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Nature-based technologies for the utilisation of technogenically disturbed lands in mining regions

Abstract. The intensive development of the mining industry in the Kryvyi Rih basin has led to the formation of significant areas of technogenically disturbed land (quarries, rock dumps, tailings storage facilities), characterised by complex engineering-geological and geo-ecological conditions and limited suitability for traditional agricultural use. The aim of the study was to analyse the current state of technogenically disturbed land in the Kryvyi Rih mining region and to justify the feasibility of applying nature-based technologies during its revitalisation through the installation of wind turbines. The methodological basis of the study comprised methods of systems analysis, a review of scientific publications, a geo-ecological assessment of technogenically disturbed areas, a comparative analysis of the engineering-geological characteristics of mining sites, and an analysis of natural and technological factors influencing the feasibility of their reuse. The findings identified the specific features of the current mining and environmental conditions of the Kryvyi Rih basin and determined the integrated potential of waste dumps, exhausted open pits, and tailings storage facilities for the safe installation of wind turbines. A detailed analysis of the engineering-geological characteristics confirmed the high potential for using spoil heaps as an alternative means of developing disturbed landscapes. Furthermore, a geo-ecological assessment demonstrated that the considerable height of rock spoil heaps allows for the effective optimisation of the interaction between wind turbines and air flows. Basic principles for the nature-based restoration of disturbed landscapes have been formulated, which envisage synergy between technical-biological reclamation and the infrastructure development of renewable energy without the appropriation of new natural land areas.

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The practical value of the study lies in the scientific justification for the reuse of land disturbed by human activity without further removal of natural areas from economic use, which contributes to improving the efficiency of land resource use, reducing the anthropogenic impact on the environment, and implementing the principles of sustainable development in mining regions

Keywords: reclamation; revitalisation; waste dumps; wind turbines; Kryvyi Rih basin

Introduction

The current stage of global industrial development requires a fundamental rethinking of approaches to sustainable land use. Prolonged mineral extraction by both surface and underground mining methods has resulted in the large-scale degradation of natural ecosystems, the formation of deep open pits, and the accumulation of extensive waste rock dumps. Restoring such areas to an environmentally safe and economically productive condition has become a major challenge for many industrialised countries, as conventional land reclamation techniques often require substantial financial investment and do not always ensure the long-term ecological stability of restored landscapes. Between 2020 and 2025, international practice has demonstrated a clear transition from the traditional reclamation model, focused primarily on the technical restoration of disturbed land, towards the broader concept of post-mining land use. This approach emphasises the long-term planning of functional land use for technogenically disturbed areas in mining regions, taking into account environmental, economic, and social considerations. As highlighted by C. Pagouni *et al.* (2024), K. Karalidis *et al.* (2024), and S. Worden *et al.* (2024), the principal criteria for determining future land use include ecosystem resilience, economic viability, societal value, and consistency with regional development strategies.

One of the most dynamic areas of research during this period is the implementation of Nature-based Solutions (NbS) in the restoration of degraded areas. According to the methodology of the International Union for Conservation of Nature (IUCN), nature-based solutions are measures aimed at the conservation, restoration and sustainable management of natural or modified ecosystems, which simultaneously deliver environmental, social and economic benefits. According to the findings of M. Cardinali *et al.* (2021), the further development of this concept is reflected in the European Commission's practical recommendations on assessing the effectiveness of nature-based solutions as a tool for implementing climate policy and sustainable land management. In this study, nature-based technologies are considered as the practical implementation of the principles of Nature-based Solutions for technogenically disturbed land in mining regions, involving the integration of engineering solutions with natural ecosystem self-recovery processes to form ecologically sustainable nature-technology systems.

Experience from countries such as Germany, the USA, Peru, Poland and Ukraine shows that one of the most promising avenues for the reuse of technogenically disturbed land is the development of renewable energy, as confirmed by the works of K. Kaczmarczyk *et al.* (2023), O.O. Medvedieva *et al.* (2024), and M.A. Cotrina-Teatino *et al.* (2025). Locating solar and wind power stations on the sites of former quarries, waste rock dumps and other mining facilities minimises the use of natural land, contributes to the decarbonisation of the economy and enhances the economic efficiency of revitalisation programmes. At the same time, the study by J.M. Kiesecker *et al.* (2024) emphasised the importance of identifying areas with a low level of environmental conflict for the deployment of wind and solar power generation facilities within the context of the pan-European energy transition. Similarly, S. Worden *et al.* (2024) argued that decisions regarding the future utilisation of technogenically disturbed land should be based on a comprehensive assessment of geotechnical, environmental, spatial, and socio-economic factors.

In Ukraine, the issue of utilising land disturbed by human activity is becoming particularly pressing due to the significant areas of land affected by both surface and underground mining. Traditional approaches have mainly focused on the regulatory and legal framework for land reclamation, improving land-use planning, the protection of land resources, and the application of strategic environmental assessment tools in the field of subsoil use. However, only a few researchers in Ukraine, notably O.S. Kovrov *et al.* (2023) and O.O. Medvedieva *et al.* (2024), have directly addressed issues relating to a comprehensive approach to the utilisation of technogenically disturbed land, its revitalisation and technical-biological reclamation. However, research combining these processes with the systematic integration of nature-based solutions principles and the direct siting of renewable energy facilities on spoil heaps currently requires further development and scientific justification. Given the level of anthropogenic impact, this aspect is of paramount importance for the Kryvyi Rih iron ore basin, one of Europe's largest mining complexes. More than a century of intensive iron ore extraction has resulted in extensive areas of technogenically disturbed land, including open pits, waste rock dumps, tailings storage facilities, and zones of ground deformation. At the same time, the morphometric characteristics, spatial distribution, and wind potential of waste rock dumps create favourable conditions for combining ecological restoration with the development of renewable energy.

Despite significant progress in scientific research into the utilisation of technogenically disturbed land, the scientific and methodological foundations for integrating nature-based technologies, land reclamation, revitalisation and the siting of wind power installations into a unified management system for anthropogenically disturbed areas remain underdeveloped. This necessitates the development of a comprehensive approach to the use of these lands, adapted to the natural, climatic and technogenic conditions of Ukraine. The aim of the study was to justify nature-based technologies for the utilisation of technogenically disturbed land in mining regions based on the principles of Nature-based Solutions, and to determine the prospects for the use of wind turbines as a component of their revitalisation. To achieve this aim, the following objectives were undertaken: to analyse the experience of European Union countries (in particular Poland and Germany) regarding post-mining land use; to investigate the spatial condition of technogenic disturbed areas in the Kryvyi Rih iron ore basin; to summarise the principles of nature-based restoration of degraded landscapes and to assess the engineering-geological prerequisites for using waste rock dumps to accommodate wind energy facilities.

Materials and Methods

This analytical and predictive study was based on a comprehensive geo-ecological assessment and spatial modelling of the potential for renewable energy on degraded landscapes. The regional case study focused on technogenically disturbed land at the largest mining enterprises in the Kryvyi Rih iron ore basin, which was formed as a result of prolonged (over 140 years) intensive open-cast and underground mining and the processing of iron ore. The criteria for selecting specific study sites were: the scale of anthropogenic disturbance, the duration of the disturbed state, the elevation and geometric parameters of the disturbed areas, as well as the presence of developed industrial infrastructure and the absence of current competition from agriculture or forestry.

The research materials comprised scientific publications, regulatory and legal documents in the field of land protection, as well as summarised geo-ecological and statistical reports from mining enterprises in the Kryvyi Rih iron ore basin for the period 2021-2025. In particular, the analysis utilised environmental impact assessment reports and post-project monitoring materials, which are publicly available on the official websites of industrial enterprises in the city of Kryvyi Rih, the Kryvyi Rih District State Administration, and on the web portal of the Ministry of Economy, Environment and Agriculture of Ukraine (n.d.). The criteria for selecting scientific sources for the analysis were: relevance to the topics of post-mining land use and Nature-based Solutions; indexing in scientometric databases (Scopus, Web of Science); geographical coverage (EU countries, the USA, Latin America); and publications no more than five years old. A general description of the sites studied within the mining concessions of Kryvyi Rih basin enterprises is presented in Table 1.

Table 1. *Sites of technogenically disturbed land at mining enterprises in the Kryvyi Rih basin*

Enterprise	Principal features	Number of features	Total area, ha
Sukha Balka Mine	Subsidence zones and waste rock dumps, disturbed land, "Dubrova Gully", and waterlogged area	6	250.2
Southern Mining and Processing Plant	Sections of the "Shymanivskyi" and "Pravoberezhnyi" waste dumps	1	68.7
Central Mining and Processing Plant	Open pits and waste dumps	3	126.5
Northern Mining and Processing Plant	Open pits, truck-operated waste dumps, and disturbed land areas	4	209.0
Ingulets Mining and Processing Plant	Waste Dumps No. 1 and No. 3	2	259.5
ArcelorMittal Kryvyi Rih	Truck-Operated Waste Dump No. 3	1	54.0
Total			967.9

Source: *compiled by the authors based on an analysis of the enterprises' geo-ecological and statistical data (Sukha Balka, n.d.; Southern Mining and Processing Plant, n.d.; Central Mining and Processing Plant, n.d.; Ingulets Mining and Processing Plant, n.d.; ArcelorMittal Kryvyi Rih, n.d.)*

The study was carried out in several consecutive stages. The first stage involved an analysis of current scientific approaches to the reuse of technogenically disturbed land, the revitalisation of post-mining areas and the implementation of nature-based technologies, as outlined in the works of M. Hendrychova *et al.* (2020), C. Pagouni *et al.* (2024), and S. Worden *et al.* (2024). A system of fundamental reclamation and energy principles was developed by integrating three key components, namely the theoretical basis drawn from the literature, from which the conceptual foundations of ecological balance and the engineering and energy compatibility of sites were derived, the requirements of Ukraine's regulatory and legal documents, in particular the Land Code and the Subsurface Code, which defined the boundaries of legal certainty and the mandatory stages of mining reclamation; and the actual regional geo-ecological characteristics of the Kryvyi Rih basin, including the physical and mechanical properties of the spoil heaps, the topographic potential of waste dumps and the parameters of the local wind climate, which set the actual technical constraints. The choice of these specific principles is dictated by the need to simultaneously address environmental objectives regarding landscape stabilisation and engineering requirements for ensuring efficient power generation.

These principles were incorporated into the conceptual model as fixed spatial filter criteria, against which each analysed waste dump was systematically assessed for compliance with the specified requirements; this made it possible to identify specific sites suitable for revitalisation and to use them as the basis for developing the final conceptual model. In the second stage, a geo-ecological characterisation of the technogenically disturbed lands of the Kryvyi Rih basin was carried out, taking into account their morphological features, types of disturbance, engineering-geological condition and current use. Particular attention was devoted to waste rock dumps, which were identified as the most promising locations for the deployment of wind energy systems owing to their considerable elevation, favourable conditions for wind flow enhancement, open terrain, and the absence of conflicts with agricultural land use. The third stage comprised a comparative assessment of the natural, technogenic, and engineering-geological factors determining the potential for the reuse of different categories of technogenically disturbed land.

The methodological basis of the study was provided by methods of systems analysis, which were applied to consider technogenically disturbed lands as complex natural-technical systems; the method of comparative analysis was used to compare different types of disturbed areas in terms of their suitability for revitalisation. The comparison criteria were as follows: the geometric parameters of the landmasses (plateau area and elevation), the degree of geotechnical stability of slopes and the riverbed, the intensity of hazardous geodynamic processes, the level of flooding and characteristics of the hydrogeological regime, proximity to existing energy infrastructure hubs of industrial enterprises, as well as the degree of surface erosion vulnerability. A geo-ecological assessment method was employed to determine the ecological status and potential for the reuse of the studied areas. Structural-functional analysis was used to establish the interrelationships between the processes of reclamation, revitalisation, and renewable energy development. In addition, the method of generalisation was applied to systematise contemporary scientific approaches to the utilisation of technogenically disturbed land, as presented in the works of C. Pagouni *et al.* (2024) and S. Worden *et al.* (2024).

The conceptual basis of the study was the adaptation of the principles of Nature-based Solutions to the conditions of technogenically disturbed land in mining regions (Cardinali *et al.*, 2021; Rendle *et al.*, 2023). When assessing the prospects for land use, the following factors were taken into account: ecological balance, adaptability to anthropogenically altered landscapes, compatibility with land reclamation and energy generation, the potential for integrated land use, safety in terms of geotechnical and hydrogeological conditions, and the energy feasibility of siting wind turbines (Guan *et al.*, 2022; Xiao *et al.*, 2022; Aska *et al.*, 2024). The limitations of this study included its focus exclusively on the specific characteristics of iron ore enterprises in the Kryvyi Rih basin, which have high waste rock dumps, without taking into account the characteristics of degraded landscapes in coal-mining regions. Furthermore, the spatial analysis was limited by the available open-access data from environmental impact assessment reports and post-project monitoring materials from the enterprises, as the imposition of martial law made it impossible to carry out a full range of detailed field engineering, geodetic and aerial surveying work directly at the sites.

Results and Discussion

Assessment of the potential of post-mining areas and the development of a model for their reclamation and energy-based revitalisation

The analysis of technogenically disturbed land in the Kryvyi Rih Iron Ore Basin demonstrated that the most promising sites for the installation of wind energy systems are waste rock dumps and exhausted open pits, which are characterised by extensive areas, well-developed landforms, and the absence of competition from other forms of land use. However, the effectiveness of their utilisation depends not only on natural conditions but also on compliance with a comprehensive set of environmental, engineering, and spatial requirements (Rahmonov *et al.*, 2022; Medvedieva *et al.*, 2024).

To provide a detailed assessment of site suitability, the proposed evaluation criteria were applied to the mining enterprises listed in Table 1. In particular, Truck-Operated Waste Dump No. 3 of ArcelorMittal Kryvyi Rih (54.0 ha) and Waste Dumps No. 1 and No. 3 of the Ingulets Mining and Processing Plant (total area 259.5 ha) were identified as potentially suitable locations for the safe deployment of vertical-axis wind turbines. The principal selection criteria included the geotechnical maturity of the waste dump masses (active dumping having ceased more than 15 years ago, allowing adequate foundation stabilisation), the extensive plateau areas available to ensure safe spacing between turbines, and elevations exceeding 40 m, which provide favourable conditions for the natural acceleration of near-surface wind flows. In contrast, the subsidence zones and waterlogged areas of the Sukha Balka Mine, despite their considerable area (250.2 ha), exhibit limited environmental and engineering potential owing to the risks of unpredictable geodynamic movements and flooding, making the construction of heavy engineering structures unsuitable. Based on a synthesis of contemporary approaches to post-mining land use, a system of principles for the nature-based utilisation of technogenically disturbed land for the deployment of wind energy systems was developed (Table 2). Unlike existing approaches, the proposed framework integrates the requirements of environmental safety, land reclamation, geotechnical reliability, and renewable energy development into a unified concept for the management of post-mining landscapes (Kovrov *et al.*, 2022; Medvedieva *et al.*, 2026).

Table 2. *Principles of nature-based utilisation of technogenically disturbed land for the deployment of wind energy systems*

Principle	Main content	Practical significance
Environmental sustainability	Minimising environmental impact, noise pollution and disruption to bird migration	Preservation of natural ecosystems and biodiversity
Adaptability to man-made landscapes	Utilising existing waste dumps, quarries and man-made elevations without significantly altering the terrain	Reduction in the volume of earthworks and improvement in energy efficiency
Compatibility with land reclamation and energy generation	Combining wind turbine construction with technical and biological restoration measures	Comprehensive land restoration
Closed-loop technological cycle	Maximising the use of existing infrastructure and recycled materials	Reduction in the consumption of natural resources
Integrated land use	Combining wind energy with other environmentally compatible activities	Creation of multifunctional post-mining landscapes
Geotechnical and hydrogeological safety	Taking into account the stability of waste dumps, and the risks of subsidence, landslides and flooding	Ensuring the long-term operational reliability of wind turbines
Energy efficiency	Using sites with sufficient wind potential and the capacity for off-grid operation	Improving the efficiency of electricity generation

Source: *compiled by the authors based on the results of the study*

The results obtained indicate that individual principles cannot be applied in isolation. For example, utilising the natural elevations of rock dumps significantly increases the efficiency of wind turbines due to the natural acceleration of air masses; however, without taking into account the geotechnical stability of the slopes and the dynamic load on the rock mass, there is a high risk of accidents occurring. Similarly, the integration of wind turbines with land reclamation measures not only ensures the production of renewable energy but also contributes to the restoration of ecosystem functions in disturbed areas. In this context, studies by M. Resak *et al.* (2022) and K. Kaczmarczyk *et al.* (2023) confirm that combining energy development with the ecological management of post-mining landscapes makes it possible to minimise cumulative anthropogenic pressure. At the same time, as K. Wang *et al.* (2025) rightly point out, it is precisely a comprehensive approach to the restoration of biogeocenoses within the impact zone of energy facilities that is the key factor in ensuring the long-term stability of reclaimed land.

The proposed system of principles significantly expands traditional approaches to the reclamation of disturbed land, shifting them from the realm of passive environmental conservation to that of active technological and energy-based regeneration. Traditional engineering solutions, which dominate current practice, are usually limited to two approaches: a technical one, involving the grading of spoil heaps and covering them with protective layers; and a biological one, aimed at applying a fertile soil layer and phytoremediation to prevent dust and erosion. At the same time, spoil heaps and quarries are viewed purely as sites of accumulated environmental damage, requiring long-term financial and technical expenditure to maintain their stability. The proposed approach broadens this paradigm in several fundamental respects, most notably by transforming such sites from environmental liabilities into valuable resources. Rather than isolating disturbed land, it advocates its valorisation through the integration of an energy-generating function directly into the structure of the post-mining landscape. Under this concept, the technogenic landform – particularly the plateaus of elevated waste rock dumps – performs a beneficial engineering function by naturally accelerating near-surface wind flows, thereby improving the efficiency of wind energy generation.

At the same time, synergy between reclamation and power generation is achieved, whereas the conventional approach often regards industrial construction on reclaimed land as a source of additional burden. In the developed system, the principles of geotechnical safety and reclamation-energy compatibility are integrated in an interrelated manner: biological reclamation, achieved by anchoring surfaces with grass roots, stabilises the top layer of the spoil heap, significantly reducing abrasive wear on the moving parts of vertical-axis wind turbines caused by dust, whilst energy generation covers the operational costs of monitoring the condition of the waste dump mass. Another important aspect of the proposed approach is the differentiation of disturbed land according to the type of technogenic landform. Unlike existing regulatory approaches, which generally prescribe uniform management strategies for disturbed land, the proposed framework enables flexible site classification. As illustrated by the enterprises presented in Table 1, it provides a practical tool for excluding inherently hazardous areas, such as the subsidence zones of the Sukha Balka Mine, while identifying geotechnically mature plateaus, including Truck-Operated Waste Dump No. 3 of ArcelorMittal Kryvyi Rih and the waste dumps of the Ingulets Mining and Processing Plant, as sites suitable for technological development. Thus, whilst traditional approaches aim to restore the landscape to a notional "original", often low-productivity state, the author's system of principles creates a forward-looking model of revitalisation. It demonstrates that the ecological restoration of mining regions can take place not in spite of, but due to, the deployment within their territory of innovative industrial infrastructure – decentralised "green" energy based on vertical-axis installations.

The nature-based use of post-mining sites for the development of wind energy

The results of the analysis indicate that the effective utilisation of technogenically disturbed land cannot be limited to the simple selection of suitable sites for the installation of wind energy systems. Achieving maximum environmental and economic efficiency is possible only through the comprehensive integration of land reclamation, revitalisation, and renewable energy development into a unified management framework for post-mining landscapes. In this context, the studies of K. Karalidis *et al.* (2024) and S. Amirshenava & M. Osanloo (2022) convincingly demonstrate that the isolated planning of individual reclamation measures reduces the overall restoration potential of industrial regions.

The synthesis of the identified principles enabled the development of a conceptual model for the nature-based utilisation of technogenically disturbed land, illustrating the interrelationships between natural restoration processes, engineering interventions, and the anticipated outcomes of their implementation. The distinctive feature of applying this model within the Kryvyi Rih Iron Ore Basin is that the theoretical principles presented in Table 2 are translated into a clearly defined technological framework, in which each component of the model (Table 3) represents a specific stage in the landscape restoration lifecycle. The transition from general environmental and engineering principles to a practical implementation model is achieved through a system of spatial filters linking the physical characteristics of individual waste dumps, such as the strength properties of the waste rock and the elevation of the plateau, with the operational parameters of vertical-axis wind turbines. Through this approach, the model evolves beyond a declarative set of objectives into a dynamic planning tool, whereby the geotechnical stabilisation of waste dump surfaces during the reclamation stage directly establishes a safe engineering platform for the subsequent installation of wind energy infrastructure while simultaneously facilitating the restoration of biogeocoenoses during the revitalisation phase.

Table 3. *Conceptual model for the nature-based utilisation of technogenically disturbed land*

Component	Natural component	Engineering component	Expected outcome
Land reclamation	Restoration of vegetation	Site planning	Land stabilisation
Revitalisation	Restoration of ecosystem functions	New functional use	Enhancing ecological value
Wind energy	Utilisation of wind energy potential	Installation of wind turbines	Renewable energy production
Nature-based Solutions	Integration of natural processes	Minimisation of human intervention	Sustainable land use

Source: *compiled by the authors*

The interrelationship between the components of the conceptual model presented is characterised by sequential determinism, whereby the successful implementation of each preceding stage is a mandatory engineering and environmental prerequisite for the deployment of the next. The logic behind the transition from the theoretical principles set out in Table 2 to the practical architecture of the model lies in the transformation of general requirements into interrelated technological stages. In particular, the principles of geotechnical safety and adaptation to technogenically transformed landscapes are directly translated into the land reclamation component. This component ensures the initial stabilisation of the disturbed massif through engineering planning and the creation of stable slope profiles, thereby minimising landslide processes.

The subsequent transition from reclamation to revitalisation implements the principles of ecological balance and reclamation-energy compatibility. At this stage, the engineered surface becomes a substrate for the implementation of nature-based solutions, which trigger the natural self-recovery of biogeocenoses and the formation of stable vegetation cover. An important innovative feature of the model is that the plant community formed during the revitalisation stage serves a protective function for the third component – wind power generation – as dense vegetation drastically reduces the level of dust in the air at ground level. This minimises abrasive wear on the moving parts and blades of vertical-axis wind turbines, significantly extending their service life and enhancing the project's overall energy efficiency.

The specific application of the developed model to the conditions of the Kryvyi Rih iron ore basin is determined by the region's unique geological, technogenic and aerodynamic parameters. Unlike conventional coal spoil heaps or sand quarries, the large waste rock dumps of the Kryvbas region consist mainly of hard rock and are characterised by considerable height, often exceeding 40-80 metres, as well as large areas of flat plateaus. This geometry of the man-made relief massif creates the effect of artificial orographic acceleration of surface wind flows, transforming the tops of the spoil heaps into areas with high wind energy potential.

At the same time, the substantial dynamic loading generated by heavy mining equipment during waste rock deposition, together with the prolonged period required for the natural consolidation of waste rock masses, necessitates strict compliance with minimum stabilisation periods before engineering development can commence. The proposed model therefore assumes that wind energy infrastructure based on vertical-axis wind turbines may be deployed only on geotechnically mature sites, where active slope adjustment and foundation settlement processes have ceased for at least 15 years. The flexibility and multifunctionality of the proposed model enable it to address two critical challenges facing the Kryvyi Rih region simultaneously: the shortage of decentralised electricity generation capacity required to meet peak industrial energy demand and the need for large-scale ecological restoration of degraded landscapes without withdrawing valuable productive land from agricultural use.

According to the data in Table 3, the proposed conceptual model is based on the sequential integration of natural and engineering solutions. In the initial stages, reclamation ensures the initial stabilisation of areas disturbed by human activity and creates the basic conditions for their subsequent safe use. In this context, studies by O. Rahmonov *et al*. (2022) and M. Tibbett (2024) confirm that high-quality technical preparation of the substrate is a fundamental basis for any post-mining landscape development scenarios. The next step in the revitalisation phase involves restoring lost ecosystem functions and establishing a new functional purpose for the areas. The subsequent integrative stage involves the direct implementation of wind energy facilities, which allows for the harmonious combination of long-term ecological restoration with the generation of renewable energy. Combining these processes within a single framework of nature-based solutions framework facilitates the comprehensive utilisation of technogenically disturbed land in accordance with the principles of sustainable development, minimises additional anthropogenic pressure, and substantially improves the efficiency of land resource utilisation. Thus, whilst Table 2 sets out in detail the fundamental principles that must be taken into account during decision-making, Table 3 clearly demonstrates the mechanism for their practical implementation, ensuring a clear logical transition from theoretical principles to the authors' proposed concept of nature-based utilisation of technogenically disturbed land.

The analysis carried out has shown that the use of vertical-axis wind turbines on technogenically disturbed land in the Kryvyi Rih mining region offers a number of significant advantages compared with the traditional use of such areas. Unlike the development of natural land, the installation of wind turbines on waste rock dumps enables the industrial reuse of degraded areas without any additional withdrawal of valuable land from the natural or agricultural land reserve. Furthermore, the design features of vertical-axis turbines allow for the effective utilisation of the complex aerodynamic conditions found in technogenic landscapes, which are characteristic of waste rock dumps and other elevated landforms. The previously cited work of M. Tibbett (2024) clearly demonstrates that vertical-axis wind turbines exhibit substantially greater tolerance to turbulent airflow and rapidly changing wind directions generated by the distinctive orography of waste rock dumps than conventional horizontal-axis turbines. The results of the comprehensive assessment of the principal environmental benefits associated with the deployment of vertical-axis wind turbines are presented in Table 4.

Table 4. *Environmental benefits of deploying vertical-axis wind turbines on technogenically disturbed land*

Assessment aspect	Description of the effect	Practical significance
Sustainable land use	Reuse of mine spoil without encroaching on natural areas	Preservation of natural ecosystems and agricultural land
Reduction of greenhouse gas emissions	Electricity generation without burning fossil fuels	Reducing the carbon footprint of mining enterprises
Impact on birdlife	Lower risk of bird strikes with the rotor compared to horizontal-axis wind turbines	Improving environmental safety
Noise impact	Lower noise and vibration levels	Reducing the impact on the population and the environment
Adaptation to wind patterns	Operation in turbulent and variable airflows without the need to align with the wind direction	Improved utilisation of technogenic landforms
Geo-ecological stabilisation	Combining wind turbine installation with land reclamation measures	Improving the stability of waste rock dumps
Formation of a post-mining landscape	Transforming degraded areas into production and environmental complexes	Implementing the principles of sustainable development

Source: *compiled and summarised by the authors based on research of D. Harrison-Atlas et al. (2022) and O. Medvedieva et al. (2024)*

According to the data presented in Table 4, the greatest environmental benefit is achieved through the synergy of two complementary processes: the revitalisation of technogenically disturbed land and the generation of renewable energy. This makes it possible to simultaneously reduce the area of degraded land that remains unused and minimise the environmental impact associated with electricity generation from conventional sources. Of particular significance for the conditions of the Kryvyi Rih basin is the ability of vertical-axis wind turbines to operate in turbulent airflows, which are characteristic of waste rock dumps. Unlike horizontal-axis turbines, they do not require constant reorientation to follow the wind direction, which ensures more stable operation in conditions of complex man-made terrain. Furthermore, their design features help to reduce noise pollution, the risk of bird strikes against the blades, and potential hazards in the event of structural failure.

The results obtained are conceptually consistent with current international research into the use of post-mining areas, which regards renewable energy facilities as one of the most effective avenues for their revitalisation. At the same time, the proposed approach expands on existing concepts by integrating the processes of land reclamation, geo-ecological stabilisation and renewable energy production into a single system for the nature-based utilisation of technogenically disturbed land. Under such conditions, wind turbines not only fulfil an energy-generation function but also become an integral part of the comprehensive transformation of degraded areas into multifunctional post-mining landscapes, in line with the principles of Nature-based Solutions and contemporary approaches to the sustainable development of mining regions, as previously outlined by researchers M. Cardinali *et al.* (2021), Q. Bo *et al.* (2024), as well as experts from the International Energy Agency (2023).

To strengthen the scientific discussion and validate the proposed model, a broader range of contemporary international studies was incorporated into the analysis. In particular, in the context of the integrated selection of post-mining land-use options, researchers S. Amirshenava & M. Osanloo (2022) emphasise the critical importance of applying strategic matrix planning, which helps to avoid haphazard land development. The model proposed in the present study advances this concept by introducing explicit spatial filtering criteria specifically adapted to waste rock massifs. The global environmental consequences of mining activities have likewise been highlighted by B. Aska *et al.* (2024), who argue that the accumulation of mining waste threatens biodiversity and that its reuse for infrastructure development should therefore be regarded as an environmental priority.

An analysis of global bibliometric data conducted by M.A. Cotrina-Teatino *et al.* (2025) clearly demonstrates a rapid rise in interest in the implementation of renewable energy sources specifically within mining operations. However, whilst most international authors focus on conventional horizontal-axis wind turbines or photovoltaic power stations, the present study demonstrates the advantages of vertical-axis wind turbines specifically for disturbed terrain. Researchers Y. Guan *et al.* (2022) demonstrate that the success of land reclamation depends on the phased restoration of vegetation cover. In the proposed model, vegetation serves not only to stabilise waste dumps but also to protect the kinematic components of vertical-axis wind turbines from abrasive dust, highlighting the technological interdependence of the different restoration stages.

The importance of assessing the spatial dynamics of wind energy deployment is confirmed by the work of D. Harrison-Atlas *et al.* (2022), which highlights the variability in land use during the long-term operation of turbines. Furthermore, whilst investigating the integration of nature-based solutions within the renewable energy sector, E.J. Rendle *et al.* (2023) proposed a three-step algorithm for aligning ecological zones with wind farms, which closely corresponds to the sequence adopted in the present study: "reclamation – revitalisation – wind energy". A further argument in favour of using vertical turbines specifically is provided by the findings of P. Robinson *et al.* (2022), whose aerodynamic tests confirmed their superior efficiency under conditions of oblique and turbulent wind, which is artificially generated by the geometry of the waste dump slopes.

Particular attention should be paid to the specific nature of the operation of facilities under the legal regime of martial law in Ukraine. As noted by O. Medvedieva *et al.* (2026), the operation of the Kryvyi Rih basin mining and processing complexes under these conditions requires the rapid introduction of decentralised energy supply sources to enhance the resilience of industrial hubs, the installation of local wind energy systems on waste rock dumps represents not only an nature-based solution but also a strategically important measure for energy security. Thus, the present study demonstrates that the integration of wind energy infrastructure based on vertical-axis turbines into the degraded landscapes of mining regions facilitates a transition from the passive conservation of disturbed land areas to their active, nature-based restoration. The proposed conceptual model, based on the sequential implementation of the stages of geotechnical stabilisation, biological revitalisation and energy generation, enables the transformation of accumulated environmental damage into a spatial and technological resource. The practical implementation of this approach in the Kryvyi Rih iron ore basin creates the conditions for the formation of sustainable, multifunctional post-mining landscapes, which is fully in line with the principles of Nature-based Solutions and ensures the environmental and energy decentralisation of the region without the additional encroachment on natural land.

Conclusions

The results of this study substantiate the feasibility of using technogenically disturbed land in mining regions as a promising spatial resource for the development of renewable energy based on the principles of Nature-based Solutions. It has been established that the integration of nature-based technologies, land reclamation, revitalisation and wind energy provides a comprehensive approach to the reuse of post-mining areas and meets modern requirements for sustainable development and the circular economy. An analysis of technogenically disturbed land in the Kryvyi Rih iron ore basin has revealed that its total area within the boundaries of the enterprises under study is 967.9 ha. Waste rock dumps and disused quarries have been identified as the most promising sites for the installation of wind turbines, as they are characterised by their considerable size, established topography, the presence of transport infrastructure and the absence of competition from traditional land use.

A system of principles for the nature-based technologies for the utilisation of technogenically disturbed lands has been summarised, taking into account ecological balance, adaptability to anthropogenically transformed landscapes, reclamation-energy compatibility, geotechnical safety and the energy feasibility of land use. Based on these, a conceptual model has been developed that integrates the processes of reclamation, revitalisation and the siting of wind turbines into a unified management system for post-mining landscapes. It has been demonstrated that the use of vertical-axis wind turbines on technogenically disturbed land facilitates the reuse of degraded areas without the additional appropriation of natural land, reduces the anthropogenic impact on the environment, cuts greenhouse gas emissions and improves the efficiency of land use. The design characteristics of such turbines enable reliable operation under the complex wind conditions associated with technogenic landforms while enhancing the environmental safety of their operation. Prospects for further research relate to the development of a multi-criteria assessment methodology for evaluating the suitability of technogenic disturbed land for the siting of wind power plants, utilising geoinformation technologies, remote sensing and mathematical modelling of wind potential. Another important area is the assessment of the technical and economic efficiency of the proposed solutions and their environmental impact throughout the full life cycle of energy facilities.

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Conflict of Interest

None.

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Природоузгоджені технології використання техногенно порушених земель гірничодобувних регіонів

Анотація. Інтенсивний розвиток гірничодобувної промисловості Криворізького басейну призвів до формування значних площ техногенно порушених земель (кар'єрів, скельних відвалів, хвостосховищ) які характеризуються складними інженерно-геологічними й геоекологічними умовами та обмеженою придатністю до традиційного господарського використання. Метою дослідження був аналіз сучасного стану техногенно порушених земель Криворізького гірничодобувного регіону та обґрунтування можливості застосування природоузгоджених технологій під час їх ревіталізації шляхом розміщення вітроенергетичних установок. Методологічну основу роботи становили методи системного аналізу, узагальнення наукових публікацій, геоекологічної оцінки техногенно порушених територій, порівняльного аналізу інженерно-геологічних характеристик гірничих об'єктів, а також аналізу природних і техногенних чинників, що впливають на можливість їх повторного використання. У результаті дослідження встановлено специфіку сучасних гірничо-екологічних умов Кривбасу та визначено інтегральний потенціал використання відвалів, відпрацьованих кар'єрів і хвостосховищ для безпечного позиціонування вітрогенераторів. Доведено, що ревіталізація відвалів дозволяє ефективно використовувати їхню висоту для оптимізації вітрового потоку. Детальний аналіз інженерно-геологічних характеристик підтвердив високу перспективність використання відвальних масивів для альтернативного освоєння порушених ландшафтів. При цьому геоекологічна оцінка довела, що значна висота породних відвалів дозволяє ефективно оптимізувати параметри взаємодії вітроенергетичних установок із повітряними потоками. Сформульовано базові принципи природоузгодженого відновлення порушених ландшафтів, які передбачають синергію техніко-біологічної рекультивації та інфраструктурного розвитку відновлюваної енергетики без вилучення нових природних угідь. Практична цінність дослідження полягає у науковому обґрунтуванні повторного використання техногенно порушених земель без додаткового вилучення природних територій із господарського обігу, що сприяє підвищенню ефективності використання земельних ресурсів, зниженню антропогенного навантаження на довкілля та реалізації принципів сталого розвитку гірничодобувних регіонів

Ключові слова: рекультивація; ревіталізація; відвали; вітроенергетичні установки; Кривбас