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STUDY OF SURFACE PROTECTION METHODS FOR IMPROVING THE EFFICIENCY OF PHOTOVOLTAIC PANELS

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Annotation. This paper investigates the mechanisms of contamination formation and deposition on the surface of photovoltaic (PV) panels under various seasonal conditions and different angles of solar incidence. The study analyzes the influence of surface treatment levels of PV panels and dust particle size on the degree of surface contamination. Experimental results demonstrate the dependence of PV panel surface загрязнение on the time of day. It is shown that covering the surface of PV panels during nighttime, prior to sunrise, leads to a significant reduction in surface contamination, thereby contributing to the improvement of photovoltaic panel performance.
Keywords: Photovoltaic panels, surface contamination, dust deposition, surface protection methods, seasonal effects, photovoltaic efficiency.

Аннотация. В данной работе исследуются механизмы образования и осаждения загрязнений на поверхности фотоэлектрических (ФЭБ) панелей при различных сезонных условиях и разных углах падения солнечного излучения. В исследовании анализируется влияние уровня поверхностной обработки ФЭБ панелей и размера пылевых частиц на степень загрязнения поверхности. Экспериментальные результаты демонстрируют зависимость загрязнения поверхности ФЭ панелей от времени суток. Показано, что покрытие поверхности ФЭ панелей в ночное время, до восхода солнца, приводит к значительному снижению уровня загрязнения поверхности, тем самым способствуя повышению эффективности фотоэлектрических панелей.
Ключевые слова: фотоэлектрические панели, поверхностное загрязнение, осаждение пыли, методы защиты поверхности, сезонные эффекты, фотоэлектрическая эффективность.

Annotatsiya. Ushbu maqolada turli mavsumiy sharoitlarda va quyosh nurlarining tushish burchaklari o‘zgarishida fotoelektrik batareyalar (FEB) yuzasida ifloslanishning hosil bo‘lishi va cho‘kish mexanizmlari tadqiq etilgan. Tadqiqotda FEB yuzasiga ishlov berish darajasi va chang zarralari o‘lchamining yuzaki ifloslanish darajasiga ta’siri tahlil qilingan. Tajriba natijalari FEB panellar yuzasining ifloslanishi kunning vaqtiga bog‘liqligini ko‘rsatadi. Quyosh chiqishidan oldin, tunda FEB yuzasini yopib qo‘yish yuzaki ifloslanishni sezilarli darajada kamaytirishi va natijada FEB samaradorligini uzoqroq vaqt saqlab qolishga xizmat qilishi aniqlangan.
Kalit so‘zlar: fotoelektrik batareya, yuza ifloslanishi, chang cho‘kishi, yuzani himoyalash usullari, mavsumiy ta’sirlar, fotoelektrik samaradorlik.

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Introduction. Central Asia is geographically isolated from cyclones and monsoons by mountain ranges. The region is characterized by an arid climate with high air temperatures (up to 40°C and above), low humidity, and a high level of atmospheric dust [1,2]. Deserts occupy a significant portion of Kazakhstan and most of the territories of Uzbekistan and Turkmenistan. Within Uzbekistan, the regions most affected by wind erosion include the Kashkadarya region, the southeastern part of the Surkhandarya region, and the western part of the Fergana Valley.

Under arid climatic conditions, wind erosion is the primary cause of increased atmospheric dust concentration. The main sources of dust and salt emissions in the country are the dried bottom of the Aral Sea, saline drainage lakes, and salt flats **[3]**. In recent years, a significant increase in dust deposition density has been observed at nearly all monitoring sites across Uzbekistan. During the summer season, sand and dust storms frequently occur in the central and southwestern regions of the country.

Saline soil particles lifted by wind are deposited on the surface of photovoltaic (PV) panels, forming a thin layer that gradually increases in thickness over time. This process leads to a reduction in the performance of photovoltaic systems and necessitates a detailed investigation of surface contamination mechanisms.

Literature Review. Recent studies conducted in various countries have confirmed that surface contamination of photovoltaic panels significantly affects solar energy output [4,5]. Researchers from the Indian Institute of Technology Gandhinagar (IITGN), the University of Wisconsin-Madison, and Duke University reported that periodic cleaning of solar panels every few weeks resulted in an efficiency increase of up to 50%. It has also been noted that China, India, and the Arabian Peninsula are among the dustiest regions in the world. Even with monthly cleaning, photovoltaic panels in these regions may still experience energy production losses ranging from 17% to 25%, while cleaning every two months can result in losses of up to 35%.

In many studies addressing the application of photovoltaic installations in hot and arid climates, insufficient attention has been paid to such an important environmental parameter as atmospheric dust concentration. It has been established that, in the southern and steppe regions of Uzbekistan, the reduction in output power of photovoltaic panels is caused not only by high temperatures but also by surface contamination, the extent of which depends on environmental conditions.

To protect photovoltaic panels from atmospheric influences, tempered glass with a thickness of 4-6 mm and either polished or textured surfaces is commonly used on the front side of PV modules. The adhesion of dust particles to the glass surface depends on the degree of surface treatment, wind speed and direction, and ambient humidity [6,7]. Since these environmental conditions vary significantly across different regions of Uzbekistan, the level of dust contamination and its impact on PV panel performance also differ accordingly.

Research Methodology. In this study, the accumulation of dust particles on the surface of photovoltaic panels was investigated from both structural and operational perspectives. Particular attention was given to the angle of incidence of particles on the glass surface and the orientation of PV panels relative to the horizontal plane. It was found that when PV panels are installed in a vertical position, surface contamination is minimal, as the particle incidence angle approaches zero, reducing the likelihood of particle adhesion.

Experimental results showed that when PV panels were tilted 7-10^0 away from the vertical position, dust accumulation over a period of 20-40 days led to a reduction in short-circuit current by

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approximately 3-5%. Increasing the tilt angle further resulted in enhanced dust adhesion on the surface of the photovoltaic panels. However, when the deviation angle exceeded 45^0, a decrease in the influence of contamination on PV performance was observed.

The study also analyzed the settling behavior of dust particles of different sizes. The results indicated that fine particles are the primary contributors to surface contamination [8,9]. In addition, based on the characteristics of arid climates-particularly in Tashkent, where daytime and nighttime temperatures differ significantly during the summer-autumn period-it was hypothesized that dust deposition predominantly occurs at night. To verify this assumption, two crystalline silicon-based photovoltaic panels with closely matched electrical characteristics (within 1% for short-circuit current and open-circuit voltage) were selected.

The experiment was conducted in an open area under the environmental conditions of Termez city, a region characterized by extreme dust pollution and minimal industrial gas emissions compared to Tashkent [10,11]. This location was chosen to ensure that the observed contamination effects were primarily due to natural environmental factors.

Results and Discussion. To ensure the maximum level of surface contamination, both photovoltaic panels were installed in a horizontal position. One of the panels (PV-1) remained continuously exposed to the environment throughout the entire day–night cycle. In contrast, the second panel (PV-2) was covered during daylight hours and exposed only at night, from 20:00 in the evening until sunrise at 6:00.

Electrical parameters of both photovoltaic panels were measured daily when the Sun reached its zenith. Under clear-sky conditions, the solar irradiance incident on the panel surfaces at this time is nearly identical, which minimizes measurement uncertainty. The following parameters were recorded: open-circuit voltage, short-circuit current, solar irradiance, ambient air temperature and humidity, and wind speed. Measurements were conducted only on sunny days when variations in wind speed and humidity were minimal.

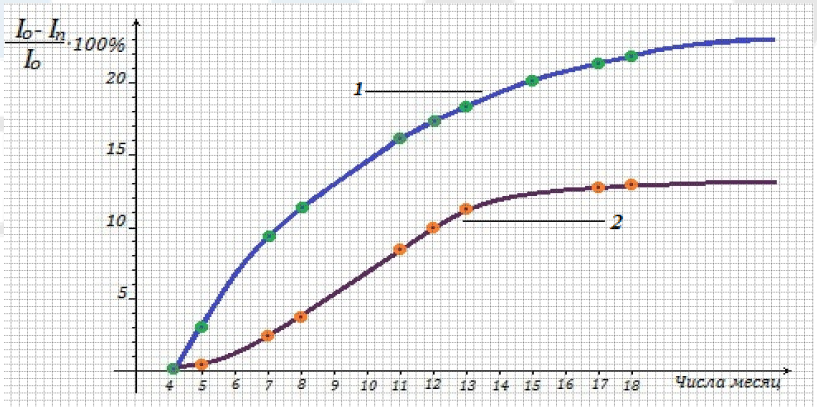

Figure 1. Dependence of surface contamination level in August: 1 - photovoltaic battery (PV) with continuously exposed surface; 2 - photovoltaic battery (PV) with surface exposed only during nighttime.

Figures 1 present the experimental results obtained for August and September 2025, respectively, showing the relative daily values of the short-circuit current for both photovoltaic panels. As illustrated in Fig. 1, the degree of surface contamination during August increases with time and

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gradually approaches saturation as the thickness of the deposited dust layer increases. In addition, a noticeable divergence between the two curves appears after August 12, which can be attributed to a reduction in the difference between daytime and nighttime temperatures.

Over the entire observation period in August, the photovoltaic panel with a continuously open surface exhibited an average contamination level of approximately 21%, whereas the panel exposed only during nighttime showed a significantly lower contamination level of about 14%. These results indicate that restricting panel exposure during daytime effectively limits the accumulation of surface pollutants.

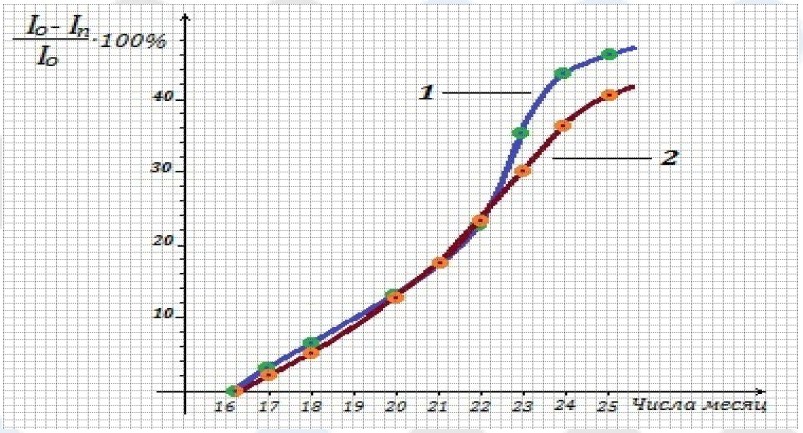

Figure 2. Dependence of surface contamination level in September 2025: 1 - photovoltaic battery (PV) with continuously exposed surface; 2 - photovoltaic battery (PV) with surface exposed only during nighttime.

Figure 2 illustrates the surface contamination behavior of both panels during September 2025. In this case, measurements were initially conducted without accounting for changes in wind speed. Up to September 22, the contamination levels for both panel configurations remained nearly identical. However, following the onset of strong southern winds between the evening of September 22 and the evening of September 23, wind speed increased by a factor of 1.5–1.7 (from 10–11 m/s to 17–19 m/s). This increase in wind speed led to a pronounced rise in the difference in contamination levels between the two panels, reaching approximately 4%, as shown in Fig. 2. Considering subsequent variations in weather conditions, it is expected that the difference in surface contamination may further increase to 5–6% in the following days. Overall, the experimental results demonstrate that covering the surface of photovoltaic panels during nighttime until sunrise can significantly reduce surface contamination.

This approach provides a practical method for mitigating soiling-related losses in photovoltaic power plants based on crystalline silicon solar cells, without the need for additional surface treatments or coatings. Nevertheless, to obtain more accurate forecasts and develop region-specific recommendations, similar studies should be conducted across different climatic zones of the republic.

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Conclusion. The experimental results confirm that surface contamination of photovoltaic panels increases over time and depends strongly on exposure conditions. A photovoltaic panel continuously exposed to the environment exhibited higher contamination levels compared to a panel covered during daytime and exposed only at night. The latter configuration reduced contamination by approximately 7% during the observation period.

The study also indicates that wind speed significantly affects the contamination process, with increased wind intensity leading to greater differences in surface soiling between panel configurations. Overall, covering photovoltaic panels until sunrise represents a simple and effective method for reducing soiling-related performance losses in crystalline silicon photovoltaic systems. Further long-term studies across different climatic regions are necessary to generalize these findings.

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