number of particles in the desert area is slightly larger than the number of particles on the mountainside and at the highway-side parking structure and much larger than that at the suburb parking. Especially for PM2.5 (i.e., particulates ≤ 2.5 μm in diameter), the number of particles in the desert, highway-side parking structure, and mountainside are more than twice that at the suburb parking. Based on these data, the frequency of panel dust cleaning can be calculated to ensure optimal power generation with minimized incurred cleaning costs.

Considering that the desert area is often windy, we used an electric fan to simulate the effect of wind speeds in the desert area on the measurement of the particle counter (Fig. 10a). As shown in Fig. 10b, the higher the wind speed is, the more particles are measured. Thus, in the desert area, knowledge of the average wind speed is needed to predict how often those panels need to be cleaned or washed.

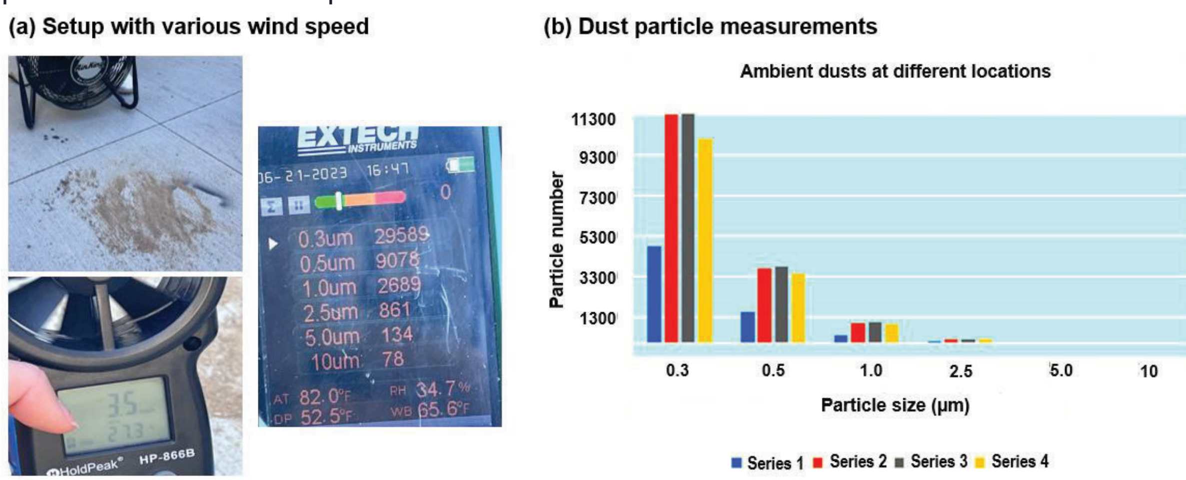

Figure 10. Ambient dust measurements: (a) different locations, (b) particle count measurement (Photo credit: Xiuhua Si.)

3.5 Panel Orientation Effects in Southern California

Figures 11a and 11b show the solar power output at three orientations on April 12, 2022 in the morning (9 am – noon) and afternoon (noon – 5:45 pm), respectively. The three orientations considered include: flat (or 0° angle toward the sun in Figs. 11a & 11b), 20°

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tilted from flat toward the sun, and 20° tilted from flat away from the sun. Measurements were taken every 30 minutes from 9:30 am to 5:45 pm.

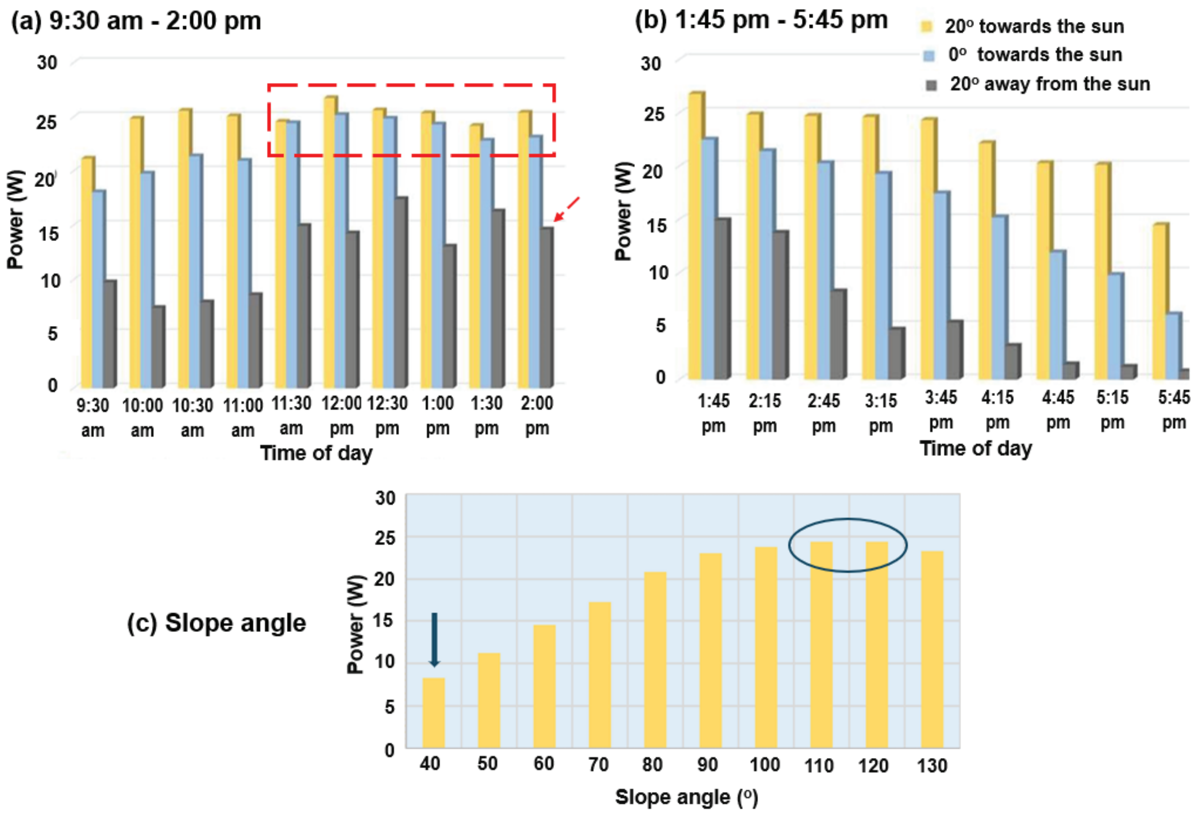

Fig. 11. Power output at three panel orientations: (a) 9:30 am – 2:00 pm; and (b) 1:45 pm – 5:45 pm; and (c) power output at different angles to the direction of the sunshine at 12:00 pm-1:00 pm.

Clearly, from 11:30 am to 2:00 pm, the flat panel and the panel tilted 20° toward the sun generated very similar amounts of power, as highlighted by the dashed rectangle in Fig. 11a. However, in the early morning or late afternoon, the panel tilted 20° toward the sun generated significantly more power, which was 20% more than the flat panel and 75% more than the panel at 20° away from the sun (Figs. 8a and 8b). This suggests the importance of the panel orientation, particularly in the early morning or late afternoon when the sunshine has large incidental angles.

To identify the optimal panel orientation, we gradually changed the panel orientation angles from flat (0°) toward the south to 40°, 50°, 60°, 70°, 80°, till 130° from noon to 2:30 pm. It is clearly observed that panels at an angle of 110° and 120° generate the highest power, while 40° generated the least, as indicated by the filled arrow in Fig. 11c. Moreover, the power output increased steadily from 40° to 100°.

4. Conclusion

1. Panels standing in a more vertical direction will greatly reduce the deposition of dust.
2. A periodic cleaning schedule depending on the dust level of different locations will greatly enhance the power generation.
3. The average power output of the solar panel at 20° toward the sun is 40% more than that generated by the same panel at a flat position.
4. The power generated at the optimal angle can be three times more than that generated at the least effective direction.
5. The flat panel can generate up to 75% more power than the panel tilted 20° away from the sunshine.
6. A sun-following solar panel can significantly increase power generation. It is more significant than periodic cleaning in most of the desert areas where dust particles are scattered on the panel without fully covering it.
7. Power-generation reduction caused by coverage with different types of dirt is less significant compared with the power-generation reduction based on the orientation of the panel. The color of the dirt and the total area covered are both factors to be considered. Periodic cleaning of the panel will increase the power generation.

Several future studies are warranted. These include designing a programmed cleaning robot to automatically clean the panel periodically, with a frequency depending on average wind speeds, dust level, and rainy weather. A sun-following control device would be designed and installed on existing and future panels. Systematically studying the effects of temperature, solar insolation, shading, and humidity is necessary to identify the optimal use of solar power in different areas according to their specific climates and to provide advice to different local governments for renewable energy-development plans.

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Conflict of 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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