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SUSTAINABLE SITING OF WIND FARMS IN KAZAKHSTAN: A CASE STUDY OF THE KARAGANDA REGION

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Abstract: This study aims to evaluate the environmental and spatial suitability of the planned Giperborey 50 MW wind power plant near Osakarovka in the Karaganda Region of Kazakhstan and to determine whether the site meets technical, ecological and socio-economic requirements for development. The appraisal combined site observations; analysis of climatic records from the nearest Kazhydromet station to characterise wind resource and seasonal extremes; field noise measurements with a class-1 sound level meter and sound-propagation modelling in WindPro; avifaunal monitoring during the autumn migration period and a first-stage Scottish Natural Heritage collision-risk calculation with seasonal adjustment; vegetation and soil transects; line-of-sight and photographic documentation of visual exposure; and an assessment of land use, access routes and proximity to the electrical grid. Instruments were field-calibrated before and after measurements, and visual checks used representative viewpoints at standard observer height. Avian surveys covered peak dawn and dusk periods within defined migration windows. Results indicate favourable wind conditions, with an annual mean speed above approximately 4.7 m/s and limited calm periods; gently undulating steppe on predominantly low-value grazing land; and the absence of critical habitats within the project footprint. Modelled operational noise remains ≤ 55 dB at the nearest residential receptors, and the 40 dB contour does not extend beyond the project boundary. Compliance held under downwind and neutral stability assumptions applied in the model. Migration counts recorded low use of the rotor-swept zone by high-risk species, and predicted collision totals fall below commonly applied screening thresholds. Visual checks show limited exposure of nearby settlements, and access logistics are feasible via existing roads with minor upgrades. Public interviews indicated neutral-to-positive attitudes associated with expectations of local employment and infrastructure improvement. Overall, under the assessed conditions, the site satisfies the study criteria for environmentally compatible development.

Keywords: wind power plant, environmental impact assessment, spatial planning, renewable energy, Kazakhstan

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INTRODUCTION

The development of wind energy is a key element in advancing sustainable energy systems. Optimal siting of wind power plants (WPPs) requires an integrated approach that accounts for geographic, environmental, economic, and technical variables. Numerous international studies have applied multi-criteria decision-making (MCDM) techniques, including the Analytical Hierarchy Process (AHP), the Best-Worst Method (BWM), and Geographic Information Systems (GIS) to improve siting efficiency and reduce environmental impacts. For example, a GIS-based MCDM model that considered wind speed, infrastructure proximity, and environmental constraints was developed (Moradi et al., 2020); the BWM method in Turkey, incorporating environmental and social criteria, was applied (Tercan, 2021), while weighted overlay models in Sri Lanka identified suitable barren lands and open forests (Kahatapitiya et al., 2023).

The role of land ownership and layout constraints in wind farm design was also explored (Wang et al., 2017).

Beyond spatial optimization, land use and socio-economic effects are critical: denser turbine configurations can improve energy output but may intensify environmental concerns (Christie & Bradley, 2012); property values may increase or decrease with proximity and landscape setting (Mai & Choi, 2025); stakeholder acceptance tends to rise when communities are involved and fairly compensated (Parkins et al., 2022). Ecological effects must likewise be considered, including species-specific changes in bird populations associated with land-use modification (Fernández-Bellon et al., 2018; World Health Organization, 2018). The visual impact of wind farms, particularly near tourism zones or rural settlements, can affect public perception; viewshed analysis has been proposed to mitigate negative effects (Nopp-Mayr et al., 2021). Socio-environmental risks of inequitable land acquisition have also been discussed (Traldi, 2021).

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Life-cycle assessment (LCA) has become essential in evaluating the full environmental footprint of WPPs: energy use and emissions across project phases have been assessed (Schleisner, 2000), and trade-offs between cost optimization and land-use constraints underscored (Christie & Bradley, 2012).

More recent studies confirm the relevance of wake modelling and biodiversity risk assessment in comprehensive planning; for instance, land suitability has been evaluated using slope, road proximity, and turbulence intensity (Thomas & Ning, 2020). The balance between energy output and noise exposure shows that land-use regulations strongly influence acoustic impacts (Sorkhabi et al., 2016), and siting models that integrate wind variability with grid constraints are pertinent where infrastructure is limited (Cetinay et al., 2017).

Circular-economy practices, including recycling turbine components, can reduce impacts (Doerffer et al., 2021), and comparative LCA work examines offshore versus onshore footprints (Piasecka et al., 2019); national case studies also quantify potential emission reductions from turbine recycling (Verma et al., 2022). Wildlife impacts, especially on migratory birds, remain a pressing issue (May et al., 2021). For Karaganda Region, Ospan et al. (2024) documented soil compaction and vegetation change in Karkaraly State National Nature Park, while Tsoy et al. (2024) found widespread exceedances of petroleum hydrocarbons in urban soils of Karaganda and Temirtau. Air-quality burdens around the Temirtau steel plant were quantified in a recent assessment (CREA & SteelWatch, 2024). At basin scale, heavy-metal risks in the Nura River have been characterised (Turdiyeva & Lee, 2023), and regional landscape sensitivity has been mapped for planning and zoning (Sagatbayev et al., 2025). The aim of this study is to provide a site-specific environmental and spatial appraisal of the planned Giperborey 50 MW wind power plant in the Karaganda Region of Kazakhstan, determining the site's compliance with technical, ecological, and socio-economic criteria for sustainable development; unlike many siting studies, this appraisal does not employ GIS-based MCDM, relying instead on field baselines, WindPro® noise modelling, and a Scottish Natural Heritage collision-risk calculation.

Recent work on onshore wind-farm appraisal has shifted from purely technical screening to integrated evaluations that combine spatial feasibility, biodiversity risk, acoustics, visual exposure, soils, and community context; updated bird collision-risk guidance requires using current, species-level avoidance rates and including all observed flight activity in estimates, thereby standardising inputs across EIAs (NatureScot, 2025a; NatureScot, 2025b), while multi-farm validation shows that modelled collision maps align with measured carcass data when post-construction searches are used to calibrate predictions (Morant et al., 2024). For noise, recent experiments report consistent annoyance responses and task-level cognitive effects under exposure to recorded turbine sound, which supports conservative residential thresholds and reliance on measured inputs in appraisal (García-Guerrero et al., 2025; Rosciszewska et al., 2025).

The visual dimension has likewise advanced: fleet-scale mapping of population exposure provides replicable methods to frame site-level line-of-sight checks and photographic simulations (Gleason et al., 2025). Alongside these impact strands, geotechnical and soil considerations are being revisited, with 2025 syntheses highlighting how foundation behaviour and construction disturbance depend on local stratigraphy and multi-hazard loading issues relevant to steppe settings with collapsible or loess soils (da Silva Medeiros et al., 2025; Fan et al., 2025).

Social acceptance remains context-dependent, influenced by perceived fairness and local cost-benefit balances, and can interact with proximity and landscape character (Parkins et al., 2022; Mai & Choi, 2025).

Taken together, these studies align with our approach a site-specific appraisal that quantifies bird flight activity and applies an SNH-based collision calculation, uses measured inputs for noise modelling, documents visibility with line-of-sight photography, and considers soils, access, and community feedback while indicating limits relevant to the Karaganda steppe that justify our emphasis on field baselines and post-construction monitoring.

MATERIALS AND METHODS

The Giperborey 50 MW wind power plant (WPP) is planned in the northern part of the Karaganda Region, Kazakhstan, near the rural settlement of Osakarovka. This region represents a typical dry steppe zone of Central Asia, marked by a combination of flat and slightly undulating terrain with low population density and minimal agricultural use. The study area lies within State Reserve land that has traditionally been used for low-intensity livestock grazing. Satellite imagery and local interviews confirm this land use pattern since at least 1985.

Geologically, the site is part of the northern slope of the Saryarka Ridge and is dominated by weathered Proterozoic and Paleozoic sandstone formations. The area exhibits a shallow hillocky relief with elevations ranging from 502 m to 573 m. Seasonal waterlogging is observed in some depressions, but no permanent water bodies exist within the immediate project boundaries. The seismic activity in the area is low, and no active surface faults have been identified despite the presence of one on geological maps.

The climate is sharply continental, with large seasonal fluctuations. Winter temperatures often fall below -20°C, while summer temperatures can exceed +35°C. Wind conditions are favorable for power generation: average wind speeds exceed 4.5 m/s annually, with frequent episodes above 8 m/s. According to the National Climatic Cadastre (2023), Osakarovka exhibits the highest mean wind speed in the Karaganda Region. The planned WPP site covers 13.5 ha under a long-term lease. The layout includes eight wind turbines with 110 m hub height and 155 m rotor diameter, spaced at a minimum of 400 m to mitigate wake losses. Additional land is allocated for internal gravel roads (9 km), a substation, and an extension of the KEGOC high-voltage infrastructure. A separate 372 ha area was temporarily designated for environmental monitoring and technical feasibility studies. The spatial configuration of the wind power plant components, buffer zones, turbine transport routes, and visual impact observation points is presented in Figure 1.

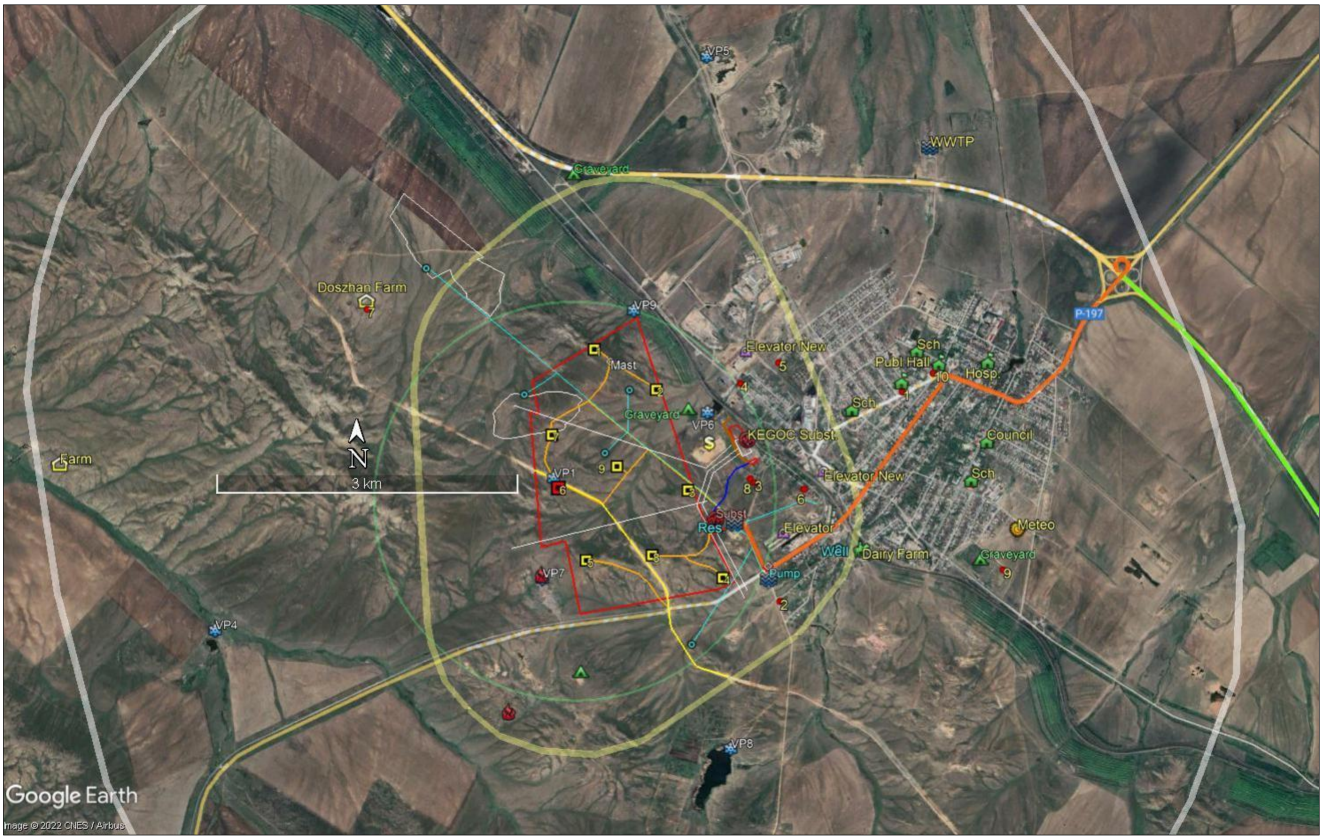

Figure 1. Overview map showing the survey area 5 km around the allocated for the WPP land (white circle), wildlife observation points: the main VP1 (with green circle as 2km the maximum extent of species recognition) and ancillary VP-4-9, 1.5km zone in which blades flickering impact is possible (yellow circle), WPP parts transportation route (green for double lane and orange for single lane) and visual impact assessment points (red dots) Base map source: Google Maps, 2025. Annotations and layout by the authors.

Environmental impact assessment was conducted following national legislation (Ministry of Ecology, Geology and Natural Resources of the Republic of Kazakhstan, 2021) and the environmental and social guidelines of the European Bank for Reconstruction and Development (European Bank for Reconstruction and Development, 2014). The project qualifies as a Category A development due to its potential regional influence.

Climatic data were obtained from the nearest Kazhydromet meteorological station, located 3 km east of the site. This data informed the evaluation of wind speed distribution, seasonal trends, and extreme weather conditions such as icing or dust storms. Air quality was assessed qualitatively; no major stationary pollution sources exist within the vicinity, apart from domestic coal-burning during winter. Comparative emission levels are shown in Figure 2.

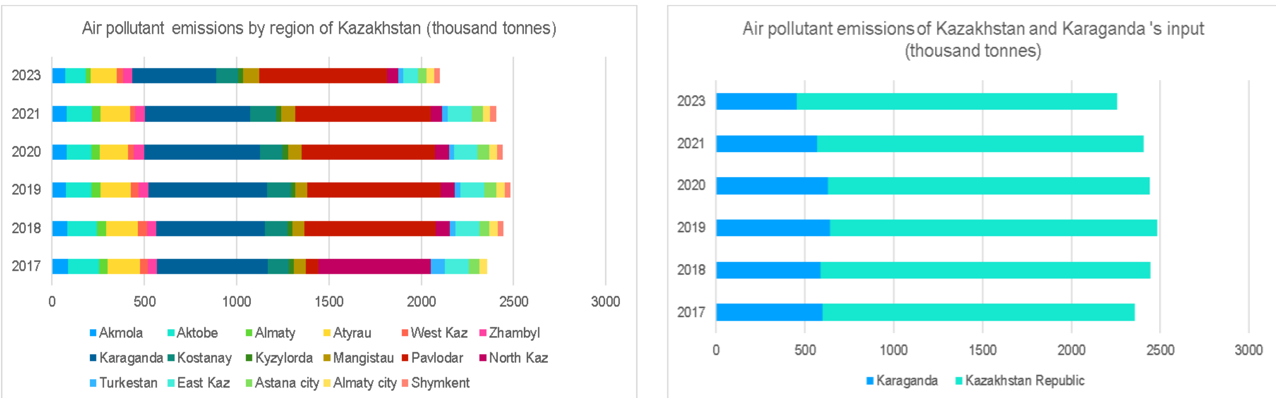

Figure 2. Air pollutant emissions of Kazakhstan and Karaganda (thousand tonnes)
based on 2017-2023 statistical data (Source: Bureau of National Statistics, 2024)

Noise assessment involved 23 hours of continuous field measurements using a certified class 1 sound meter (Shi-01, Zaschita). Measurements were taken near residential areas adjacent to the access road and substation infrastructure. Readings were evaluated against WHO guidelines and national thresholds, accounting for impulse and continuous noise levels.

Ornithological monitoring was carried out from mid-August to mid-October 2022 to capture autumn migration activity. A combination of fixed-point vantage observations (VP1-VP9) and transect surveys were employed across a 5 km radius.

Sites included ecologically sensitive habitats such as ponds, waste dumps, tree belts, and grain storage areas. A total of five key vantage points were selected based on topography and visibility. Observation sessions focused on birds flying within the risk altitude (20-200 m) and included flight behavior, frequency, direction, and time spent in the risk zone.

Species classified as high-risk for blade collision, such as pigeons, swans, and raptors, were prioritized for impact estimation. The Scottish Natural Heritage **(**SNH) methodology (Scottish Natural Heritage, 2000) was used to calculate theoretical collision risk, based on rotor dimensions, bird flight speed, and occupancy within the swept volume. Due to the absence of species-specific avoidance data, the second stage of SNH calculations was not applied. Seasonal adjustment factors were introduced to estimate annual mortality based on autumn data, accounting for migratory behavior and population presence in different seasons. Wildlife observations also recorded mammal presence through visual and indirect signs (e.g., tracks, droppings). Dominant species included bobak marmot (*Marmota bobak*) and mountain hare (*Lepus timidus*). No bats or roosts were detected, despite site inspections and interviews with local residents.

Vegetation was documented along ecological transects to determine the degree of natural cover and habitat value. The site is characterized by feather grass steppe with Artemisia species, saline-tolerant plants in depressions, and tree lines along infrastructure. Soil profiles were evaluated in situ and classified as chestnut and solonetzic types with low organic matter. There was no evidence of soil erosion, contamination, or invasive plant species. A social baseline assessment was conducted in nearby settlements, including structured interviews with local residents. Feedback was generally favorable, citing employment opportunities and minimal concern regarding visual or noise impacts. Viewshed and turbine transport modeling were also conducted to assess spatial compatibility with surrounding infrastructure and communities.

This multifaceted methodology ensured a robust evaluation of both natural and anthropogenic aspects of the proposed site. Based on the combined analysis, the Osakarovka area demonstrates high suitability for wind energy deployment, with minimal expected environmental disruption and strong alignment with national goals for sustainable energy development.

RESULTS AND DISCUSSION

The environmental and spatial assessment of the Giperborey 50 MW wind power plant in the Karaganda Region revealed favorable conditions for sustainable wind energy deployment. The findings are based on a comprehensive evaluation of climatic parameters, topography, air quality, noise propagation, biodiversity, and socio-economic conditions. The results are interpreted in the context of site suitability for wind energy deployment and its environmental sustainability, with reference to international assessment methodologies and national regulatory standards.

Climatic Conditions and Site Suitability

Climatic parameters represent a fundamental determinant in evaluating the appropriateness of wind power plant (WPP) siting, particularly in terms of wind potential and atmospheric extremes. The selected site for the Giper borey WPP is located in a zone characterized by an arid and sharply continental climate, which presents both opportunities and challenges for wind energy exploitation. Climatic data analysis revealed significant seasonal temperature fluctuations: average January temperatures reached -16°C, with nighttime lows dropping to -22°C, while in July, mean daytime temperatures rose to +18°C and occasionally exceeded +26°C. Nighttime temperatures during summer typically stabilized around +11°C. The absolute temperature range recorded for the area spans from -45°C in winter to +39°C in summer, indicating high climatic amplitude. The observed depth of seasonal soil freezing in the project area reaches 2.05 meters, aligning with national construction norms (Committee for Construction and Housing of the Republic of Kazakhstan, 2017). While this necessitates structural adaptation in the design phase, it does not pose a critical barrier to implementation. Prevailing wind conditions further substantiate the feasibility of wind energy development.

The average annual wind speed in Osakarovka exceeds 4.7 m/s, with predominant southwest and southern wind directions. Wind rose data obtained from the nearest meteorological station confirm the presence of consistent wind flow throughout the year (Figure 3). Calm wind conditions account for only 5% of recorded time, which implies an operationally favorable environment for turbine deployment.

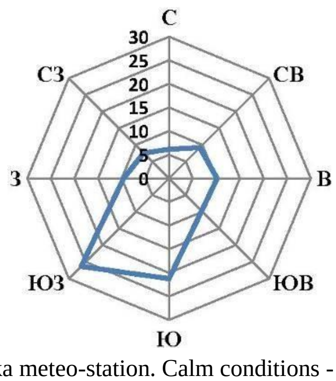

Figure 3. Wind rose at Osakarovka meteo-station. Calm conditions - 5% (Source: Kazhydromet, 2024)

Topography, Drainage, and Transport Access

The topographical configuration of the site is defined by gently sloping hills and shallow depressions characteristic of the Saryarka Ridge's northern foothills. Elevation varies from 573 meters in the western section to 502 meters in the northeastern portion. Drainage is primarily seasonal, with thaw water accumulating in temporary creeks that discharge into Toksumak Lake, approximately 10 km to the north. The topographic map (scale 1:200,000) clearly delineates the WPP boundaries and natural hydrological features (Figure 4).

Figure 4. 1:200 000 topographical map updated in 1985 with the area allocated for the study area (red line) and the Project components. Relief is drawn in 20 m increments

Access to the site is facilitated by existing regional roads, although the final 700-meter segment requires structural reinforcement to accommodate oversized turbine components. Blade transport modeling highlighted a critical turning radius that necessitates off-road deviation and terrain adaptation (Figure 5).

Figure 5. The blades transporting trailers right-angle turn after Osakarovka (brown line) allows for the blades (white line trajectory) to avoid the powerline poles but will require ground enforcement for driving outside the road (red lines trajectory). (Source: Base map source: Google Maps, 2025. Annotations and layout by the authors)

Air Quality Assessment

Air pollution remains a significant environmental concern across the Karaganda Region, largely attributed to its legacy of mining and heavy industrial operations. According to official environmental statistics, the region contributed over 20% of Kazakhstan's total air pollutant emissions in 2023. This trend is visualized in Figure 2, which illustrates the comparative emissions load across Kazakhstan's regions. However, the immediate WPP site is located at a considerable distance from industrial zones and exhibits favourable air quality parameters. Ambient air monitoring indicated the absence of significant local emission sources aside from domestic heating emissions during winter.

Consequently, no additional mitigation measures are required for the operational phase of the WPP.

Acoustic Modelling and Noise Impact

Noise emissions from wind turbines are an important consideration in determining the acceptability of a wind power plant, particularly in rural areas with dispersed settlements. To quantify potential acoustic impacts, noise propagation modelling was conducted using WindPro software, a widely adopted tool for environmental sound prediction. The modelling incorporated turbine specifications (hub height 110 m, rotor diameter 155 m), local topography, prevailing wind conditions, and residential receptor locations.

The modelling results indicated that the maximum noise levels in the project vicinity do not exceed 55 dB, which complies with national noise regulations and WHO guidelines for residential zones. Contour mapping of modelled sound levels shows that the 40 dB threshold does not extend beyond the designated project boundaries (Figure 6). These findings suggest that turbine operation will not cause significant acoustic disturbance to nearby residents or wildlife.

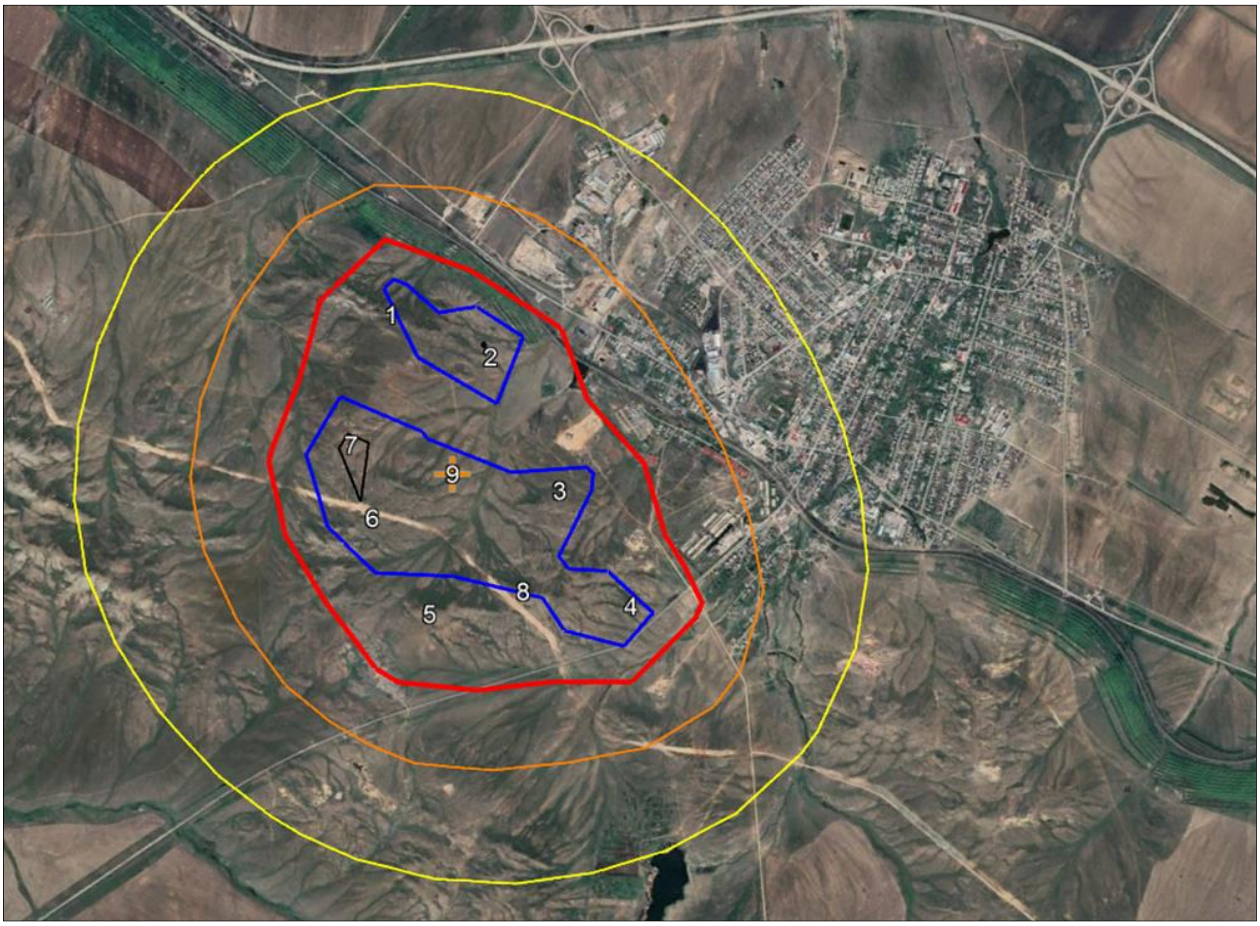

Figure 6. Results of the turbines noise modelling in WindPro showing that 55 dB (black contour), 50 dB (blue contour), 45 dB (red contour) 40 dB (orange contour) 35 dB (yellow contour). Number of turbines (1-9). The nearest houses are at the edge of the red contour. (Source: Base map source: Google Maps, 2025. Annotations and layout by the authors)

Avifauna and Collision Risk Assessment

To evaluate the potential impacts of the WPP on local and migratory bird species, ornithological monitoring was conducted during the autumn migration season (August-October 2022). Observations were carried out from five strategically positioned vantage points within a 5 km radius of the proposed site. The study focused on identifying flight trajectories, altitudes, and behaviors of birds entering the rotor-swept zone (27-183 m).

Target species included large-bodied birds such as swans, pigeons, and raptors, which are more susceptible to blade collisions due to their size and flight patterns. Smaller passerine species were observed but were not prioritized for collision modeling, as they typically fly below or above the risk envelope.

Collision risk was estimated using the **Scottish Natural Heritage (SNH, 2000)** model, which provides a theoretical calculation of avian fatalities assuming no avoidance behavior.

Due to the lack of local data on species-specific avoidance behavior, only the first stage of the SNH methodology was applied. However, the calculated mortality risk remained below internationally accepted thresholds. Seasonal correction factors were also applied, based on comparative data from a similar wind farm 80 km to the north, which recorded an 87% decline in bird abundance during winter months. These adjustments significantly reduce predicted annual collision figures.

Terrestrial Fauna and Habitat Conditions

Mammal presence within the project area was assessed through both direct visual observation and indirect evidence (e.g., tracks, scat). The most frequently recorded species were the bobak marmot (*Marmota bobak*) and mountain hare (*Lepus timidus*). No bat roosts or colonies were detected in nearby structures or natural shelters.

Interviews with local residents confirmed the rare occurrence of bats in the region, likely due to climatic and habitat limitations.Vegetation surveys confirmed the dominance of feather grass steppe with patches of *Artemisia* and salt-tolerant flora in depressions. Habitat conditions were stable, with no observed signs of erosion, invasive species, or overgrazing. This baseline supports the classification of the site as moderately sensitive, with sufficient ecological resilience to accommodate planned WPP infrastructure.

Socio-Economic Context and Community Perception

As part of the integrated environmental assessment, structured interviews were conducted in the nearest settlements, including Puteyschiki and Zhasulan Farm, to evaluate the social acceptability of the wind energy project. The surveyed residents expressed neutral to positive attitudes toward the proposed development. Anticipated benefits included the creation of local jobs during the construction phase and potential improvements to local infrastructure such as roads and electricity reliability. Importantly, no culturally or historically significant sites were identified within the project boundary, based on consultations with the Karaganda Regional Department of Culture and archival resources. Furthermore, viewshed analysis revealed minimal visual intrusion from the turbines, given the topographical buffering and sparse residential dispersion in the region.The alignment of the transport corridor with existing roads, combined with low local traffic volume, indicates that turbine delivery and maintenance operations are unlikely to cause significant disruption.

Synthesis of Environmental Impacts and Site Viability

The multi-criteria assessment demonstrates that the selected site near Osakarovka offers favorable conditions for wind energy development with minimal adverse environmental consequences. Key environmental parameters - including wind availability, topographical compatibility, land stability, and low levels of biodiversity conflict - collectively support the technical and ecological feasibility of the project. No significant long-term risks were identified in relation to air quality, noise, soil degradation, or disruption of wildlife corridors. While some short-term impacts are anticipated during the construction phase (e.g., dust generation, equipment noise), these are temporary and manageable through standard mitigation measures. Moreover, the project’s potential to displace fossil fuel-based energy sources aligns with Kazakhstan’s national climate strategy and emissions reduction goals.

Cumulatively, the evidence presented supports the classification of the site as highly suitable for wind energy deployment, both in terms of technical viability and environmental sustainability. The Giperborey 50 MW WPP is expected to contribute meaningfully to the region’s renewable energy capacity while maintaining ecological integrity and community support.

Our site-specific findings are in line with recent EIAs and impact studies that combine bird-collision estimation with post-construction validation (Morant et al., 2024), measured-input noise appraisal and human-response evidence (García-Guerrero et al., 2025; Rosciszewska et al., 2025), and landscape/visibility framing at population scale (Gleason et al., 2025); geotechnical syntheses further support the need for local soil-foundation checks in steppe settings (da Silva Medeiros & de Lima, 2025; Fan et al., 2025). The findings of this study indicate that the selected site near Osakarovka village in the Karaganda Region presents highly favorable conditions for wind energy development.

The region’s stable and strong wind regime, combined with low population density and limited ecological sensitivity, ensures both technical and environmental feasibility. These results are consistent with global site selection studies that emphasize the importance of wind speed, land use compatibility, and minimal biodiversity conflict (Al-Yahyai et al., 2012; Moradi et al., 2020). Noise modelling revealed that turbine operation would remain within accepted thresholds, with no exceedance of 55 dB at any residential receptor. These outcomes align with similar assessments conducted for wind farms in Central Europe, where modern turbine designs and setback distances have significantly mitigated community noise complaints (May et al., 2021). Moreover, the lack of sensitive fauna such as bats or nesting raptors within the project zone further supports its ecological acceptability. From a land-use perspective, the project makes efficient use of marginal land previously subjected to low-intensity grazing.

This contrasts favorably with wind farm projects in more densely settled or agriculturally productive regions, where land conflicts and stakeholder resistance are more common (Traldi, 2021; Christie & Bradley, 2012). The applied methodology, which integrates international modeling tools (e.g., WindPro®, SNH avian risk model) with national environmental legislation, provides a replicable framework for future site assessments in Kazakhstan.

The project also contributes to Kazakhstan’s broader commitment to renewable energy expansion and climate mitigation under its national determined contributions (NDCs). Taken together, the results suggest that the Giperborey WPP can serve as a model for sustainable territorial planning in steppe regions, where wind energy potential is high but ecological risks remain moderate.

CONCLUSION

This study provides a comprehensive environmental assessment of the Giperborey 50 MW wind power plant project in the Karaganda Region of Kazakhstan, with a particular focus on the site’s climatic, ecological, and spatial characteristics. The findings demonstrate that the selected location near Osakarovka village meets the key criteria for wind energy development: favorable wind conditions, low ecological sensitivity, limited land-use conflicts, and minimal socio-environmental risks. Climatic data confirm the area’s suitability in terms of wind speed and temperature stability, while noise and air quality analyses indicate that both construction and operation phases will comply with national and international standards. Wildlife monitoring and avifaunal risk modeling reveal a low probability of significant biodiversity disturbance, particularly when combined with appropriate spatial planning and mitigation strategies.

The integration of international assessment tools such as WindPro® modeling and the SNH collision risk formula into a locally grounded evaluation framework enhances the replicability of the methodology for other steppe regions in Kazakhstan. Moreover, the alignment of the project with Kazakhstan's broader energy transition goals underscores its relevance from a policy and sustainability perspective.

In conclusion, the Giperborey WPP represents a viable and environmentally sound model for wind energy deployment in Central Asia. Its successful implementation can serve as a reference for future renewable energy initiatives that seek to balance technical efficiency with ecological responsibility and territorial planning principles.

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