Experimental analysis of the performance efficiency of bifacial PV panels under dust exposure

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Abstract. In this study, the energy production efficiency of bifacial solar panels under dust contamination was investigated under real operating conditions in Termez, one of the southern and hottest regions of Uzbekistan. The effects of dust aerosols on the optical characteristics and power output of the panels were analyzed based on experimental observations. The obtained results provide practical insights for assessing the performance stability of PV systems in arid climates and for developing measures to enhance their operational efficiency.

INTRODUCTION

Currently, the global demand for energy resources is rapidly increasing. Traditional energy sources such as oil, gas, and coal are limited, and their combustion releases harmful gases into the atmosphere, exacerbating global warming. Therefore, transitioning to environmentally friendly, sustainable, and renewable energy sources has become one of the most pressing issues of our time. Among such sources, solar energy is considered the most promising. In utilizing solar energy, photovoltaic (PV) panels are one of the most prospective renewable energy technologies. Today, they account for the second-largest share of installed renewable energy capacity worldwide. To reach the solar photovoltaic capacity, a tripling of the existing capacity at the end of 2024 (2,243 GW_p) is required (Figure 1) [1].

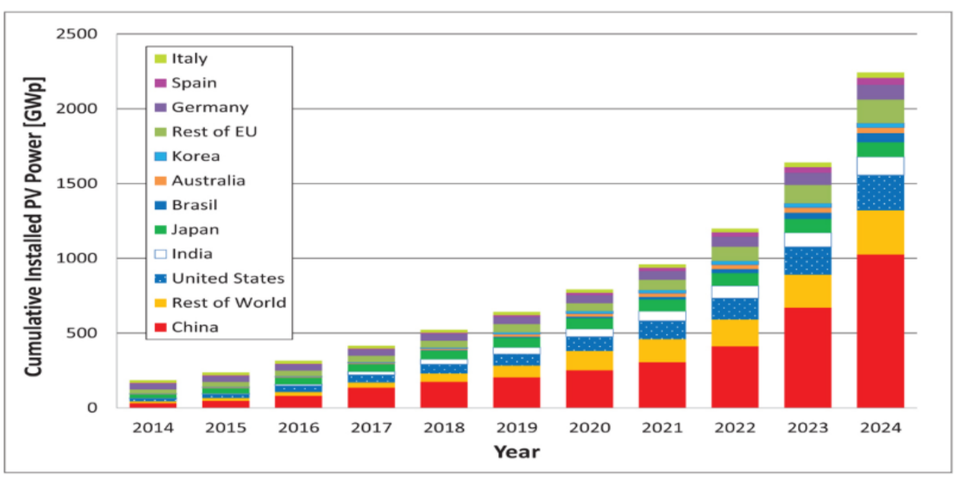

FIGURE 1. Cumulative photovoltaic installations from 2014 to 2024.

According to research, the efficiency of BPV systems worldwide is higher compared to the power output efficiency of conventional PV modules, ranging from 15–25% for small-scale systems and 5–15% for large commercial-scale systems [2–4]. In Tashkent, located in the northern region of our country, this value reaches 9% [5]. Studies should focus on improving PV cell efficiency, module reliability, and optimizing the placement of bifacial panels. Furthermore, research aimed at enhancing the efficiency of monofacial PV cells also benefits bifacial PV technology [6]. Bifacial solar cells may produce more output energy than monofacial solar cells because both sides of the cell, front and rear, can absorb solar radiation [7]. In designing solar PV systems, it is important to consider the height of bifacial PV arrays above the ground [8]. The temperature effects on the main photovoltaic parameters of power plants with conventional and bifacial silicon solar panels have been reported [9].

Development of energy production based on renewable energy sources. In recent years, bifacial photovoltaic (BPV) modules have experienced rapid development and garnered considerable attention in the global market [10]. At present, BPV modules represent approximately 20% of the overall photovoltaic technology market, with projections indicating that this share could rise to 70% by 2030 [11].

The aim of this study is to determine the operational performance of BPV modules under real conditions and under the influence of dust in the city of Termez.

EXPERIMENTAL RESEARCH

In recent years, a decrease in precipitation intensity has been observed at nearly all meteorological monitoring stations across Uzbekistan. At the same time, during the summer months, the central and southwestern regions of the country frequently experience sand and dust storms [12]. Strong wind currents transport saline soil particles, which settle on the surface of photovoltaic (PV) modules, gradually forming a thin layer of contamination whose thickness increases over time [13].

The experiment was conducted on the roof of TDMAU in Termez, located at 37°13'57" N latitude and 67°17'8" E longitude. The tests were performed under standard test conditions (STC) on bifacial photovoltaic (BPV) modules with a nominal power of 580 W, arranged in two rows and installed adjacently (Figure 2).

FIGURE 2. Procedure for measuring PV module parameters under real-world conditions
1− Photovoltaic module cleaned of dust, 2− Dust-soiled photovoltaic module

The main electrical parameters of the BPV module used in the study are presented in Table 1.

TABLE 1. Electrical and mechanical parameters of bifacial solar panels

Model Type: Monocrystalline SN580-144MTB	**Electrical Mechanical**	**Solar Cell: M-Mono (BPV)**	**Mechanical Specifications**
Rated maximum power (P_{mp})	580W	Front glass	3,2mm tempered glass
Open-circuit voltage (U_{oc})	51.41V	Maximum series fuse rating	25A
Voltage at $P_{\mathrm{mp}}(U_{\mathrm{mp}})$	43.22V	PV Module Level	Class A
Short-circuit current (I_{sc})	14.22A	Size	2279*1134*30mm
Current at $P_{\mathrm{mp}}(I_{\mathrm{mp}})$	13.42A	Weight	26,0 kg (±3%)
Power tolerance	±5%	Fire rate	Class C (TUV)
Temperature coeffcient (P_{max})	-0,34%/C	Maximum load capacity	5400Pa/2400Pa

Three principal methods are commonly employed to measure the electrical parameters of different types of photovoltaic (PV) modules [14]. In the present study, we utilized the method designed for stationary PV installations. The electrical parameters of the modules were recorded at 20-minute intervals to ensure adequate temporal resolution for performance assessment.

In this configuration, the PV modules were installed following conventional practices typically used in large-scale photovoltaic power plants. Specifically, for locations in the Northern Hemisphere, the modules were oriented toward the south to maximize solar irradiance and enhance energy yield. This standardized orientation ensures consistent exposure to sunlight throughout the day and facilitates reliable comparison of performance metrics.

RESERCH RESULTS

The electrical parameters of the photovoltaic (PV) modules were measured on 9 November 2025, between 9:00 and 16:00, under ambient conditions characterized by an air temperature of 13–15 °C, a wind speed of 11 km/h, and an atmospheric pressure of 769 mmHg. Solar irradiance is a key factor influencing the performance of PV modules, as it directly determines their power generation potential. Although higher irradiance typically enhances energy output, its adverse thermal effects must also be taken into account. Increased irradiance elevates the temperature of the modules, which can reduce their conversion efficiency and adversely affect their long-term reliability. As the module temperature rises, the internal resistance of the PV cells increases, leading to additional energy losses [15].

The temporal variation of solar irradiance incident on the PV module surfaces during the measurement period is illustrated in Figure 3.

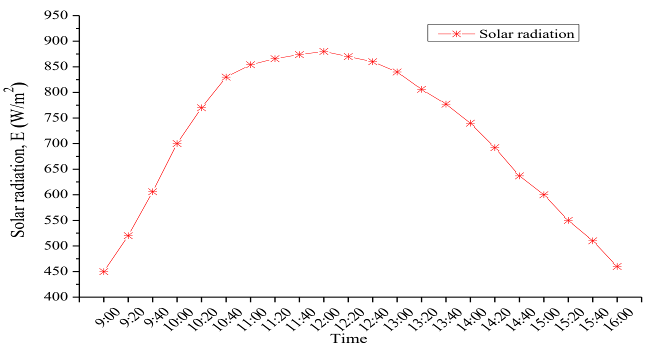

FIGURE 3. Time dependence of the intensity of solar radiation falling on the surface of PVs

As the graph clearly shows, the maximum value of solar irradiance was recorded at a tilt angle of 31°, reaching 875 W/m². The irradiance was measured using a DT-1307 piranometer. It should be noted that aerosol particles (dust) in the atmosphere as well as cloud cover significantly reduce the intensity of incident solar radiation, thereby decreasing the irradiance available to the PV modules [16].

The short-circuit current (ISC) of PV modules is primarily determined by the intensity of incident solar radiation. As the solar irradiance increases, the number of photons striking the semiconductor material of the PV module rises, which generates more electron–hole pairs and thus increases the electric current. ISC is consequently a crucial parameter for evaluating the performance, responsiveness to irradiance, and operational state of a PV module [17]. Under real conditions, the short-circuit current was computed based on expression 1 [18].

$$\boldsymbol{I_{SC} = I_{SC,STS} \cdot \frac{G}{G_n} \cdot [1 + \alpha_I \cdot (T_C - T_{C,STC})]} \quad (1)$$

where I_{SC} –the actual (real-world) short-circuit current; G – the solar irradiance incident on the module under real operating conditions (W/m²); G_n – the irradiance under Standard Test Conditions (STC), typically 1000 W/m²; I_{SC} – the short-circuit current under STC, as specified in the module datasheet (A); Tc – the actual temperature of the module (or cell) under operating conditions (°C); $T_{C,STC}$ – the module temperature under STC, typically 25°C.

In Figure 4, the time-dependence of short-circuit current is shown, clearly illustrating the correlation between daily variations in solar irradiance and the module's I_{SC} behaviour.

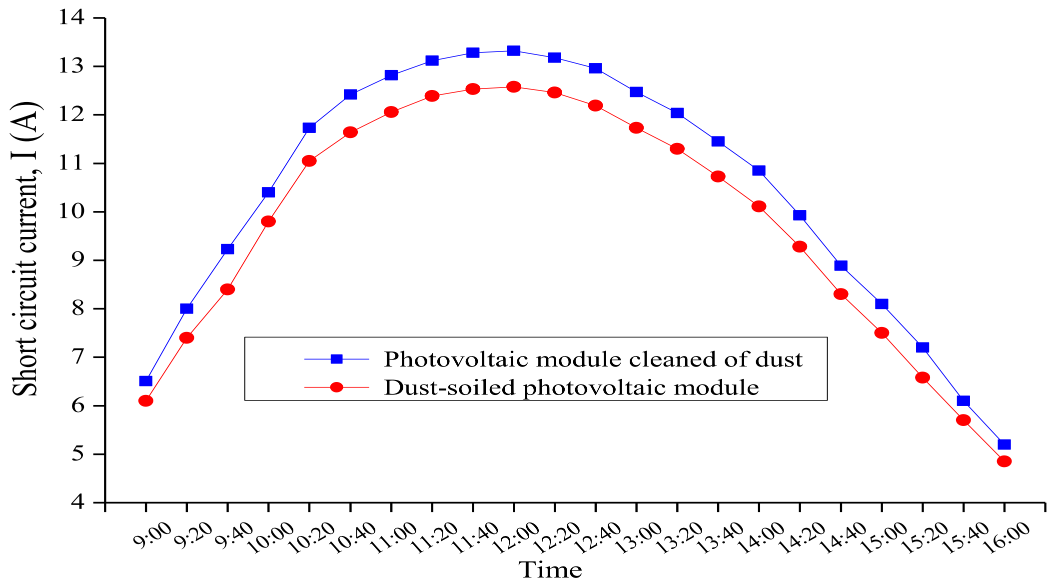

FIGURE 4. Time dependence of the short-circuit of a BPV module during the day

Typically, the electrical parameters indicated on a PV module's certification label are specified under Standard Test Conditions (STC), which include an irradiance of 1000 W/m² and a module temperature of 25 °C. In the present experimental study, the short-circuit current (I_{SC}) of the BPV module under STC was 14.22 A. Under real operating conditions, the dust-cleaned BPV module exhibited an average short-circuit current of 10.42 A over the course of a day. In contrast, the BPV module contaminated with dust showed a short-circuit current of 9.76 A. These results clearly demonstrate the significant impact of surface dust accumulation on the electrical performance of PV modules.

Among the electrical characteristics of PV modules, the short-circuit current (I_{SC}) and the open-circuit voltage (U_{OC}) are considered the most critical parameters. These quantities are interrelated and are highly sensitive to variations in solar irradiance and temperature. The open-circuit voltage represents the maximum voltage measured at the output terminals of a PV module when no external load is connected.

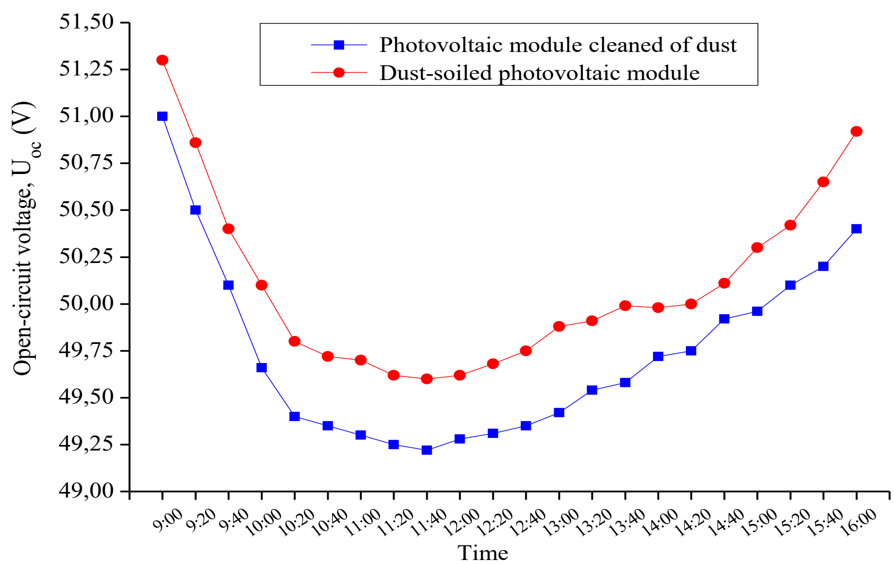

FIGURE 5. The time-dependent variation of the open-circuit voltage of PV modules throughout the day

As a result, elevated operating temperatures lead to a reduction in both the efficiency and the power-generation capability of PV modules. This temperature – voltage dependence is depicted in Figure 5, which illustrates the temporal variation of the open-circuit voltage throughout the day. The figure clearly shows how fluctuations in module temperature correspond to a progressive decrease in the measured open-circuit voltage.

The experimental results indicate that, between 09:00 and 11:40, the open-circuit voltage (U_{OC}) of the cleaned BPV module reached approximately 1.98 V, whereas that of the dust-covered BPV module decreased to about 1.7 V. The relatively higher U_{OC} drop observed in the cleaned module can be attributed to lower optical losses. In this case, more light passes through the clean glass and reaches the solar cells, causing the module to heat up more. The increased temperature, in turn, leads to a further reduction in the open-circuit voltage.

It is noteworthy that a single crystalline silicon solar cell, widely used today, typically exhibits an open-circuit voltage of approximately 0.6 V between its contacts. Moreover, the temperature coefficient of the open-circuit voltage for PV modules is reported to decrease linearly by approximately –2.3 mV/°C for every degree above 25 °C [19].

$$\frac{\partial U_{s.yu.}}{\partial T} = -2{,}3mV/℃ \quad (2)$$

The temporal variation of the electrical power output of the BPV modules throughout the day was derived from the measured short-circuit current (I_{SC}) and open-circuit voltage (U_{OC}) data presented above. By systematically analyzing these parameters at different times of the day, it became possible to estimate how the instantaneous power generation of the module evolved under changing environmental conditions.

These measurements enabled the construction of a detailed diurnal power profile for the PV module, which is illustrated in Figure 6. As shown in the figure, the module's output power undergoes noticeable fluctuations over time, reflecting the dynamic interplay between solar irradiance, temperature, and other atmospheric factors. This profile not only highlights periods of peak performance but also reveals intervals when power generation declines due to reduced sunlight or increased thermal stress, thereby offering a comprehensive understanding of the module's daily operational behavior.

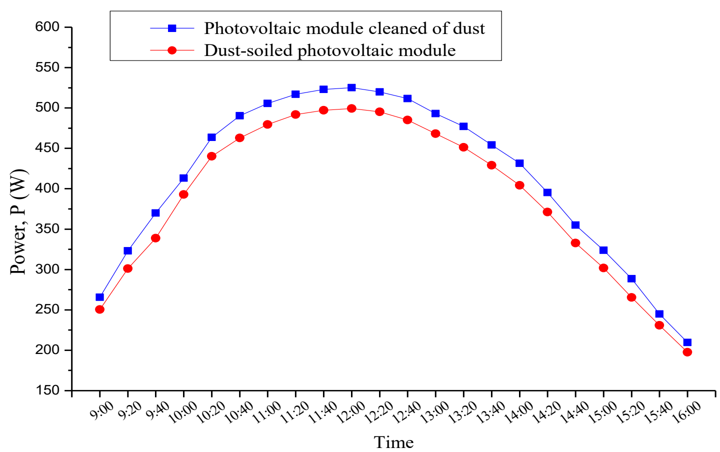

FIGURE 6. Time-dependent variation of the PV modules' output power throughout the day

Equation (3) was used to calculate the power of the PV module.

$$P = ff \cdot I_{s.c.} \cdot U_{o.c.} \quad (3)$$

where, $I_{s.c.}$ – short-circuit current, $U_{o.c.}$ – open circuit voltage ff – is the filling factor of the volt-ampere characteristic (VACh) of the PV module, an important parameter determining the efficiency of energy generation. It is used to assess the energy losses during the filling process of the modules and their operating efficiency. The filling factor of modern PV modules is 0.75 – 0.8, and it varies depending on the PV module manufacturing technology [20].

The power curve presented in Figure 6 shows that the daily average power output of the cleaned BPV module reached 413.7 W. In contrast, the module installed at the same tilt angle but with a dust-covered front surface exhibited a reduced average power output of 390 W.

This decrease in power can be attributed to optical losses introduced by the dust layer, which affects the photoelectric conversion process. Dust particles scatter and absorb a portion of the incident solar radiation, thereby reducing the amount of useful irradiance reaching the module. Consequently, the generated photocurrent and the overall electrical power output decline.

These findings demonstrate that the performance of BPV modules is highly sensitive to surface contamination and confirm that regular cleaning is an important factor in maintaining optimal operational efficiency.

CONCLUSIONS

The experimental study revealed that the electrical performance of BPV modules is strongly influenced by dust accumulation on their surface. Under real operating conditions, the short-circuit current (ISC) decreased from 14.22 A (STC) to 10.42 A (26.7 %**)** for the cleaned module and to 9.76 A **(**31.4 %**)** for the dust-covered module, while the open-circuit voltage (UOC) dropped from 1.98 V to 1.7 V in dusty conditions. The daily average power also declined, with the cleaned module producing 413.7 W and the dust-covered module 390 W, corresponding to 28.7 % and 32.8 % reductions relative to the STC maximum power of 580 W. Dust scattering and absorption reduced the useful irradiance reaching the solar cells, causing additional efficiency losses of approximately 4 %. These results underscore the critical importance of regular surface cleaning to minimize power losses and maintain stable, long-term performance of BPV modules in real-world conditions.

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