Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Radiation factors of photovoltaic farms in the landscape

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How to cite this article:
Miao, H., Dusza – Zwolińska, E., Saran – Brosędzka, E., Łukaszewski, T., Gawlik, A. and Łopatka, A. (2026) Radiation factors of photovoltaic farms in the landscape. *Acta Montanistica Slovaca,* Volume 31 (1), 279-289

DOI:
https://doi.org/10.46544/AMS.v31i1.21

Abstract
The aim of the study was to analyze the impact of photovoltaic farms on the landscape and assess their visibility in the context of a planned investment located on plots no. 436/1 and 436/2 in the Witankowo area. A detailed analysis of landscape conditions was conducted, taking into account the land cover structure and landscape-shaping elements within a 5 km radius of the plot boundaries. A key research element was the assessment of the visual impact of a 25 MW photovoltaic farm using a numerical terrain coverage model (NTCM) and visibility simulations. The research methods included the placement of 156 measurement points in a 20x20 m grid across the investment area and an analysis of the visibility range at the maximum planned panel height (5 m). The simulation used NTCM data with a 1 m resolution, incorporating existing vegetation and buildings. The results were presented as visibility range maps across various spatial scenarios. The findings indicate that the photovoltaic farm will be effectively screened by existing vegetation and terrain features, minimizing its impact on the landscape. Maximum visibility is mainly confined to the investment plots and their immediate surroundings (up to 330 m). Detailed analyses confirm that the farm will not be visible from the nearest built-up areas. The final conclusions emphasize the importance of location in reducing the visual impact of photovoltaic farms on the landscape.

Keywords
Visibility of photovoltaic farms, visual impact on the landscape, Numerical Terrain Coverage Model (NTCM)

Introduction

The contemporary development of renewable energy technologies, including photovoltaics, presents planners and infrastructure designers with a range of challenges in integrating new facilities into the landscape (Vasylieva et al., 2025; Tomczyk et al., 2025). This issue is particularly significant in the context of photovoltaic farms, which, despite their small dimensions and low spatial profile, can significantly impact the aesthetic and functional perception of the surrounding landscape. Given the growing demand for renewable energy and the landscape changes resulting from visibility of such facilities within the space (Bajerowski et al., 2007; Lyeonov et al., 2025a,b; Štreimikienė, 2024).

The objective of this study is to evaluate the impact of photovoltaic farms on the landscape, with a particular focus on the determinants of their visibility across different landscape types. The application of modern geoinformatics and spatial methods enables precise modeling of the visual effects of such investments. This study integrates a multidisciplinary approach, with both geomorphological analyses and perceptual modeling techniques, based on geographic information system (GIS) algorithms and visual simulations, playing crucial roles. The analysis specifically focuses on determining the visibility range of photovoltaic farms, identifying visual obstructions, and assessing the potential impact of these investments on landscape aesthetics.

To achieve this objective, a detailed morphological analysis of the investment area was conducted, accounting for topographic, geographic, and land-cover data. The applied methods enabled the identification of key factors that may influence the visibility of photovoltaic farms. Visual simulations played a particularly important role in this process, enabling a realistic representation of the impact of these structures on the landscape under varying lighting, atmospheric, and seasonal conditions. Beyond technical analysis, the study also includes perceptual aspects, allowing for an understanding of subjective aesthetic assessments associated with the presence of photovoltaic farms in both natural and cultural landscapes.

Particular attention was also given to analyzing the specific characteristics of the landscape in which the planned investments are located. The study area, situated within the Wałcz Lake District, is characterized by diverse terrain morphology and a richness of natural elements that significantly influence the visual perception of the structures. In the context of this region, spatial analysis considered, among other factors, the distribution of vegetation elements, including forests and tree stands, which may serve as natural visual barriers, as well as the degree of integration of photovoltaic farms into the existing landscape (European Landscape Convention, 2000).

This study, therefore, represents an attempt to integrate modern analytical and perceptual tools to assess the visual impact of photovoltaic investments, while providing results that can serve as a basis for planning decisions on the location of such facilities. The findings of this analysis also constitute a vital component in the process of sustainable development planning, taking into account both the ecological and aesthetic aspects of human living space.

Through the applied methodology, it was possible to obtain precise information on the impact of photovoltaic farms on landscape perception, which constitutes valuable knowledge in the context of contemporary challenges related to the development of renewable energy sources and the need to protect and preserve landscape values.

Literature Review

Landscape, as a spatial phenomenon, is a fundamental element of the natural environment. Its complexity and diversity result in multiple definitions of the term, depending on the adopted research perspective. In the context of contemporary landscape studies, the definition provided in the European Landscape Convention of 2000, ratified by Poland in 2004, holds particular significance. According to this definition, the landscape is "an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors" (Lenartowicz, 2007). This approach enables a multifaceted understanding of the landscape, treating it not only as a sum of physical elements but also as a dynamic phenomenon perceived and shaped by humans (Mikulski, 2012; García-Esparza, 2022).

Under this framework, the landscape becomes a space co-created by humans rather than merely a product of natural forces. Humans not only perceive the landscape but also attribute meaning to it and influence its shape through actions and decisions (Myczkowski, 1998). This understanding incorporates both "hard" aspects, such as landform and land cover, and "soft" elements referring to landscape functions, its uses, and the cultural relationships between people and space. The European Landscape Convention emphasizes that landscape is a crucial component of the quality of life, regardless of whether it is in an urban, rural, degraded, or aesthetically significant area (Raszeja, 2013).

The landscape, whether considered exceptional or ordinary, deserves attention and inclusion in spatial planning and investment processes. According to the concept arising from the European Landscape Convention, the landscape is not merely an object of protection but also a space where social, economic, and cultural aspects intertwine. Contemporary approaches to landscape emphasize the need to integrate diverse research perspectives and to adopt systemic landscape management. This approach, known as landscape policy, is not limited to landscape protection but also accounts for its dynamic transformations resulting from social and economic activities (Litwin et al., 2009; Mapa UMP-pcPL, 2014).

For an extended period, both in Poland and globally, landscape conservation methods were primarily based on traditional conservation theories, using concepts such as "conservation," "restoration," and "revitalization." However, these classical approaches have proven insufficient for addressing contemporary challenges posed by the dynamic transformation of landscapes. These changes necessitate a new approach to landscape protection, which encompasses not only landscape resources but also the processes of spatial change, including those induced by human activities (Raszeja, 2008). Modern approaches to landscape protection focus on a broad spectrum of actions, including resource protection, spatial planning, and space management (Swanwick, 2003).

In recent years, a noticeable shift in landscape conservation theory has occurred, moving away from a narrow focus on areas of natural or cultural value toward a broader perspective that considers the landscape as a whole. Contemporary landscape conservation concepts highlight the value of landscapes resulting from the interaction of dynamic natural and cultural phenomena (Derczyński, 2003; Kot & Norek, 1996). Consequently, landscape conservation methods now take into account not only areas of special value but also landscapes serving everyday social and cultural functions, such as traditional agricultural landscapes (Ozimek et al., 2013).

The key document defining the principles of modern landscape policy is the European Landscape Convention. This convention proposes a range of actions that can be effective in the context of landscape transformations driven by evolving social and economic needs (Pawłowska, 2001; Raszeja, 2009). Within this policy, various forms of landscape protection are distinguished, including both active conservation of areas of special value and adaptive measures to adjust the landscape to changing social and economic conditions. The convention also underscores that every landscape - whether valuable or "ordinary" - deserves protection and should be considered in planning processes (Raszeja, 2022; Blandford, 2023; Bogdanowska, 2024).

Spatial planning, particularly within the framework of landscape policy, should be integrated with landscape conservation and development processes. Studies on landscape identification and assessment should be an integral part of spatial development plans, enabling the inclusion of diverse social interests and minimizing conflicts related to land use (Dąbrowska-Budziło, 2001; Myga-Piątek, 2012; Jacques, 2023). The European Landscape Convention also highlights the need for legislative changes, public education, and improvements to theoretical and practical methods for landscape protection.

Understanding the landscape as a phenomenon resulting from the interaction of natural and human factors is fundamental to contemporary landscape research. Lorzing (2001) distinguishes four levels of interaction concerning different landscape functions: (1) perceived landscape - as an object of perception, (2) actual landscape - as an object of objective studies, (3) emotional landscape - as an object of individual and collective experiences, and (4) shaped landscape - as an object of planning, protection, and intervention (Ricoeur, 2007; Szyszko et al., 2013; Fry, 2000). These levels of interaction provide a theoretical basis for landscape research, enabling a more comprehensive understanding of its complexity and dynamic nature.

Contemporary landscape studies focus on analyzing landscape identity, identifying its characteristic features, and examining the impact of various factors, including social and cultural aspects, on landscape perception. Understanding how different social groups perceive the landscape is crucial for developing effective methods of landscape conservation and management. From a planning practice perspective, incorporating landscape perception—shaped by diverse attitudes, values, and social experiences - is essential for effective management of landscape spaces (Court et al., 2023; Forczek-Brataniec, 2018).

Research Methods

To determine the visibility determinants of photovoltaic farms within the landscape structure, an interdisciplinary research approach was applied, incorporating both quantitative and qualitative methods. This approach integrates geoinformatics analysis, geomorphological assessment, and perceptual modeling. The research procedure used advanced geoinformatics tools and spatial modeling methods to enable a precise assessment of the investment's impact on landscape perception.

Geomorphological and Structural Landscape Analysis

The first research stage involved a morphometric and structural analysis of the terrain based on a Digital Terrain Model (DTM) and a Digital Surface Model (DSM) with a 1-meter resolution, obtained from the resources of the Main Office of Geodesy and Cartography (GUGiK). To accurately characterize terrain relief, topographic indices such as slope, aspect, and the terrain roughness index were calculated. These indicators enabled the identification of key landscape elements that may influence the perception of the photovoltaic farm. Additionally, a structural landscape analysis was conducted using fragmentation and landscape connectivity indices, which enabled the determination of the degree of visual integration between the farm and its surroundings.

Visibility Range Modeling

An analysis of the potential visibility of the photovoltaic farm was conducted using Geographic Information System (GIS) algorithms, specifically Viewshed Analysis methods implemented in ArcGIS Pro. The modeling process used algorithms for digital elevation data interpolation and line-of-sight radiation analysis, enabling precise delineation of areas from which the planned investment may be visible. To minimize errors related to interpolation and visibility range, a grid of 156 observation points was established within a 20x20 m spatial framework, at a height corresponding to the maximum height of photovoltaic panels (5 meters above the ground surface).

Land Cover and Visual Obstruction Analysis

The study incorporated land cover data from the Corine Land Cover (2018) database and high-resolution orthophotomaps, enabling a detailed inventory of visual obstructions. Land cover classification methods were applied based on the spectral analysis of remote sensing data, facilitating the identification of both natural and anthropogenic elements that limit the visibility of the investment. A detailed assessment of tree stands and landforms within a 3 km radius of the planned investment was conducted, taking into account their potential to reduce the photovoltaic farm's landscape exposure.

Perceptual Modeling and Visual Simulations

To evaluate the perceptual integration of the photovoltaic farm into the landscape, computer-based visual simulations were conducted using 3D modeling and rendering technologies (SketchUp, Lumion). These simulations accounted for variable lighting conditions, atmospheric factors, and different seasons, enabling a comprehensive assessment of the investment's visibility in various landscape contexts. Additionally, perceptual analyses were conducted using an experimental approach in which respondents assessed the farm's visual impact on the landscape using realistic visualizations.

The applied research methods enabled a comprehensive analysis of the impact of photovoltaic farms on landscape perception, integrating advanced geoinformatics tools with spatial and perceptual modeling. This approach enabled the acquisition of precise results, which can serve as a basis for planning the location of investments in a manner that minimizes their negative visual impact on the environment.

Landscape Description

The study covers investment plots Nos. 436/1 and 436/2, located in the Witankowo area, are the subject of landscape analysis. These sites are situated within the Wałcz Lake District mesoregion (314.64), part of the West Pomeranian geographical region. The Wałcz Lake District is characterized by significant terrain variability, dominated by glacial landforms of diverse origin. The northern and southwestern parts of the region feature moraine hill landscapes, with distinct undulating glacial forms, while the southern part is dominated by flat, plain-like fluvioglacial landscapes.

In the northwestern part of the Wałcz Lake District, south of Lake Lubie, prominent terminal moraines are present, constituting a typical element of the glacial landscape. The morphology of this terrain is distinctly shaped by glacial processes, including the Pleistocene glacier. In contrast, the southeastern part of the region is characterized by flat glacial landscapes, resulting from the accumulation of glacial sediments and sedimentary processes associated with glacial activity.

The central part of the region contains numerous water bodies, including Lakes Betyń and Raduń (Dybrzno), which are key structural elements of the aquatic landscape within this geographical unit. A hydrological analysis indicates a significant concentration of surface water in this area, which influences biodiversity and the functioning of aquatic ecosystems.

Within the study area, within a 5 km radius of the planned investment, agricultural land dominates, covering approximately 52% of the total analyzed area. Among these, arable land accounts for about 45% of the total surface area. Additionally, forested areas play a significant role in land cover, accounting for approximately 42% of the region, with Scots pine forests (Pinus sylvestris) dominant, a characteristic component of the regional phytocenosis. The structure of land cover in this area results from both anthropogenic activities and natural ecological processes that shape the landscape in this region.

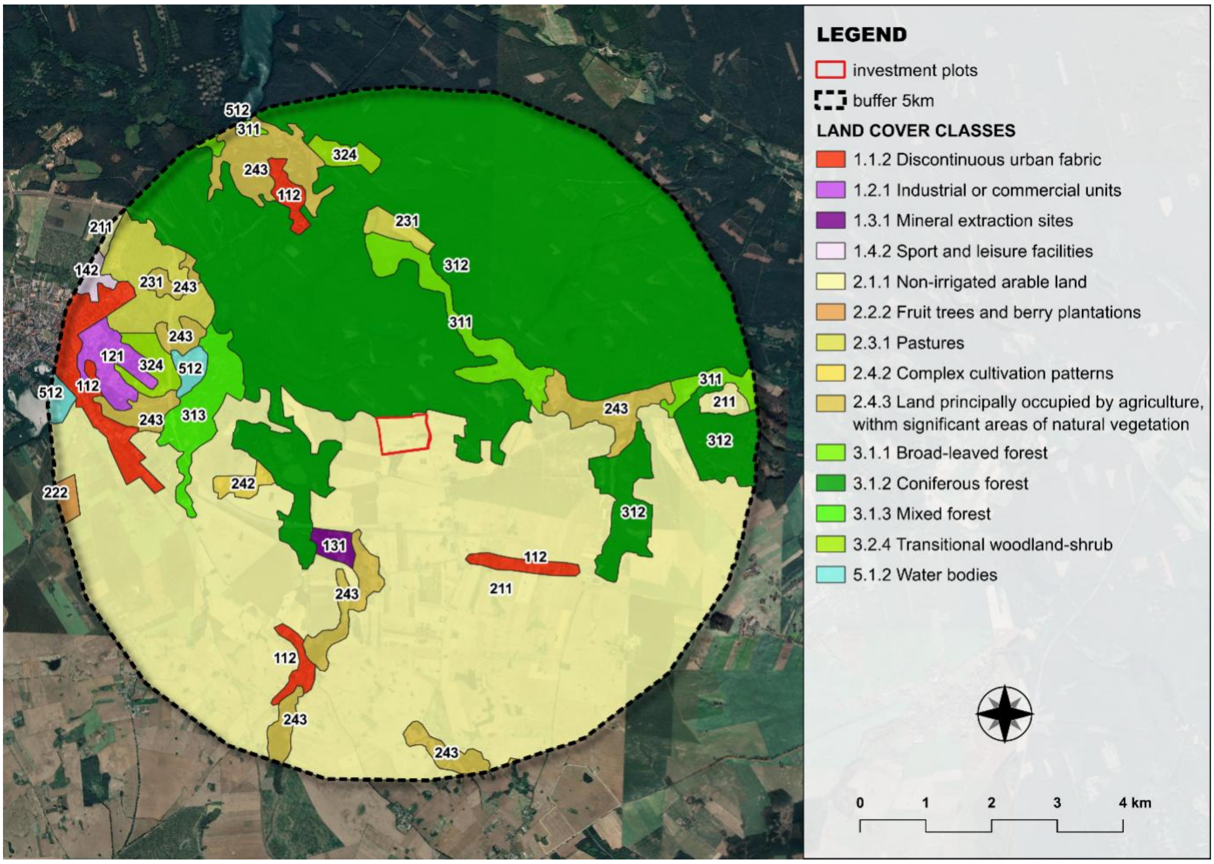

Figure 1. Land cover structure within a 5 km radius of the investment site (Corine Land Cover, 2018). Source: Own Study

The analysis of spatial structure and land cover dynamics within the study area provides a more comprehensive understanding of the potential impacts of the planned investment activity on the natural environment. Particular attention should be given to maintaining ecological balance and to implementing sustainable development solutions that minimize the negative impact on local ecosystems and biodiversity.

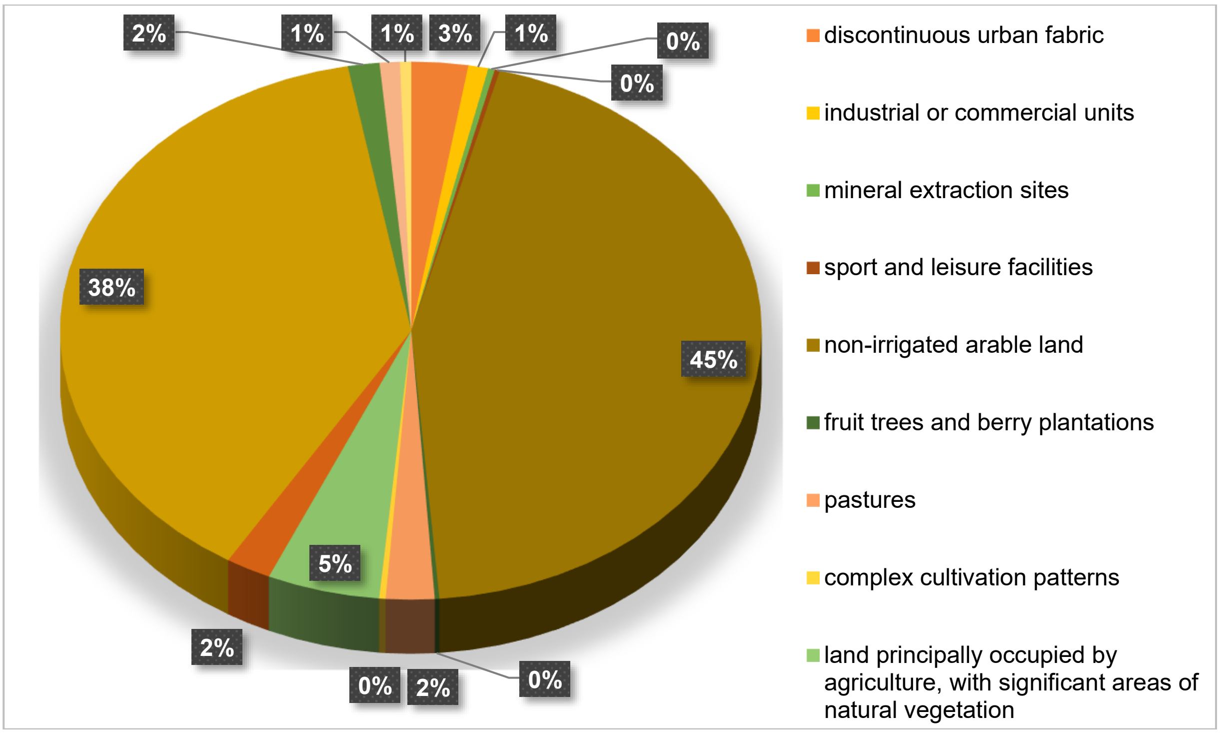

Figure 2. Percentage share of different land cover types within a 5 km radius of the investment site boundaries (CLC, 2018). Source: Own Study

Landscape-Shaping Elements

Within a 3 km radius of the analyzed investment plots, forested areas dominate the landscape, interspersed with agricultural fields. These areas serve as natural visual barriers, effectively reducing landscape sensitivity within the studied region. The presence of forests alters landscape perception, stabilizing its character.

Among the anthropogenic elements significantly shaping landscape features are the transportation network and power transmission lines. These infrastructural components integrate into the spatial structure, modifying both its structural and visual characteristics.

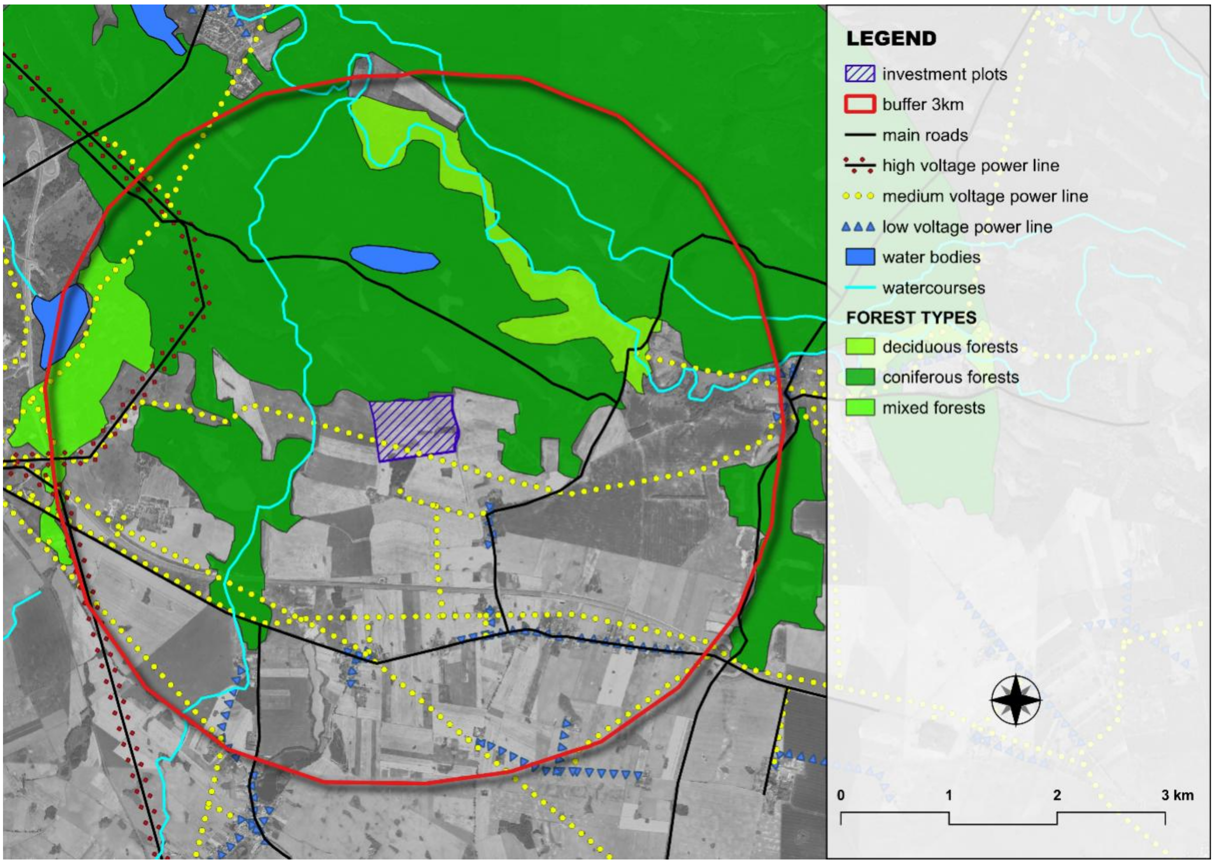

Figure 3. Investment plots in the context of landscape-shaping elements. Source: Own Study

Classification of Cultural Landscapes

As part of the classification of cultural landscapes developed for the landscape audit, the studied unit can be classified as type B6d, which includes agricultural landscapes characterized by a mosaic distribution of farmland, forming medium-sized fields. The size of the agricultural plots in this landscape is primarily determined by environmental variability, such as terrain topography, soil structure, and microclimatic conditions. Within this landscape, numerous non-productive areas are present, including wooded areas, wetland depressions, small water bodies, and settlements, which significantly modify the spatial organization of the agricultural landscape. As a result of these factors, the average field size in the analyzed area ranges from 5 to 25 hectares, reflecting the landscape's characteristic structural and spatial features.

Visual Impact of the Investment on the Landscape

Photovoltaic farms, in the context of their visual impact on the landscape, generally exhibit minimal interference with the visual aspect due to their low height and uniform structure. Typically, panel heights do not exceed 6 meters, which facilitates their integration into the landscape and allows effective concealment in appropriate terrain. However, in cases where the farm covers a large area or is prominently exposed in panoramic views, especially from long distances, it may become a dominant, artificial element in the landscape. A key factor in minimizing the perceptual impact of the investment is selecting appropriate locations that enable effective concealment of the farm through terrain adaptation and tall vegetation strips.

The visual environment within the municipality near the planned investment is characteristic of a cultural-agricultural landscape. This anthropogenic landscape, transformed by human activity, exhibits a high degree of urbanization relative to its natural features. The dominant landscape composition consists of open agricultural spaces, particularly cultivated fields. The boundaries of these spaces are defined by small forested areas, tree lines along watercourses (both natural and drainage canals), tree rows along transportation routes in the form of avenues and windbreaks, and rural buildings, including farmsteads.

To precisely assess the visual impact of the planned investment, a detailed visibility range analysis was conducted for a photovoltaic farm with a capacity of up to 25 MW, planned for plots Nos. 436/1 and 436/2 in Witankowo. Within the plot boundaries, a system of 156 measurement points was planned, positioned 5 meters above the ground surface (the maximum designed height of the farm). These points were arranged in a regular 20x20 m grid. To determine the visibility range, a Digital Surface Model (DSM) with a 1-meter resolution, obtained from the Main Office of Geodesy and Cartography (GUGiK), was used. This model was generated from an ALS point cloud scan as part of the ISOK project, incorporating data on land cover, vegetation, and built structures, enabling a realistic simulation of visibility ranges.

Since no tree or shrub removal is planned as part of the investment (no interference with existing vegetation), the conducted simulation represents a maximum scenario, reflecting the potential visibility range under conditions of minimal landscape intervention. However, the possibility of implementing protective vegetation further to reduce the farm's impact on the visual landscape should be considered. The visibility range (hierarchical scale) for the planned investment was adopted in accordance with the guidelines of the General Directorate for Environmental Protection. The analysis results include visibility maps showing the simulated distribution of control points that may be visible in the vicinity of the planned investment.

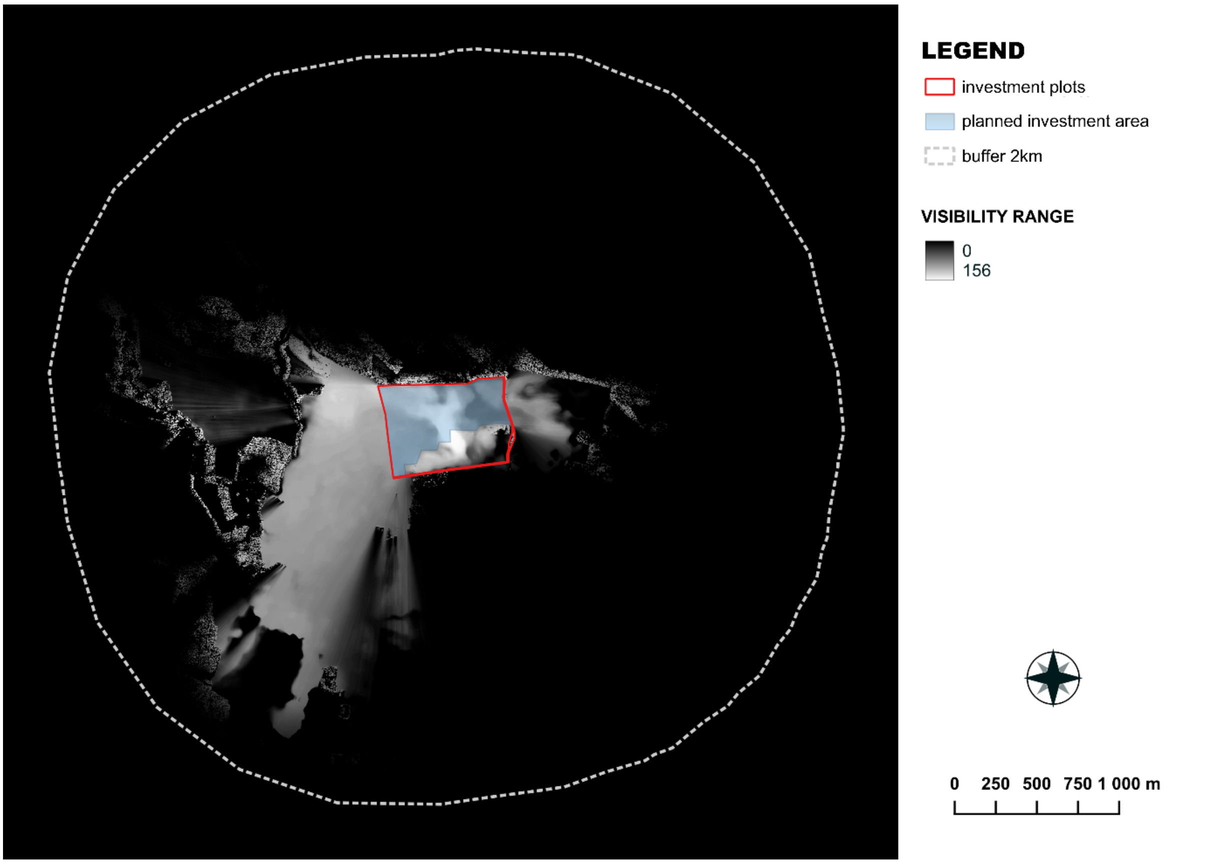

Figure 4. Visualization of the visibility range of the photovoltaic farm. Source: Own Study

Based on the conducted research and spatial-environmental analysis, it was determined that the planned photovoltaic farm will be effectively screened by vegetation zones, whose distribution within its immediate surroundings plays a crucial role in minimizing its visibility. In addition to the role of vegetation, the project's location within a natural land depression further limits visibility across a significant portion of the analyzed plots. Due to the terrain's characteristics, the investment will be most exposed within a range of 0 to 330 meters, where the land is flat, used for agriculture, and lacks significant terrain obstacles or large wooded complexes, resulting in low optical absorption.

In this area, there are zones of tall vegetation, including roadside avenues and forests, which effectively serve as natural screens, reducing the visual impact of the facility. Furthermore, the visibility range of the photovoltaic farm is minimized within a radius of up to 1,600 meters in the southwest direction, where agricultural fields, partially shielded by vegetation, allow for the observation of no more than 25% of the facility's surface.

Consequently, the facility remains invisible from neighboring built-up areas, particularly from the village of Witankowo, which is located in close proximity to the investment site.

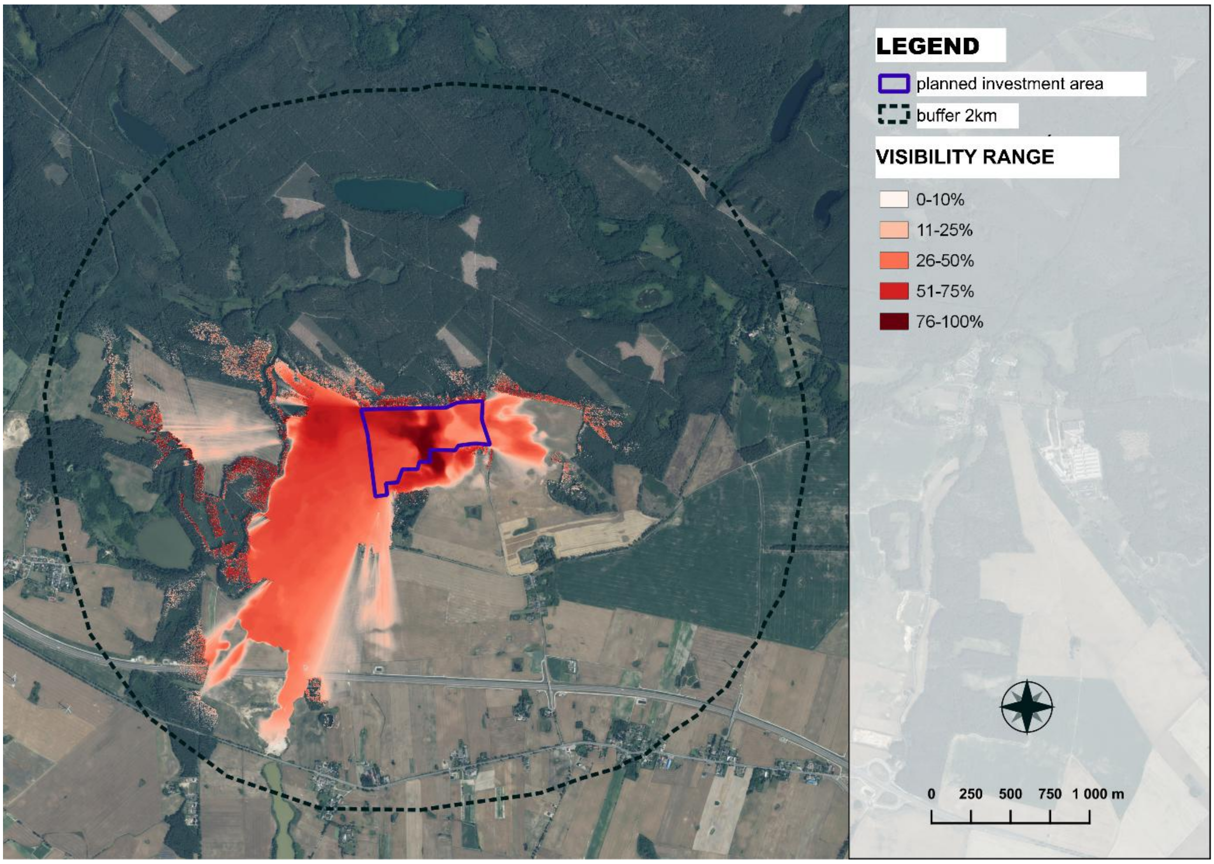

Figure 5. Visibility range of the planned photovoltaic farm. Source: Own Study

According to the conducted spatial analysis and terrain condition assessment, the potential maximum visibility of the planned photovoltaic farm (ranging from 76% to 100%) is primarily confined to the boundaries of the investment plots, with its extent largely determined by the area's topography. Maximum visibility may also occur in small areas west of the planned facility, where agricultural land, including cultivated fields, dominates. It is important to note that these areas do not experience a constant human presence, which minimizes potential visual impacts.

Additionally, point-based maximum visibility may be recorded in forested areas; however, due to the dispersed nature of the tree stands and specific topographical conditions, its occurrence is sporadic and marginal in the context of the overall visual impact analysis. A key finding from the analysis is that the planned photovoltaic farm, even at maximum exposure, will remain invisible from the nearest residential areas, indicating a limited visual impact of the investment on inhabited areas.

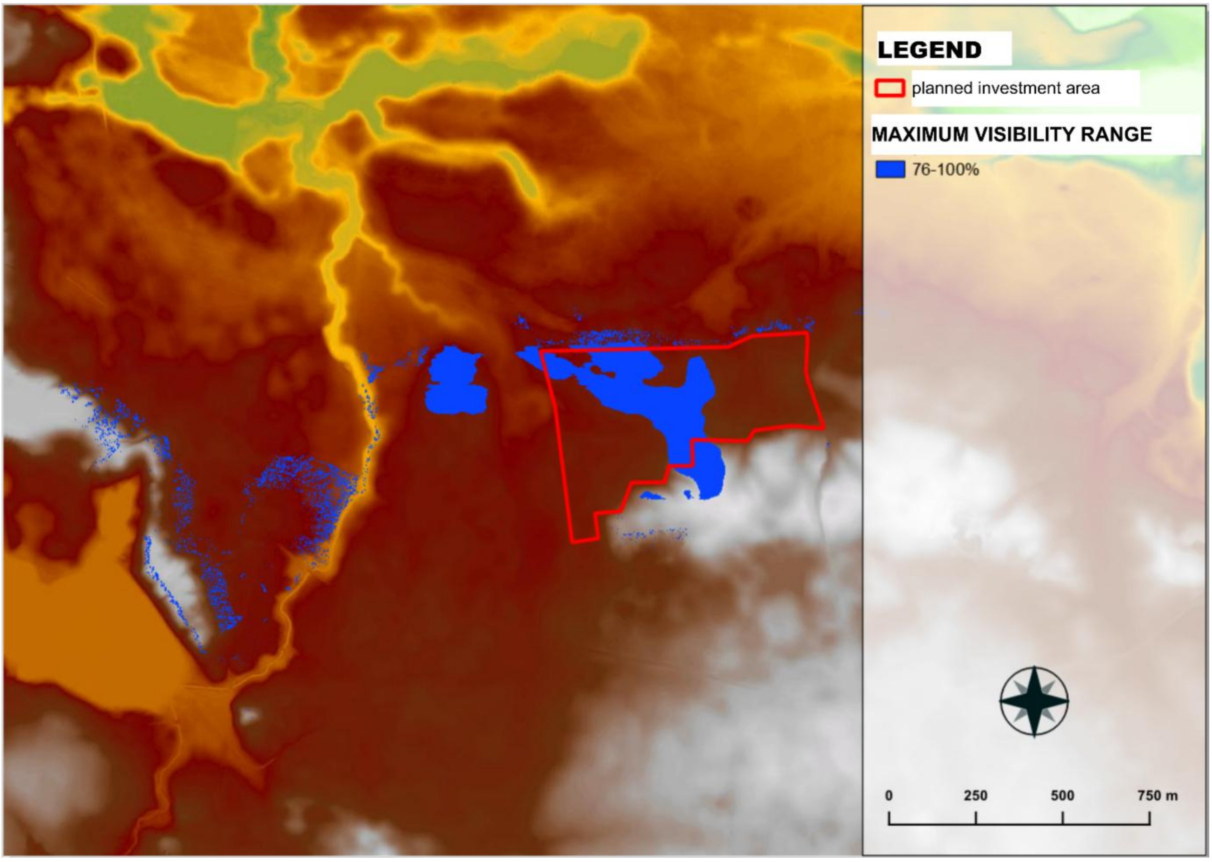

Figure 6. Maximum visibility range of the planned photovoltaic farm. Source: Own Study

It is essential to emphasize that, in the final assessment of the photovoltaic farm's visibility, all landscape elements that may interfere with the facility's perception play a crucial role. These elements include individual trees and shrubs, dispersed buildings, and the height of mid-field tree stands, which can significantly influence the visual perception of the farm. Additionally, observers' subjective landscape preferences must be considered, as they shape distinct aesthetic interpretations of the facility.

The placement of the photovoltaic farm in an area with distinctly varied terrain, particularly in a moraine landscape, significantly increases the potential for screening its individual components. The terrain's morphology, including undulations and natural topographical barriers, reduces the facility's visibility, thereby limiting the extent to which the technical infrastructure affects the landscape. Such terrain conditions help minimize the investment's negative impact on spatial structure and landscape functionality while ensuring greater coherence between the natural environment and the new infrastructure.

Conclusion

This study aimed to assess the impact of photovoltaic farms on landscape perception, accounting for visibility determinants across spatial, structural, and perceptual contexts. The interdisciplinary research approach, integrating geoinformatics, geomorphology, and perceptual modeling, yielded comprehensive results that serve as a valuable tool for spatial planning processes.

The results of the geomorphological and structural landscape analysis indicate that terrain morphology, including the presence of moraine hills and variations in landform, is a key factor in determining the visibility of photovoltaic farms. The use of a Digital Surface Model (DSM) and a detailed landscape fragmentation analysis demonstrated that natural barriers, such as tree stands and landforms, effectively reduce the investment's exposure in specific areas, particularly around natural topographical features.

The visibility-range modeling conducted using Geographic Information Systems (GIS) revealed that, while photovoltaic farms are visible in certain areas, they are largely screened by vegetation and terrain features. Tall vegetation, including roadside tree avenues and forests, plays a crucial role in minimizing the investment's visibility, allowing it to integrate into the landscape almost imperceptibly. Computer-based simulation analysis confirmed that photovoltaic farms are best concealed in areas with variable topography, particularly in regions characterized by a hilly moraine landscape.

Perceptual simulations indicated that the planned investment, despite its presence in the landscape, will remain invisible from built-up areas, including the village of Witankowo. These findings provide strong support for the minimal visual impact of the photovoltaic farm, particularly when appropriate vegetation barriers and optimal site selection are implemented. The farm's visibility range is primarily limited to agricultural areas within a radius of up to 330 meters, where flat terrain and the absence of natural barriers make the investment potentially visible in long-range panoramas.

The final visual impact assessment suggests that photovoltaic farms have a limited effect on the landscape, particularly concerning residential areas and high-vegetation zones. The key to minimizing the investment's perceptual impact is careful selection of its location and the incorporation of landscape elements that influence visual perception, such as the height of tree stands and the strategic placement of vegetation barriers.

In summary, the study demonstrated that a well-planned location for photovoltaic farms, combined with the adaptation of natural landscape elements, can significantly reduce their visual impact, facilitating the integration of the investment into the landscape and minimizing its negative effects on the surroundings. This approach supports sustainable development, balancing energy needs with the protection of landscape aesthetic values.

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