



## Effect of Wind Speed on the Performance and Self-cleaning of PV Modules in Iraqi Desert Environment

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### ABSTRACT

Wind drives two contradicting effects on solar panels. High velocity wind induces soiling phenomena that cause dust accumulation on the surface of Photovoltaic panels and degrade solar panel performance. At the same time, high-velocity wind generates aerodynamic forces that lift fine dust particles from the surface of the panel due to resuspension phenomena, promoting the natural cleaning of the solar panels. Wind also reduces solar panel temperature through a convection mechanism, enhancing solar panel performance. Experimental and mathematical investigations were conducted to examine the conflicting effects of wind on Photovoltaic panels. The study was applied in a simulated desert environment. Natural dust with a particle size of 0.1 mm was used for the emulation. The experimental results suggested considerable power losses in the solar panel under low-speed wind conditions (less than 2 m/s). Increasing the wind velocity beyond 4 m/s resulted in a significant improvement in the solar panel's output power, demonstrating a 9-21% enhancement in output power. The major conclusion of this study is to support investors and decision-makers in determining the best operational and environmental conditions to minimize power losses in solar panels. The experimental work was conducted through controlled experimental analysis in a simulated desert environment.

**Keywords:** Soiling, PV Cleaning Mechanisms, Wind – PV Interaction

### 1. Introduction

Iraq receives approximately 3,000 sunshine hours per year, resulting in a potential solar irradiation of 2,000 kWh/m<sup>2</sup>/year [1]. The daily average solar irradiation in the desert area of Iraq ranges between 5378 and 5596 Wh/m<sup>2</sup> [2]. Therefore, implementing Photovoltaic (PV) energy conversion systems to produce electricity in Iraq is a promising approach. The efficiency of a PV cell is measured under standard test conditions: 25°C ambient temperature, 1000 W/m<sup>2</sup> irradiance, and 1.5 air mass (AM). Outdoor ambient conditions deviations from the standard test conditions result in a noticeable impact on the efficiency of the PV module. The PV cell temperature increases proportionally with the ambient temperature, causing a considerable reduction in the open-circuit voltage of the PV module. Mattei et al. [3] reported that the open-circuit voltage of a PV module decreases by 0.45% per 1°C increase. Amy de la Breteque [4] reported that the output power and energy efficiency of the PV panel decrease by 0.5% to 0.65% as the PV cell temperature increases by 1 °C. The output voltage of the PV panel is very dependent on the operating temperature. An increase in operating temperature leads to a considerable reduction in the output voltage generated by the PV module [5]. However, the temperature of a PV module decreases as wind flows over its surface. This temperature decrease is due to the cooling effect resulting from natural convective heat transfer between the wind and the surface of the PV module. Idir et al. [6] concluded that increasing the air mass flow rate passing over the surface of a PV module, from 200 g/s to 400 g/s, resulted in a considerable improvement in PV module performance due to lowering the temperature of the PV surface. The cell temperature has a significant impact on the performance of PV modules [7]. Mani and Pillai [8] demonstrated that wind movement impacts PV module efficiency by affecting the



accumulation or cleaning of dust from the PV surfaces. Wind currents have been shown to reduce the operating temperature of PV modules by removing part of the surface heat through convective heat transfer. Both the voltage and efficiency of PV modules decrease with increasing temperature.

Increasing the cell temperature by 1 °C results in a 0.35% reduction of the power output of the PV panel [9]. The cell temperature of PV modules is strongly dependent on wind speed rather than wind direction [10]. The PV module's operating temperature directly drops with an increase in wind speed, producing high-efficiency electricity. Although high-speed wind is favorable for reducing the temperature of PV cells, it also causes soiling phenomena, especially in desert environments. The wind-driven emission, transport, and deposition of sand and dust are collectively referred to as Aeolian processes [11], which primarily occur in deserts. The transport of particles by wind depends on particle size and wind speed [12]. Sand and dust particles with diameters of  $\sim 100 \mu\text{m}$  are typically lifted and moved by fluid drag [13]. Figure 1 illustrates the wind effect on the Saltation of sand and dust particles.

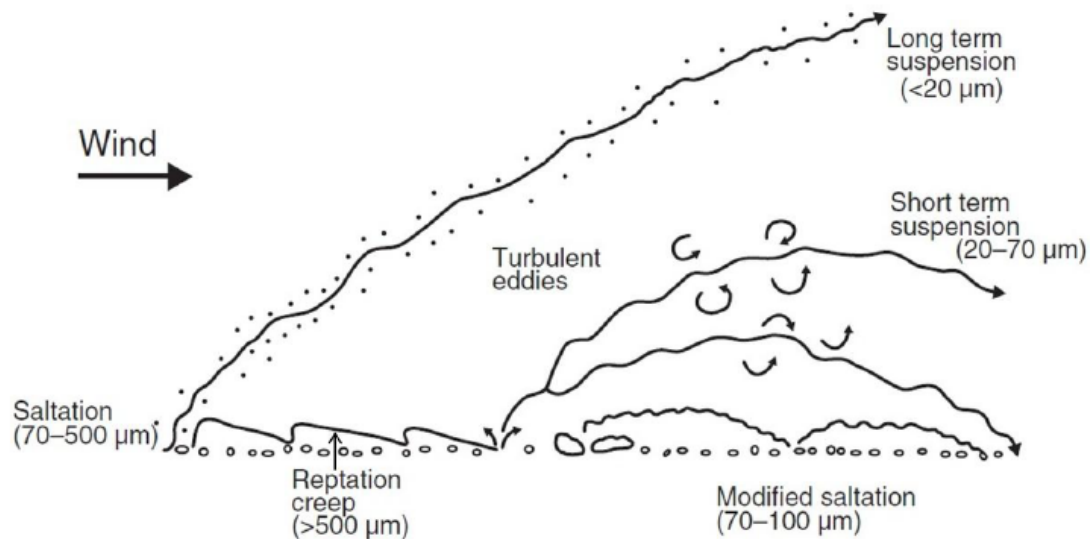


Figure 1. Schematic of the different modes of Aeolian transport. Adopted from Nickling and McKenna Neuman (2009) [14].

Suspension of dust particles of 20-70  $\mu\text{m}$  diameter takes place because of the turbulent fluctuations of the wind [15, 16]. Saltation is initiated when the wind stress  $\lambda$  is sufficient to lift surface particles from the ground.

( $\lambda \sim 0.05 \text{ N/m}^2$ ) into the fluid stream [17]. Figure 2 demonstrates the forces acting on a dust particle when wind passes by it.

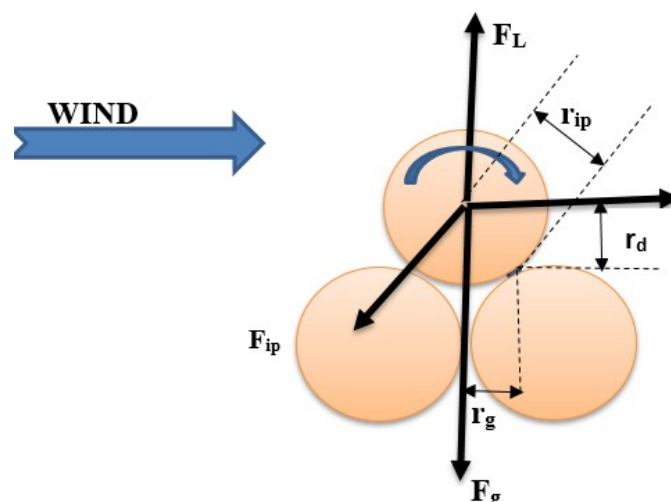


Figure 2. Schematic representation of the force balance of a dust particle resting on a bed of other particles [18].  $F_L$  and  $F_D$  are lift and drag forces.  $F_{ip}$  is the interparticle force.  $F_g$  is the gravitational force.  $r_{ip}$ ,  $r_d$ , and  $r_g$  are moment arms.

There are three different types of dust particles: fine, coarse, and giant particle categories [19, 20]. Fine particles are dust particles with  $D \leq 2 \mu\text{m}$ , coarse particles are particles with  $D$  between  $2 - 20 \mu\text{m}$ , and the giant particles are particles with  $D \geq 20 \mu\text{m}$  [21].

To study the dust-related effects on the performance of PV modules as a function of wind speed, atmospheric dust models are used to simulate the dust cycle [22, 23, 24]. For dust particles with diameters of up to  $70 \mu\text{m}$ , the Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model was adopted by Ginoux (2003) [25]. The results of applying the model revealed that the settling velocity significantly decreased when the aspect ratio was equal to or greater than 5.

Maring et al. [26] applied a simple empirical model and suggested that an upward velocity of  $0.33 \text{ cm/s}$  is necessary to predict particle size distribution changes during transport accurately.

Schwingschackl et al. [27] studied known models for assessing the PV cell temperature relying on solar irradiation, air temperature, and wind speed. They found that wind is a significant factor in predicting PV cell temperatures. Mekhilef et al. [28] investigated the impact of humidity, dust, and wind speed on the energy efficiency of solar cells. They reported that as wind velocity increases, module temperature decreases due to the increased heat absorbed by the PV panel surfaces, thereby enhancing cell efficiency. The temperature of the cell varies linearly with air temperature and inversely with wind speed. Israa et al. [29] successfully modeled the effect of dust and wind on solar panel performance in Iraq.

Wind speed has been proven to be the primary atmospheric parameter affecting the performance and soiling of PV modules. Therefore, this research focuses on the effect of wind velocity on the temperature of PV cells and also determines the impact of wind velocity on the surface dust coverage fraction of the PV surface, which directly affects the performance of the PV module. The study is based on comparing the obtained results with those of other works. Additionally, a comparison is presented between the effects of zero-velocity wind and variable-velocity wind on the performance of PV modules. Therefore, the objective of this research is to explicitly quantify the dual impact of wind velocity on PV cooling and dust soiling/cleaning, and to test the hypothesis that higher wind speeds (above  $4 \text{ m/s}$ ) enhance PV performance through both natural cooling and dust resuspension.

## 2. Methodology and experimental setup

Wind has three significant effects on the performance of PV modules:

- Wind velocity effect on the cooling of PV modules via convective heat transfer between the PV surface and the ambient, which results in a PV cell temperature reduction. This temperature reduction will significantly enhance the performance of the PV module.
- Wind velocity effect on the self-cleaning of a PV module through the saltation mechanism and lifting surface particles into the air stream to enhance the performance of the PV module.
- Wind velocity effect on the soiling of PV modules through the Aeolian process, which is termed as surface dust coverage fraction. The surface dust coverage fraction will negatively impact the performance of the PV module.

As a significant conclusion, wind speed has two positive impacts and one negative impact on the performance of PV modules.

### 2.1. Setup Description

Two types of solar modules (monocrystalline and polycrystalline) were used to investigate the effect of wind speed on the output power of the three inclined PV modules partially covered with natural dust. Table 1 demonstrates the characteristics of the three solar modules.

Table 1. General Characteristics of Lab-scale Monocrystalline and Polycrystalline PV Modules

No.	Characteristics	Monocrystalline Silicon panel	Polycrystalline Silicon panel
1	Model	Copex Solar SFM-20	Copex Solar SFPVP-20
2	Max Power (w)	20	20
3	Tolerance	$\pm 3\%$	$\pm 3\%$
4	Voltage (V)	18	18
5	Current (A)	1.11	1.11
6	Open Circuit Voltage (V)	21.6	21.6

7	Short Circuit Current (A)	1.22	1.22
8	Weight (kg)	1.9	2
9	Dimensions (mm)	645x285x18	645x285x18

The experimental setup was installed on the roof of a building located at the boundary of the University of Al-Qadisiyah's campus in Ad Diwaniyah, Iraq. The setup consists of;

- An adjustable solar panel mount that allows for vast changes in tilt (inclination) angle. The mount is flexible, allowing for manual adjustment of the solar panel's angle of inclination. A 0-90-degree protractor governs the tilt angle of the solar panel.
- Two types of PV panels. Type 1; Copex Solar SFPVP-20 polycrystalline panel of 20-watt power output, Type 2; Copex Solar SFM-20 monocrystalline panel of 20-watt power output,
- Arduino card of 16 MHZ processor, 2KB SRAM& 32KB FLASH memory, 14 digital I/O, and six analog I/O. The Arduino card is equipped with voltage and current sensors.
- Solar radiation intensity measuring device (solar power meter; Model: SM206-SOLAR).
- Air fan-controlled air flow generator.
- Digital Anemometer.
- Laptop with A/D interfaces and software.
- Electrical and data connections.

The measurements were performed under variable wind velocity (2, 4, and 6 m/s). The wind velocity was manipulated through a controlled airflow generator. To ensure a uniform layer of dust on the PV panels, natural desert dust was sieved evenly across the module surfaces. The mass of deposited dust (e.g., 12 g, 24 g) was verified by weighing the panels before and after application by using two different weights, we can study how negative impact on light absorption and cell efficiency increases with increasing dust accumulation, create a comparative analysis the first weight (12 g) represents light or medium accumulation, the second weight (24 g) represents heavier accumulation. To achieve even dust distribution, raise the baby powder sprinkler we used to distribute the dust a short distance from the board (40-50 cm). Use a visual or grid-like motion (right-left, then up-down). Care was taken to distribute the particles uniformly across the surface to maintain methodological consistency.

## 2.2 Models and calculations

Models for Wind-related PV cooling via Convective heat removal and PV surface dust coverage fraction through soiling and Saltation were adopted to investigate the effect of the wind velocity on the performance of PV modules.

### 2.2.1 Wind-related cooling of PV module

Idir et al. [6] developed a model to determine the temperature reduction of PV cells under the effect of wind speed. The model is based on the thermal balance for the PV cells (silicon).

$$Q_{si} = \alpha_{si} \tau_g R_G / e_{si} \quad (1)$$

Where  $Q_{is}$  is the heat rising (source) of silicon,  $\alpha_{is}$  is the absorption coefficient of silicon (1.175),  $\tau_g$  is the transmissivity of glass (0.9),  $R_G$  is the solar radiation (1000 W/m<sup>2</sup>), and  $e_{si}$  is the thickness of the silicon cell layer (0.3mm).

$$\nabla T + Q_{is} / \lambda_{is} = 0 \quad (2)$$

Where;  $\nabla T$  is the temperature gradient, and  $\lambda_{si}$  is the thermal conductivity of silicon (148 W/m.K).

Having determined the temperature gradient, convective heat transfer can be calculated using Newton's Law of Cooling.

$$Q = h.A.\nabla T \quad (3)$$

Where;  $Q$  is heat dissipated by convection,  $h$  is the convective heat transfer coefficient, and  $A$  is the area of PV module.

It was found that the convective heat transfer coefficient is strongly dependent on wind speed.

$$h = 12.12 - 1.16W + 11.6\sqrt{W} \quad (4)$$

Where;  $W$  is the wind speed (m/s)

Having determined the convective heat transfer coefficient  $h$  as a function of wind speed, we can calculate  $\nabla T$  for each case and determine the enhancement of the PV power. Equation 5 estimates the effect of the temperature drop of the PV cells on the output power of the PV module.

$$P = P_{STC} + P_{Temp-Coeff} (T_{Cell} - 25)C^0 \quad (5)$$

Where;  $P$  is the output power of the PV module,  $P_{STC}$  is the output power of the PV module at standard conditions,  $P_{Temp-Coeff}$  is the temperature coefficient of power (- 0.3% /  $C^0$ ) to (-0.5% /  $C^0$ ),  $T_{Cell}$  is the cells temperature.

### 2.2.2 Wind-related soiling and surface dust coverage fraction

Israa et al. [29] had developed a model to determine the PV surface dust coverage fraction under wind speed conditions. The model has been validated through an extensive experimental program. Their experiments reflected the strong relationship between the rate of dust particle deposition due to the soiling effect and the rate of dust removal (surface cleaning) due to wind-related suspension and Aeolian phenomena. Equation 6 determines the surface dust coverage fraction of PV modules under deterministic and stochastic parameters.

$$\varepsilon = \frac{1}{-(F_R + F_S)} e^{-(F_R + F_S)t} - \frac{F_R}{-(F_R + F_S)} \quad (6)$$

Where;  $\varepsilon$  is the surface dust coverage fraction,  $F_R$  is the retarding force that holds the dust particle on the surface of the tilted PV module under wind effect, and  $F_S$  is the slipping force exerted on the dust particle on the surface of the PV module to drag it downwards.

It was found that the surface dust coverage fraction is strongly dependent on the tilt angle of the PV module, the size of dust particles, and wind speed. However, as the dust particle size decreases, wind becomes the primary influencer parameter.

## 3. Results and discussions

### 3.1 Effect of the wind speed on the cooling and performance of PV modules

Figure 3 clearly shows the impact of wind velocity on the quantity of heat extracted from the surface of two types of PV modules (monocrystalline and polycrystalline modules). Both PV modules have a surface area of 645 x 285 mm. Increasing the wind speed from 2 m/s to 6 m/s resulted in a 28.5% increase in dissipated heat from the surface of the PV modules. This agrees with the conclusion of [6].

The heat dissipation with the increase in wind speed passing over the surface of the PV modules was reflected in a considerable temperature drop of the PV cells, bringing the temperature closer to ambient temperature and enhancing the performance of the PV module by raising the output power. Figure 4 demonstrates the relationship between the heat dissipated and the temperature difference between the PV cells' temperature and the ambient temperature. Figure 4 shows a 21% temperature drop of the PV cells when the wind velocity increased from 2 m/s to 6 m/s. This resulted in a significant improvement and enhancement of the PV module's performance, as shown in Figure 5, which describes how increasing wind speed from 2 m/s to 6 m/s led to a 13% increase in output power. This is well agreed with the conclusions of [30]. Ahmed et al. [30] carried out an extensive

experimental program to investigate the effect of environmental parameters on the performance of PV modules, reporting that PV efficiency increases to approximately 14.8% - 16.5% at a wind velocity of 5 m/s. The wind acts as a natural cooling mechanism, removing dust and thus decreasing cell temperature. Error bars representing the standard

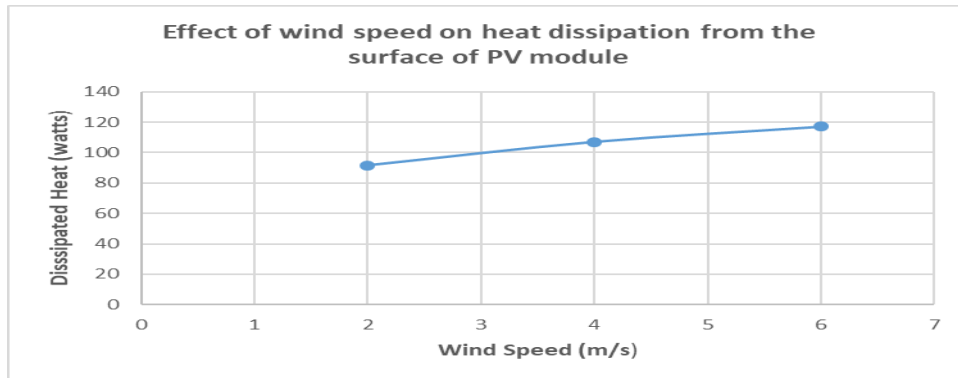


Figure 3. Wind-related Dissipated Heat from The Surface of the PV Module

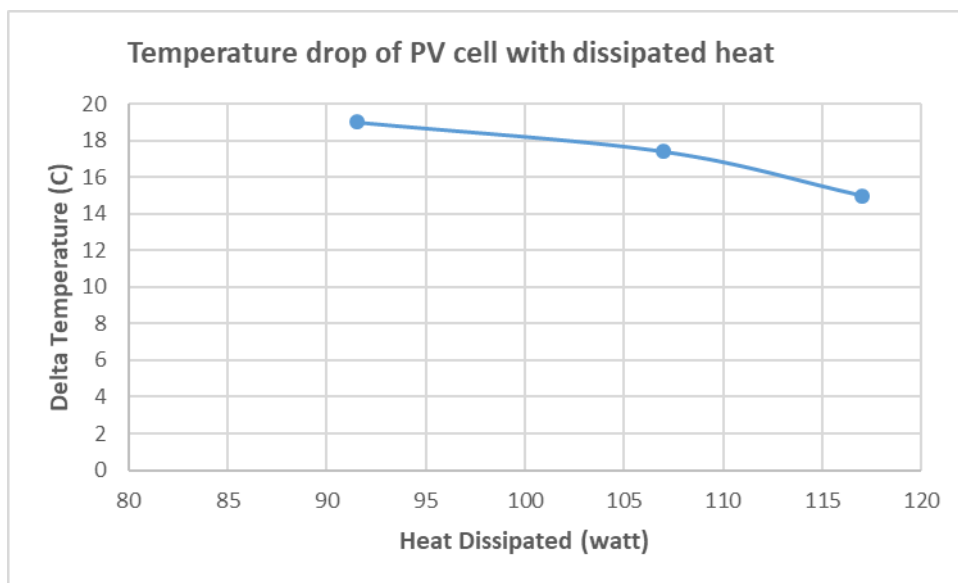


Figure 4. Relationship between Heat Dissipation from PV Surface and the Temperature of PV Cells

Deviation from repeated trials is recommended for future work to strengthen statistical confidence. In this study, limited repetitions were conducted, which is acknowledged as a limitation.

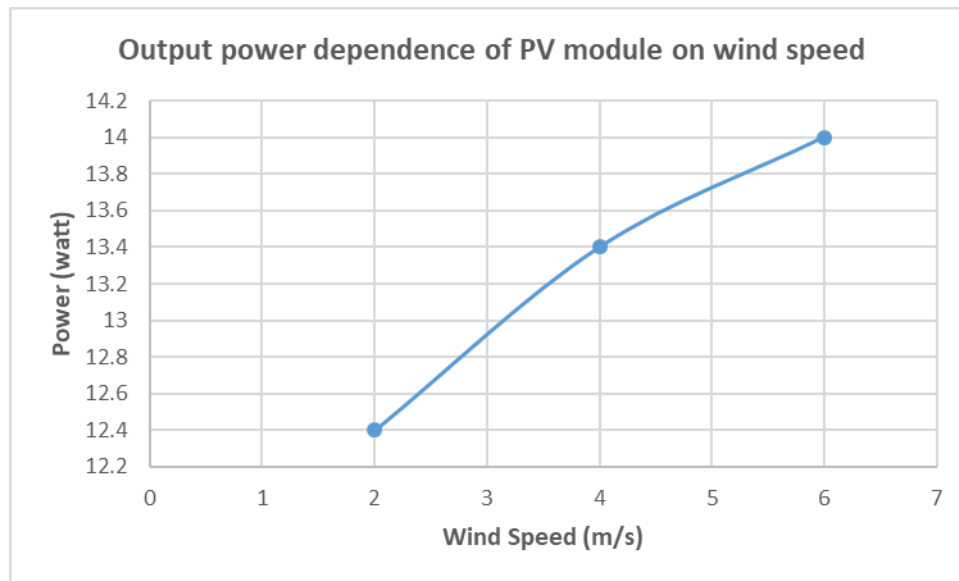


Figure 5. Effect of Wind Speed on PV Output Power

### 3.2 Effect of wind velocity on PV soiling and surface dust coverage fraction

The combined effect of wind on PV soiling and PV surface cleaning was successfully represented by Equation 6, where wind velocity was shown to have a significant impact on fine particles. Figure 6 shows that higher wind velocities can suspend fine dust particles despite the interparticle forces between the dust particles. This effectively reduces the PV surface dust coverage fraction. When the coverage fraction is reduced, the performance of the PV module improves, resulting in higher PV power output. Increasing the wind velocity from 2 m/s to 6 m/s resulted in a 22% drop in PV surface dust coverage fraction and increased the portion of the PV surface that is exposed to solar irradiation. The higher the exposed area of the PV surface to solar irradiance, the higher the output power, as shown in Figure 7.

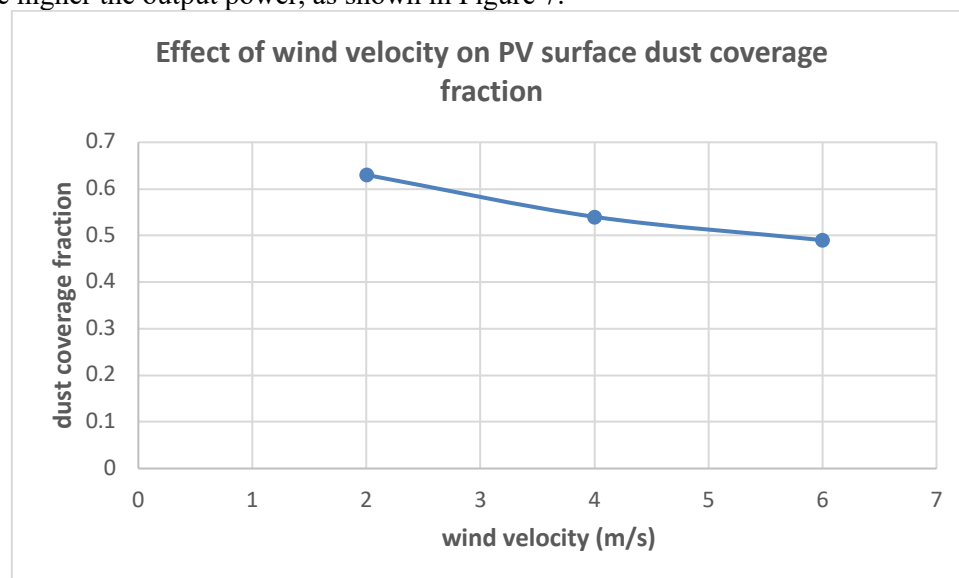


Figure 6. Effect of Wind Speed on Dust Accumulation and Surface Dust Coverage Fraction of PV Module

Figure 7 demonstrates a considerable improvement in two types of PV modules (monocrystalline and polycrystalline) in response to the effect of the wind speed on the PV surface dust coverage fraction. Both types of photovoltaic modules (monocrystalline and polycrystalline) exhibited a proportional increase in output power with increasing wind velocity. Still, the monocrystalline PV module outperformed the polycrystalline PV module. The superior performance of monocrystalline modules compared to polycrystalline modules under dusty conditions can be attributed to differences in surface texture, reflectivity, and anti-reflective coating properties, which reduce adequate dust adhesion and allow for more light transmission. The advantage of mono

in terms of reflective surface is that it enables precise processing, which reduces reflection and enhances light absorption, one of the main reasons behind its higher efficiency compared to poly.

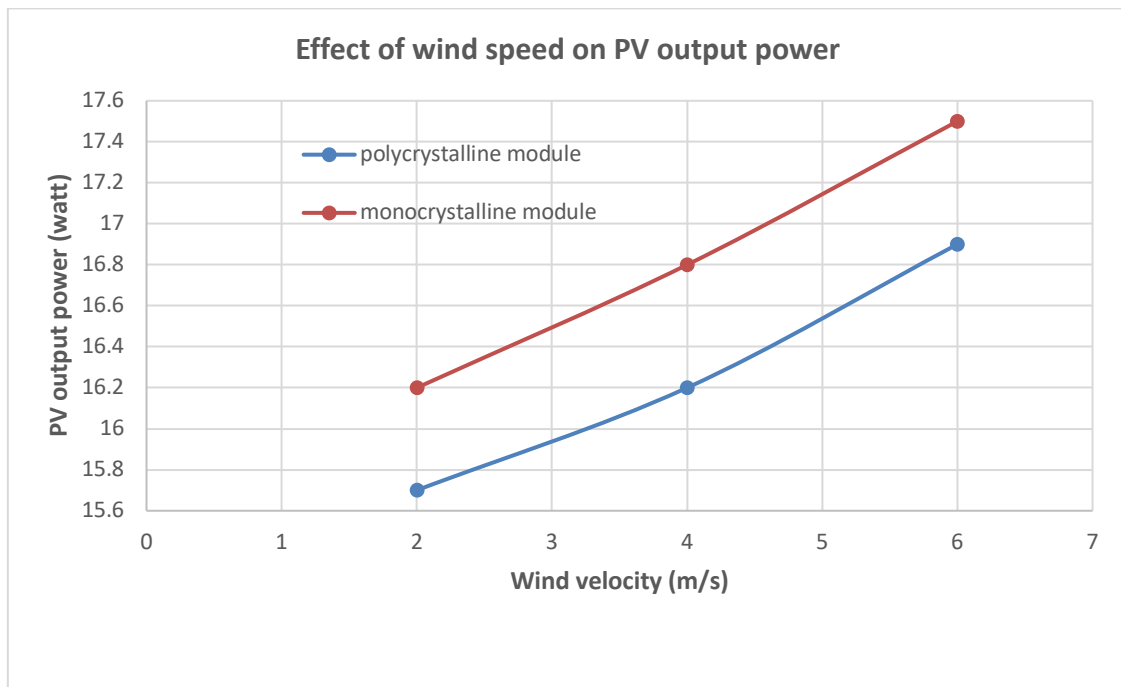


Figure 7. Effect of Wind Velocity on Monocrystalline and Polycrystalline PV Output Power Under Dust Conditions

### 3.3 Comparison between PV performances under Zero and 6 m/s wind velocities

A comparison study was conducted to assess the effect of varying mass densities of accumulated dust on the performance of a monocrystalline PV module under both zero and 6 m/s wind velocities. The results revealed that unpolluted PV modules exhibited similar performance to a monocrystalline PV module under two different wind velocities at standard ambient temperature. The performance of the PV module drastically declined when dust particles were uniformly spread over its surface under zero wind velocity. However, when the PV module was exposed to a 6 m/s wind velocity, its performance was considerably enhanced. Table 2 demonstrates about 9 – 21% efficiency improvement of a monocrystalline PV module when 6 m/s wind passes by its surface, causing air-lifted particles to be suspended and removed from the surface of the PV module.

Table 2. Comparison of the Effect of Zero and 6 m/s Wind Velocity on the Performance of a Lab-scale Monocrystalline PV Module

No	Dust Particle Size (µm)	Mass of Dust Deposited (gm)	Layer Thickness (µm)	VOC (V)		ISC (A)		P <sub>max</sub> (watt)		Normalized Output Power%	
				0 m/s Wind Speed	6 m/s Wind Speed	0 m/s Wind Speed	6 m/s Wind Speed	0 m/s Wind Speed	6 m/s Wind Speed	0 m/s Wind Speed	6 m/s Wind Speed
1	≤ 100	0	0	17.83	17.84	1.25	1.24	22.28	22.28	100	100
2	≤ 100	12	0.237	10.26	11.84	1.24	1.25	12.72	14.8	57	66
3	≤ 100	24	0.574	5.34	9.2	1.25	1.24	6.67	11.4	30	51

#### 4. Conclusion

The effect of wind velocity on the performance of PV modules was investigated. The wind has two contradicting impacts on the performance of the PV module. The higher the wind velocity, the larger the effect on the performance of the PV modules. High wind velocity induces higher PV surface soiling and causes a significant drop in PV power due to heavy dust deposition on their surfaces. However, high wind velocities can air-lift small particle-size dust (less than 100  $\mu\text{m}$ ). The higher the wind speed, the higher the self-cleaning efficiency of PV modules. Therefore, better PV performance was achieved when its polluted surface was exposed to wind.

Additionally, it has been proven that high-velocity winds can cause cooling of the PV cells, which is strongly reflected in the efficiency of the PV module. Therefore, winds can enhance the performance of PV modules, while also bringing dust particles to deposit on their surface via soiling phenomena. A performance improvement of up to 21% was achieved during the course of this research.

#### Declaration of Competing Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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#### Author Contributions

All authors contributed to the conception and design of the research problem. Israa Amer Dahham collected and organized recent related works. Muhammad Ammirul Atiqi Mohd Zainuri and Ali Abdulabbas Abdullah verified the recommendations in the proposed framework. Mohd Faizal Fauzand contributed to the design and formulation of the proposed approach. Qais Hamid Jeflawe provided detailed discussions and critical analysis of the proposed design. All authors participated in reviewing the results and approved the final version of the manuscript.

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