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Experimental Study on the Effect of Sand and Dust on the Performance of Photovoltaic Modules in Desert Areas

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Abstract: Photovoltaic power generation is one of the most effective measures to reduce greenhouse gas emissions, and the surface of photovoltaic modules in desert areas is mainly affected by sand erosion and cover, which affect power output. Therefore, a wind–sand erosion system was established to simulate the desert wind–sand environment, analyze the influence of dust erosion on the output power of the component, and observe the surface erosion morphology of the component. Then, dust particles of different sizes were selected to cover the surface of the photovoltaic module, and the temperature change and output characteristics of the backplane of the module were studied. The results show that the erosion rate increases with the increase in the erosion angle. When the erosion rate is 25 m/s and 30 m/s, the output power decreases by 9.82%~16.00% and 15.42%~24.46% at different erosion angles, respectively. As the particle size (0.05 mm~0.30 mm) deposited on the surface of the photovoltaic module gradually increases, the open-circuit voltage of the module changes little, and its maximum difference is 0.25 V. Short-circuit current and output power vary greatly; the maximum difference in short-circuit current is about 13.00%, and the maximum difference in output power is about 17.00%. Through our research, this study provides a certain reference for maximizing power generation efficiency and the clean planning of desert photovoltaic power stations.

Keywords: photovoltaic modules; desert regions; erosion rate; dust particle size; output characteristics

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1. Introduction

1.1. Research Background

Due to the increase in the world's population and the advancement of science and technology, mankind's demand for electricity is increasing. Currently, electricity generation relies heavily on the combustion of fossil fuels, the consumption of which produces large amounts of carbon dioxide, thus affecting climate change. Numerous countries have therefore turned their attention to renewable energy sources, and the use of solar power is one of the main forms of renewable energy use, the main components of which are photovoltaic modules. And the output performance of PV modules is usually affected by weather factors [1,2]. In desert environments, the accumulation of sand and dust particles on the PV module's surface and erosion are the main problems leading to the degradation of PV module performance [2]. The temperature parameters of the PV module itself also affect the output performance of the module [3].

China's northern Inner Mongolia Autonomous Region contains China's seventh largest desert, Kubuqi Desert, with an average annual sunshine duration of 3117 h and high-intensity solar radiation, which are very suitable for the construction of photovoltaic power plants. China's largest ecological desert photovoltaic power plant is located here. However, PV performance in this region is highly affected by factors such as sand erosion and sand accumulation on the module surface [4]; as such, the output performance and efficiency of photovoltaic power stations are reduced.

1.2. Research Status and Challenges

Research related to the erosion and wear of the surface of an object by sand and dust mainly focuses on the erosion of its surface by particles of a certain size at a certain speed and angle, and many scholars have carried out different studies. Zhang Lian et al. [5] carried out a numerical simulation of gas–solid two-phase flow in the 90° bend of a ventilation and dust removal pipeline based on the discrete particle model (DPM), and the experimental results showed that when the inlet wind speed and particle size are certain, the wear rate of the bend decreases and then increases with the increase in bend diameter ratio, and the wear of the bend is smaller when R/D = 3~4; when the R/D is certain, the relationship between the wear rate E and the velocity V of the 90° bend is E = KV~(1.08~1.32); when V = 0~5 m/s, the wear rate is small with the change in velocity; and when V > 5 m/s, the wear rate is large with the change in wind speed. Lin Z et al. [6] used the URNS (SST)-DPM method to study the effect of particle erosion on a horizontal ideal cavity. The erosion distribution of the downstream bottom wall was explored, the initial erosion location was extracted and analyzed, and they found that slightly lowering the back wall of the cavity drastically reduced the erosive effect of particles. Hurol Kocoglu et al. [7] investigated the tribological properties of composites consisting of discarded carbon fiber (CF), glass fiber fabric (GF), and polyamide 6.6 (PA6.6) through solid particle and scratch experiments and found that the blade of pure PA6.6 had a low erosion rate and the incorporation of CF and GF materials reduced the erosion resistance; the blade of pure PA6.6 had the highest erosion rate in the range of a 15~30° impact angle, and the composite laminate had the highest erosion rate in the range of a 30~45° impact angle. Ren Bo et al. [8] established a prediction model for the erosion rate of an annular air channel based on the flow rate, mass flow rate, and particle size and found that the maximum erosion rate increased exponentially with the increase in flow rate and a larger mass flow rate led to a decrease in the erosion rate, and the critical mass flow rate was determined to be 5.23 kg/s. In addition, the erosion rate first decreased and then increased with the increase in the particle size, and the critical particle size was 0.7 mm. Xiaobo Kang [9] analyzed the effects of wind angle, incoming wind speed, and PV module mounting tilt angle on the distribution of the sand erosion rate on the surface of PV modules, and the results showed that with the gradual increase in wind speed, the maximum erosion rate gradually increases; with the gradual increase in the PV module mounting tilt angle, the maximum erosion rate of the surface of the PV module gradually decreases; and with the gradual increase in the wind angle, the erosion rate on the surface of the PV module shows a gradual increase in the trend of change and reaches the maximum value when the wind angle is 75°.

Current research shows that the study of the effect of sand and dust on photovoltaic modules is a more complex problem that is influenced by the specific local climate and weather [10,11]; sand accumulation on the surface of photovoltaic modules is the main cause of their reduced output performance [12,13]. Walwil et al. [14] investigated the effect of lime, cement, and carbon particles adhering to the surface of PV modules on their output characteristics and found that the smaller the particle size, the more pronounced the effect on the PV modules. This result has also been verified by other research scholars [15]. Kazem et al. [16] conducted an experimental study on the effect of dust on the output characteristics of photovoltaic modules in six different regions selected in northern Oman, and the majority (64%) of the dust particles selected were analyzed to be concentrated in the range of 2 to 63 μm in diameter. Javed et al. [17] conducted an experimental study in the Qatar region to analyze the characteristics of dust deposited on the surface of PV modules at different times of dust accumulation and found that the average particle size of dust accumulated on the surface of PV modules decreases with the increase in exposure time and reaches a relatively stable state with the increase in the exposure time, whereas with the increase in exposure time, dust particles accumulated on the surface of the PV modules will coalesce. Mani et al. [18] summarized the effect of dust on the performance of solar PV modules by providing the cleaning cycle of PV modules in different climatic zones and with different climatic characteristics.

From the above study, it can be seen that the main factors affecting the output characteristics of PV modules are sand and dust erosion of the module surface and sand and dust covering the module surface. In essence, the performance change in solar photovoltaic modules is produced under the joint influence of the two factors of particle size and temperature. Many scholars have studied the influence of component surface temperature on component performance, but the study of the influence of backplane temperature on component output performance has not been developed. In addition, there are more studies on the erosion of solid particles on the surface of objects, but there are fewer studies on the effect of solid particle erosion on the power generation efficiency of photovoltaic modules. Different regions have different characteristics of sand and dust, which have different effects on the performance of PV modules, but there are fewer studies on the effects of PV module performance under erosion of different wind speeds and coverage of sand and dust with different particle sizes. Therefore, this paper takes the Kubuqi Desert in Inner Mongolia as the background; first, we use the airflow-holding sand jet method to simulate the wind and sand erosion in the desert environment and examine the influence of wind and sand erosion on the output power of photovoltaic modules under different conditions; secondly, we analyze the temperature change of the module backplane when covered by different sand particle sizes and finally analyze the influence on the output characteristics of the module according to the change in the different particle sizes and the temperature of the backplane.

1.3. Contribution and Paper Organization

In this manuscript, the sand erosion characteristics of photovoltaic modules are extensively simulated, the damaging mechanism of sand erosion is meticulously examined, and the impact of sand erosion on the performance of photovoltaic modules is assessed. Subsequently, dissimilar particle sizes of dust are deposited on the surface of the photovoltaic module to scrutinize its influence on the photovoltaic module temperature, open circuit voltage, short circuit current, and output power. Finally, pertinent laws are derived, which can furnish a particular reference for optimizing the power generation efficiency and maintenance scheduling of actual photovoltaic power stations.

2. Experimental Study on the Influence of Dust Erosion on the Surface and Power of Photovoltaic Modules

2.1. Erosion Experiments and Impact Studies

2.1.1. Experimental Material

The sand dust utilized in the experiment was procured from an area adjacent to a photovoltaic power plant situated within the Kubuchi Desert within the Inner Mongolia Autonomous Region of China; the chosen sand dust specimens were meticulously analyzed for particle size utilizing the sieving methodology. As a result of the measurements, the volumetric content of sand particles with a particle size of less than 0.05 mm in the implemented sand dust was found to be less than 0.20%; the quota of sand particles with a particle size of 0.05 to 0.30 mm stands at 99.57%; and the portion of sand particles with a particle size of more than 0.30 mm is less than 0.23%. Through the aforementioned processes, it becomes evident that the particle size of the sand grains employed in the experiments should primarily range from 0.05 to 0.30 mm. Moreover, the results suggest that the hardness of the utilized sand dust is 6.75 GPa and its density is 2.70 g/cm^3.

The laminated glass utilized in the experimental process was selected to be the toughened velvet glass frequently employed atop solar photovoltaic modules, with a modulus of elasticity of 74 GPa, a hardness of 6.40 GPa, a density of 2.50 g/cm^3, and a length, width, and height of 60 mm, 80 mm, and 3 mm. The characteristics of the solar photovoltaic modules used in the experiments are listed in Table 1.

Table 1. Parameters of solar photovoltaic modules.

Working Parameter Name	Parameters
Maximum power operating point/W	0.495
Maximum operating power point voltage/V	4.5
Maximum used operating power point current/A	0.11
Open circuit voltage/V	5.0
Short-circuit current/A	0.115

2.1.2. Experimental Methods and Equipment

The experimental platform constructed in this section is a desert wind and sand erosion simulation system, whose structure is shown in Figure 1.

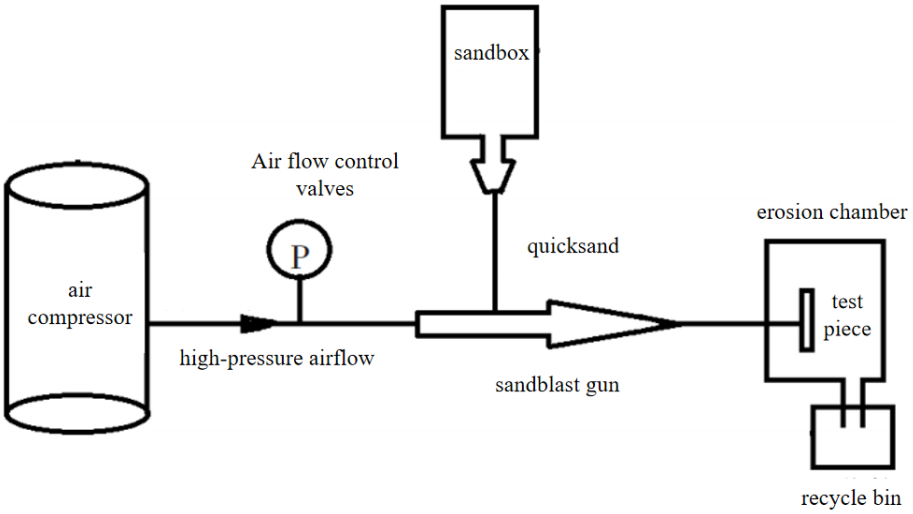


Figure 1. Desert wind and sand erosion simulation system.

As can be seen in Figure 1, the experimental platform constructed consists of equipment such as an air compressor, airflow control valves, a sandbox, a sandblast gun, an erosion chamber, and a recycle bin.

The experimental process involves the following: first of all, the use of air compressors to provide high-pressure airflow, the airflow control valves to control the erosion rate of the high-pressure airflow; secondly, the sand flow from the sandbox and high-pressure airflow mixing by the sandblast gun guidance sent to the erosion chamber for erosion; and finally, the end of the erosion of the sand particles into the recycle bin, of which the recycling of sand particles collected by the recycle bin can be repeated for use in other experiments.

Pre- and post-erosion experiment comparison process: The mass of the tempered glass specimen is calculated meticulously before and after the experiment by utilizing a precision electronic balance, and then, the surface of the tempered glass specimen is examined under a high-powered electron microscope (SEM) to discern the erosion morphology, and the alterations in the output attributes of the photovoltaic module prior and subsequent to the erosion are documented by using the Fluke Norma 500 power analyzer and the PROVA 200A solar cell analyzer, respectively.

This section focuses on the analysis when the erosion speed of sand and dust are V_1, and V_2 (the speeds of 25 m/s and 30 m/s are the maximum and extreme wind speeds under extreme sand and dust weather, respectively), and the erosion angle was selected to be 15°, 30°, 45°, 60°, 75°, and 90° to analyze the erosion of sand and dust on the PV module and the impact on the performance parameters. Because the particle size of the sand particles used in the experimental process is small and the erosion of tempered glass by wind and sand is a long process, the time of the erosion experiment was set to 3 min [19].

2.1.3. Evaluation of Erosion Results

The degree of erosion damage to the PV module can be characterized by the relative erosion rate E_0 [20], which is expressed as shown in (1).

$$E_0 = \frac{m_1 - m_2}{mt} = \frac{\triangle m}{mt} \quad (1)$$

2.1.4. Evaluation of Power Generation Efficiency of Photovoltaic Modules

The expression equation of the power loss rate of the PV module is shown in (2).

$$\eta = \frac{P - P_1}{P} \quad (2)$$

2.2. Discussion and Analysis of the Results of the Erosion Experiment

2.2.1. Relative Erosion Rate of Tempered Glass in Relation to the Angle of Erosion

Figure 2 shows the change in the relative erosion rate E_0 of tempered glass with the erosion angle under the conditions of two erosion speeds. It can be seen in Figure 2 that when the erosion speeds were 25 m/s and 30 m/s, the tempered glass on the surface of the photovoltaic module increased with the increase in the erosion angle. When the erosion angle was 90°, the relative erosion rate of the tempered glass reached the maximum value, with this being 0.018 mg/g and 0.09 mg/g, respectively. The main reason for this is that tempered glass is a brittle material, and its relative erosion rate is proportional to $\sin^2 a$. It was also found that the maximum relative erosion rate occurs when the erosion angle is 90°.

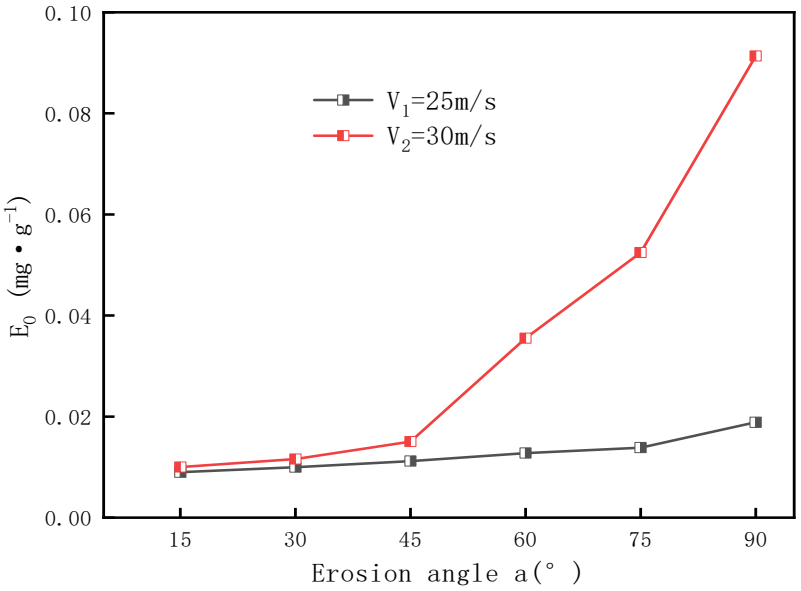


Figure 2. Variation in the relative erosion rate of tempered glass at different erosion rates.

It can be seen in Figure 2 that under different erosion rates, when the erosion angle is small, the relative erosion rate of tempered glass is small and increases with the increase in the erosion angle. This is the main reason tempered glass has high hardness and a large modulus of elasticity. When the erosion angle is small, the quality loss of tempered glass is mainly caused by the micro-cutting action of sand particles. At this time, the normal velocity of the tempered glass sand particles is small, so the kinetic energy of the sand particles and the impact energy are relatively small. At this time, the normal direction of the kinetic energy of the sand particles is not enough to cause damage to the larger cracks. With the increase in the erosion angle, the normal velocity of the sand particles on the surface of the tempered glass gradually increases and the initial kinetic energy carried by

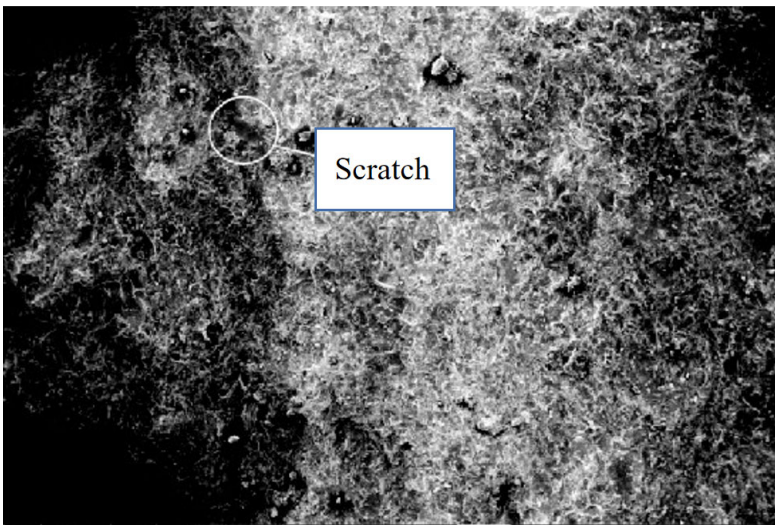
the sand particles increases, which makes the contact area between the sand particles and the tempered glass gradually increase and then causes an increase in transverse and radial cracks in the impacted parts of the surface of the tempered glass, and the relative erosion rate also gradually increases.

2.2.2. Mechanistic Analysis of Erosion Damage

Erosion damage is generally divided into two types: low-angle micro-cutting action and high-angle elastic-plastic deformation caused by erosion damage and low-angle micro-cutting action and high-angle fatigue cracks caused by the expansion of the cross-over of erosion damage. Therefore, in this erosion experiment, the change in erosion angle has a more critical role in the erosion damage experiment and the change in relative erosion rate.

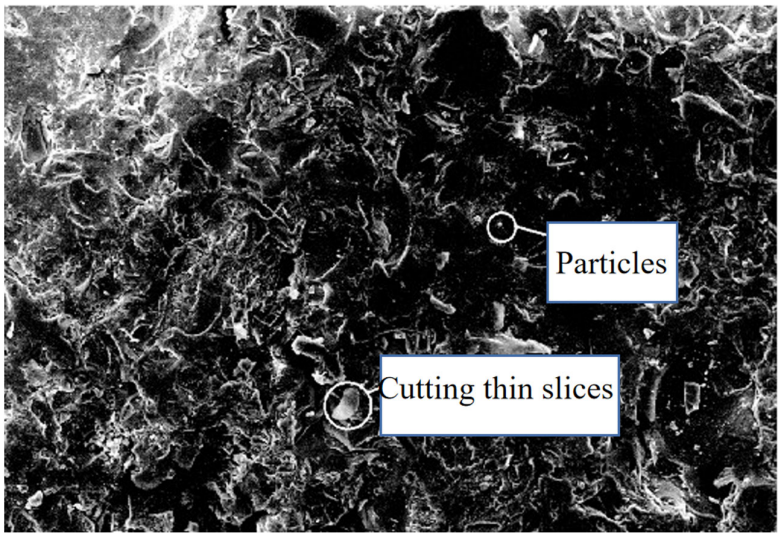
Figure 3 shows the SEM morphology of tempered glass under different erosion angles at an erosion speed of 30 m/s.

In Figure 3a, it is apparent that there are scratch marks and plow grooves present on the surface of the tempered glass at an erosion angle of 30°. The scratch marks are more uniformly distributed, but their length is inconsistent. Some pits of varied dimensions can also be observed, and some of the glass material surrounding the pits is extruded from the surface under force, accompanied by the evolution of micro-cracks, which is primarily attributed to the degradation of tempered glass under low-angle erosion conditions predominantly due to the diminution of quality under the influence of micro-cutting. Examination of Figure 3b,c suggests that there are brittle fracture pits present on the surface of the tempered glass, and there is a substantial quantity of granular material surrounding the pits, with cutting flakes being present in exceedingly few areas. This is predominantly because when the erosion angle is 90°, the normal velocity of the sand particles impacting the surface of the tempered glass peaks, thereby leading to the maximum value of kinetic energy of these sand particles. In the erosion process, scratches, cracks, increases in the length and depth of the cracks, and an increase in the severity of damage are generated. At this juncture, as the tempered glass's force is non-uniform and its own stress is excessively concentrated in the region of stress, a pronounced brittle fracture occurs, generating a large volume of particulate material and insignificant amounts of fragmented material, ultimately leading to the deterioration of the quality of tempered glass. In summary, when the erosion angle is minimal, the quality decay of tempered glass is primarily attributed to micro-cutting; as the erosion angle progressively increases, the quality loss of tempered glass evolves into a combination of cutting and cracking; and when the erosion angle reaches 90°, the quality loss of tempered glass is primarily rooted in crack formation.

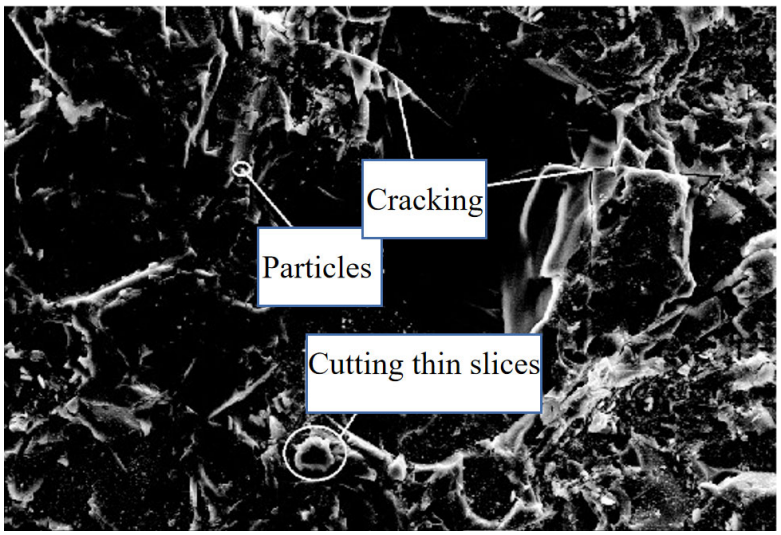


(**a**) a = 30°; low magnification topography

Figure 3. *Cont.*



(**b**) a = 90°; low magnification topography



(**c**) a = 90°; high magnification topography

Figure 3. SEM morphology of tempered glass with different erosion angles at 30 m/s erosion speed.

2.2.3. Effect of Erosion on the Performance of Photovoltaic Modules

The irradiation direction and photovoltaic module are used to maintain a relatively vertical direction. As can be seen from the change curve in Figure 4, the solar radiation intensity F remained stable within a certain range during the experiment. At both erosion speeds, the output power P of the PV module increases first and then decreases as the erosion angle gradually increases. This is due to the fact that when the erosion angle is small, the erosion profile on the surface of tempered glass mainly shows an elliptical shape with openings on both sides, and the erosion area is large. During this erosion process, the degree of erosion of sand and dust particles on the tempered glass is relatively low, but the transmittance of the tempered glass decreases, resulting in the consequent reduction in the output power of the photovoltaic module. With the gradual increase in the erosion angle, the erosion profile of the tempered glass surface from the two sides of the opening gradually changes from an ellipse shape into a more complete ellipse shape, and the erosion area is gradually reduced. When the erosion angle gradually increases from 15° to 45°, the output power of the PV module gradually increases; when the erosion angle is 45°, the output power of the PV module reaches the maximum value; when the erosion angle gradually increases from 45° to 90°, the output power of the PV module gradually decreases; and when the erosion angle is 90°, the output power of the PV module reaches

the minimum value. This is because when the erosion angle is large (especially when the erosion angle is 90°), although the erosion area of the tempered glass surface is scant when the sand particles impinge upon the surface of the tempered glass, a contingent of the sand particles appears to be irregularly rebounded, and then, with the subsequent collision of the sprayed sand particles, which will again impact on the surface of the tempered glass under conditions deviating from the original impact trajectory, this results in a larger erosion area and causes the tempered glass to produces more severe wear and tear, which is the secondary erosion of the tempered glass, ultimately culminating in PV modules with marginal output power.

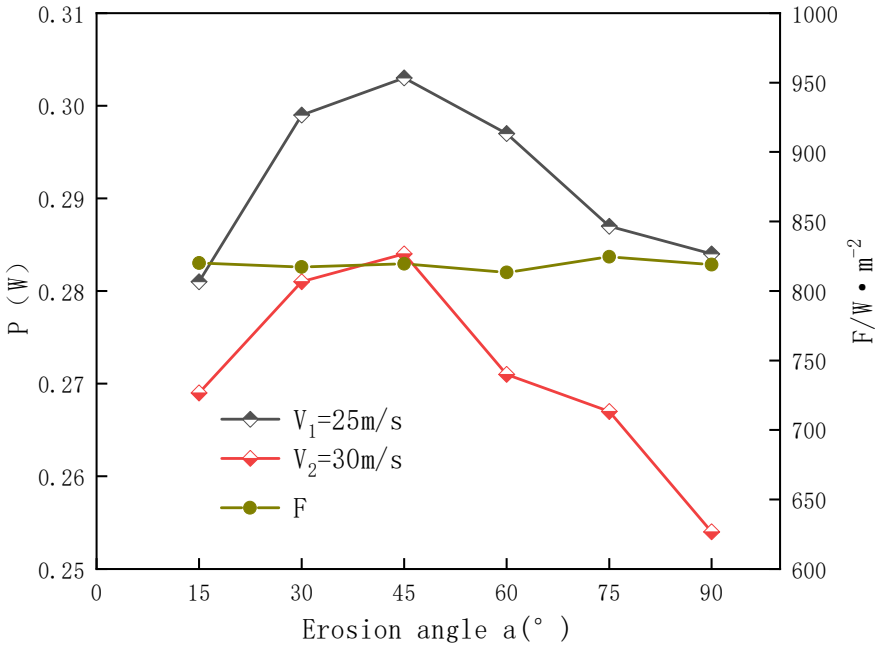


Figure 4. When the radiation intensity is constant, with the change in the erosion angle and the erosion speed, the output power of the photovoltaic module is changed.

The output power of the PV module used in this section can be determined from actual experimental measurements to be 0.362 W when it is not eroded. It can be seen in Figure 4 that when the erosion velocity is 25 m/s, in comparison with the output power of the undamaged PV module, the output power of the damaged PV module is diminished by 9.82% to 16% under varied erosion angle scenarios, with a mean diminution of 13%. Under this erosion velocity scenario, when the erosion angle is 15°, the output power of the PV module is lesser than that of the photovoltaic module when the erosion angle is 90°. This is due to the fact that when the erosion velocity is minimal, the secondary erosion triggered by the elevated erosion angle exerts a minor erosion impact on the PV module, which can even be disregarded. Furthermore, at an erosion speed of 30 m/s, the output power of the PV modules was decreased by 15.42% to 24.46%, with an average reduction of 19.39%, compared with the output power of undamaged PV modules under diverse erosion angle scenarios. Under this erosion speed scenario, the difference between the output power of the PV module and the output power of the undamaged PV module is the maximum, 24.46%, when the erosion angle is 90°.

3. Effects of Different Dust Particle Sizes on Photovoltaic Module Output Characteristics and Backplane Temperature

3.1. Experimental Setup

Desert environments are geographically more expansive and environmentally more variable, and the range of sand and dust particles deposited on the surface of photovoltaic modules in natural environments is fraught with uncertainty. The choice of laboratory

testing can better control the range of sand and dust particle sizes on the surface of PV modules and help to quantitatively analyze the effect of sand and dust particle sizes on the performance of PV modules.

Polycrystalline silicon photovoltaic modules with a rated power of 10 W were selected as the experimental equipment, and their parameters are shown in Table 2. A Fluke Norma 500 power analyzer and a PROVA 200A solar cell analyzer were used to record the changes in the various parameters of the photovoltaic modules before and after erosion, and a TP700 multi-channel data logger connected to a Pt100 thermal resistance was used to measure the temperature changes on the back of the photovoltaic modules when the surface area was sandy.

Table 2. Parameters of the solar photovoltaic modules.

Working Parameter Name	Parameters
Maximum power operating point/W	10.00
Maximum operating power point voltage/V	17.20
Maximum used operating power point current/A	0.59
Open circuit voltage/V	21.50
Short-circuit current/A	0.88
Sizes (L × W × D)/mm	340 × 280 × 17

The sand particles were selected as above, all of which were chosen from the surface near a photovoltaic power plant in the Kubuchi Desert of Inner Mongolia, far away from towns and cities, without anthropogenic influences. Because the main dust particle size is concentrated between 0.05 and 0.30 mm, seven groups of particle sizes of 0.05~0.06 mm, 0.06~0.07 mm, 0.07~0.08 mm, 0.08~0.09 mm, 0.09~0.10 mm, 0.10~0.20 mm, and 0.20~0.30 mm were therefore selected as the experimental materials by using a standard caliber separator. Seven groups of particle sizes were weighed at 2.5 g each to cover the surface of the PV modules numbered 1, 2, 3, 4, 5, 6, and 7, and the surface of PV module No. 8 was cleaned as shown in Figure 5. Eight photovoltaic modules of the same size were mounted on the bracket at regular intervals with a tilt angle of 30°. The whole experiment site was empty, without the influence of obstacles, and no human factors disturbed the experiment.

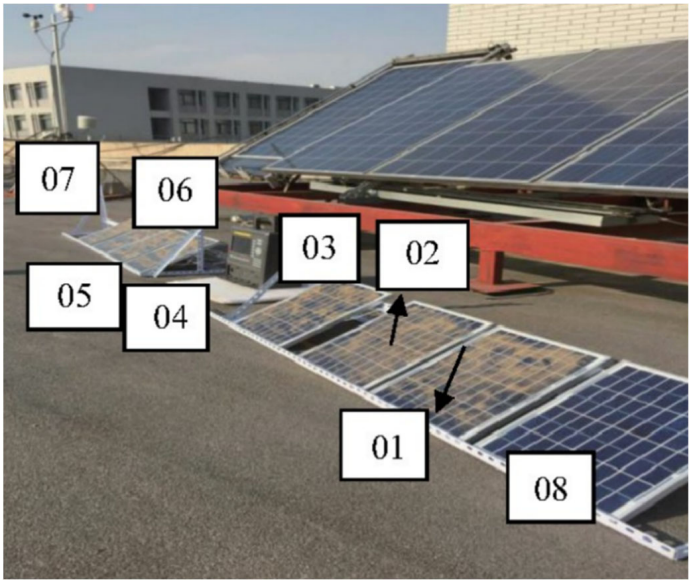


Figure 5. Photovoltaic modules covered by different dust particle sizes.

Simultaneously, in the actual experiment, the sediment quality of 0.05~0.06 mm sand particle size was less, and the difference was very small compared to the clean component, so the two groups of 0.05~0.06 mm and 0.06~0.07 mm are discussed together. The output of the PV module was measured using a solar cell analyzer. A Pt100 thermal resistor was attached to the center of the backside of the PV module, and any temperature changes on its surface caused by sand accumulation were recorded using a multi-channel data recorder. The duration of the experiment ranged from 12.5 to 16.0 h.

The wind speed on the day of the experiment is shown in Figure 6, and the ambient temperature and irradiance are shown in Figure 7. The wind speed on the day of the experiment was low, the sand and dust particles covering the surface of the PV module could not be blown up, and the temperature difference between different time periods during the experiment was relatively small, so the accuracy of the experiment was less affected.

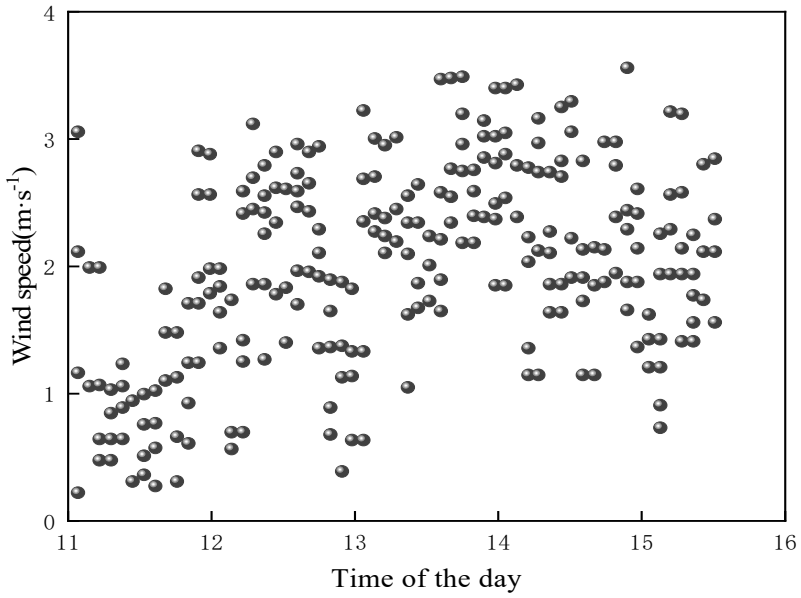


Figure 6. Wind speed scatter plot.

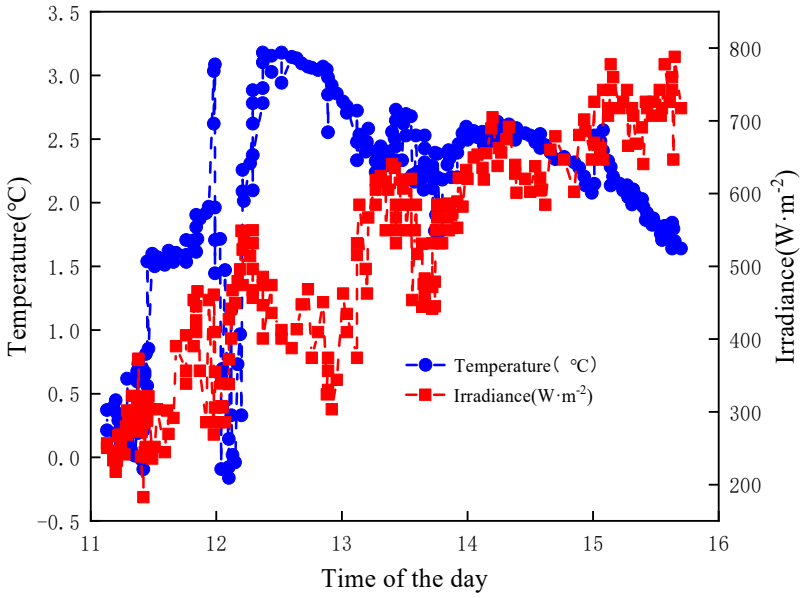


Figure 7. Changes in ambient temperature and irradiance.

3.2. Analysis of the Experimental Results

3.2.1. Influence of Different Dust Particle Sizes on Component Temperature

In the case of a fixed mass, the screened particle size is evenly spread on the surface of the module, and the temperature of the photovoltaic module backplane is measured and recorded in real-time. Figure 8 shows the change in PV module temperature over time under the same dust mass and different dust particle sizes.

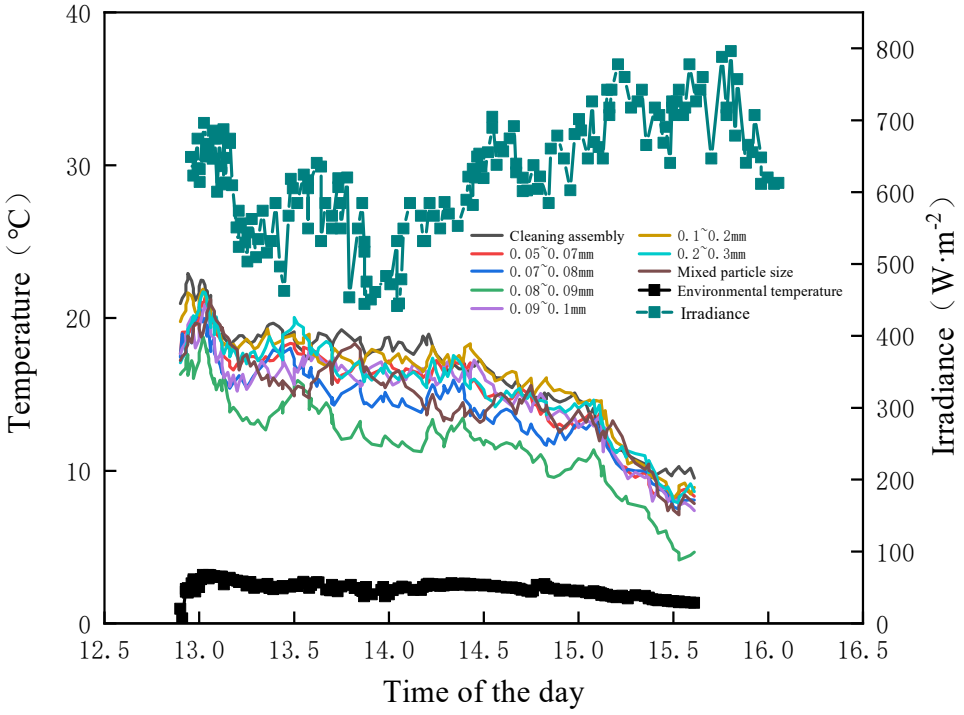


Figure 8. The temperature change of the photovoltaic modules under different dust particle size coverage.

As can be seen in Figure 8, the temperature variation of the PV module with sand accumulation is positively correlated with solar irradiance and ambient temperature. The temperatures of PV modules covered by sand and dust particles of different grain sizes are smaller than the temperatures of clean modules. This is because when the sunlight irradiates the surface of the PV module, part of the light heat is absorbed by the sand particles covering the surface of the module, and the sand dust material itself has weak thermal conductivity; weak thermal conductivity and quicksand in the desert quartz [17,21] accounted for the main components. The module's thermal conductivity is even lower, the heat absorbed by the sand particles on the surface of the module is slow to be transferred downward, and most of them are retained in the internal part of the dust particles, resulting in a rapid increase in the temperature on the surface of the sand particles. At the same time, the heat capacity of the sand and dust material itself is also low, and the ability to eliminate the temperature difference between the levels is weak [21]. When measured from the back of the module, the temperature of the sand accumulation module is lower than that of the clean module, so the accumulation of sand on the surface of the module is conducive to lowering the backplane temperature of the module, and when the particle size is 0.08~0.09 mm, the temperature of the module is significantly lower than that of the other groups of particle sizes, which will be explained in this paper with the specific explanation given in Figure 9. Figure 9 shows the temperature changes in the PV modules under the same sand quality and different particle size coverage conditions for six moments on the day of the experiment: 13, 13.5, 14, 14.5, 15, and 15.5.

From the results shown in Figure 9, it is revealed that under the circumstance of sand and dust contamination, the temperature of the photovoltaic module decreases initially and subsequently rises with the augmentation of the particle size of the sand and dust

particles. Specifically, the temperature of the module reaches its nadir when the particle size is 0.08~0.09 mm, the module's temperature ascends precipitously when the particle size fluctuates between 0.10~0.20 mm, and the magnitude of the module's temperature under a mixture of these particle sizes falls somewhere in between the two. Once sand and dust envelop the surface of a photovoltaic module, they influence the module's temperature by both obstructing solar radiation and decelerating the module's heat dissipation. Within the same sand quality, the smaller the particle size of the sand particles, the greater the number of sand particles it encompasses, and the smaller the distance between particles; as previously mentioned, with the surge in sand particles, the sand particles no longer align uniformly but exhibit an overlay or agglomeration phenomenon; thus, under the combined influence of both methods, the temperature of the photovoltaic module appears to be the lowest value [17].

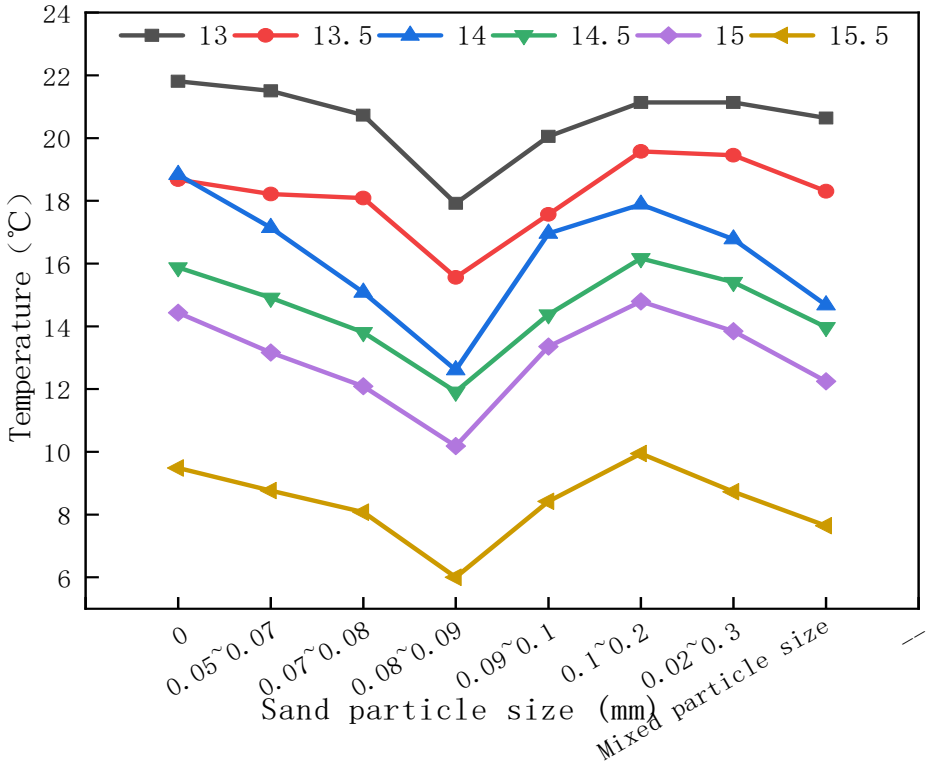


Figure 9. The temperature of photovoltaic modules varies with the particle size of dust at different times.

The accumulation of sand on the surface of solar photovoltaic modules will directly affect the temperature of the module, and the temperature in turn affects the output characteristics of the module. In essence, the performance impact of solar photovoltaic modules is generated by the joint effect of sand particle size and temperature, which belongs to the correlation relationship. In conjunction with the effect of particle size on the temperature variation of the module backplane above, the output characteristics of the module are analyzed next.

3.2.2. Effect of Different Sand Particle Sizes on the Output Performance of Photovoltaic Modules

Figure 10 shows the variation in the open-circuit voltage of PV modules four times on the day of the experiment, including 13, 13.5, 14, and 15.5, under the condition of covering the ground with different dust particle sizes of the same sand quality. It can be seen from the figure that when the particle size of the dust-covered surface of the photovoltaic module is from 0 (that is, the surface of the photovoltaic module is clean) to 0.3 mm particle size,

the open circuit voltage of the module changes little, and the maximum difference is 0.25 V and the change amplitude is about 1.2%. At the same time, the open-circuit voltage is less affected by the radiation intensity, and the open-circuit voltage changes little under different radiation intensities under the same particle size.

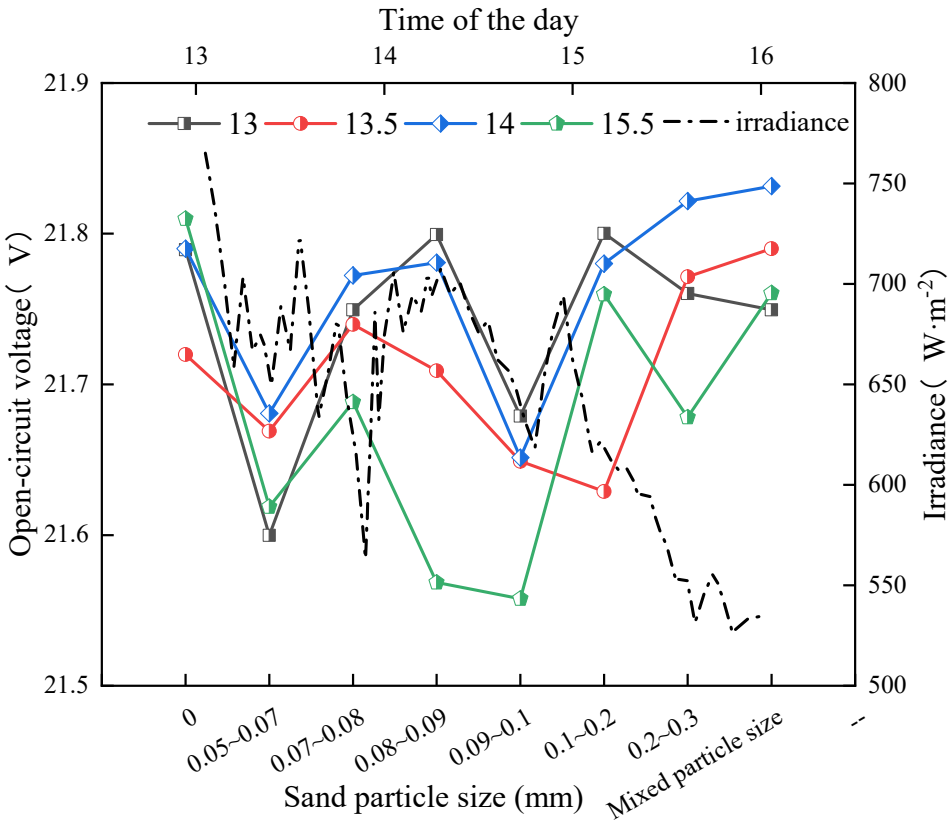


Figure 10. The open-circuit voltage of photovoltaic modules varies with the particle size of the dust particles.

Figure 11 shows the variation in the short-circuit current of PV modules under the condition of different sand particle sizes covering the ground with the same sand quality for four moments on the day of the experiment, such as 13, 13.5, 14, and 15.5. It can be seen from the figure that the short circuit current is proportional to the irradiance, and when the irradiance decreases, the short circuit current of the photovoltaic module also decreases. When the surface of the photovoltaic module is covered by 0.05~0.07 mm sand, the short-circuit current of the module drops sharply, and the decrease is about 20%. However, when the surface of the photovoltaic module is covered by other sand with different particle sizes, the short circuit current does not change significantly, and the maximum difference is about 13%, wherein the short circuit current of the component covered by the particle size of 0.05~0.07 mm is slightly lower than that of other particle sizes. This is because, under the condition of the same mass, the smaller the particle size of the dust particles in the unit area, the more dust particles there are and the larger the shielding area of the photovoltaic module [22,23], and the accumulation of sand weakens the irradiance of the incident on the surface of the module and causes the corresponding weakening of the short-circuit current. Therefore, the short circuit current of components covered by dust particles of 0.05~0.07 mm is smaller than that of components covered by other dust particles.

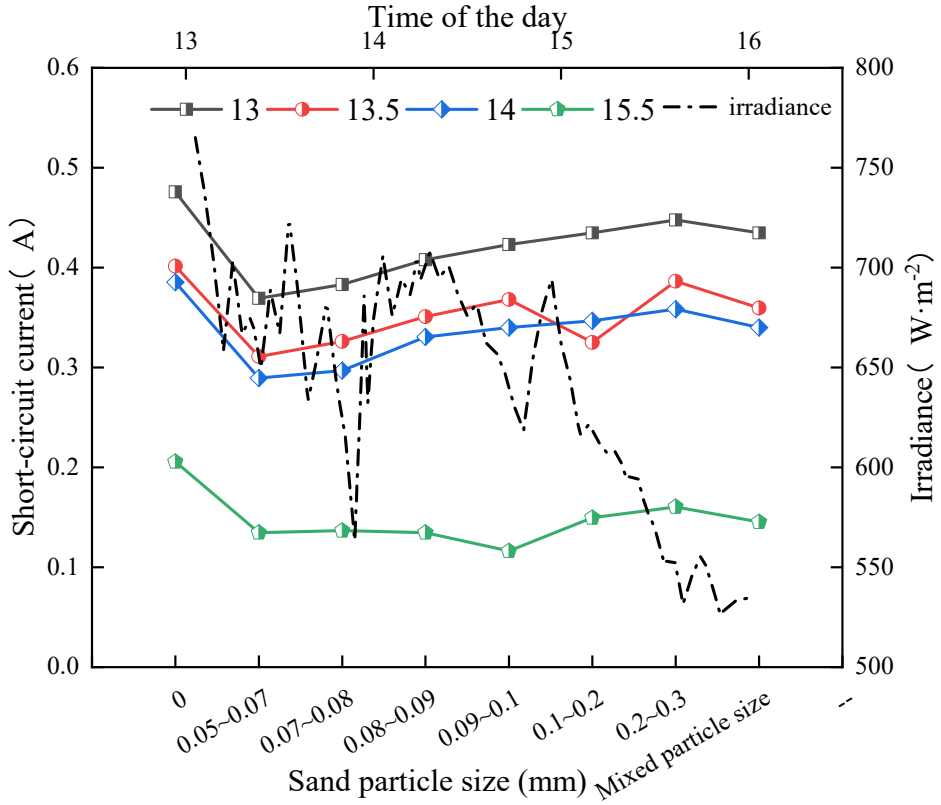


Figure 11. The short-circuit current of photovoltaic modules varies with the particle size of dust.

Figure 12 shows the variation in the output power of PV modules under the condition of covering the ground with different sand particle sizes with the same sand quality four times on the day of the experiment, including 13, 13.5, 14, and 15.5. It can be seen from the figure that the output power of the sand-deposited photovoltaic module is significantly lower than that of the clean photovoltaic module. The smaller the particle size, the greater the influence on the output power, and the maximum difference is about 17%. With the increase in the particle size of the dust, the output power of photovoltaic modules generally shows an upward trend, but the power at the mixed particle size decreases, mainly because, under the same mass bar, the smaller the particle size of dust per unit area, the more dust particles and the larger the shielding area of photovoltaic modules, and with the increase in dust particles, dust accumulation is no longer evenly distributed. Instead, there is a superposition or cluster [24], and the range of mixed particle sizes is just between 0.08 and 0.30 mm, so there is a trend of power decline. Among them, when the dust particle size increases from 0.08~0.09 mm to 0.09~0.10 mm, the output power of the photovoltaic module decreases significantly. It can be seen from previous studies that the output power of photovoltaic modules decreases with the increase in temperature, and it can be seen in Figure 9 that when the particle size ranges from 0.08~0.09 mm to 0.09~0.10 mm, the temperature increases significantly. Hence, as the dust particle size persists in increasing, although the temperature keeps ascending, the increase is modest and insufficient to have a broader influence on the output power of the component; hence, the power will persist in rising.

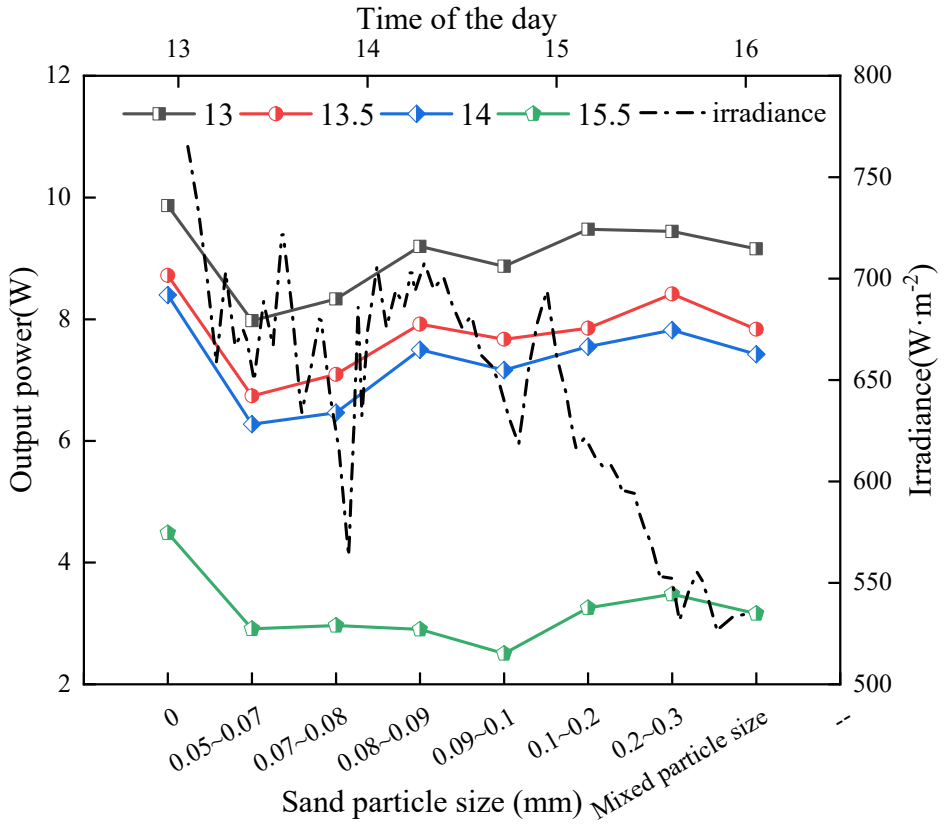


Figure 12. The output power of photovoltaic modules varies with the particle size of dust.

4. Discussion

The experimental results show that the most important factors for determining the performance of photovoltaic modules include a short-circuit current, an open-circuit voltage, and the output power. They are all affected by incident irradiance and photovoltaic module temperature, while dust accumulation affects these factors by affecting irradiance and temperature [25]. Sand on the solar photovoltaic module surface area directly affects the module temperature, and temperature is an important factor affecting module output characteristics; in essence, the performance of the solar photovoltaic module changes is produced under the joint influence of the particle size and temperature. The erosion experiments show that different erosion angles cause different forces to cause the loss of tempered glass on the surface of photovoltaic modules. The low angle is mainly caused by micro-cutting. As the angle increases, the proportion of crack superposition gradually increases.

Presently, pioneering research predominantly focuses on the erosion of solid particulates on the surface of components, such as tool steel [26] and transportation pumps [27]. Numerous scholars have examined the influence of component surface temperature on component performance [28], yet the effect of backplane temperature on component output efficiency remains underdeveloped.

Through the above work, the influence law of related erosion and dust particles on the performance of photovoltaic modules is obtained, which provides some reference for maximizing the power generation efficiency and cleaning planning of actual photovoltaic power stations. However, this paper only studies the impact of dust accumulation on the performance of photovoltaic modules in the natural environment and does not mention the corresponding solutions. For example, coatings can be sprayed on the surface of photovoltaic modules to reduce damage and power reduction caused by sand erosion, and sand particles can also slide more easily on the surface of photovoltaic modules to reduce block irradiance.

5. Conclusions

In the study in this paper, the effect of wind and sand erosion on the output efficiency of photovoltaic modules was analyzed, and the temperature change in the back sheet of solar photovoltaic modules was observed in a case covered by different sand particle sizes, and then, its effect on the output characteristics of solar photovoltaic modules was analyzed according to the different particle sizes and the change in the back sheet temperature, and the following conclusions were obtained:

When the erosion speed was 30 m/s, the erosion rate of tempered glass increased with the increase in the erosion angle; when the erosion angle was 90°, the erosion rate reached the maximum value, and this result is in line with the typical brittle material erosion law; when the erosion angle was low, the quality loss of tempered glass was mainly generated by the micro-cutting effect; with the gradual increase in the erosion angle, the quality loss of tempered glass was gradually caused by the superposition of cutting and cracking together; when the erosion angle reached 90°, the quality loss of tempered glass was mainly caused by the superposition of cracks; when the erosion velocity was 25 and 30 m/s, the output power of PV modules was reduced by 9.82%~16% and 15.42%~24.46%, respectively, under different erosion angle conditions compared with the output power of uneroded PV modules; and when the erosion speed was 30 m/s and the erosion angle was 90°, the maximum difference between the output power of the photovoltaic module and the output power of the non-eroded photovoltaic module was 24.46%.

The temperature change in the PV module is positively correlated with the ambient temperature of the solar irradiance and the surface area of the module and is beneficial to reduce the back panel temperature of the module. As the particle size of sand and dust increases, the temperature of the PV module first decreases and then increases; the temperature of the module reaches its lowest value when the particle size is 0.08~0.09 mm and the temperature of the module is the highest when the particle size is 0.01~0.20 mm. Changing the particle size of sand and dust has a small effect on the open-circuit voltage of the module, with a maximum difference of 0.25 V and a variation of about 1.2%, and the open-circuit voltage is also less affected by the intensity of radiation. The short-circuit current is directly proportional to irradiance; when the surface of the module is covered by sand and dust, the short-circuit current of the module plummets, and its maximum difference is about 13%; under the condition of the same quality, the smaller the particle size of sand and dust particles per unit area, the more sand and dust particles it hosts, and the larger the impact on the short-circuit current of photovoltaic modules. The power generation of sand-infiltrated photovoltaic modules is inferior to that of pristine photovoltaic modules, and the lesser the particle dimension, the larger the impact on the power generation, with a maximum drop of about 17%; with the increase in dust particle size, the output power of photovoltaic modules increased steadily to a stable trend.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

m_1	The mass of tempered glass before the erosion test, mg
m_2	The quality of tempered glass after erosion test, mg
Δm	The quality of tempered glass before and after the erosion test is poor, mg
m	The flow of dust particles, g/min
t	Time of the erosion experiment, min
E_0	Relative erosion rate
η	Power loss rate
P	The output power of the photovoltaic module before the erosion test, W
P_1	The output power of the photovoltaic module after the erosion test, W

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