

Optimizing solar panel placement on mine spoil heaps: Aerodynamic approach to dust deposition minimization

Vadym Shchokin¹ , Viktoriia Tkachuk^{2*} , Roman Makareiko² 

¹ Scientific Research Mining Institute, Kryvyi Rih National University, Kryvyi Rih, Ukraine

² Kryvyi Rih National University, Kryvyi Rih, Ukraine

*Corresponding author: e-mail viktoriia.tkachuk@gmail.com

Abstract

Purpose. The research aims to substantiate the possibility of optimizing solar panel placement on mine spoil heaps, accounting for aerodynamic dust transport processes, thereby minimizing dust deposition on module surfaces and enhancing energy generation efficiency.

Methods. The study employs numerical modelling of turbulent airflow using Computational Fluid Dynamics (CFD) based on Reynolds-Averaged Navier-Stokes (RANS) equations with the Shear Stress Transport (SST) $k-\omega$ turbulence model in ANSYS Fluent, discrete modelling of dust particle deposition trajectories using Discrete Phase Model (DPM), field measurements of dust deposition intensity at test sites, and parametric optimization of the geometric characteristics of solar panel placement.

Findings. The optimal tilt angle for solar panels was determined to be 28-32°, reducing dust deposition by 18-25% due to enhanced near-surface shear flow. The recommended inter-row spacing-to-panel height ratio was set at $S/H \geq 2.5$ to minimize stagnation zones. Orienting rows at 10-15° deviation from the prevailing wind direction reduces dust deposition by 12-18%. Model validation showed that the discrepancy between the model predictions and experimental data ranged from 12 to 18%.

Originality. For the first time, a CFD-DPM methodology has been specifically adapted and validated for the aerodynamic and geomorphological conditions of mine spoil heaps, incorporating their complex terrain geometry, multi-source dust emissions, and regional wind rose data to optimize solar panel placement.

Practical implications. The developed methodology determines the rational parameters for solar panel placement on mine spoil heaps, reducing annual productivity losses due to dust soiling by 5-8%. The results can be applied to spoil heap reclamation and to the design of solar power plants at industrial sites with elevated dust levels.

Keywords: solar panels; mine spoil heaps; surface soiling; aerodynamic optimization; CFD modelling; renewable energy

1. Introduction

The development of renewable energy in industrial territories is an essential component of the transition to a low-carbon economy and of improving environmental efficiency in the mining industry. One of the most promising solutions is the utilization of mine spoil heaps as sites for solar panel installation. Such territories are typically degraded and unsuitable for traditional agricultural use, yet they have sufficient land area to install solar panels without additional land acquisition [1], [2]. The integration of solar generation on spoil heaps helps reduce the carbon footprint, enhance energy efficiency in production, and advance sustainable development principles [3].

The escalating global demand for sustainable energy has spurred interest in the widespread deployment of solar panels. Concurrently, there is growing impetus to repurpose brown-field sites, such as mine spoil heaps, for renewable energy generation, thereby addressing both energy needs and land remediation challenges [1], [4]. These sites, often unsuitable for agriculture or urban development, offer significant potential for large-scale solar installations, thereby contributing to land-use

efficiency and sustainability goals [5], [6]. The successful implementation of such projects requires not only technical expertise, but also the training of qualified mining engineers to integrate innovative technologies into mining operations [7].

However, the successful implementation of solar panel arrays on mine spoil heaps is often hindered by a critical operational challenge: dust deposition. The dusty environment is shaped by the unstable structure of the spoil heaps, the fine-grained composition of the rock, transport operations, and local wind regimes. Numerous studies demonstrate that dust soiling is a major factor in the degradation of solar panel performance, with power losses reaching 20-40% depending on particle-size distribution and dust intensity [8], [9]. Dust not only reduces light transmission, but also causes hot spots, accelerates material ageing, and increases operational costs.

Although dust soiling has been well documented in scientific literature, most existing models and engineering approaches are oriented towards desert or flat, open terrain. Numerous reviews emphasize that these models do not account for the complex geometry of technogenic landscapes, local dust sources, and the turbulent airflow over spoil heaps [8]-

Received: 27 January 2026. Accepted: 10 August 2026. Available online: 26 September 2026

© 2026. V. Shchokin, V. Tkachuk, R. Makareiko

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

[10]. For instance, CFD studies demonstrate that traditional assumptions about flow uniformity and wind direction do not hold true in areas with artificially constructed embankments, which create complex aerodynamic effects [11], [12]. It has also been established that dust processes at industrial sites differ from those in natural desert conditions: dust can originate from multiple sources, exhibit different vertical distributions, and undergo recirculation, which dramatically complicates predictions of deposition on panels [9], [10].

Traditional dust mitigation strategies, including manual cleaning, automated cleaning systems, and anti-soiling coatings, are often costly, labor-intensive, water-dependent, and environmentally burdensome, particularly on steep or unstable terrain [13]. This necessitates exploring more sustainable, passive mitigation techniques. Modern control systems based on fuzzy logic and neuro-fuzzy approaches have demonstrated their effectiveness in optimizing energy consumption in mining operations [14], [15], paving the way for the development of intelligent dust mitigation management systems.

Furthermore, contemporary reviews highlight the lack of methodologies that integrate spatial planning for solar panel arrays with dust-soiling models [10], [16]. Parameters such as panel tilt angle, installation height, orientation relative to dust sources, and row spacing critically affect the intensity of contamination on the panel surface. Wind-tunnel experiments demonstrate that altering the geometry of solar panel arrays can both significantly reduce and increase dust deposition, depending on the configuration [12]. At present, comprehensive, scientifically grounded recommendations for the spatial optimization of solar panel placement on mining enterprise spoil heaps do not exist.

Thus, developing a scientifically grounded approach to optimizing solar panel placement on technogenic spoil heaps, accounting for environmental aerodynamic characteristics and dust deposition processes, is highly relevant. Such a methodology will minimize generation losses, increase the efficiency of green electricity production, and create new opportunities for the reclamation of degraded lands through energy-focused repurposing. This study aims to address this gap by developing and validating a CFD-based model for mine spoil heaps, ultimately quantifying reductions in dust accumulation and improvements in energy yield.

2. Literature review

2.1. Impact of dust deposition on solar panel performance

The problem of dust contamination of solar panels (soiling) has been the subject of intensive scientific research over the past two decades. A comprehensive review of the impact of dust on solar energy is presented in the work of Sarver et al. [8], which systematizes the history of research, experimental results, and approaches to mitigating dust deposition. The authors emphasize that power losses due to contamination can reach 20-40%, depending on climatic conditions and the particle-size distribution of the dust.

Dust accumulation on solar panel surfaces is a well-documented phenomenon that severely reduces energy conversion efficiency and overall performance [17], [18]. Studies have shown that even a thin layer of dust can significantly reduce solar panel power output, with reported losses ranging from 5 to over 50%, depending on environmental conditions, dust characteristics, and cleaning frequency [17]. El-Shobokshy

and Hussein [19] investigated how dust with different physical properties affects the performance of photovoltaic modules, experimentally establishing relationships between dust type and concentration and reductions in panel efficiency.

Subsequently, Costa et al. [9] presented an updated literature review covering 2012-2015 on dust and soiling in solar energy systems, emphasizing the need to develop region-specific forecasting models. The problem is particularly acute in arid or dusty environments, as well as at industrial sites such as mine spoil heaps, where airborne particulate matter is abundant [17], [20]. More recent studies have confirmed these findings and provided further insight into the mechanisms of dust-induced performance degradation [21], [22].

2.2. Computational fluid dynamics in dust deposition studies

Computational fluid dynamics (CFD) has emerged as a powerful tool for investigating complex airflow patterns and dust particle behaviour around solar panels [12], [17]. CFD simulations enable researchers to model gas-solid flows, predict dust deposition rates, and identify key parameters that influence accumulation [23]. A significant contribution to the development of numerical dust deposition modelling methods was made by Lu and Zhao [24], [25], who used CFD to predict contamination in isolated, ground-mounted solar panel systems.

In their work [24], the authors employed the SST $k-\omega$ turbulence model and the Discrete Phase Model (DPM) to simulate gas-solid flow. Results showed that the dust deposition rate initially increases and then decreases with particle diameter, reaching a maximum of 13.71% at 100 μm at a wind speed of 1.3 m/s. In a subsequent study [25], the authors extended the model to solar panel arrays, revealing complex aerodynamic interactions between panel rows.

Detailed CFD modelling of dust deposition on solar panels was conducted by researchers at Cairo University [11], [17] using ANSYS Fluent 18.2 with the SST $k-\omega$ turbulence model. The study was carried out under Egyptian climatic conditions, with wind speeds ranging from 1 to 11.5 m/s. It was found that increasing wind speed reduces the dust deposition rate, whilst at speeds above 2 m/s, an increase in particle diameter or dust density leads to increased deposition intensity. Model validation was performed by comparing the model output with experimental data obtained in a wind tunnel.

A study by Peng et al. [26] presents a 3D model of dust deposition on solar panels installed on buildings, using the SST $k-\omega$ turbulence model with inlet profiles and a discrete particle model. The authors thoroughly examined the influence of dust size, wind speed, and building roof inclination on deposition behavior. The study established that 3D modelling shows significant differences in flow structure compared with 2D modelling, with the separation vortex size in the 3D model being significantly smaller. The maximum deposition rate of 2.54% was observed for particles with a diameter of 150 μm .

Zhang et al. [11] proposed a promising CFD-DEM (discrete element method) approach for modelling the dynamic dust deposition process on solar panels in railway systems. Unlike previous studies, a soft-sphere model was used to capture dust-panel surface interactions. The simulations showed that most clay particles ($d = 10 \mu\text{m}$) bypass the panel with the airflow (deposition rate only 4.6%), whilst the deposition rate of fine sand ($d = 100 \mu\text{m}$) reaches 32%.

Hu et al. [27] conducted a numerical study of dust deposition on solar panels using a 3D simulation model. They

applied the results to optimize panel installation parameters. The study examined how inter-row spacing affects actual dust deposition in arrays. A commercial CFD software package with the SST $k-\omega$ turbulence model and a discrete particle model was employed. Results demonstrated that wind speed is the primary factor affecting dust deposition.

Wang et al. [12] present experimental studies of dust deposition characteristics on solar panel arrays conducted in a wind tunnel. The authors emphasize that CFD has become widely used among researchers to study dust deposition phenomena and panel cooling under wind influence. The research aims to quantify the environmental factors affecting solar generation and to integrate the results into intelligent power plant management systems.

2.3. Aerodynamic approaches and passive dust mitigation

Insights from CFD simulations have paved the way for aerodynamic approaches to passive dust mitigation. These methods aim to harness natural wind forces to minimize dust accumulation, often by optimizing the physical configuration of the solar panels or introducing specific design elements.

Research indicates that optimizing installation parameters, such as tilt angle, orientation, and height, can significantly affect dust deposition [22]. Higher installation heights and specific tilt angles can alter local wind flow, potentially reducing soiling [23]. Wind-tunnel experiments show that modifying the geometry of solar panel arrays can either significantly reduce or increase dust deposition, depending on the configuration [12].

The strategic placement of wind barriers or dust shields has been explored as a means of modifying airflow around solar panels. These structures can reduce wind velocity in certain areas, preventing dust from reaching the panel surface, or, conversely, create turbulence that dislodges settled particles [28]. Studies have demonstrated that dust shields can reduce deposition rates by a notable percentage by obstructing dust paths and inducing air drafts [29].

Dagher and Kandil [17] investigated vortex generators as a novel passive cleaning method and demonstrated their potential to reduce dust deposition. This highlights the potential of engineering airflow to actively prevent or remove dust.

2.4. Solar panel placement on mine spoil heaps and tailings

The potential to utilize tailings impoundments as sites for solar panel installation is supported by Wies et al. [30], who analysed the long-term economic benefits (payback period) of installing solar panels on mining facilities. The authors note that, because extraction, processing, and transportation of minerals are energy-intensive, most mines already have developed electricity transmission infrastructure, which eliminates one of the principal costs associated with solar farms. Energy can initially be used for mining operations and, following mine closure, fed into the power grid.

Geotechnical aspects of solar panel placement on mining tailings are detailed in another publication [31]. It was established that active tailings deposition zones consist of a coarse-grained, freely draining, relatively stable solid mass around the perimeter, with a fine-grained mass of low shear strength around the supernatant pond. Assessing the geotechnical stability of solar panel supports, the foundations of which are placed on mining tailings, is critical for maintaining panel orientation within acceptable limits.

A comprehensive review of opportunities to utilize and recover mining waste is presented in Mancini et al. [32], which

discusses various sustainable rehabilitation schemes, with particular emphasis on the technical viability of developing renewable energy infrastructure. The authors note that more than 4.7 billion tons of mining waste and 1.2 billion tons of tailings are stored across the European Union, representing a significant opportunity for energy-focused repurposing.

The SUMAD (Sustainable Use of Mining Waste Dumps) project [33] presents a comprehensive approach to spoil heap rehabilitation, emphasizing renewable energy infrastructure, including solar panels and wind farms. The project aims to deepen understanding of the heterogeneity and time-dependent mechanical behaviour of spoil heap rock and to advance new modelling methods to support spoil heap reuse. An assessment of the advantages and limitations of placing solar panels on abandoned dumps has been conducted [1], whilst the broader potential for deploying solar panels in open-pit mines worldwide to support the clean energy transition has been evaluated [4].

2.5. Research gap and study objectives

Whilst significant progress has been made in understanding dust deposition on flat solar panel surfaces and in developing mitigation strategies, a notable research gap remains regarding the specific application of aerodynamic optimization to complex topographies such as mine spoil heaps. The unique geometry and material properties of these heaps are likely to create distinct wind-flow patterns and dust-generation mechanisms that warrant dedicated investigation. Existing CFD studies have primarily focused on standard ground-mounted or rooftop installations [23], [24].

Therefore, there is a clear need for studies that model wind flow over representative spoil heap geometries and identify optimal panel orientations and elevations to harness natural airflow for passive dust minimization. Furthermore, comprehensive, scientifically grounded recommendations for the spatial optimization of solar panel placement on mining enterprise spoil heaps do not currently exist. This study aims to address this gap by developing and validating a CFD-based model for mine spoil heaps, ultimately quantifying reductions in dust accumulation and improvements in energy yield.

3. Methods

The research methodology adopts an integrated approach that combines numerical modelling of aerodynamic processes and dust particle transport with experimental validation. The aerodynamic characteristics of airflow in the zone of solar panel placement on mine spoil heaps were determined using Computational Fluid Dynamics (CFD) based on Reynolds-Averaged Navier – Stokes (RANS) equations with the Shear Stress Transport (SST) $k-\omega$ turbulence model. The transport and deposition of polydisperse dust particles were modelled using the Discrete Phase Model (DPM), accounting for particle size distribution, aerodynamic forces, and particle – surface interactions. Within the parametric analysis framework, the geometric parameters of panel placement (tilt angle, inter-row spacing, and azimuthal orientation) and airflow velocity were varied according to regional climatic conditions. The reliability of the numerical results was verified by comparing them with field measurements of dust deposition intensity at test sites, thereby ensuring the validity of subsequent spatial optimization of solar panel placement. The conceptual framework for aerodynamic dust transport processes on industrial spoil heaps with solar panels is illustrated in Figure 1.

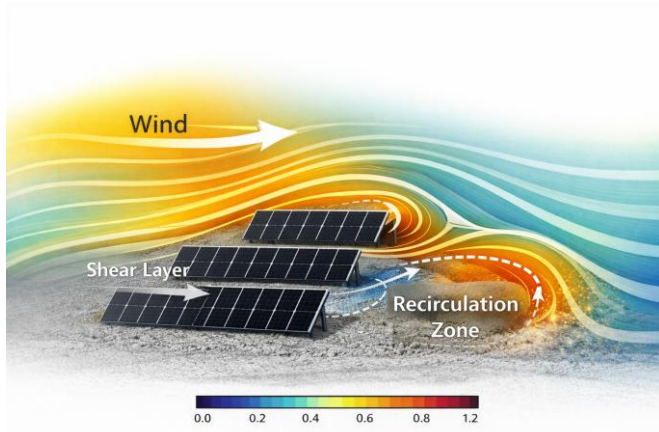


Figure 1. Aerodynamic processes of dust particle transport on industrial spoil heaps with solar panels

These complex flow patterns require a robust mathematical framework that can capture turbulent structures, separation zones, and particle-flow interactions. To accurately represent these phenomena, the airflow field is described by the Reynolds-Averaged Navier-Stokes equations, coupled with the SST $k-\omega$ turbulence model:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \frac{\partial u_i}{\partial x_j} \right], \quad (1)$$

where:

- ρ – air density, kg/m³;
- u_i – the velocity vector components, m/s;
- p – pressure, Pa;
- μ – dynamic viscosity of air, Pa·s;
- μ_t – turbulent viscosity, Pa·s.

The turbulent viscosity is determined as:

$$\mu_t = \frac{\rho k}{\omega} \cdot \frac{1}{\max \left[1/\alpha, SF_2 / (a_1 \omega) \right]}, \quad (2)$$

where:

k – turbulent kinetic energy, and ω is the specific dissipation rate.

The SST $k-\omega$ model was selected for its ability to accurately capture near-wall flows and separation zones, which are critical for modelling flow around solar panels. Unlike the standard $k-\epsilon$ model, the SST model provides a superior description of recirculation zones behind obstacles. The RANS approach is employed as a compromise between physical accuracy and computational efficiency for serial optimization variants.

The logarithmic law of the atmospheric surface layer describes the inlet velocity profile of the airflow at the entrance of the computational domain:

$$U(z) = \frac{u^*}{\kappa} \ln \left(\frac{z}{z_0} \right), \quad (3)$$

where:

- u^* – friction velocity, m/s;
- κ – von Kármán constant (0.41);
- z – height above the surface, m;
- z_0 – surface roughness parameter, m.

For industrial spoil heaps, $z_0 = 0.03$ m was adopted, corresponding to a coarse-textured surface in the Davenport classification. The inlet roughness profile was matched to the wall roughness using the equivalent aerodynamic roughness.

The inlet profiles of turbulent kinetic energy and dissipation rate are given by:

$$k(z) = \frac{u^2}{\sqrt{C\mu^*}}; \quad (4)$$

$$\omega(z) = \frac{u}{\left(C\mu^* (1/4) \cdot kz \right)^*}, \quad (5)$$

where:

$C\mu$ – turbulence model constant (0.09).

Numerical modelling was performed using ANSYS Fluent 2023 R1. The computational domain was discretized with a hybrid unstructured mesh comprising hexahedral elements in the main domain and tetrahedral elements in regions of complex geometry. The total number of elements ranged from 3.2 to 4.8 million, depending on the configuration. Near-wall resolution was achieved by placing the first layer at $y^+ < 1$ and using 5 prismatic layers with a growth ratio of 1.2. Element dimensions were specified as follows: 0.02 m on panel surfaces; 0.05–0.1 m in the spoil heap zone; and 0.5–1.0 m in the far-field region. Mesh quality criteria were maintained with Orthogonal Quality > 0.25 , Aspect Ratio < 35 , and Skewness < 0.85 .

The computational domain represents a section of the solar panel array with the following characteristic dimensions: length (along the main flow direction) of 200 m (50 m upstream of the panels, 100 m panel zone, 50 m downstream) and width of 120 m. The spoil heap geometry was modelled as a conical structure with a 30° slope, a height of 25–35 m, and a base diameter of 80–100 m. Each row of solar panels comprised 8–12 individual modules, each measuring 2.0×1.0 m.

The following boundary conditions were applied: inlet boundary-velocity inlet with logarithmic profile; velocity range of 3–12 m/s at 10 m height; turbulence specified through k and ω profiles. Outlet boundary – pressure outlet with $p = 0$ Pa (gauge pressure) – upper and lateral boundaries – symmetry condition. Spoil heap and panel surfaces-no-slip wall with roughness; spoil heap roughness $k_s = 0.05$ m; panel roughness $k_s = 0.0001$ m (smooth surface). The numerical scheme employed the SIMPLE method for pressure – velocity coupling, second-order schemes for momentum and turbulent quantities, a time step of 0.01 s for transient calculations, and convergence criteria of residuals $< 10^{-4}$ for all equations, with stabilization of integral characteristics to $< 1\%$. Each calculation variant was executed until reaching 3000–5000 iterations or until the convergence criteria were met.

The dust particle transport and deposition model is based on the Discrete Phase Model (DPM), in which the equation determines the particle trajectory:

$$m_p \frac{d\vec{v}_p}{dt} = \frac{1}{2} C_d \rho A_p |\vec{u} - \vec{v}_p| (\vec{u} - \vec{v}_p) + m_p \vec{g}. \quad (6)$$

Deposition occurs when particles contact the panel surface and is determined by particle size (1–100 μm) and local flow velocity. The drag force is defined as:

$$F^d = \frac{1}{2} C^d \rho A_p |u - v_p| (u - v_p), \quad (7)$$

where:

- C^d – drag coefficient;
- A_p – particle cross-sectional area ($A_p = \pi d_p^2/4$);
- u – air velocity, m/s;
- d_p – particle diameter, m.

The drag coefficient is computed using the Morsi-Alexander correlation:

$$C^d = \left(\frac{24}{Re_p} \right) \cdot \left(1 + 0.15 Re_p^{0.687} \right), \quad (8)$$

where:

Re_p – particle Reynolds number ($Re_p = \rho d_p |u - v_p| / \mu$).

Based on analysis of industrial dust composition from spoil heaps of the Kryvyi Rih Basin, the following particle parameters were determined. The size distribution follows a log-normal distribution with a median diameter $d_{50} = 25 \mu\text{m}$ and a geometric standard deviation $\sigma^g = 2.1$. It is modelled over the range 1-100 μm , divided into 10 fractions. Physical properties include particle density $\rho_p = 2650 \text{ kg/m}^3$ (iron oxides and silica) and sphericity form factor $\Phi = 0.85$. Particle velocity at the inlet equals the air velocity, with a mass flow rate of 0.001-0.01 kg/s, depending on dust emission intensity, at a temperature of 293 K.

Upon particle contact with the panel surface, one of three scenarios occurs: deposition when $St < St_{crit}$; rebound when $St > St_{crit}$ and the impact angle $> 45^\circ$; or sliding for fine particles at small impact angles. The deposition criterion is based on the Stokes number:

$$St = p_p d_p^2 v_n / (18 \mu Dc), \quad (9)$$

where:

v_n – standard velocity component at impact, m/s;

Dc – characteristic dimension of surface inhomogeneity, m.

The selection of $St_{crit} = 0.15$ was based on a combination of literature evidence and experimental calibration. Theoretical studies of particle impaction on surfaces report critical Stokes numbers in the range of 0.10-0.30, depending on surface roughness, particle shape, and impact angle. For rough industrial surfaces ($k_s > 0.01 \text{ m}$) with irregular mineral particles (sphericity $\Phi = 0.80-0.90$), values in the range of 0.12-0.18 are typically reported.

To identify the optimal value for the specific conditions of spoil heap dust from the Kryvyi Rih Basin, a sensitivity calibration was conducted by running the DPM model with St_{crit} values of 0.10, 0.12, 0.15, 0.18, and 0.20, and comparing the predicted deposition fluxes with the field measurements described in above Equation (3). The root mean square error (RMSE) between simulated and measured values was minimized at $St_{crit} = 0.15$, yielding an RMSE of 0.09 g/m²·day, compared with 0.14-0.21 g/m²·day for the other tested values. This result aligns with mid-range values reported in the literature for similar particle – surface systems, confirming that $St_{crit} = 0.15$ is an appropriate engineering parameter for the present study.

To account for the influence of air humidity on dust deposition, an empirical correction factor was introduced:

$$k_{humid} = 1 + 0.35 \cdot (RH - 30) / 70, \quad (10)$$

where:

RH – relative humidity, %.

At $RH > 70\%$, particle agglomeration increases the average particle size by 20-40%.

Modelling was conducted for the climatic conditions of the Kryvyi Rih Basin area (Dnipropetrovsk Oblast, Ukraine). Wind rose data from meteorological station records (2018-2023) indicate that the dominant directions are north-westerly (32%) and northerly (24%), with a mean annual wind speed of 4.2 m/s and a maximum speed (5% exceedance probability) of

12 m/s. The temperature regime comprises a summer period (May-September) of +18 to +28°C and a winter period of -5 to +2°C, with an air density of 1.15-1.25 kg/m³. Mean annual relative humidity is 65%, with a minimum of 45-50% in July and a maximum of 80-85% in December. Dust emission intensity ranges from a baseline of 0.2-0.5 g/(m²·day) to up to 2.0 g/(m²·day) during strong winds exceeding 8 m/s.

The optimization criterion minimizes the mean dust deposition flux J (g/m²·day):

$$J = \frac{1}{A} \sum_{i=1}^N \frac{m_i}{\Delta t}, \quad (11)$$

where:

J – deposition intensity, g/(m²·day);

A – total panel area, m²;

N – number of deposited particles;

m_i – mass of the i -th particle, g;

Δt – observation period, days.

Simultaneously, energy yield is considered:

$$E = E_0 (1 - k_{dust} \cdot \delta), \quad (12)$$

where:

E – actual energy yield, kWh;

E_0 – yield of clean panels, kWh;

δ – dust mass per unit area;

k_{dust} – power-loss coefficient ($\approx 0.004-0.007$).

For fine dust ($d_{50} < 20 \mu\text{m}$) – $k_{dust} = 0.007 \text{ m}^2/\text{g}$; for coarse dust ($d_{50} > 40 \mu\text{m}$) – $k_{dust} = 0.004 \text{ m}^2/\text{g}$.

The comprehensive economic indicator accounts for the balance between generation losses and cleaning costs:

$$NPV = \sum_{t=1}^T \frac{(R_t - C_t - M_t)}{(1+r)^t} - I_0, \quad (13)$$

where:

NPV – net present value;

R_t – revenue from electricity sales in year, t;

C_t – panel cleaning costs;

M_t – losses due to underproduction from dust;

r – discount rate (8%);

T – service life (25 years);

I_0 – initial investment, subtracted as a lump sum at $t = 0$.

To determine the optimal configuration, a series of calculations was performed with variations in the following parameters: panel tilt angle (20, 25, 28, 30, 32, 35°); relative inter-row spacing S/H (1.5, 2.0, 2.5, 3.0, 3.5); azimuthal angle deviation from the wind direction (0, 10, 15, 20, 30°); wind speed at 10 m height (4, 6, 8, 10, 12 m/s); and wind direction (NW, N, NE). The total number of variants was 216. For each configuration, temporal averaging was performed over 600 seconds of real time after steady state was established, with spatial averaging over the entire area of 8-12 panels, and 5 realizations with different initial conditions to assess variability. Statistical measures included the mean value $\bar{J}$, standard deviation σ_j , and the 95% confidence interval: $\bar{J} \pm 1.96\sigma_j / \sqrt{n}$. Modelling error estimates comprised: discretization error (Grid Convergence Index) 3.2%; turbulence model error ~10%; total error 15-20%. All calculations were performed in accordance with ISO 50001:2018, IEC 61724-1:2021, and ASME V&V 20-2009.

Field measurements were conducted at two test sites on spoil heap No. 5 of the Ingulets Mining and Processing Plant

(Kryvyi Rih, Ukraine) during the summer monitoring period (June-August 2025). Site 1 was on the windward slope (south-western exposure) at an elevation of 18 m above the heap base; Site 2 was on the leeward slope at 12 m elevation. Both sites are characterized by fine-grained iron ore dust with a median particle diameter $d_{50} = 22\text{--}27\text{ }\mu\text{m}$, consistent with the modelled particle distribution.

Dust deposition intensity was measured at 12 fixed points per site (24 points in total), distributed across the panel surface to capture spatial variability. Passive dust collectors (Bergerhoff-type glass cylinders, 80 mm diameter) were installed at panel height (1.2-1.5 m above ground) and replaced every 14 days, yielding 6 measurement cycles over the three months.

Deposited dust mass was determined gravimetrically: collectors were dried at 105°C for 2 hours and weighed on an analytical balance ($\pm 0.1\text{ mg}$ accuracy) before and after exposure. Deposition flux was calculated as mass per unit collector area per day ($\text{g/m}^2\cdot\text{day}$).

Meteorological conditions were recorded by an automatic weather station installed at the site: wind speed and direction (10-minute averages), air temperature, and relative humidity. The mean wind speed during the monitoring period was 4.6 m/s; the dominant direction was north-westerly (NW, 315°), consistent with the long-term wind rose. No significant precipitation events ($> 5\text{ mm/day}$) occurred during the measurement cycles; cycles affected by rainfall were excluded from validation. Panel surfaces were not cleaned during the monitoring period to ensure comparability with model predictions.

The measured deposition values were compared with CFD-DPM simulation results for identical geometric configurations and meteorological boundary conditions. A summary of mean values across six measurement cycles (field measurements, uncertainty $\pm 8\%$) is presented in Table 1.

Table 1. Comparison of measured and simulated dust deposition values

Test point	Location	Measured, $\text{g/m}^2\cdot\text{day}$	Simulated, $\text{g/m}^2\cdot\text{day}$	Difference, %
P1	Site 1, panel centre	0.84	0.97	+15.5
P2	Site 1, panel top edge	0.61	0.71	+16.4
P3	Site 1, panel bottom edge	1.12	1.28	+14.3
P4	Site 2, panel centre	0.53	0.60	+13.2
P5	Site 2, panel top edge	0.38	0.43	+13.2
P6	Site 2, panel bottom edge	0.79	0.90	+13.9

To enable consistent comparison across 216 modelling variants, a baseline configuration was defined as follows: panel tilt angle 25°; inter-row spacing-to-height ratio $S/H = 2.0$; wind speed at 10 m height $U_{10} = 8\text{ m/s}$; dominant wind direction NW (315°); relative humidity $RH = 65\%$; particle size distribution log-normal with $d_{50} = 25\text{ }\mu\text{m}$ and $\sigma^g = 2.1$; spoil heap geometry – conical structure with slope angle 30°, height 30 m, and base diameter 90 m. This configuration represents a typical, non-optimized installation on a spoil heap of the Kryvyi Rih Basin area and serves as the reference point for all reported percentage reductions in dust deposition and gains in energy yield.

4. Results and discussion

The CFD modelling results were validated against field measurements at two test sites. As summarized in Table 1 and illustrated in Figure 2, CFD predictions show good agreement with experimental data, with discrepancies ranging from 12% to 18% and no systematic bias, confirming the adequacy of the RANS-SST/DPM approach for industrial spoil heap conditions. Velocity profile deviations did not exceed 8%.

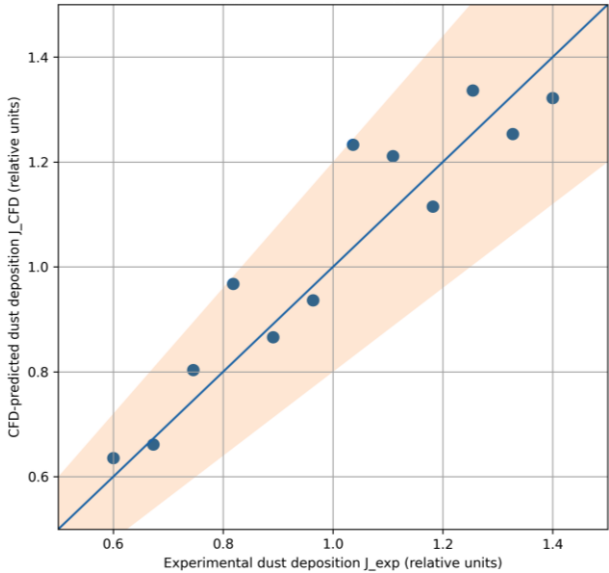


Figure 2. Validation of CFD-DPM model against experimental dust deposition measurements

Experimental points represent field measurements at 24 monitoring locations across two test sites on spoil heap No. 5 of the Ingulets Mining and Processing Plant (summer 2025), supplemented by wind tunnel measurements conducted at Kryvyi Rih National University ($Re = 105\text{--}106$). Error bars on the experimental points represent the combined measurement uncertainty ($\pm 8\%$), comprising gravimetric weighing error ($\pm 0.1\text{ mg}$) and spatial variability across replicate collectors. Error bars on the CFD predictions represent the 95% confidence interval derived from 5 simulation realizations with different initial conditions ($\pm 1.96\sigma/\sqrt{n}$). The comparison shows good agreement between numerical predictions and field data, with deviations within $\pm 20\%$, consistent with the estimated total model uncertainty of 15-20%. A sensitivity analysis of the results with respect to key parameters was conducted to identify the most influential factors on dust deposition predictions. As shown in Table 2, wind speed and dust dispersity have the greatest influence on the results, underscoring the need for accurate measurements of these variables for reliable predictions.

Analysis of airflow characteristics provides essential insights into dust transport mechanisms. The logarithmic velocity profile over the spoil heap surface, shown in Figure 3, compares CFD-simulated and theoretical profiles and confirms their close agreement (deviation $< 8\%$).

Table 2. Model sensitivity analysis

Parameter	Variation	Effect on J
Wind speed	$\pm 20\%$	$\pm 28\%$
Particle size	$\pm 30\%$	$\pm 42\%$
Panel tilt angle	$\pm 5^\circ$	$\pm 15\%$
Inter-row spacing S	$\pm 20\%$	$\pm 22\%$
Surface roughness	$\times 2$	$+8\%$

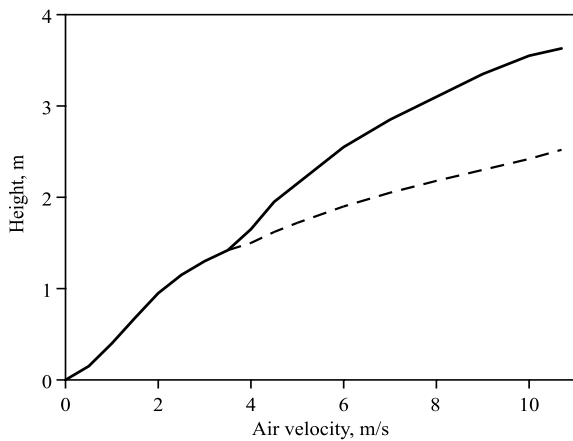


Figure 3. Air velocity profiles over the spoil heap surface at the panel installation zone

Both profiles show a sharp increase in velocity from 0 to 4 m above the surface, which explains the intensity of dust uplift in the near-surface layer.

The solid line shows the CFD-simulated velocity profile obtained with the RANS SST $k-\omega$ model; the dashed line shows the theoretical logarithmic profile calculated from Equation (3) using friction velocity $u^* = 0.31$ m/s and surface roughness $z_0 = 0.03$ m. The close agreement between the two profiles (deviation $< 8\%$) confirms the correct implementation of the inlet boundary conditions and the adequacy of the roughness parameterization adopted in the model. All results below are reported relative to the baseline configuration defined in Section 3. Modelling showed that increasing the tilt angle from 20° to 30° reduces dust deposition by 18-25% owing to enhanced near-surface shear flow. CFD simulations revealed that placing solar panels at the summit of the spoil heap leads to high deposition rates due to turbulence. In contrast, optimal placement is on slopes oriented at 45° to the wind direction. Particle trajectories in these zones were computed using motion Equation (6), with drag and gravitational forces as the governing terms.

The relationship between dust deposition and the inter-row spacing ratio S/H reveals a critical threshold. As shown in Table 3, increasing the spacing ratio from 2.0 to 3.0 reduces dust deposition to 69% of the baseline value. At $S/H < 2.0$, stagnation zones form, increasing deposition sharply, whilst $S/H \geq 2.5$ effectively minimizes recirculation effects.

Table 3. Dust deposition as a function of inter-row spacing ratio

S/H (spacing-to-height ratio)	Dust deposition, % of baseline
2.0	100
2.5	81
3.0	69

In this analysis, H denotes the panel height above ground level. All reported values are normalized relative to the baseline configuration, defined as a tilt angle of 25° , a spacing-to-height ratio (S/H) of 2.0, a wind speed (U_{10}) of 8 m/s from the north-west (NW) direction, and a relative humidity (RH) of 65%.

The azimuthal orientation of panel rows also plays a significant role in minimizing dust deposition. Minimum deposition occurs when panel rows are oriented at a 10 - 15° deviation from the dominant north-westerly wind direction (32% of the frequency), thereby reducing particle flux in the near-surface layer by 12-18% compared with a perpendicular arrangement.

This effect is associated with reduced particle flow in the surface layer and a modification of the turbulence structure around the panels.

The complete dataset of 216 variants underpins the contour maps shown in Figure 4, providing a continuous visual representation of the design space. In the following, representative numerical values are reported for the most practically significant parameter combinations; a summary of key results across the main parameter ranges is provided in Table 4.

Table 4. Summary of dust deposition reduction for selected modelling variants ($U_{10} = 8$ m/s, NW wind direction, $RH = 65\%$)

Tilt angle, $^\circ$	S/H	Azimuth deviation, $^\circ$	Dust deposition, % of baseline	Energy yield gain, %
20	2.0	0	118	-1.2
25	2.0	0	100	0 (baseline)
28	2.5	10	83	+4.1
30	2.5	10	79	+5.6
32	2.5	15	76	+6.3
32	3.0	15	72	+7.1
35	3.0	20	75	+5.8
25	1.5	0	138	-3.5
30	3.5	15	71	+7.4

Note: baseline configuration – tilt = 25° , $S/H = 2.0$, $U_{10} = 8$ m/s, azimuth = 10° , $RH = 65\%$. Negative energy yield gain indicates losses relative to baseline

The dependence of the dust deposition rate on panel tilt angle and inter-row spacing ratio is markedly non-linear, as illustrated in Figure 4. The minimum relative deposition rate (70-85% of the baseline value) occurs at tilt angles of 28° - 32° combined with $S/H \geq 2.5$. At smaller spacing ratios ($S/H < 2.0$), near-surface recirculation zones form, causing rapid increases in deposition that can exceed baseline levels by up to 40%. The contour map highlights the optimal region, characterized by a 15-30% reduction in dust deposition relative to the baseline case (tilt = 25° , $S/H = 2.0$, $U_{10} = 8$ m/s, azimuth = 10° , $RH = 65\%$).

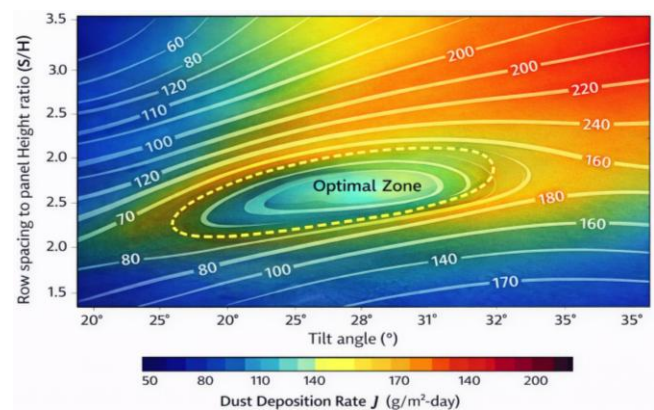


Figure 4. Relative dust deposition rate J_{rel} as a function of panel tilt angle and inter-row spacing ratio S/H

All values are normalized relative to the baseline configuration, defined as a tilt angle of 25° , a spacing-to-height ratio (S/H) of 2.0, a wind speed (U_{10}) of 8 m/s, an azimuth of 10° , and a relative humidity (RH) of 65%. Integrated optimization of geometric parameters for solar panel placement on mine spoil heaps increases annual electricity generation by 5-8% due to reduction of dust-related losses. The economic efficiency of the optimized configuration is further enhanced by less frequent panel cleaning and an extended effective

operational lifespan. These findings provide a quantitative basis for engineering design recommendations applicable to solar installations on industrial sites with elevated dust levels.

The findings of this study have direct implications for the reclamation and productive reuse of mine spoil heaps – a priority challenge for the mining industry in Ukraine and globally. Spoil heaps are a significant legacy of extractive activity: in the Kryvyi Rih Basin area alone, more than 30 active and abandoned spoil heaps occupy over 2500 hectares of degraded land, most of which is currently unsuitable for agricultural or urban development [32], [33]. The proposed methodology provides a site-specific engineering basis for converting these areas into productive renewable energy assets without requiring land remediation.

From a mining engineering perspective, the aerodynamic optimization approach developed in this study addresses a key barrier to deploying solar panels on spoil heaps: accelerated soiling of panels caused by ongoing dust generation from unstabilized heap surfaces and active mining transport operations in adjacent zones. By quantifying the relationship between panel geometry, heap topography, and dust accumulation, the methodology enables engineers to design solar installations that remain economically viable even under high-dust conditions typical of active mining sites. The recommended parameters – tilt angle $28\text{--}32^\circ$, $S/H \geq 2.5$, and azimuthal deviation $10\text{--}15^\circ$ – were derived specifically for the geomorphological and aerodynamic conditions of conical spoil heaps and are therefore directly applicable to mine closure planning, post-mining land use assessments, and environmental impact documentation for new heap formations.

Furthermore, integrating solar generation infrastructure into spoil heap reclamation plans creates a revenue stream during the post-operational period, improving the financial sustainability of mine closure programs and easing the burden on mining companies and regional administrations. This aligns with circular economy principles, increasingly adopted in European and Ukrainian mining regulation, and supports the broader transition of the Kryvyi Rih Basin mining district towards sustainable land use.

The present model was calibrated and validated for summer conditions (June–August 2025), when dust emission intensity is highest due to dry surface conditions and prevailing wind speeds. Seasonal variations in dust emission intensity, reduced in winter due to precipitation and surface freezing, and elevated in spring during snowmelt, are not captured by the current steady-state parametrization. Therefore, applying the model to annual energy yield estimates requires a seasonal correction factor, which is identified as a priority for future work.

The DPM model also treats each deposition event independently and does not account for the progressive consolidation of accumulated dust layers on panel surfaces. In practice, older deposited layers develop cohesive bonds through humidity cycling and partial cementation, altering surface roughness and modifying subsequent deposition behavior. This effect is particularly relevant to assessments that extend beyond the 14-day validation cycle.

A further limitation concerns the idealized geometry of the spoil heap, which was modelled as a symmetric cone with a fixed slope angle and height. Real spoil heaps exhibit asymmetric profiles, surface irregularities, and variable slope stability zones that may create localized aerodynamic effects not captured by this geometry. Site-specific adaptation of the model geometry is recommended for design applications.

In addition, the RANS approach with fixed inlet velocity profiles assumes steady-state wind conditions and does not capture transient events such as gusts, directional shifts, or local thermal convection. These phenomena can produce short-duration deposition spikes that contribute disproportionately to total accumulation but are absent from time-averaged predictions.

Finally, the influence of relative humidity on particle agglomeration is accounted for using a simplified empirical correction coefficient (Eq. (10)), derived from literature data rather than from site-specific measurements. Under extreme humidity conditions ($RH > 85\%$), the actual agglomeration behaviour may deviate from the linear approximation assumed in the model.

Notwithstanding these limitations, the model provides a robust engineering tool for comparative optimization of panel placement parameters under the prevailing summer dust conditions in the Kryvyi Rih Basin area, which account for the dominant share of annual soiling losses.

5. Conclusions

An integrated CFD-DPM model was developed and validated (12–18% deviation from field data) to optimize solar panel placement on mine spoil heaps, accounting for aerodynamic dust transport. The optimal panel tilt angle for spoil heap conditions was found to be $28\text{--}32^\circ$, reducing dust deposition by 18–25% compared with the conventional 25° configuration, while maintaining optimal insolation for the Kryvyi Rih Basin area ($47\text{--}48^\circ$ N). A critical inter-row spacing-to-height ratio of $S/H \geq 2.5$ was identified; below this, recirculation zones increase dust deposition by 30–40%. Orienting panel rows $10\text{--}15^\circ$ from the dominant wind direction further reduces deposition by 12–18%. Combined optimization of these parameters increases annual electricity generation by 5–8% through reduced soiling losses, less frequent cleaning, and an extended operational lifespan.

The novelty of this research lies in the first application of the CFD-DPM framework to the specific conditions of mine spoil heaps, including conical topography, multi-source dust emissions, and industrial wind regimes, rather than to installation on flat surfaces or on building roofs. In practice, the methodology provides site-specific design parameters for solar deployment on active and post-mining land, supporting mine closure planning and the energy-focused reclamation of degraded spoil-heap territory (over 2500 ha in the Kryvyi Rih Basin region), in line with circular-economy principles for the mining industry.

Future research will extend the model to account for seasonal variations in dust regimes, incorporate the effects of humidity and temperature on deposition, and integrate intelligent monitoring systems to support predictive panel-cleaning schedules.

Author contributions

Conceptualization: VS; Data curation: VT; Formal analysis: VS, VT; Investigation: VS, VT, RM; Methodology: VS, VT; Project administration: VS; Resources: RM; Software: VT, RM; Supervision: VS; Validation: RM; Visualization: VT; Writing – original draft: VS, VT; Writing – review & editing: VT. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Acknowledgements

Claude (Anthropic) was used as an assistant in research development, particularly for editing and translation. All theoretical frameworks, data interpretations, and conclusions were developed by the researchers, ensuring that AI enhanced rather than replaced human expertise in the research process.

The authors express their gratitude to Rudomine LLC for organizational support in conducting long-term experiments and for providing industrial sites for the research. Special thanks are extended to the State Militarized Mine Rescue (Emergency Rescue) Unit of the State Emergency Service of Ukraine for modelling aerodynamic processes using specialized software.

We would like to extend our heartfelt appreciation to the anonymous peer reviewers who generously dedicated their time and expertise to reviewing this research paper and providing constructive feedback.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

References

- Heib, M.A. (2022). Assessment of the advantages and limitations of installing PV on abandoned dumps. *Górnictwo Odkrykowe*, 4, 4. <https://doi.org/10.5604/01.3001.0053.8051>
- Winde, F. (2020). Turning water pollution sources into assets: Exploring innovative options of using abandoned mines for generating and storing renewable energy. *Geography Environment Sustainability*, 13(2), 6. <https://doi.org/10.24057/2071-9388-2020-03>
- Shchokin, V., & Tkachuk, V. (2025). DECARBUST: Decarbonization and dust technologies for sustainable mining operations. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, 5, 51-60. <https://doi.org/10.33271/nvngu/2025-5/051>
- Wang, K., Zhou, J., Yang, R., Xu, S., Hu, Z., & Xiao, W. (2025). Deploying photovoltaic systems in global open-pit mines for a clean energy transition. *Nature Sustainability*, 8(9), 1037. <https://doi.org/10.1038/s41893-025-01594-w>
- Macknick, J., Lee, C., Mosey, G., & Melius, J. (2013). *Solar development on contaminated and disturbed lands*. Golden, United States: National Renewable Energy Laboratory. <https://doi.org/10.2172/1260337>
- Murphy, D., Fromm, J., Bairstow, R., & Meunier, D. (2019). A repurposing framework for alignment of regional development and mine closure. *Proceedings of the 13th International Conference on Mine Closure*, 789-802. https://doi.org/10.36487/acg_rep/1915_64_murphy
- Bakum, Z., & Tkachuk, V. (2014). Mining engineers training in the context of an innovative system in Ukraine. *Metallurgical and Mining Industry*, 6(5), 29-34.
- Sarver, T., Al-Qaraghuli, A., & Kazmerski, L.L. (2013). A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. *Renewable and Sustainable Energy Reviews*, 22, 698-733. <https://doi.org/10.1016/j.rser.2012.12.065>
- Costa, S.C.S., Diniz, A.S.A.C., & Kazmerski, L.L. (2016). Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012-2015. *Renewable and Sustainable Energy Reviews*, 63, 33-61. <https://doi.org/10.1016/j.rser.2016.04.059>
- Redondo, M.I., Illanes, R., Alonso-Abella, M., Daliento, S., & Piliouge, M. (2024). Review and comparison of methods for soiling modelling in large grid-connected PV plants. *Sustainability*, 16(24), 10998. <https://doi.org/10.3390/su162410998>
- Zhang, J., Hu, Y., Huang, R., Fan, J., & Duan, Y. (2022). CFD-DEM simulation of dust deposition on solar panels for desert railways. *Applied Sciences*, 13(1), 4. <https://doi.org/10.3390/app13010004>
- Wang, J., Hu, W., Wen, Y., Zhang, F., & Li, X. (2025). Dust deposition characteristics on photovoltaic arrays investigated through wind tunnel experiments. *Scientific Reports*, 15, 1582. <https://doi.org/10.1038/s41598-024-84708-2>
- Kachi, M., & Bechkoura, H. (2025). Experience and modelling of a rotating electrode for the removal of sand particles on PV panels. *Journal of Engineering Science and Technology Review*, 18(1), 80. <https://doi.org/10.25103/jestr.181.08>
- Mykhailenko, O., Baranovskyi, V., Shchokin, V., Karabut, N., & Kolomits, H. (2023). Power consumption control of multi-pump systems of the main water drainage in underground mines based on the Mamdani fuzzy inference system. *IOP Conference Series: Earth and Environmental Science*, 1254(1), 012046. <https://iopscience.iop.org/article/10.1088/1755-1315/1254/1/012046>
- Shchokin, V., & Tkachuk, V. (2014). Automatisatization of agglomerative production based on the application of Neuro-Fuzzy control systems at the bottom level. *Metallurgical and Mining Industry*, 6(6), 32-39.
- Said, S.Z., Islam, S.Z., Radzi, N.H., Wekesa, C.W., Altmanian, M., & Uddin, J. (2024). Dust impact on solar PV performance: A critical review of optimal cleaning techniques for yield enhancement across varied environmental conditions. *Energy Reports*, 12, 1121-1141. <https://doi.org/10.1016/j.egyr.2024.06.024>
- Dagher, M.M., & Kandil, O.A. (2022). Computational prediction of dust deposition on solar panels. *Environmental Science and Pollution Research*, 30(5), 12545. <https://doi.org/10.1007/s11356-022-22993-y>
- Vedulla, G., Geetha, A., & Senthil, R. (2022). Review of strategies to mitigate dust deposition on solar photovoltaic systems. *Energies*, 16(1), 109. <https://doi.org/10.3390/en16010109>
- El-Shobokshy, M.S., & Hussein, F.M. (1993). Effect of dust with different physical properties on the performance of photovoltaic cells. *Solar Energy*, 51(6), 505-511. [https://doi.org/10.1016/0038-092X\(93\)90135-B](https://doi.org/10.1016/0038-092X(93)90135-B)
- Khan, M.A.Z., Wahab, A., Ali, F., Ahmad, N., Kamran, M.A., & Hassan, A. (2023). Performance of solar rooftop panels with disparate particulate accumulation: Exergy analysis on an indoor lab study. *PLoS ONE*, 18(9). <https://doi.org/10.1371/journal.pone.0291018>
- Rusănescu, C.O., Rusănescu, M., Istrate, I.A., Constantin, G.A., & Begea, M. (2023). The effect of dust deposition on the performance of photovoltaic panels. *Energies*, 16(19), 6794. <https://doi.org/10.3390/en16196794>
- Chiteka, K., Arora, R., & Jain, V. (2019). CFD prediction of dust deposition and installation parametric optimisation for soiling mitigation in non-tracking solar PV modules. *International Journal of Ambient Energy*, 42(11), 1307. <https://doi.org/10.1080/01430750.2019.1594373>
- Arora, R., Chiteka, K., & Sridhara, S.N. (2021). A method to predict fouling on multi-storey building-mounted solar photovoltaic panels: A computational fluid dynamics approach. *Journal of Thermal Engineering*, 7(3), 700. <https://doi.org/10.18186/thermal.890150>
- Lu, H., & Zhao, W. (2018). CFD prediction of dust pollution and impact on an isolated ground-mounted solar photovoltaic system. *Renewable Energy*, 131, 829. <https://doi.org/10.1016/j.renene.2018.07.112>
- Lu, H., & Zhang, L.Z. (2019). Influences of dust deposition on ground-mounted solar photovoltaic arrays: A CFD simulation study. *Renewable Energy*, 135, 21-31. <https://doi.org/10.1016/j.renene.2018.11.096>
- Peng, H., Lu, H., Chang, X., Zheng, C., & Wang, Y. (2022). 3D CFD modelling of dust deposition characteristics and influences on building-mounted photovoltaic systems. *Case Studies in Thermal Engineering*, 38, 102336. <https://doi.org/10.1016/j.csite.2022.102338>
- Hu, S., Wang, J., Zhang, Y., Liu, Y., & Li, X. (2023). Research on dust deposition of PV modules based on three-dimensional numerical simulation and its application in installation parameter optimisation. *Journal of Cleaner Production*, 423, 138743. <https://doi.org/10.1016/j.jclepro.2023.138743>
- Chiteka, K., Arora, R., Sridhara, S.N., & Enweremadu, C.C. (2020). Optimising wind barrier and photovoltaic array configuration in soiling mitigation. *Renewable Energy*, 163, 225. <https://doi.org/10.1016/j.renene.2020.08.155>
- Shenouda, R., Abd-Elhady, M.S., Kandil, O.A., & Dagher, M.M. (2023). Numerical investigation of the effect of dust shields on the accumulation of dust over PV panels. *Environmental Science and Pollution Research*, 30(22), 62905. <https://doi.org/10.1007/s11356-023-26502-7>
- Wies, R.W., Crittenden, T.H., Li, X., & Baring-Gould, I. (2009). An investigation to use tailing ponds as solar photovoltaic farms. *Proceedings of the 2009 National Meeting of the American Society of Mining and Reclamation*, 1416-1431.
- Wies, R.W., & Baring-Gould, I. (2009). Geotechnical considerations for solar panel installation on mine tailings. *Proceedings of the 2009 National Meeting of the American Society of Mining and Reclamation*, 1432-1449.
- Mancini, S., Casale, M., Tazzini, A., & Dino, G. A. (2024). Use and recovery of extractive waste and tailings for sustainable raw materials supply. *Commodities*, 4(1), 149-167. <https://doi.org/10.3390/mining4010010>
- Koryčanová, E., Kvasnička, P., & Mašín, D. (2017). *Sustainable use of mining waste dumps: Handbook*. Research Fund for Coal and Steel, European Commission.

Оптимізація розміщення фотоелектричних панелей на гірничих відвалах: аеродинамічний підхід до мінімізації запилення

В. Щокін, В. Ткачук, Р. Макарейко

Мета. Обґрунтування можливості оптимізації розміщення сонячних панелей на гірничих відвалах з урахуванням аеродинамічних процесів переносу пилу для мінімізації запилення поверхні модулів і підвищення ефективності енергогенерації.

Методика. Дослідження базується на чисельному моделюванні турбулентних повітряних потоків методом CFD із застосуванням RANS-моделі турбулентності SST $k-\omega$ у програмному комплексі ANSYS Fluent, дискретному моделюванні траєкторій осідання пилових частинок методом DPM, польових вимірюваннях інтенсивності запилення на тестових ділянках протягом трьох місяців та параметричній оптимізації геометричних характеристик розміщення сонячних панелей.

Результати. Встановлено оптимальний кут нахилу сонячних панелей 28-32°, що забезпечує зниження запилення на 18-25% завдяки посиленню пристінного зсувного потоку. Визначено рекомендоване відношення міжрядної відстані до висоти панелі $S/H \geq 2.5$ для мінімізації застійних зон. Доведено, що орієнтація рядів з відхиленням 10-15° від домінуючого напрямку вітру знижує інтенсивність осідання пилу на 12-18%. Валідація моделі підтвердила розбіжність із експериментальними даними у межах 12-18%.

Наукова новизна. Вперше цілеспрямовано адаптовано методологію CFD-DPM до специфічних умов гірничих відвалів – складної конічної топографії, багатоджерельного полідисперсного пилоутворення та промислових вітрових режимів – на відміну від наявних досліджень, орієнтованих на рівнинні наземні або дахові установки.

Практична значимість. Розроблена методологія дає змогу обґрунтувати раціональні параметри розміщення сонячних панелей на гірничих відвалах, знижуючи втрати продуктивності від запилення на 5-8% на рік. Результати можуть застосовуватися під час рекультивації відвалів і проектування сонячних електростанцій на запилених промислових майданчиках.

Ключові слова: фотоелектричні панелі; гірничі відвали; запилення поверхні; аеродинамічна оптимізація; CFD-моделювання; розміщення панелей; відновлювана енергетика

Publisher's note

All claims expressed in this manuscript are solely those of the authors and do not necessarily represent those of their affiliated organisations, or those of the publisher, the editors and the reviewers.