Chapter

Wind Energy and Multicriteria Analysis in Making Decisions on the Location of Wind Farms: A Case Study in the North-Eastern of Poland

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Abstract

This chapter presents an investigation of different methods of multicriteria analysis and different rules of proceedings that have to be taken into account for making decision about location of a wind farm with application in the north-eastern (NE) Poland. Ten multicriteria analyses were discussed taking into account the main criteria on which they are based on utility functions (MAUT, AHP, and DEMATEL), relationship outranking (ELECTRE, PROMETHEE, and ARROW-RAYNAUD), distances (TOPSIS), and decision support (BORDA ranking methods and their modified and COPELAND). Taking into account of nine criteria that should be met by the location of 15 wind turbines in Krynki and Szudzialowo communities, the main three criteria (C3, C8, and C9) were found to differentiate location of eight wind turbines (T-6–T-13), according to two variants (I and II). The Borda ranking method proved that from among the two variants considered, the more suitable location of wind turbines is second variant W II than first variant W I. Variant W II had a higher altitude of the terrain (C3) and less risk of impact on birds (C8) and bats species (C9) than variant W I.

Keywords: wind energy, wind farms, multicriteria decision analysis, optimum variant, ranking methods

1. Introduction

Management in conditions of sustainable development requires making rational decisions [1, 2]. Each decision-making process has multicriteria character due to the complexity of the problem, and the selection of the optimal solution is complicated [3, 4]. The use of multicriteria analyses, during which a set of related criteria and variants are analyzed, enables creating, justifying, and transforming preferences in the decision-making process [5, 6]. Multicriteria Decision Making (MCDM) or Multicriteria Decision Analysis (MCDA) methods were used to support decision making in case of problems where conflicting environmental, technical, economic, societal, and esthetic objectives are involved [7–13]. MCDA is suitable for supporting decision making dealing with sustainability issues and can use the location of wind turbines, which should meet a number of criteria in development of wind energy production [14, 15].

Multiple criteria decision analysis for energy and environmental security, as well as planning the location of wind turbines, depends on many factors [16–20]. Decision problems associated with determining the suitability of the site for the location of the wind farm can be solved by using multicriteria analysis, which allow to select the optimal solution of the many available options [16, 17]. The selection is made on the basis of established criteria, which have a significant impact on the implementation and operation of the project [21, 22]. This chapter presents the discussion of different methods of multicriteria analysis and different rules of proceedings that have to be taken into account for making decision about location of a wind farm made of 15 turbines in the area of Krynki and Szudzialowo communities in the NE Poland.

There are numerous methods of multicriteria decision; therefore, the choice of optimal method for the decision-making process is very important [23, 24]. Each of the presented methods has its advantages as well as disadvantages and limitations, which makes it necessary to examine them to find the best solution [25]. The choice of particular method can itself reach the dimension of a multicriteria problem [26]. In this study, 10 multicriteria decision analysis (MCDA) methods were discussed taking into account the main criteria on which they are based on utility functions (MAUT, AHP, and DEMATEL) [27, 28], relationship outranking (ELECTRE, PROMETHEE, and ARROW-RAYNAUD) [29, 30], distances (TOPSIS) [31], and decision support (BORDA ranking methods and their modified and COPELAND) [32] (**Figure 1**). The final location of the wind farm made up of 15 turbines in the NE Poland was solved on the basis of multicriteria analysis and choosing the optimum variant.

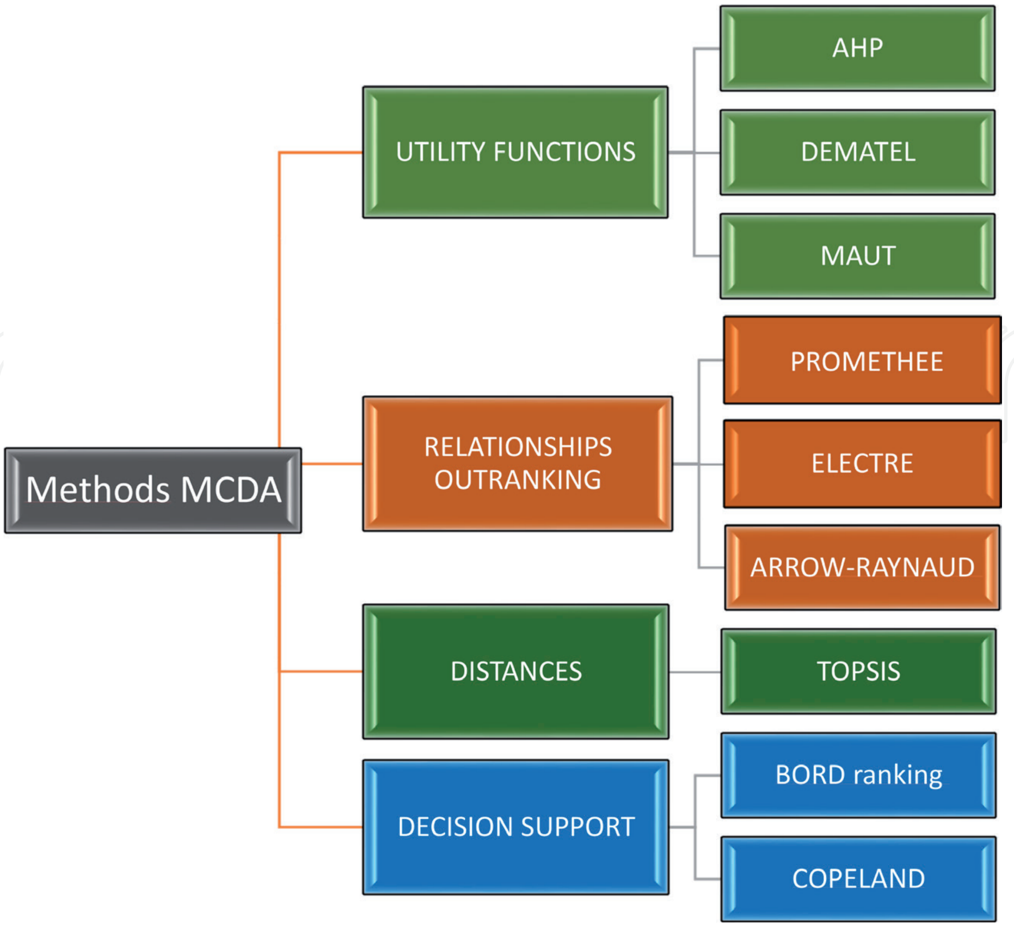

Figure 1.
Ten multicriteria decision analysis (MCDA) in making decisions on the location of wind farms

2. Methods of multi-criteria analysis

The problems with making decision on farm location were analyzed taking into account the nine criteria having essential effect on the realization of a given investment [15]:

- Criterion 1 (C1)—The presence of natural environment elements under legal protection, including nature reserves, protected landscape, and monuments of nature determined based on the interactive map of protected areas [33] and results of a year-long vegetation inventory [34]; C1 was present or absent.

- Criterion 2 (C2)—Evaluation of wind energy resources on the basis of maps defining the area of wind energy in Poland [35] and maps illustrating the wind speed in the area of the country [36]; C2 was analyzed as very highly favorable, very favorable, favorable, little favorable, or unfavorable.

- Criterion 3 (C3)—Difference in the altitude of the terrain of turbine possible location on the basis of topographic maps from Geoportal [37]; C3 was expressed in meters above mean sea level (AMSL).

- Criterion 4 (C4)—Terrain roughness on the basis of the table class roughness [18]; C4 had a value of 0 (water surface) to 4 (urban agglomerations).

- Criterion 5 (C5)—No risk of floods or flooding on the basis of the flood risk maps [38]; C5 was present or absent.

- Criterion 6 (C6)—Technological infrastructure and communication possibilities on the basis of "Local Developmental Plans" in Krynki [39] and Szudzialowo communities [40]; C6 was analyzed as very good, good, bad, and very bad.

- Criterion 7 (C7)—Culture and landscape valors of Krynki [41] and Szudzialowo communities [42] on the basis of "Theories of urban planning"; C7 was present or absent.

- Criterion 8 (C8)—Results of a year-long ornithological monitoring [34]; C8 was analyzed as the number (1–5) of protected bird species occurring in a given area.

- Criterion 9 (C9)—Results of a year-long chiropterological monitoring [34]; C9 was analyzed as the level of activity of bats expressed on the scale—very high, high, low, or very low.

The field study of the vegetation inventory, ornithological, and chiropterological monitoring was performed from July 2017 to July 2018. The field study included the phytosociological analyses of plant communities, cartographic study of vegetation, and sites of protected plant species with the use of GPS technique and identification of habitats of the plant patches studied. In field study in the location of 15 wind turbines in Krynki and Szudzialowo communities, 132 phytosociological Braun-Blanquet releves were taken [34].

3. Selection of MCDA in making decisions on the location of wind farms

The purpose of the analysis is to find the way that will lead to a better solution than the others. Multicriteria decision support is usually defined as making decisions in the presence of many criteria, taking into account several, often contradictory, points of view [4, 43]. The goal is to achieve such an effect that maximizes the multicriteria objective function, which can be written as follows (Eq. (1)):

$$F(x) = \max\left(f1(x), f2(x), \ldots, fj(x)\right), \tag{1}$$

with restriction $x \in A^{\text{dop}}$,

where A^{dop} is a set of acceptable solutions; and $fj(x)$ is the individual partial criterion functions for $j = 1, 2, \ldots, J$.

The analysis begins with a selection of decision variants that will be considered during the decision procedure [44–48]. The next step is the selection of criteria that are the measures of evaluation and the ranking of criteria according to their importance (by assigning weights to them) [21, 22]. Criteria that are benefits are called stimulants [49, 50]. They allow the variants to be ordered, so that the more benefits they bring, the higher the weight values in the light of a given criterion. On the other hand, the criteria, which are of a cost nature, are referred to as destimulants [51, 52]. In assigning weights to individual criteria, the decision-maker preferences are expressed, and they often determine the choice of a particular variant. In these types of cases, it is recommended to perform a sensitivity analysis that focuses on considering changes in function coefficients or free words. The result of the multicriteria decision support process also depends on the accuracy of the option assessments [53, 54]. It is important to carry out a synthetic assessment of individual variants by appropriate aggregation of partial assessments [55].

In this study, 10 multicriteria methods were used, with their names used the acronym for the English or French word. The effectiveness of the multicriteria method for the choice of location of 15 wind turbines in the NE Poland was evaluated. The multicriteria analysis was discussed taking into account the main criteria on which they are based on utility functions (MAUT, AHP, and DEMATEL), relationship outranking (ELECTRE, PROMETHEE, and ARROW-RAYNAUD), distances (TOPSIS), and decision support (BORDA ranking methods and their modified and COPELAND method; **Figure 1**).

3.1 Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (*AHP*) was created by Thomas L. Saaty at the University of Pittsburgh in the 1970s [56–58]. This method is based on a linear additive utility function [58]. The basis of AHP is hierarchical decomposition evaluation criteria, which allows to connect the criteria quantified and not quantified and objectively measurable with subjective [59–61]. AHP is based on three basic rules [57, 58] as follows:

- The structure of the decision problem is presented in the form of a hierarchy of goals, criteria, subcriteria, and variants.
- Preference modeling is carried out by comparing pairs of elements at each level of the hierarchy.
- Ordering of variants takes place through the synthesis of preference assessments from all levels of the hierarchy.

AHP method involves a hierarchic decomposition of the problem decomposed into components and followed by evaluation of criteria and variants by their comparison in pairs (**Figure 2**). The AHP method is based on functionality and is

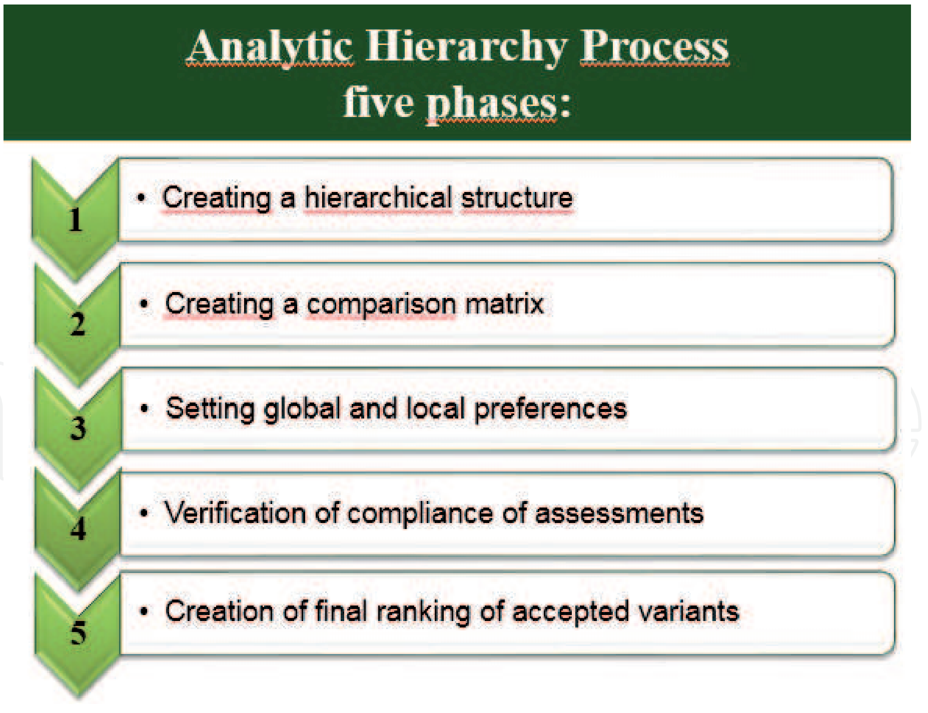

Figure 2.
The five phases of Analytic Hierarchy Process.

hierarchical approach to the problem. The concept of hierarchy has its application on different levels of analyses [62, 63]. Hierarchical problem analysis is useful when not you can determine the functional relationship between the components of the dilemma decision making. The method is characterized by the occurrence of subjective criteria assessments and variants because they result from the decision-maker's nonobjective assessments. Characteristic of this method is to compare the criteria adopted with each other, what the result is a comparison matrix (**Figure 2**). The next step is determining global and local preferences based on a comparison matrix and calculating the compliance factor. The final stage is to create a final ranking of the alternatives adopted. It is possible by calculating the utility function of given variants (**Figure 2**).

The hierarchy of values in the AHP method is well-defined, at the highest level is the superior aim, which is the choice of wind farm location, the lower levels are the criteria that must be met for making the right decision presented in the methodology, and the lowest levels are the variants of decision. The evaluation of criteria and variants is exclusively subjective and depends on decision-making body, which can hardly be accepted for the proper choice of wind farm. The AHP method allows the use of a nine-level verbal scale transformed on a numerical scale. This should facilitate making decisions, however, often leads to situations where relationships are difficult to define between variants and criteria due to their nature. The final assessment in AHP may not give an unequivocal answer as to which of the analyzed variants is the most advantageous too, because with a slight change in the decision-maker preferences the ranking will change, which does not guarantee the choice of the best solution.

3.2 Multiattribute Utility Theory (MAUT)

Multiattribute Utility Theory (MAUT) is used to evaluate trade-offs between alternatives and their effects on objectives [3, 4, 53]. MAUT is applied to identify variants of locations. It is based on the defined function of utility $u_i(K_j)$ and helps settle the hierarchy and ranks of particular variants, and then it orders the criteria which a given location must meet. This method cannot be applied for the choice of location of wind turbines depending on many environmental criteria as the criteria of this method need to be normalized, i.e., their units must be uniform. It is then necessary to define partial function of utility, hence the preferences of the decision-making organ (persons) regarding the variants. The preferences are always subjective and do not take into account the limitations imposed by significant environmental factors.

3.3 DEcision MAking Trial and Evaluation Laboratory (DEMATEL)

The next method is to DEcision MAking Trial and Evaluation Laboratory (DEMATEL) used for direct analysis and intermediate cause-and-effect relationships between elements of the system (factors or criteria) with respect to its kind and severity [64–68]. DEMATEL is a good tool for evaluating the direct and indirect cause and effect relations between the criteria. The method assumes the three types of relations between two criteria: the first criterion has impact on the second one, and the second one has impact on the first one, or they are not related. In the DEMATEL method, it is possible to model the interactions between the criteria taking into account the direct and indirect relations between them. This method was found to be inadequate for making decisions about location of wind turbines as it is totally subjective and the decision depends on the opinions of the deciding body. In this method, the relations between criteria are analyzed, but the list of criteria and the assigned values describing their interaction in pairs depend on the information provided by the decision-making persons in the form of interviews or questionnaires.

3.4 ELimination and Choice Translating REality (ELECTRE)

The another method named ELECTRE is the acronym for the French word for the ELimination Et Choix Traduisant la REalité. In this method, the preferences of the decision maker were modeled on the basis of binary relation outranking [4, 48, 69]. ELECTRE methods are most often used when dealing with a greater set of criteria that can be assigned to much differing values. At the first step, the values of particular criteria are established and assessed to certain weights, so that the sum of the weights gives one. Then, all the variants are compared in pairs using the outranking relation, which boils down to the acceptance of the risk of treating one variant as definitely better than the other one even if the two variants are similar. The ordering of variants on the basis of the outranking relation and recommendation of one variant over the other depends entirely on the preferences of the decision-making persons, which is a definite limitation of the objective choice [70, 71].

3.5 Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEE)

The method of Preference Ranking Organization METHod for Enrichment Evaluations (PROMETHEEs) was used to determine the synthetic ranking alternatives and pairwise comparisons and outranking relation [5, 72, 73].

PROMETHEE is also based on outranking relation. This method involves construction of a decision matrix in which particular variants are compared in the light of established criteria. On the basis of a comparison of variants, the preferences of the decision-making body are expressed by the preference function taking values from 0 to 1. The result of 1 corresponds to a strong preference of one variant over the other, and the value of 0 informs about no relation between the variants. The last stage of PROMETHEE is determination of preference indices referring to each pair of variants. This method is also inadequate for the objective choice of wind farm location because of the limitation of employing the preferences of the decision-making body [74].

PROMETHEE methods are characterized by the analysis of the diversity of assessments of individual variants for all criteria. The more varied the assessments are in the light of a given criterion, the better one of the variants is, whereas when the difference does not take large values, the equivalence of the variants occurs or one of the variants slightly outweighs the others. The criteria are assigned to a preference function that measures the strength of preferences. The function presents the transformation of the difference in evaluation of the analyzed alternatives due to the given criterion (Trzaskalik 2014). The final ranking is obtained on the basis of flows, which are determined using aggregated preference indices [75].

The PROMETHEE method takes into account the decision-maker preferences without the need for a series of onerous comparisons and points. The disadvantage of this method is the need to determine the value and dependence of individual specific parameters, of which the interpretation can cause great difficulties.

3.6 Arrow-Raynaud method

Arrow and Raynaud belong to the "Outranking methods" and constitute a class of ordinal ranking algorithms for multicriteria decision making [9]. The authors of this method argue that the axiomatic formulation offers the surest path to a solution that is as objective as possible, minimally distorted by the unwitting imposition of personal values [29]. They then develop a system of consistent and appealing axioms, confront the paradoxes that put axiomatic systems in general at risk, and demonstrate the applicability of their system to realistic industrial outranking problems. Even within the axiomatic framework, however, some leeway remains for subjective choice and conscious value decisions [49]. One ad-hoc criterion of choice the authors selected was that their method should be neither so flexible and open that personal biases might easily slip in nor so artificially rigid that the play of intuition and creativity was systematically excluded.

3.7 Technique for Order Preference using Similarity to Ideal Solution (TOPSIS)

TOPSIS is a Technique for Order Preference using Similarity to Ideal Solution. This is a multicriteria method developed in the early 1980s by C.L. Hwang and K. Yoon, and its other variation—fuzzy model—proposed by C.T. Chen in 2000 [6]. Among other multicriteria methods, it is distinguished by the use of the relative distance value of individual decision alternatives to the reference (ideal) and worst (anti-ideal) solution. In this situation, the most advantageous variant is one that is relatively closest to the pattern and relatively furthest anti-patterner [64]. The calculation procedure in the TOPSIS method consists of six phases (**Figure 3**).

The TOPSIS method is a similarity method to an ideal solution, which is one of the distance methods. Variants are assessed by determining their distance from the pattern (ideal) and anti-pattern (anti-ideal) [76, 77]. Determination of the preferential sequence requires taking into account the weightings of the criteria and normalizing the option assessments in the light of the criteria. The best solution is characterized by the closest position to the ideal and the furthest relative to the anti-ideal. It allows to determine the values of the synthetic measure, which indicates the place of individual variants in the ranking [76, 77].

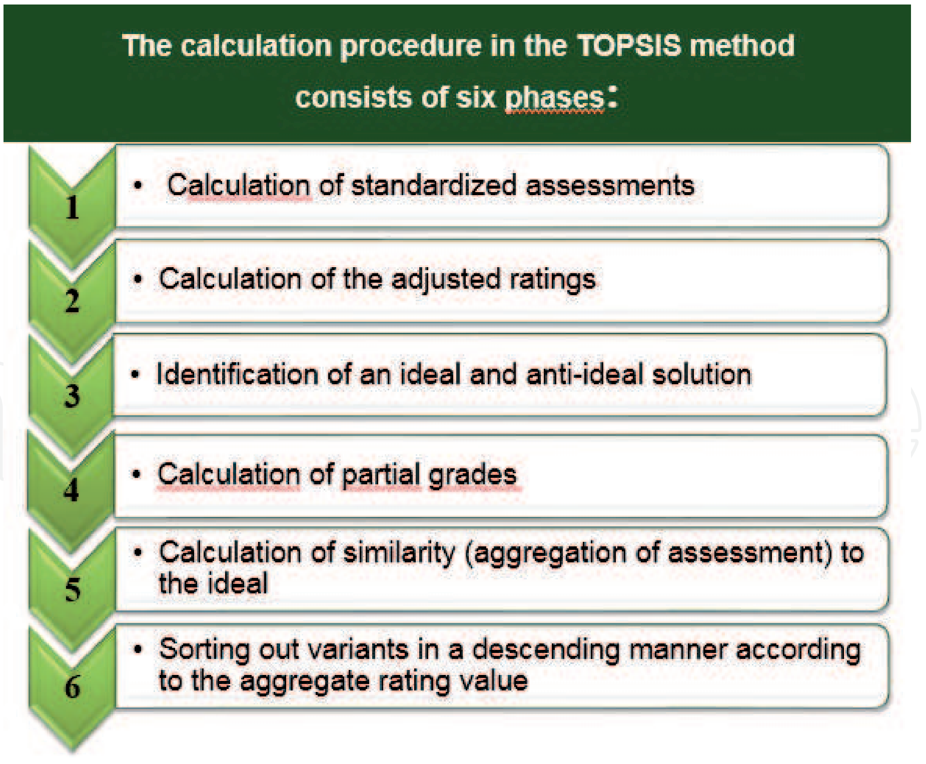

Figure 3.
The calculation procedure in the TOPSIS method.

The TOPISIS method does not take into account the subjective feelings of the decision maker at all, which results in obtaining a ranking and choosing the location of the investment that is not entirely in the most favorable position.

3.8 The Borda count ranking method

The very important for decision support was Borda ranking method, which did not use standardized assessments to the criteria and giving them weights in order to determine their validity [14, 15, 19, 20].

In the Borda method, all criteria are numbered according to their importance. Particular variants are considered taking into account subsequent criteria numbered from the most to the least important one, with the numbers making a scale from 1 to n. If a few variants have the same score, so take the same position, the averaging of score is made [78, 79]. The best variant is that to which the maximum Borda count is assigned. Simple criteria do not require normalization and do not take into account the preferences of decision-making body, which excludes the subjective character of decision on the location of wind farm.

3.9 Copeland's method

Copeland's method belongs to the decision support, but it concerns the choice of the winning option [4]. It consists in comparing variant A with B and determining the number of criteria for which variant A is better than variant B (s+), as well as the number of those criteria for which variant A is worse than variant B (s–). In this case, the variable A is incremented (the value of the variable increases by one), when s+ > s–, or the variable B is incremented otherwise. This follows the designation of the number of wins for all determined criteria and selected of the winner variant, which means (Copeland rule) that the winner is the one for whom the difference in the number of wins and the number of lost with other candidates (pair comparisons) is maximum.

4. Multicriteria analysis of a wind farm location by the Borda method

The problems with making decision on farm location were analyzed taking into account the nine criteria having essential effect on realization of a given investment [14, 15]. Taking into account of nine criteria that should be met by the location of 15 wind turbines in Krynki and Szudzialowo communities (**Tables 1** and **2**), the main three criteria (C3, C8, and C9) were found to differentiate location of eight wind turbines (T-6–T-13), according to two variants (I and II). Criterion 3 (C3—stimulant) regards the difference in the terrain altitude expressed in meters above sea level. Criterion 8 (C8—destimulant) is the number of protected bird species occurring in a given area, and Criterion 9 (C9—destimulant) is the level of activity of bats expressed on the scale from low to very high (**Tables 1** and **2**).

Criteria turbines	C1	C2	C3 [AMSL*]	C4	C5	C6	C7	C8	C9
1	Absent	Favorable	185	0.5	Absent	Very good	Absent	2	Low
2	Low	Favorable	170	0.5	Absent	Very good	Absent	2	Low
3	Absent	Favorable	170	0.5	Absent	Very good	Absent	2	Low
4	Absent	Favorable	170	0.5	Absent	Very good	Absent	2	Low
5	Absent	Favorable	180	0.5	Absent	Very good	Absent	2	Low
6	Absent	Favorable	170	0.5	Absent	Very good	Absent	4	High
7	Absent	Favorable	170	0.5	Absent	Very good	Absent	4	High
8	Absent	Favorable	175	0.5	Absent	Very good	Absent	4	High
9	Absent	Favorable	180	0.5	Absent	Very good	Absent	5	Very high
10	Low	Favorable	180	0.5	Absent	Very good	Absent	5	Very high
11	Absent	Favorable	185	0.5	Absent	Very good	Absent	4	High
12	Absent	Favorable	185	0.5	Absent	Very good	Absent	5	Very high
13	Absent	Favorable	185	0.5	Absent	Very good	Absent	5	Very high
14	Absent	Favorable	177.5	0.5	Absent	Very good	Absent	1	High
15	Low	Favorable	187.5	0.5	Absent	Very good	Absent	1	High

**AMSL—above mean sea level.*

Table 1.
Adopted criteria in relation to the location of a wind farm made up of 15 turbines in the area of Krynki and Szudzialowo communities—Variant I.

Criteria turbines	C1	C2	C3 [AMSL*]	C4	C5	C6	C7	C8	C9
1	Absent	Favorable	188.5	0.5	Absent	Very good	Absent	0	Low
2	Absent	Favorable	175	0.5	Absent	Very good	Absent	0	Low
3	Absent	Favorable	175	0.5	Absent	Very good	Absent	0	Low
4	Absent	Favorable	175	0.5	Absent	Very good	Absent	0	Low
5	Absent	Favorable	182.5	0.5	Absent	Very good	Absent	0	Low
6	Absent	Favorable	175	0.5	Absent	Very good	Absent	1	Low
7	Absent	Favorable	172.5	0.5	Absent	Very good	Absent	1	Low
8	Absent	Favorable	180	0.5	Absent	Very good	Absent	1	Low
9	Absent	Favorable	190	0.5	Absent	Very good	Absent	2	High
10	Absent	Favorable	190	0.5	Absent	Very good	Absent	2	High
11	Absent	Favorable	187.5	0.5	Absent	Very good	Absent	1	Low
12	Absent	Favorable	195	0.5	Absent	Very good	Absent	1	High
13	Absent	Favorable	195	0.5	Absent	Very good	Absent	1	High
14	Absent	Favorable	180	0.5	Absent	Very good	Absent	0	Low
15	Absent	Favorable	192.5	0.5	Absent	Very good	Absent	0	Low

**AMSL—above mean sea level.*

Table 2.
Adopted criteria in relation to the location of a wind farm made up of 15 turbines in the area of Krynki and Szudzialowo communities—Variant II.

Criterion 3 (stimulant) and criteria 8–9 (destimulant) in the Borda method proved that from among the two variants considered the more suitable location of wind turbines is second variant W II than first variant W I (**Table 3**). Variant W II had a higher altitude of the terrain (C3) and less risk of impact on birds (C8) and bats species (C9) than variant W I. The analysis was made on the basis of the initial data, ordering of variants, determination of Borda count, and final ranking of variants.

5. Conclusions

The different methods of multicriteria analyses (MAUT, AHP, DEMATEL, ELECTRE, PROMETHEE, ARROW-RAYNAUDA, TOPSIS, and COPELAND) are to a high degree subjective. Their final outcome often depends exclusively on

Turbines	Criteria					
	C3		C8		C9	
	Variants					
	I	II	I	II	I	II
T6	3	**6**	3	**6**	3	**6**
T7	3	**6**	3	**6**	3	**6**
T8	3	**6**	3	**6**	3	**6**
T9	3	**6**	6	**5**	3	**6**
T10	3	**6**	3	**6**	3	**6**
T11	3	**6**	3	**6**	3	**6**
T12	3	**6**	3	**6**	3	**6**
T13	3	**6**	3	**6**	3	**6**

The calculated number of Borda taking into account variants and criteria.

Table 3.
The Borda count ranging for two Variants—I and II in relation to the location of wind farms in the area of Krynki and Szudzialowo communities.

the preferences and priorities of decision-making persons [4]. For this reason to analyze the choice of location of wind farm in the area of Krynki and Szudzialowo communities, the Borda ranking method was used. This method does not require standardization of evaluations following from the criteria and endowing the criteria with weights. A uniform ordering scale is assumed, and all criteria are treated as equally important. The method provided an objective result that really depends on the criteria that should be met by the wind farm location [20].

The study in Krynki and Szudzialowo communities proved that the planned construction of wind farm would have a positive effect on the production of energy from renewable sources [80–85]. The choice of the optimum location of wind turbines was shown to have no negative impact on the natural environment, which is of key importance in the application of sustained technologies, that is to ensure a balance between economic and environmental factors and the needs and expectations of society [86–91].

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Conflict of interest

The authors declare no conflict of interest.

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