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Revealing the Hidden Benefits of Dust for Photovoltaic Performance in Hot Climates

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Abstract

This study investigates the combined impact of temperature and dust on the performance of a photovoltaic (PV) system. The investigation took place during the summer of 2022 in Baghdad (33.28°N, 44.39°E), known for its extremely high temperatures. Two distinct scenarios were examined: a dusty day and a dusty panel (typically occurring after a dusty day). The research initially compared the performance of clean and dusty PV modules under severe summer conditions and later extended its analysis to the on-grid PV system of the Renewable Energy and Environment Research Center building. The results reveal that temperature predominantly reduces voltage, while dust primarily diminishes current. However, during dust storms, temperatures significantly drop below their average, potentially leading to an increase in PV output. This creates a dual effect where the negative impact of temperature is partially offset by dust because dust mitigates the ambient temperature, resulting in a relatively smaller decrease in PV output. This phenomenon is most pronounced at high temperatures. For instance, the loss ratio for a clean module was 24%, whereas for a dusty module, it was 6%, highlighting this beneficial impact of dust. However, at low and moderate temperatures, dust continues to have a detrimental effect. This finding is significant for optimizing PV system efficiency in similar environmental contexts.

1. Introduction

Single-crystal silicon solar cell technology stands as the most established, constituting approximately 90% of total PV shipments (>90 GWP in 2016) [1]. Despite the 64 years that have transpired since the inaugural demonstration of the first silicon solar cell [2], extensive research on this device persists to the present day [3–6]. The thermodynamic limit, known as the Shockley limit, constrains the output power per unit area for p-n junction silicon solar cells. The monojunction silicon cell faces a fundamental limitation with a maximum efficiency capped at ~29% [7]. This restriction stems from unabsorbed photons with energy less than the silicon bandgap and/or phonon loss due to the absorption of photons with energy higher than the silicon bandgap.

The performance of PV systems, typically gauged by the performance ratio (PR) [8], is further restricted by environmental conditions, notably high temperatures, dust, and irradiance. Elevated panel temperatures result in a substantial PR drop of up to 37%, especially in hot climate locations such as Baghdad, which may reach to 80°C. Conversely, severe dust storms can reduce irradiance by up to 40%, leading to a corresponding 40% reduction in PR due to the linear relationship between irradiance and PR [9]. However, dust storms also coincide with a noticeable decline in environmental temperature, sometimes reaching a drop of 8ºC [10]. This temperature drop, in turn, elevates the PR, representing a positive effect of dust. This effect can be particularly significant in extremely hot climates, such as that in Iraq.

The thrust of this work is to investigate the dual impact of dust storms and accumulated dust on PV panels from two perspectives: (i) the reduction in PR due to decreased irradiance reaching the panel and (ii) the increase in PR due to the decline in environmental temperature. Therefore, this research aims to identifying the equilibrium point where dust can be somewhat beneficial, leading to an increase in PR due to the dual interaction.

2. Theoretical Analysis

Iraq experiences some of the highest temperatures globally [11]. The average daily temperature for a specific month is calculated by summing up the hourly temperatures (in Celsius) during the daylight hours of each day, dividing this sum by the total number of daylight hours in that day, and then averaging these daily averages over the entire month. Typically, the PV temperature surpasses the ambient temperature, given that silicon panels absorb over 95% of solar radiation. Table (1) illustrates the average temperatures in Baghdad for each month in 2019, alongside the corresponding PV surface temperatures. The table further outlines the decline in power with temperature for a selected PV panel (250W at STC). It is evident from the table that temperature exerts a substantial impact on PV productivity. For instance, at an average temperature of 14.54ºC, the panel's power is 230W, constituting a 10% reduction compared to the STC nominal power.

Table (1): Monthly Variation in Average Temperatures and Photovoltaic Panel Performance Metrics.

Month	Average Temperature (ºC)	Average PV Panel Temperature (ºC)	Power Drop for a 250W Panel
January	14.54	26.45	230.093
February	16.76	31.21	226.332
March	21.58	36.53	223.181
April	28.43	42.12	220.6735
May	34.61	49.31	216.2645
June	38.97	55.19	212.3465
July	41.71	57.17	211.5995
August	41.40	57.88	210.75
September	37.82	53.28	213.739
October	31.70	44.88	219.385
November	22.82	34.23	226.039
December	16.22	27.37	229.929

Basically, the drop in PV module power with the temperature increase of the PV front surface is approximately given by the following equation [12]:

$$\textbf{Power Drop} = (T - 25) \times \textbf{Temp. Coeff.} \quad \text{...... (1)}$$

where: Temp. Coeff. is the temperature coefficient of the PV module (–0.50%/°C for the panels used in this study as appears in the datasheet), T is the surface temperature of the PV module at a certain ambient temperature. T can be approximately estimated using the well-known Homer method [13]. To calculate PV panel’s surface temperature at a certain ambient temperature, two factors have to be calculated for a particular panel (A & B):

$$A = (NOCT - 20)/R \quad \text{......... (2)}$$

$$\mathbf{B = 1 - (PCE/0.9)} \text{ .... (3)}$$

where: NOCT is panel's operating temperature (50 °C in our panels), 20 is the ideal pn junction temperature, R is the measured solar radiation, PCE is the power conversion efficiency of the panel, and 0.9 is a constant related to the semiconductor type. If the radiation is 0.8kW/m^2 and PCE is 13%, for an example, then factor A = (50 – 20)/0.8 = 37.5, and factor B = 1 – (0.13/0.9) = 0.85. The PV panel's surface temperature is [14]:

$$\textbf{Panel Temp. (T) = Ambient Temp + (Radiation} \times \textbf{A} \times \textbf{B)} \text{ .... (4)}$$

$$T = 50 + (0.8 \times 37.5 \times 0.85) = 89.15\ °C$$

The power drop due to PV surface temperature is calculated from the Eq. (1) mentioned elsewhere is:

$$\text{Power drop} = (89.15 - 25) \times (-0.5\%/°C) = -32\%.$$

For a PV panel of 250W power, the actual power at 50°C ambient temperature will be 170W. Therefore, for a PV system comprising of 540 panels, the power will drop from 135kW to 91kW.

Indeed, temperature exerts a significant impact on PV performance, resulting in a considerable 32% loss in power at an ambient temperature of 50°C. It's worth noting that Iraq experiences severe summer weather, particularly in the southern and central regions, with temperatures exceeding 50°C on some days in July and August.

The influence of dust on a PV panel's performance is akin to the impact on irradiance since dust effectively diminishes irradiance. Therefore, when discussing the effect of dust on PV panel performance, it is appropriate to consider the effect on radiation density. Figure (1) illustrates the effect of radiation on a 300W PV module, as derived from simulation using the PVSyst program [15]. As depicted in the figure, voltage is marginally affected by irradiance, while current experiences a significant impact. Consequently, the overall power decreases due to the concurrent decrease in current with irradiance. Conversely, in high temperatures, voltage is more affected than current.

Burech's equation [16] that was developed from Shockley model of the diode can be used to investigate the impact of irradiance and temperature on V_{OC} and J_{SC}:

$$\mathbf{I_{SC} = [I_{SCr} + K_I(T_{Panel} - T_r)]\frac{G}{G_r}} \text{ .... (5)}$$

$$\mathbf{V_{OC} = V_{OCr} + K_V(T_{Panel} - T_r)} \text{ .... (6)}$$

where: T_r is the standard ambient temperature (25ºC), T_{Panel} is the actual panel's temperature, I_{SCr} & V_{OCr} are short circuit current and open circuit voltage at the standard conditions (1000W/m^2, temp. 25°C) respectively, K_I & K_V are the I_{SC} & V_{OC} temperature coefficients respectively, G_r is the standard irradiance (1000W/m^2), and G is the actual irradiance. Equation (5) shows that I_{SC} is a temperature and irradiance dependent parameter where it obeys a direct relationship with T and G. V_{OC} shows no dependence on irradiance and it is linearly proportional to temperature only as expressed in Equation (6). V_{OC} arising from the built-in potential at the junction which in turn is a function of doping concentration and the junction properties in which irradiance has no influence on these parameters. Basically, increasing temperature reduces the band gap of the silicon according to Varshni's empirical equation [16] (Equation 7) which results in an increase in the saturation current (so-called leakage current) according to Shockley's model (Equation 8) [17]:

$$\mathbf{E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}} \text{ .... (7)}$$

$$\mathbf{I_S = AT^3 \exp\left(-\frac{E_g}{nkT}\right)} \text{ .... (8)}$$

where: E_g is the silicon bandgap at the given temperature, $E_g(0)$ is the silicon band gap at zero Kelvin, α & β are fitting parameters characterized by the material, I_S is the saturation current (leakage current), A is Shockley constant of silicon, n is the ideality factor of the diode, k is Boltzmann constant, and T is temperature in Kelvin. The V_{OC} is correlated logarithmically with I_S by the following equation [17]:

$$V_{OC} = \frac{kT}{q} \ln\left[\frac{I_{SC}}{I_S}\right] \quad .... (9)$$

As discussed earlier, the combined impact of temperature and dust can result in a dual effect by reducing both voltage and current in PV systems. However, in real-world scenarios, this interaction may not unfold precisely as predicted. When considering the potential reduction in temperature due to the presence of dust, it becomes plausible that dust might mitigate the adverse effects of high temperatures, potentially averting a significant drop in power. This hypothesis gains particular relevance in regions experiencing extremely hot weather, such as Iraq in the summer. Given the frequent occurrence of dust storms in the last decade, the interplay between dust and temperature may indeed present a moderating influence. This could result in a more nuanced and less severe decline in power than initially predicted. Ongoing research and observations in such environments are crucial to refining our understanding of these complex interactions and their practical implications for PV system performance.

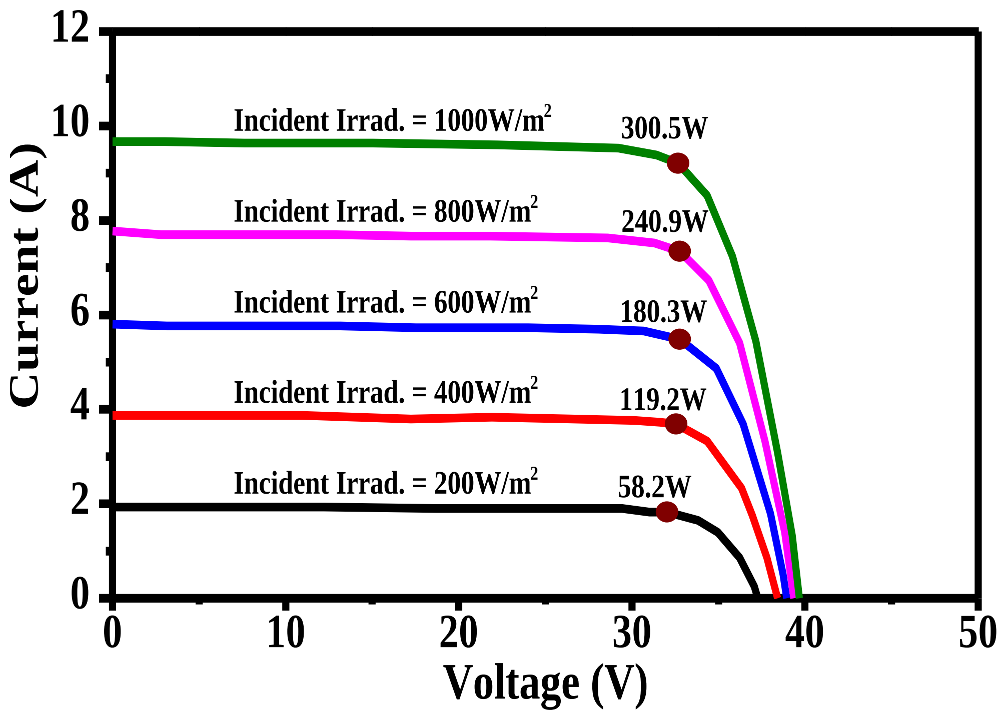

Figure (1): IV characteristics at various irradiance densities according to PVSyst simulation.

3. Experimental Procedure

PV system of the Renewable Energy and Environment Research Center (REERC) served as the subject of investigation. The system comprises 560 PV modules, with each module consisting of a monocrystalline silicon PV panel rated at approximately 250W under Standard Testing Conditions (STC). Each panel is constructed with 96 p-n junction rectangular cells connected in series to yield an open circuit voltage of around 48V, covering a total area of 2 m². The system is grid-tied and features three on-grid inverters. While the total nominal power is 135kW at STC, the actual output power does not surpass 90kW. Several factors contribute to this variance, including partial shading from maintenance bridges, degradation of panels over the 8 years of operation, and, notably, the influence of weather conditions. Figure (2) visually represents the REERC PV system.

Figure (2): The 135kW REERC PV system.

The study was conducted during the summer of 2022, a period marked by severe and recurrent dust storms in Baghdad. Figure (3) visually depicts the accumulated dust on the REERC PV system, observed one day after the dust storm on May 17, 2022. The collected dust from a single panel weighed approximately 35g, as showcased in the beaker in Figure (4). Extrapolating from this, it can be inferred that around 19kg of dust had accumulated across the entire system.

Figure (3): The REERC PV system a day after the May 17, 2022 dust storm.

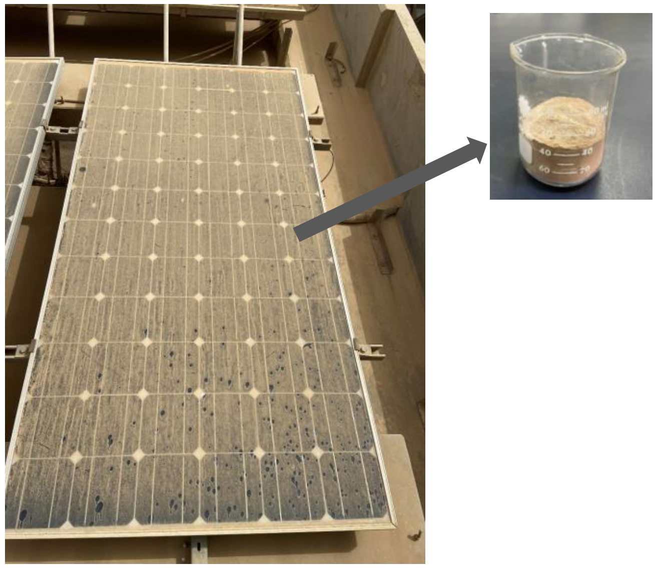

Figure (4): Dust collected from one panel.

4. Results and Discussion

Figure (5) shows the IV curves during illumination for a tested panel, comparing the conditions without dust (left) and with dust (right). The measurements were taken at 11:00 AM and 12:30 PM on July 17, 2022. The dust was intentionally added to examine its impact on PV performance. The irradiance was 820W/m² at 11:00 AM and increased to 930W/m² by 12:30 PM. Upon comparison, it's evident that the dusty PV panel exhibits a lower rated power. For instance, at 11:00 AM, the rated power is 193W/m² for the clean panel and 122W/m² for the dusty panel. A similar reduction in power is observed at 12:30 PM, attributed to the decrease in light reaching the PV junction due to the presence of opaque dust [18]. Surprisingly, the rated power for both clean and dusty panels at 12:30 PM (irradiance = 930W/m²) is lower than that at 11:00 AM (irradiance = 820W/m²). Despite the increase in irradiance, the power decreased in the afternoon. Examining the temperature data reveals an increase from 41°C to 44°C, contributing to the decrease in power despite the elevated irradiance. This underscores that the impact of temperature on PV performance is more substantial than the effect of irradiance.

Further analysis of the data unveils even more surprising results. The reduction ratio due to the heat for the clean panel is 24% (from 193W to 148W), while it is only 6% for the dusty panel (from 122W to 115W). This can be explained by the positive effect of dust. Dust appears to significantly reduce PV surface temperature by obstructing direct exposure to sunlight, resulting in a slight decrease in the overall loss percentage.

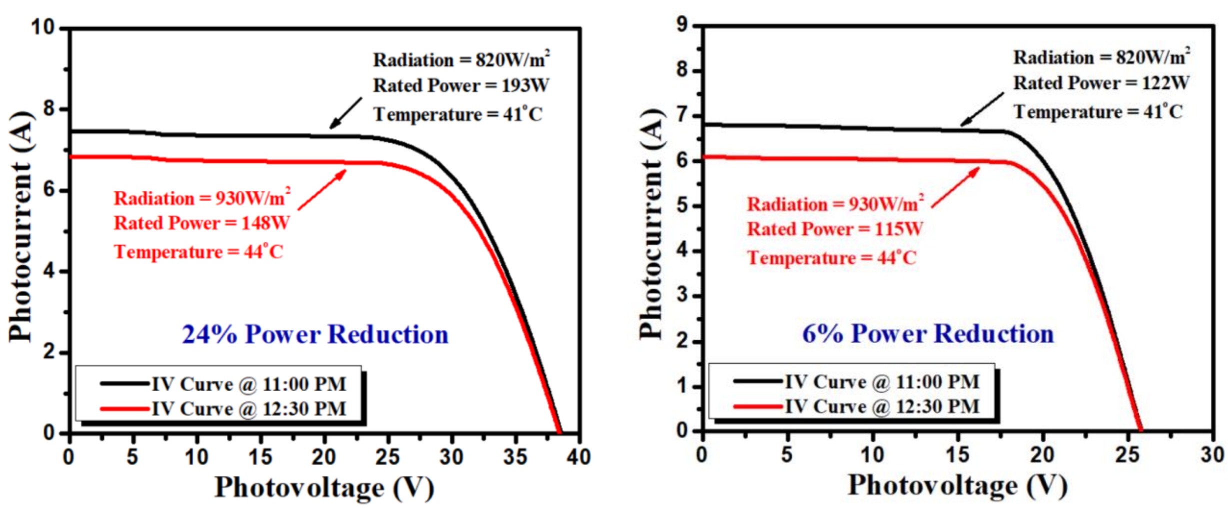

Figure (5): IV characteristics of a tested panel without dust (left) and with dust (right) both measured at 11:00AM and 12:30PM in July 17, 2022.

To comprehend these findings in a real-world context, the 135kW operational PV system of REERC was examined as an example. The study was conducted on August 28, 2022, a day when Baghdad experienced a dust storm with the highest temperature recorded at 44°C. This was then compared with the results from August 31, 2022, when the system was cleaned of dust, and the highest temperature reached 48°C. It's noteworthy that the temperature on August 28 was lower than that on August 31, a phenomenon likely attributed to the dust storm, as these events often lead to a decrease in temperature. Figure (6) depicts the power plot of the system recorded by the SMA Sunny Portal platform. On August 28, the maximum rated power was 80kW, whereas on August 31, it was 79kW. Despite the cleaning of the PV system on August 31, the rated power did not increase. This can be attributed to the temperature effect, where the temperature on August 28 was 4°C lower than that on August 31. This observation emphasizes the substantial impact of temperature on PV system performance, even when dust is removed.

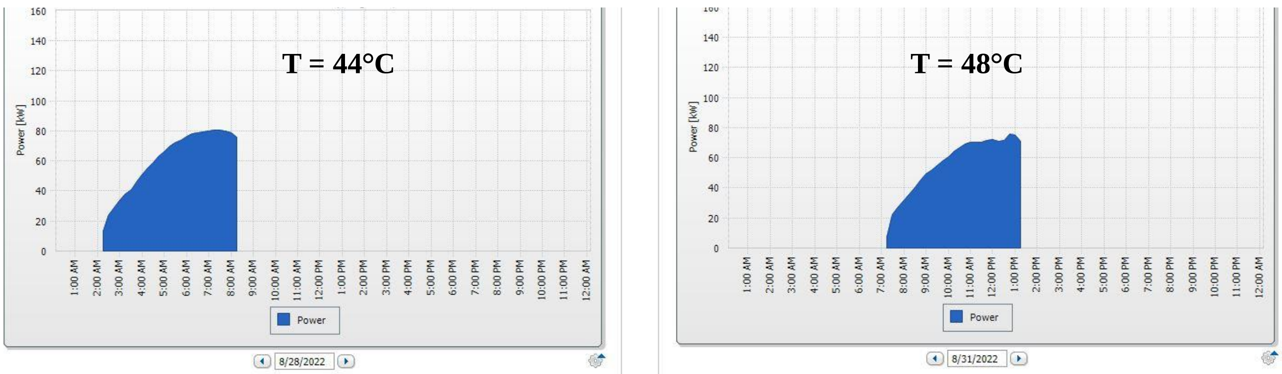

Figure (6): Rated power plot of PV system of REERC; Left: PV system power profile in a dusty day (Maximum Power = 80kW), and Right: PV system power profile in a clear day (Maximum Power = 78kW).

5. Conclusions

Based on the earlier discussion, it can be concluded that both temperature and dust contribute to a decrease in PV output. Temperature primarily leads to a drop in voltage, while dust results in a reduction in current. However, during dust storms, the temperature decreases significantly below the average, potentially enhancing PV output. This creates a balancing point where the adverse impact of temperature is offset by the negative effect of dust, resulting in a slight decrease in PV output. This phenomenon can be termed the positive effect of dust. It's important to note that this effect is particularly pronounced and valid at high temperatures. In contrast, at low and moderate temperatures, dust is generally considered detrimental to PV performance.

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