

Article

Visual Assessment of Wind Turbine Impacts on Rural Landscapes in Poland: A Model-Based SBE Study Considering Distance from Residential Areas

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Abstract

Wind turbines can affect perceived landscape quality, particularly in open rural settings where their scale and distinctive form make them a strong visual dominant. This article presents model-based research on how turbine setback distance from residential buildings influences the visual perception of rural landscapes in Poland. A modified Scenic Beauty Estimation (SBE) method was applied, using standardized computer-generated visualizations instead of real-world photographs of seven rural landscape types. For each type, four variants were assessed: a reference view and three scenarios with turbines located 500, 750, and 1000 m from residential buildings. Shorter setback distances significantly reduced visual ratings (ANOVA, $p < 0.001$). The lowest ratings occurred at 500 m, particularly in the large-scale arable farming landscape ($Z = -0.886$), while the highest ratings were recorded for reference variants, especially in the mountain agricultural landscape ($Z = 1.20$). Landscape type was also significant, with open areas proving more sensitive to turbine presence than structurally complex landscapes. Linear trend analysis confirmed that increasing setback distance is associated with higher visual ratings ($F(1, 2140) = 31.60$; $p < 0.001$; $R^2 = 0.01$). These findings indicate that perceptual landscape assessment supports wind turbine siting and, when combined with geographic information systems (GIS) and Landscape and Visual Impact Assessment (LVIA), enables a more comprehensive evaluation of project-related environmental effects.

Keywords: landscape perception; landscape visual assessment; SBE method; wind turbines; turbine distance; rural landscape



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1. Introduction

One of the most serious challenges facing the modern world is mitigating climate change and its environmental impacts [1–7]. In response to the need to reduce carbon dioxide emissions and support sustainable development, the European Commission developed the European Green Deal in 2019, aiming to achieve climate neutrality in Europe by 2050 [8,9]. Poland, as a country with a highly developed mining industry, faces the difficult task of decarbonizing the economy and undergoing an energy transition [10]. The development of renewable energy sources is crucial in this regard, requiring infrastructure with implications for the landscape and its visual quality [11,12].

Wind energy has been developing rapidly across Europe. In 2023, new wind installations exceeded 18.3 GW, including 14.5 GW from onshore wind farms, and forecasts for

2024–2030 indicate a further increase of 260 GW, including 200 GW within European Union countries [13]. A similar trend is observed in Poland, where installed wind power capacity reached 9553.2 MW in 2024, accounting for over 31% of the country's total installed renewable energy capacity and is expected to rise to 14.5 GW by 2030 [14,15]. This expansion is accompanied by increases in both total installed capacity and turbine size [13].

It is also worth noting that the expansion of wind energy brings challenges related to appropriate siting. The most favourable conditions for harnessing wind potential occur in flat and coastal areas [16,17], a pattern also reported in studies from other world regions (e.g., Nigeria) [17]. Due to the specific characteristics of wind farms, turbines are typically located in open areas with limited built development, which makes rural landscapes the most common setting for such projects [18,19].

Due to their scale and distinctive form [20,21], wind turbines are clearly distinguishable elements of the landscape. The shape and height of turbines make them highly visible, even from long distances, often exceeding 10 km [22].

For these reasons, the visual impact of wind farms on the landscape is among the most frequently cited challenges associated with their development. Despite growing public awareness of the need to deploy alternative energy sources and the important role of wind power in this transition, many countries—including Poland—still face difficulties in securing local community acceptance for wind turbine siting [23–26]. This reluctance is largely linked to the strong visual presence of turbines, which may influence the way their surroundings are perceived. The issue is particularly pronounced in open landscapes, especially those with high visual and cultural value.

Key factors shaping the aesthetic perception of space include, above all, the setback distance between wind turbines and residential buildings and the landscape type in which they are located [25,27]. Shorter setbacks increase turbine exposure within the visual field and intensify their visual impact, which may, in turn, deteriorate aesthetic evaluations and reduce social acceptance of new investments.

Wind farms in Poland are subject to detailed legal regulations. The primary legal act governing the siting of wind turbines is the Act of 20 May 2016 on Investments in Wind Farms, commonly referred to as the “Wind Farm Act” (Journal of Laws 2016, item 961) [28]. The Act defines the principles for the location, construction, reconstruction, and operation of wind farms, as well as the rules for locating new residential development in the vicinity of existing turbines [29,30]. Pursuant to Article 3 of the Act, the siting of wind farms is permitted exclusively on the basis of a local spatial development plan [28].

The original version of the Act introduced the so-called “10H rule”, which required wind turbines to be located at a distance of at least ten times their total height from residential buildings. In practice, this corresponded to a distance of approximately 1.5–2 km [28,29]. An amendment to the Act of 9 March 2023 (Journal of Laws 2023, item 553) introduced the possibility of reducing this minimum distance to 700 m, provided that specific planning and environmental requirements are met [31]. In 2025, another draft amendment was processed, proposing a further reduction in the minimum distance to 500 m; however, it ultimately did not enter into force due to a presidential veto [32].

Onshore wind farms are classified as projects that may have a significant impact on the landscape; therefore, they require the preparation of an Environmental Impact Assessment (EIA) and the issuance of an environmental decision. The guidelines of the General Directorate for Environmental Protection (GDOŚ) define the methodology for assessing the impact of wind farms on the landscape within environmental impact assessment procedures, including their influence on the visual quality of the surroundings [33,34]. The document recommends conducting visibility analyses (ZTV/ZVI), delineating landscape perception zones, and identifying key viewpoints and visual corridors. For the selected

locations, visualizations illustrating the landscape before and after the implementation of the investment are prepared. It should be emphasized that the GDOS guidelines are recommendatory in nature and do not constitute a legally binding act [34].

In both Polish and international scientific literature, methods for assessing the visual impact of wind turbines are classified as qualitative and quantitative. More detailed classifications distinguish descriptive, indicator-based, and indirect methods [22].

Descriptive methods (corresponding to qualitative approaches) are based on the characterization of landscape features and the analysis of how wind turbines are perceived within the landscape [11,22,35]. They are often supported by photographic documentation and visualizations. A particularly important approach within this group is Landscape and Visual Impact Assessment (LVIA), which is regarded as a standard in planning and environmental procedures, especially in Western European countries [35]. However, such assessments require specialist expertise and may be influenced by individual perceptual differences [27,36].

Indicator (quantitative) methods are based on mathematical parameters and use numerical values to determine the degree of impact of wind farms on the landscape. Studies of this type often rely on digital terrain and surface models (DTM/DSM) as well as GIS [37,38]. The use of quantitative data enables an objective assessment of alternative wind turbine location scenarios and reduces the influence of subjective expert judgment [39–41]. At the same time, such methods may fail to fully reflect the social and perceptual ways in which wind farms are experienced and interpreted within the landscape [42,43].

Indirect (mixed) methods combine both research paradigms by integrating descriptive landscape analysis with quantitative indicators. This approach makes it possible to capture both the visual attributes influencing landscape perception and the social determinants shaping the reception of energy investments, supported by numerical data. Such methods are particularly relevant in the case of energy projects implemented in rural areas, where social acceptance often plays a decisive role in the decision-making process related to the siting of wind farms [44–46].

It should be emphasized that international studies highlight both expert approaches based on GIS/LVIA [35,41] and observer-based perceptual assessments. Accordingly, experimental methods are increasingly being used to enable the quantitative assessment of visual landscape quality. Visual landscape assessment is important not only in aesthetic terms but also in social terms, as it influences the level of local community acceptance of energy investments. One of the best-established methods of this type is Scenic Beauty Estimation (SBE). It is based on the evaluation of space by a group of observers who are presented with photographs depicting different landscape types. Respondents rate the photographs on a 10-point scale, and the results are then statistically analyzed by calculating mean scores and normalizing them [47,48]. The SBE method has been successfully used in studies on the impact of technical infrastructure on the visual perception of landscapes, including the assessment of wind turbine visibility and acceptability depending on distance and landscape context [27,44,49,50]. Most SBE-based studies use images of real-world scenes, where variability in composition and viewing conditions may make it difficult to isolate the effects of specific variables [47,48].

The current state of research in Poland on the impact of wind turbines on the landscape indicates that studies focus primarily on spatial analyses and visibility models [16,37,51]. These approaches provide important information on the extent of exposure and the potential visibility of objects; however, they offer limited insight into how these parameters translate into observer-based visual assessments of the landscape. There is still a lack of studies employing perception-based methods, such as SBE, which

enable a quantitative, statistical assessment of landscape perception, particularly research conducted under controlled conditions using standardized visual stimuli.

Considering the current state of both international and Polish research, the present study reports model-based research on the impact of wind turbines on rural landscapes in Poland, with particular emphasis on the distance between turbines and residential buildings. The research presented in this article addresses the above-mentioned gap by undertaking a comparative analysis of different rural landscape types under uniform conditions of visual-stimulus presentation. This approach extends GIS/LVIA-based analyses by incorporating observer-based perceptual evaluation under controlled and standardized visual conditions. Furthermore, the study examines the significance of turbine distance from residential buildings as a potential planning scenario and treats it as a possible threshold factor influencing perception.

To address this, a modified Scenic Beauty Estimation (SBE) method was applied, based on visual ratings of computer-generated simulations. The modification consisted of using standardized computer visualizations instead of real-world photographs. Visualizations were prepared for seven representative types of rural landscapes, in which wind turbines were located at three distances: 500 m, 750 m, and 1000 m. The selection of these distances was guided by their legal, planning, and perceptual relevance. The 500 m distance corresponds to the minimum setback values discussed in proposed amendments to regulations governing the siting of wind farms in Poland. The 750 m distance reflects values commonly applied in planning practice and environmental impact assessments as a compromise spatial buffer [28,31,52]. In turn, the 1000 m distance is frequently adopted in the scientific literature as a threshold at which the visual prominence of wind turbines is noticeably reduced in open landscapes [27,35,37]. In addition, the use of equal intervals of 250 m allows for the analysis of gradual changes in the impact of wind farms on the visual quality of the landscape.

This study aimed to verify whether there is a statistically significant relationship between the distance of wind turbines from residential buildings and the visual value of rural landscapes. The research question was: How do the distance of wind turbines from residential buildings (500–1000 m) and the type of rural landscape influence the visual assessment of the landscape using the SBE method?

The following research hypotheses were formulated:

H1. *As the distance of wind turbines from residential buildings decreases, the assessed aesthetic quality of the landscape declines.*

H2. *The type of rural landscape has a significant influence on the visual perception of wind turbines.*

The obtained results may provide a basis for further research on the planning of wind turbine locations in rural landscapes. The application of the Scenic Beauty Estimation (SBE) method may complement the most commonly used visual impact assessment standards, such as GIS-based analyses and Landscape and Visual Impact Assessment (LVIA). This approach enables a more comprehensive understanding of the impact of wind turbines on the landscape. Moreover, the research findings may support spatial planning processes, landscape protection efforts, and the development of sustainable rural development policies in Poland.

2. Materials and Methods

2.1. Study Design and Methodological Framework

In the traditional approach, the Scenic Beauty Estimation (SBE) procedure involves assessing the attractiveness of real landscapes presented in photographs by a group of

respondents [47,48]. In this study, the method was adapted to the nature of model-based analyses by introducing three modifications: (1) the stimuli consisted of standardized computer visualizations rather than photographs of actual locations; (2) within a given landscape type, constant compositional elements (e.g., buildings, roads, tree cover, field layout) and consistent presentation conditions were maintained to limit the influence of random compositional differences; (3) only two experimental variables were systematically varied: rural landscape type (by adjusting the arrangement of components to the variant) and the distance of wind turbines from residential buildings. The visualizations do not refer to specific locations but present model-based visual features of the analyzed landscapes. This approach allowed the assessment to focus on the influence of two key factors, enabling comparisons under controlled visual conditions while maintaining scene repeatability and perceptual consistency.

2.2. Determination of Rural Landscape Types

For the purposes of this study, seven rural landscape types were distinguished. They are characteristic of Poland and represent the main spatial structures occurring in agricultural areas. The classification considered landform, land use (land cover), and the degree of anthropogenic transformation. It was based on Polish specialist literature [53–56], with simplified terminology tailored to the needs of the present visual assessment.

The number of landscape types was deliberately limited to seven, reflecting the model-based nature of the study. The selected types represent spatial settings with dominant morphological or structural–functional characteristics that are relevant to visual perception. The aim of this paper was not to develop a comprehensive typology of Poland’s rural landscapes, but rather to distinguish a set of diverse spatial models enabling a comparative analysis of visual ratings.

The typology does not include industrial landscapes, which occur mainly in suburban zones and in the vicinity of industrial facilities. Owing to the high degree of anthropogenic transformation and the presence of technical infrastructure, these landscapes differ in visual character from traditional rural landscapes and are not aligned with the aims of a study focused on areas with predominantly agricultural functions. The SBE analysis also excludes legally protected landscapes, i.e., areas of high natural and cultural value (e.g., national parks, landscape parks, and nature reserves). Because of their protected status and the associated planning and environmental constraints, such areas require separate, more in-depth analyses. Moreover, in most cases, they are not eligible for wind energy infrastructure siting.

The authors acknowledge that not all of the identified landscape types would be equally suitable for wind turbine siting under real-world conditions (e.g., mountain agricultural landscape). Nevertheless, these types were included in the analysis because the adopted research concept focused on comparing visual perception across diverse spatial structures rather than on assessing actual development feasibility.

Descriptions of the individual landscape types are provided in Table 1.

Table 1. Types of rural landscapes in Poland adopted for the modeling study.

No.	Landscape Type	Characteristics
1.	Large-scale arable farming landscape	An open landscape typical of central Poland. The terrain is flat or gently undulating and intensively used for agricultural purposes. Development is scattered, consisting mainly of individual farmsteads located among arable fields. Large-scale arable fields dominate the landscape.
2.	Agricultural–forest landscape	A landscape with gently rolling terrain, where arable fields and meadows are interspersed with forest complexes. Scattered development predominates, often located along roads or at the edges of forested areas.
3.	Mosaic agricultural landscape	Characterized by diversified terrain, including ravines, valleys, and hills. Land use is mosaic-like, with smaller arable fields, orchards, tree belts, and meadows. Both scattered and compact settlement patterns occur, concentrated primarily in valley areas.
4.	Agricultural–settlement landscape	Typical of lowland and upland areas with low relative relief. This landscape is dominated by compact settlement patterns, often arranged linearly along roads. Arable fields and home gardens adjoin residential buildings. This type of landscape is strongly transformed by human activity.
5.	Meadow–pasture landscape	Occurs primarily in river valleys, floodplains, and adjacent flood-prone areas. Land cover consists of extensive meadows, pastures, and riparian woodlands. Development is often located on slight elevations, which protect buildings from flooding.
6.	Orchard and horticultural landscape	Characteristic of gently sloping terrain in lowland or upland areas. Fruit orchards and horticultural crops dominate, often arranged in regular patterns. Development is concentrated around farmsteads.
7.	Mountain agricultural landscape	Characteristic of southern Poland. It includes rolling terrain, slopes, and basins. Small fields, pastures, and meadows are surrounded by forests. Development is scattered, often terraced, and adapted to slope morphology.

2.3. Development of Computer-Based Visualizations

Computer-based visualizations of the designated rural landscape types were prepared using SketchUp 2026 [57]. Spatial models were developed to represent terrain morphology and characteristic landscape components, including vegetation, watercourses, residential buildings, road networks, and wind turbines (four units). In all models, the spatial arrangement of the basic components—roads, residential buildings, fences, and wind turbines—was kept constant in order to limit the influence of compositional differences on visual assessment results. These elements (with the exception of wind turbines) were placed in the foreground. Subsequent visual planes were developed by introducing features specific to individual landscape types, such as field structure, vegetation patterns, the presence of forests or rivers, and terrain configuration. This means that while the location of the base elements remained unchanged across all variants, land cover type, vegetation composition and distribution, development character, and terrain form were modified in

accordance with the characteristics of each landscape type. Additionally, in each model the distance of wind turbines from residential buildings was systematically varied.

For each landscape type, four visualization variants were developed: a reference landscape (without wind turbines) and variants with turbines located at distances of 500 m, 750 m, and 1000 m from residential buildings. The assumed turbine height was 150 m (hub height), and the rotor diameter was 90 m, which corresponds to the technical parameters of wind turbines commonly used in Poland [58].

The models were rendered in Lumion [59]. A simplified visual style was applied—schematic outlines rather than photorealistic representations. The proposed research approach is model-based; its aim was not to replicate real-world landscape perception in full detail, but to identify general relationships between spatial structure and visual ratings. Such an approach is consistent with experimental research designs and is commonly used in perceptual studies [60,61]. Using neutral-coloured outlines minimises the influence of factors unrelated to spatial arrangement (e.g., textures, colour, and lighting), allowing the analysis to focus on spatial form and object proportions, thereby increasing comparability and supporting a more objective assessment [62].

The rendering parameters were identical for all visualizations. The viewpoints were set at the average observer’s eye level (1.6 m), from a location on a road adjacent to residential buildings, which constituted the viewing axis toward the turbines. This setup reflects the perspective of a rural resident. The camera focal length was set to 22 mm, the tilt angle to 3°, and scene lighting was maintained under uniform daylight conditions. These settings reduce perspective distortions and prevent artificial reduction in the perceived turbine scale in the visualizations.

Additionally, a neutral background in the form of a bright, cloudless sky was applied. Strong lighting contrasts, shadows, and atmospheric effects that could influence the emotional perception of the landscape were deliberately avoided.

To improve the clarity of the analysis and the presentation of the results, each visualization was assigned an abbreviation corresponding to the landscape type and the turbine distance variant. The set of symbols used is presented in Table 2.

Table 2. Overview of visualizations applied in the SBE assessment.

Landscape Type	Reference	500 m	750 m	1000 m
Large-scale arable farming landscape	RU-Ref	RU-500	RU-750	RU-1000
Agricultural–forest landscape	RL-Ref	RL-500	RL-750	RL-1000
Mosaic agricultural landscape	RM-Ref	RM-500	RM-750	RM-1000
Agricultural–settlement landscape	RO-Ref	RO-500	RO-750	RO-1000
Meadow–pasture landscape	ŁP-Ref	ŁP-500	ŁP-750	ŁP-1000
Orchard–horticultural landscape	SO-Ref	SO-500	SO-750	SO-1000
Mountain agricultural landscape	RG-Ref	RG-500	RG-750	RG-1000

2.4. SBE Test Procedure

When conducting a visual landscape assessment using the SBE method, it is essential to follow standards regarding the diversity and size of the observer group. According to the basic guidelines of the method [47], a group of at least 20 participants is sufficient to obtain reliable results. In line with this recommendation, 104 respondents participated in the present study. The sample size exceeds the minimum recommended in the literature by more than fivefold, which increases the reliability and repeatability of the results. The sample encompassed multiple demographic categories (gender, age, education, and place of residence); however, it should be noted that it was demographically skewed, with a predominance of women and respondents under 25 years of age. This sample composition

may affect the external validity of the study. At the same time, it should be emphasized that the aim of this work is to identify perceptual patterns under controlled conditions rather than to generalize the findings to the entire population. Future research should replicate the study using a more demographically diverse sample, which would allow for a more comprehensive assessment of the role of age and gender in landscape perception.

The study group consisted of 23.1% men and 76.9% women. Participants were divided into four age groups. The largest group comprised respondents under 25 years of age (60.6%), followed by those aged 25–39 (27.9%), 40–54 (6.7%), and over 55 years (4.8%). Most respondents had secondary education (45.2%), while 27.9% had higher education and 26.9% had primary education. Among the respondents, 44.2% lived in urban areas and 55.8% in rural areas. In addition, 61.5% of the participants had professional experience related to agriculture, landscape architecture, or forestry.

The study was conducted as an online survey using Google Forms (Supplementary Materials). Participants were recruited using convenience sampling. Inclusion criteria were age 18 years or older and voluntary participation. The questionnaire was distributed online via social media. Before completing the survey, participants were provided with study information (aim, rating instructions, anonymity, and data use) on the introductory page of the questionnaire and gave informed consent electronically by proceeding to the survey. No personally identifiable data were collected, and participants could withdraw at any time. The questionnaire consisted of three sections: respondent characteristics, core questions related to visual assessment, and control questions. Images presenting individual landscape variants were displayed in a random order to avoid suggesting any particular evaluations. Each participant rated the landscapes using a 10-point scale, where 1 indicated the least visually attractive area and 10 represented the landscape with the highest aesthetic value. No time limit was imposed for the evaluation of individual visualizations, allowing respondents sufficient time to familiarize themselves with each image. Additionally, the questionnaire included instructions indicating that the assessment should be based on the overall aesthetic impression and perceived spatial harmony, without focusing on technical details.

The study yielded a total of 2912 ratings provided by 104 respondents. Each participant evaluated 28 computer-generated visualizations representing seven rural landscape types presented in four variants. During the initial data processing stage, a quality control of the responses was conducted. As a result, two respondents were excluded from further analysis because they assigned identical scores to all visualizations, which resulted in a standard deviation of zero. The lack of score variability made it impossible to calculate standardized SBE values for these cases. Consequently, a total of 2856 ratings were included in the final analysis. The results were standardized in accordance with the classical Scenic Beauty Estimation (SBE) approach using the following formula:

$$Z_{ij} = (R_{ij} - R_j) / s_j,$$

where Z_{ij} denotes the standardized score for the i -th rating given by respondent j , R_{ij} represents the i -th rating of respondent j , R_j is the mean of all ratings provided by respondent j , and s_j is the standard deviation of all ratings given by respondent j [47].

Based on the standardized SBE results, mean visual assessment values were calculated for each visualization. Subsequently, comparisons were conducted between the different rural landscape types and the wind turbine distance variants.

Statistical analyses were used to examine the effects of the analyzed factors on perceived landscape visual quality. A two-way analysis of variance (ANOVA) was performed within the general linear model (GLM) framework for repeated-measures data, as each respondent rated all visualization variants. Notably, the ANOVA was conducted using

respondents' raw visual ratings rather than standardized Scenic Beauty Estimation (SBE) scores. This decision was made because standardization is intended to remove inter-individual differences in rating scale use and is primarily applied to facilitate comparisons among landscapes. Accordingly, raw ratings were treated as the appropriate dependent variable for the statistical analysis. Demographic variables (e.g., age, gender, and professional background) were not included in the statistical model, as the aim of the study was to examine perceptual responses to controlled visual stimuli rather than to test the demographic determinants of landscape evaluation.

The ANOVA analysis was used to determine the main effects of the analyzed variables (landscape type and distance from residential development). Additionally, for the turbine distance variants for which ANOVA revealed a statistically significant main effect, a Tukey post hoc test was applied. This test allowed the identification of pairs of distance variants that differed significantly from each other ($p < 0.05$). Furthermore, a linear trend analysis was conducted to determine the direction and strength of the relationship between the distance of wind turbines from residential development and the visual assessment of the landscape. Reference variants without technical infrastructure were excluded from this analysis due to the lack of a defined distance value. Differences in distance-related patterns across landscape types were interpreted descriptively on the basis of mean standardized SBE values, rather than tested as interaction effects in the inferential model.

Tukey's post hoc test was not applied to landscape types, as the objective of the study was to determine whether landscape type influences the perception of wind turbine impacts, rather than to conduct detailed pairwise comparisons between all landscape categories. Differences in ratings between landscape types were therefore described based on the analysis of mean SBE values, which is considered more appropriate from the perspective of landscape perception research. All statistical analyses were performed using Statistica 13.3 software [63].

3. Results

3.1. Results of the SBE Study

The results of the visual assessment are presented in Figure 1 as mean standardized Z values for seven rural landscape types and wind turbine distance variants. The interpretation of the results refers to the visualization labels presented in Table 2.

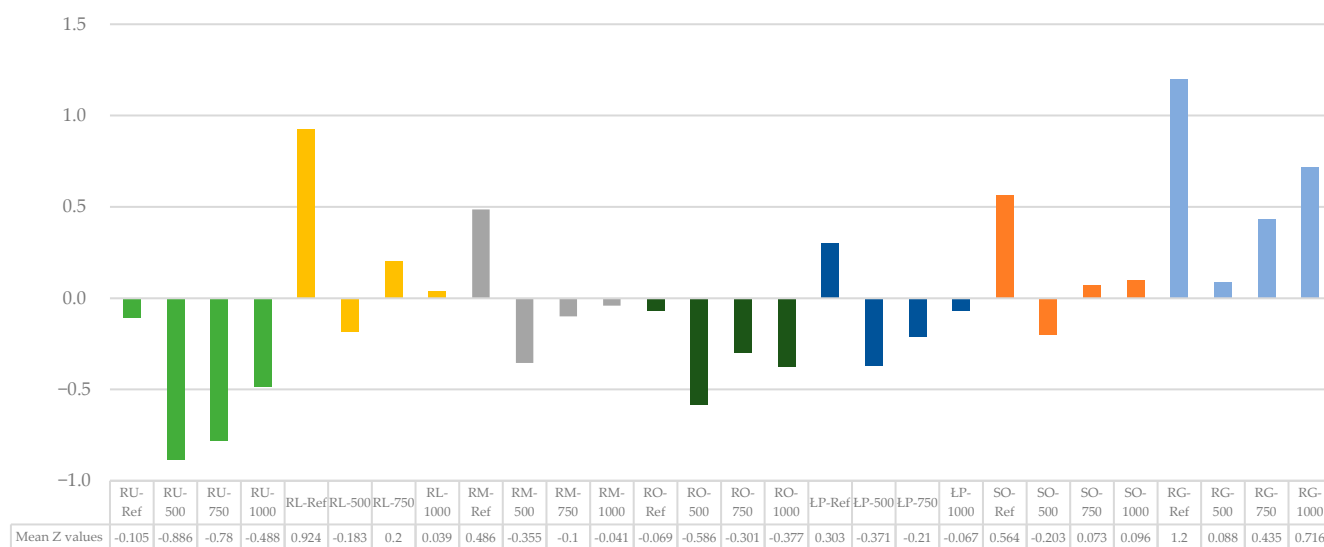


Figure 1. Mean values of standardized SBE scores for seven types of rural landscapes. Higher values indicate more positive visual perception.

Data analysis revealed clear differences in visual assessments among the presented visualizations, both with respect to the distance of turbines from residential buildings and between rural landscape types. All reference visualizations were characterized by higher mean Z values compared to variants including wind turbines. The lowest ratings were obtained for landscape illustrations depicting turbines located at a distance of 500 m from residential development.

The lowest mean SBE rating was recorded for the large-scale arable farming landscape with wind turbines located 500 m from residential buildings (RU-500), for which the mean Z value was -0.886 (Figure 2). For this landscape type, the 750 m ($Z = -0.780$) and 1000 m ($Z = -0.488$) variants also yielded negative visual ratings. Despite the increasing setback distance, the turbines' negative effect on landscape perception remained evident.



Figure 2. Visualization of the large-scale arable farming landscape with a wind turbine located 500 m from residential buildings (RU-500), which received the lowest mean SBE rating ($Z = -0.886$).

Respondents identified the mountain agricultural landscape as the most visually attractive (Figure 3). The reference visualization of this landscape achieved the highest mean Z value ($Z = 1.20$). The results of the control question (“Which landscape do you consider the most attractive?”) were consistent with the ratings obtained in the SBE assessment. The mountain agricultural landscape was selected most frequently (59 responses, 56.7%).

It is worth noting that in most landscape types, mean SBE values increased with increasing distance between the wind turbines and residential buildings. At the same time, the distance-related pattern was not identical across landscape types: in structurally open landscapes the increase tended to be more pronounced, whereas in more complex landscapes it was weaker or less regular, as indicated by the mean SBE values. Analysis of the mean SBE values revealed three exceptions in which the intermediate variant (750 m) received higher ratings than the most distant variant (1000 m), observed in the agricultural–forest, orchard–horticultural, and agricultural–settlement landscapes (Figure 4).



Figure 3. The highest-rated visualization: reference view of the mountain agricultural landscape (without wind turbines).

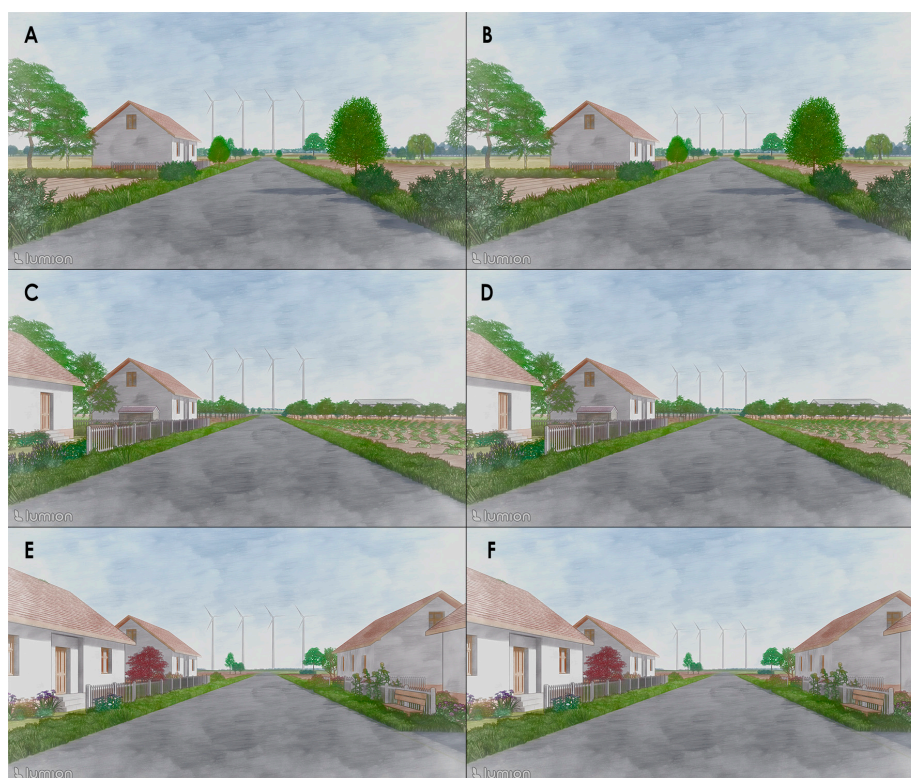


Figure 4. Visual comparison of landscape types showing deviations from the general distance-related trend: (A,B) agricultural–forest landscape (750 m and 1000 m), (C,D) orchard–horticultural landscape (750 m and 1000 m), (E,F) agricultural–settlement landscape (750 m and 1000 m).

3.2. Statistical Analysis of Results (ANOVA)

To verify the effects of the analyzed factors on visual landscape assessment, a two-factor analysis of variance (ANOVA) was performed. Rural landscape type and the distance of wind turbines from residential buildings (variants: reference, 500 m, 750 m, and 1000 m) were adopted as independent factors. The dependent variable consisted of respondents' raw, non-standardized visual ratings.

The analysis showed that both rural landscape type ($F(7, 2845) = 30.65, p < 0.001$) and turbine distance ($F(3, 2845) = 63.04, p < 0.001$) had a statistically significant effect on visual

ratings. Statistical power was high for both factors (1.00). For landscape type, the partial eta-squared value (η^2_p) was 0.070, indicating that approximately 7% of the variance in visual ratings (raw scores) was explained by differences among rural landscape types. For turbine distance, the partial eta-squared value (η^2_p) was 0.062, meaning that approximately 6.2% of the variance in visual ratings was explained by changes in distance. Thus, both effects may be interpreted as moderate in magnitude and broadly comparable. However, their practical significance should be considered with caution, as each explains only a limited proportion of the variance in visual assessments.

Tukey's post hoc test revealed significant differences between the reference landscapes and all variants containing wind turbines (500 m, 750 m, and 1000 m; $p < 0.001$). No statistically significant differences were found between visualizations depicting turbines located at distances of 750 m and 1000 m from residential development ($p = 0.36$). This result suggests that within the tested range, improvements in visual ratings may level off beyond 750 m.

Differences in visual landscape assessments between wind turbine distance variants from residential buildings are presented in Figure 5 as estimated marginal mean visual scores with 95% confidence intervals.

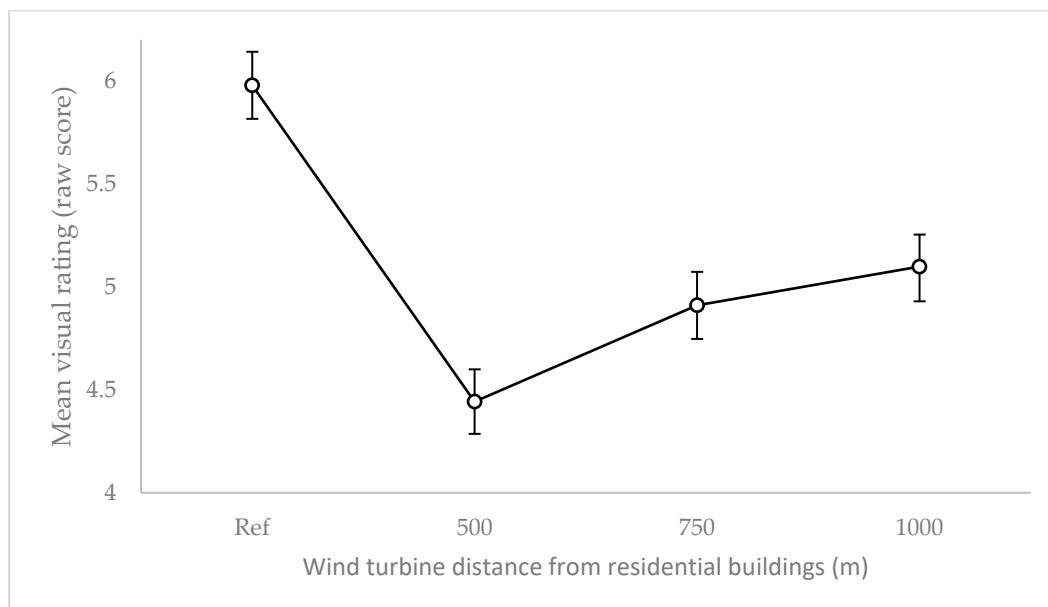


Figure 5. Estimated marginal means of visual landscape ratings by wind turbine distance from residential buildings ($\pm 95\%$ CI).

Regression analysis revealed a statistically significant positive linear trend between wind turbine distance from residential buildings and visual landscape assessment ($F(1, 2140) = 31.60, p < 0.001$). The results indicated that increasing turbine distance was associated with a systematic increase in visual ratings. However, the very low coefficient of determination ($R^2 = 0.01$) indicated that turbine distance explained only a small proportion of the variance in visual assessments. Therefore, although the direction of the relationship was consistent with the ANOVA results, the observed trend should be interpreted as weak and not sufficient to explain visual ratings on its own. The linear relationship between turbine distance from residential buildings and visual landscape assessment is presented in Figure 6.

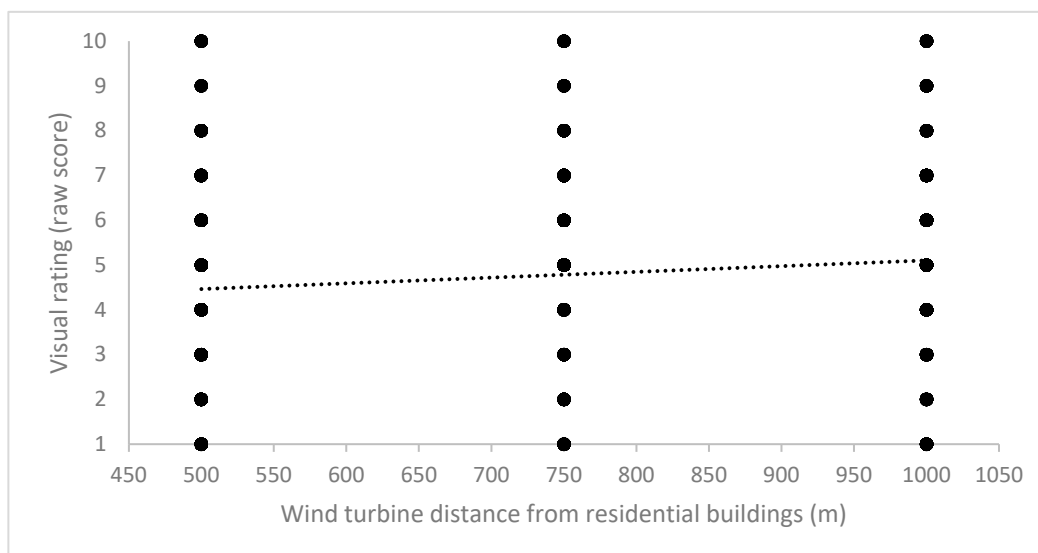


Figure 6. Linear relationship between wind turbine distance from residential buildings and visual ratings (raw scores) based on individual observations. Black dots represent individual ratings, and the dotted line indicates the fitted linear trend.

4. Discussion

4.1. The Influence of Wind Turbine Distance and Landscape Type on Visual Landscape Assessment

The results presented in this article demonstrate that both the distance of wind turbines from residential buildings and the type of rural landscape have a significant influence on visual landscape assessment. However, neither of these factors proved to be dominant, which highlights the complexity of the process of perceiving the visual impact of wind farms on the landscape.

Increasing the distance between wind turbines and residential buildings was associated with higher visual ratings across all landscape types. At a distance of 500 m between turbines and residential buildings, their visual impact on spatial perception was the strongest, resulting in the lowest SBE scores. At the same time, the analyses performed did not indicate statistically significant differences between the 750 m and 1000 m variants. This suggests that beyond a certain threshold, further increases in setback distance may not lead to a substantial improvement in perceived visual quality within the tested range [40]. However, because the interval between 750 m and 1000 m is relatively small, future studies should test a wider distance range to further examine potential threshold effects. These findings are consistent with the view that shorter viewing distances increase turbine exposure and may enhance the perceived lack of visual integration with the surrounding landscape [12,27,38,40,43]. The research conducted by the authors is relevant in the context of the planned changes in Poland regarding wind turbine siting regulations. The results indicate that a minimum distance of 500 m from residential buildings was associated with lower visual attractiveness ratings. This suggests that solutions in which wind energy investments are located at the minimum permissible distances may be perceived as poorly integrated into the existing landscape structure.

Equally important in the visual impact assessment of wind turbines is the type of landscape in which they are located. The lowest SBE scores were obtained for variants representing open landscapes characterized by a low degree of terrain differentiation. These areas contain a limited number of visual screening elements and are therefore particularly sensitive to turbine exposure. In such landscapes, wind turbines often function as visual dominants, clearly standing out within the spatial structure. This effect was especially evident in the large-scale arable farming landscape, which received negative visual ratings

across all visualization variants. It is worth emphasizing that in this type of landscape, even with increasing distance between the power plant and residential buildings, their negative impact on visual perception remained clearly noticeable. Other rural landscapes that also received low SBE scores were those with simplified spatial structures, such as agricultural-settlement and orchard-horticultural landscapes. In these landscape types, the regular arrangement of fields, meadows, and orchards increased the visibility of technical structures. The linear structure of land-cover elements guided observers' visual attention toward the turbines, further enhancing their visual prominence.

In turn, landscapes with greater structural diversity and complexity received higher visual ratings compared to open landscapes. The presence of tree cover, forest complexes, and varied terrain reduced the visibility of wind turbines and weakened their visual dominance within the landscape. In such areas, increasing the distance of wind turbines from residential buildings was associated with a more noticeable increase in visual ratings; however, this relationship was not always linear, as observed in agricultural-forest, orchard-horticultural, and agricultural-settlement landscapes. This may be explained by the fact that, in these areas, the spatial structure facilitates partial screening of turbines and their better visual integration with the surrounding landscape. At greater distances, however, wind turbines remain visible in more distant landscape planes, which leads to an increased contrast with the landscape background.

The highest visual ratings were assigned to the mountain agricultural landscape. This was evident both in the reference variant and in the variants with wind turbines located at greater distances from residential development. This type of landscape is characterized by the greatest diversity of landform features and a mosaic arrangement of fields, pastures, and meadows. The high level of landscape complexity results in greater resistance to the negative visual impact of wind turbines.

These findings are consistent with previous studies addressing the visual impact of wind turbines in relation to landscape characteristics. In open areas, wind turbines tend to assume the role of visual dominants more rapidly [12,43]. Landscapes characterized by greater complexity and a richer spatial structure—such as varied topography, a mosaic of land cover, and the presence of tree cover—are less visually sensitive to wind turbine installations compared to simpler and more homogeneous landscapes [12,40,43]. The greater the number of elements composing a given landscape type, the lower the visual impact of technical infrastructure [12]. Moreover, the location of wind turbines in areas of higher scenic attractiveness leads to a deterioration of aesthetic evaluations [40].

Polish expert studies emphasize that wind turbines can strongly transform rural landscapes, particularly in areas of high natural and historical value. These studies indicate that wind energy installations may be perceived as visually disruptive to spatial composition and overall landscape character. Consequently, in landscapes characterized by higher structural complexity, the appropriate siting of wind turbines may be more challenging [34,36,64].

4.2. Visual Landscape Assessment Based on the SBE Method

The Scenic Beauty Estimation (SBE) method enables the visual assessment of landscapes in terms of wind turbine impacts on aesthetic quality by comparing standardized ratings across landscape variants. Standardization reduces the influence of inter-individual differences in rating scale use and improves the comparability of results among the analyzed rural landscape types. Although SBE is more time-consuming than other approaches used in visual landscape quality research, it provides deeper insight into how landscapes are perceived. It captures perceptual responses to visual change resulting from the presence of wind turbines and their visual relationship with the surrounding landscape. Nevertheless,

SBE is not yet widely applied in studies assessing wind turbine impacts. In this field, GIS-based analyses and LVIA procedures typically dominate, focusing primarily on the extent of turbine visibility within the landscape [35,37,41,51]. While these methods can precisely delineate areas that may be problematic for turbine siting, visibility alone is not necessarily equivalent to a negative visual appraisal [51]. Because they lack a social/perceptual component, relying on these approaches alone is insufficient for a robust assessment of turbine effects on perceived landscape quality [35,51]. Therefore, a comprehensive visual impact assessment requires combining spatial analyses with perceptual methods.

In Poland, Environmental Impact Assessment (EIA) practice relies mainly on expert-based and indicator-based approaches, which are largely grounded in visibility analyses, GIS-based spatial modelling, and landscape composition assessment [11,36]. Reviews of national landscape-related studies indicate substantial variation in both their level of detail and scope. The use of mathematical indicators does not necessarily ensure an objective evaluation of project impacts, as results depend on the parameters adopted in the calculations [11].

It should also be emphasized that guidelines for assessing wind farm impacts on the landscape are advisory and do not constitute legally binding regulations; consequently, the selection of analytical methods largely remains at the discretion of the report author/preparer. The absence of a uniform, mandatory methodology for visual impact assessment may lead to considerable differences in landscape interpretation and in assessments of landscape sensitivity [11].

The method presented in this article introduces a participatory and perceptual perspective to research on the visual impacts of wind farms on the landscape. It enables the incorporation of landscape users' opinions into the investment planning process at an early stage, prior to formal siting decisions. By expanding the analytical framework to include social and perceptual dimensions—still only weakly represented in planning practice—this approach provides a valuable complement to the expert-based methods currently applied in Poland.

When interpreting the results presented in this article, it is important to consider the sample composition. The study included a higher proportion of women and respondents under 25 years of age, which may influence external validity and may reduce the extent to which the obtained assessments can be generalized to the broader population. Therefore, the findings should primarily be viewed as perceptual patterns observed under controlled conditions and used for comparing stimulus variants (rural landscape type and turbine setback distance). Accordingly, they should not be interpreted as direct estimates of average societal preferences. Future research could replicate the study using a more demographically diverse sample, including residents of areas adjacent to planned developments, to provide a more comprehensive understanding of the role of age and gender in landscape perception.

5. Conclusions

The analyses confirm that the visual impact of wind turbines on rural landscapes is multifaceted. Both the setback distance from residential buildings and the rural landscape type proved to be comparably important in shaping visual assessments. Within the tested scenarios, a setback distance of 500 m from residential buildings was associated with lower SBE scores and, consequently, lower perceived visual attractiveness of the landscape. This may contribute to a reduction in perceived visual quality in the vicinity of residential areas, which may increase the likelihood of concerns in local siting discussions.

Higher-rated landscapes were characterized by greater spatial diversity and structural complexity, which reduced the visual prominence of turbines. In contrast, open landscapes

are more susceptible to negative visual effects due to the lack of natural visual barriers; as a result, technical elements function as stronger spatial dominants in these settings. This highlights the significant role of landscape structure in shaping the perception of space containing wind energy infrastructure.

Although GIS tools and LVIA procedures provide effective support for landscape analysis, their capabilities remain limited, as they do not fully capture the perceptual experience of the landscape. Spatial perception is inherently human, emotional, and experiential. Therefore, combining spatial analyses with perceptual methods such as Scenic Beauty Estimation (SBE) enables a more comprehensive assessment of the visual impact of wind energy investments and a better understanding of how they are perceived by landscape users.

Appropriate wind turbine siting is one of the key factors shaping social acceptance of wind energy in rural areas, particularly in landscapes with high natural and cultural value. Therefore, incorporating residents' perspectives into landscape analyses can help identify potential conflict areas at an earlier stage and increase the transparency of decision-making on wind energy infrastructure siting.

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