Received: 09 June 2025; Revised: 14 Aug. 2025; Accepted: 19 Oct. 2025
https://doi.org/10.22306/al.v13i1.726

Optimisation of wind park location

Ivan Brezina
Bratislava University of Economics and Business, Faculty of Economics Informatics, Dolnozemská cesta 1, 852 35, Bratislava, Slovak Republic, EU, ivan.brezina@euba.sk
Juraj Pekar
Bratislava University of Economics and Business, Faculty of Economics Informatics, Dolnozemská cesta 1, 852 35, Bratislava, Slovak Republic, EU, juraj.pekar@euba.sk
Marian Reiff
Bratislava University of Economics and Business, Faculty of Economics Informatics, Dolnozemská cesta 1, 852 35, Bratislava, Slovak Republic, EU, marian.reiff@euba.sk (corresponding author)

Keywords: wind parks, location models, multi-criteria evaluation of variants, PROMETHEE II.
Abstract: The development of wind farms within each country's energy system is a significant step towards reducing greenhouse gas emissions and enhancing energy security. Given Slovakia's high potential for wind energy and the limited exploitation of this resource, this study conducted a multi-criteria analysis of factors influencing decisions on the location of wind farms. The effective integration of this renewable source requires optimized planning and management of material, information, and investment flows, which are key elements of logistics management in the construction and operation phases of wind farms. The correct location of wind farms requires an analysis of several logistical and technical elements, such as infrastructure availability, transport flows, energy flows, information flows, legal and environmental constraints, as well as wind conditions (e.g., average wind speed, wind energy density). The PROMETHEE II method was used to assess potential sites, allowing for the comparison of alternatives based on preference flows. The output of the analysis is a map of the logistical suitability of different locations, along with a ranking of areas derived from net flow calculations (location-based logistics). The findings of this study can contribute to the effective management of logistics processes in the renewable energy sector, as well as to better management of investment, information, and material flows in the construction of wind farms in Slovakia.

1 Introduction

In general, sustainable development makes it possible to meet the needs of present generations without compromising the demands of future generations to meet their needs. The United Nations has articulated global priorities for achieving sustainable development in the 2030 Agenda (endorsed by the UN General Assembly in September 2015, https://sdgs.un.org/2030agenda). The 2030 Agenda sets out 17 Sustainable Development Goals (SDGs) elaborated into 169 related sub-goals to guide the structural political, economic, and social transformation of countries around the world. It expresses the intention of countries to guide their development towards sustainability and to set their national policies, strategies, and planning to contribute to the achievement of the global goals.

The overall economic development of any country is dependent on high energy consumption, which is why the 2030 Agenda is also paying increased attention to measures to increase the use of renewable energy sources in order to reduce greenhouse gas emissions. Although the share of renewable energy in the energy mix has been increasing in recent years (although fossil fuels still remain the basis of the energy mix), it is essential that countries implement green policies and comply with the targets set in their national energy climate plans.

Slovakia has long been below the EU average in the use of renewable energy sources (RES), including wind energy, with RES accounting for 23% of final energy consumption, according to data from OKTE [1]. One of the challenges to increase the share of RES in final energy consumption is the robust use of wind energy. This is to be ensured by legislative at the European Union level (Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources) as well as at the national level (Act No. 251/2012 Coll. on Energy and on Amendments to Certain Acts, as amended, Act No. 309/2009 Coll. on the Promotion of Renewable Energy Sources and High Efficiency Combined Generation and on Amendments to Certain Acts, as amended).

As one of the most promising renewable energy sources, wind energy offers significant potential to promote energy security and reduce greenhouse gas emissions. Although wind energy has some disadvantages (e.g., its instability, impact on the landscape, risk of bird deaths, etc.), its advantages are very high (e.g., the cheapest source of electricity, environmentally friendly, reduced dependence on fossil fuels, etc.). The reality is that more clean and renewable energy

CC BY NC

sources are now needed in light of sustainable development policies. Unlike energy produced from non-renewable sources, wind energy cannot be depleted, and its production does not pollute the environment.

Despite the fact that Slovakia does not have the same conditions for the implementation of wind energy in its energy mix as some other European countries, the appropriate deployment of wind farms can ensure the efficient use of available resources.

The most important determinants for the efficient use of wind energy are mainly financial incentives, a stable regulatory framework, but also the identification of optimal locations for wind power plants [2].

The structure of the work is based on the implementation of a sequence of steps. Following the introduction and a brief literature review, the third methodological part focuses on eliminating unsuitable locations for wind farms based on geographical and legislative requirements. The criteria for determining the suitability of sites for wind farms in the Slovak Republic are also formulated in the third part. The method of evaluating individual criteria for eliminated sites is described in the methodological part. The actual application of wind farm location in the Slovak Republic based on the PROMETHEE II method is described in the fourth part. The result of the solution is a ranking of wind farm sites in each area based on the calculated net flow values, and this approach is presented in the discussion on the general procedure for solving decision-making problems related to the location of wind farms. The results achieved are evaluated in the conclusion.

2 Literature review

Effective location of wind farms plays a key role in reducing costs, optimizing revenues, and minimizing negative impacts on the population and the environment (e.g., [3-5]). Currently, there is a relatively large number of contributions devoted to this topic, many of which focus on linking multi-criteria decision-making methods and geographic information systems (GIS) as tools for acquiring, analyzing, visualizing, and managing data with spatial or map representation.

Sotiropoulou, et al. [6] presented a hybrid model for selecting suitable locations for the construction of onshore wind farms in northeastern Greece, which combines AHP (Analytic Hierarchy Process): used to determine the weights of individual criteria in multi-criteria decision-making, PROMETHEE II: used for the final ranking of alternatives (sites) based on calculated preference flows, Machine learning – kNN (k-Nearest Neighbors) and SVM (Support Vector Machines): used for regression analysis of spatially specific inputs, in particular for modeling and interpolating wind potential in areas with limited measurements. Josimović, et al. [7] applied a two-phase location selection model in which GIS removed unsuitable areas and PROMETHEE II subsequently evaluated the remaining sites. Their methodology enabled transparent selection of sites for wind farms by legislative and planning requirements. Latinopoulos and Kechagia [8] used a combination of AHP-GIS to locate wind farms in Greece, highlighting the advantages of a weighted approach to spatial criteria such as distance from settlements, protected areas, altitude, and wind speed. Al-Yahyai, et al. [9] analyze the possibilities and limitations of wind prediction models in wind farm planning.

Although location-based logistics methods are often used in the localization of wind farms, combined approaches based on GIS and Multi-Criteria Decision-Making methods (MCDM) [10-14] are increasingly being used, which allow for the analysis of areas in terms of technical, environmental, logistical, and socio-economic criteria. The PROMETHEE II method from the MCDM category was used in the analysis of wind farm locations, and examples of its successful application in various areas include: [15,16]

• Evaluation of economic regions [17]: Using the PROMETHEE II method, the economic indicators of the different regions were evaluated to identify the areas with the best performance.

• Hospital evaluation [18]: In the health care sector, the PROMETHEE II method was used to evaluate the performance of public hospitals, which helped to identify areas for improvement.

• Transportation Planning [19]: evaluating roadway alternatives.

• Selecting investment projects [20]: a multi-criteria assessment of returns.

• Environmental decision making [21]: evaluating ecological impacts.

In recent years, the PROMETHEE II method has been further developed and applied in various fields:

• Sustainability Assessment of Renewable Energy in Morocco [22]: The March 2023 study used the PROMETHEE II method to assess different renewable energy technologies in Morocco. The results showed that solar PV is the most sustainable technology, followed by wind power, hydropower, CSP, and biomass.

• Integration of PROMETHEE II with DEA for assessing the efficiency of water services in Malaysia [23]:

The 2023 study combined the PROMETHEE II method with efficiency analysis using DEA to assess and fully rank the efficiency of water services in 14 states in Malaysia. The results showed that this combination provides a complete and reliable efficiency ranking.

The literature shows that combining GIS tools with PROMETHEE II is an effective way to identify optimal locations to maximise revenues and minimise environmental and logistical costs.

3 Methodology

3.1 Elimination areas

3.1.1 Geographical location requirements

The International Electrotechnical Commission (IEC, https://webstore.iec.ch) standardises the issue of wind turbines in its standard IEC 61400 (https://webstore.iec.ch/en/publication/31267) and classifies turbines according to the wind conditions for which they are designed. These standards are elaborated in the directive of the Ministry of the Environment of the Slovak Republic "Standards and limits for the siting of wind power plants and wind parks in the Slovak Republic", where the legislative criteria are divided into three main groups:

Category A Limits - Areas suitable for development. These are areas with potential for wind energy where there are no significant environmental or legal constraints, they may include lowlands, uplands, mid-mountains and areas with Grade 1 nature conservation designations, they exclude: Residential areas; Protected areas with Grade 3, 4 and 5 nature conservation designations; Protected areas with Grade 3, 4 and 5 nature conservation designations. Areas of wetlands, UNESCO sites and biosphere reserves of European importance; Areas designated for the performance of tasks of the Ministry of Defence of the Slovak Republic; Protection zones of airports and aviation facilities; Protection forests and forests of special designation; Water resources - protection zones I. Protection zones of natural healing and mineral resources of the I. degree; Spa places and natural healing spas, where laws prohibit other uses; Cultural monuments and protection zones of the UNESCO World Heritage List; Mining areas and areas with permit for mineral extraction; Protection zones of linear objects - roads and highways, railways, electric power lines, gas pipelines, product pipelines, nuclear facilities, burial grounds and crematoria

Category B Limits - Areas conditionally suitable for development. These are areas that require further research and the establishment of more stringent criteria, which include protected areas up to the 2nd degree of protection, zones D of protected areas, sites with the occurrence of protected species of birds and bats, the surrounding areas of tourist centres, lazos, archaeological sites, are thus excluded: areas of forests and the surroundings of watercourses; areas with good quality agricultural soils (bonitated units 1. to 4. Groups 1 to 5); Areas designated for the tasks of the Ministry of Defence of the Slovak Republic; Areas of European importance without 3rd to 5th degree of protection; Forest stands and areas within 50 m from the border; Areas of protected landscape areas; Biocentres and biocorridors of local, regional and supra-regional ecological stability; Surroundings of watercourses and areas up to 100 m and hydric biocorridors up to 200 m; Tourism regions of category I or higher; Areas outside the protection zones of airports and their facilities.

Category C Limits - Areas unsuitable for development. These include the surroundings of residential zones, national parks and protected areas with high levels of protection (3rd, 4th and 5th level), animal migration routes, areas with rare birds, cultural monuments, UNESCO sites, protection zones of airports and spas, thus are excluded: protected areas with 2. Protected areas, important bird territories and areas of migration routes; Surroundings of supra-regional hydric bio-corridors and important tourist centres; Tourism regions of national importance and surroundings of linear constructions with safety risks; Territories outside the protection zones of airports and areas of avalanche settlements; Archaeological sites and quiet areas with potential for cultural heritage protection; Protected water supply areas, water resource zones and natural healing resources; Areas climatically suitable for healing, spas and natural healing baths; Areas in visual contact with cultural, historical and landscape landmarks; Agricultural and forest areas with land reclamation measures and woody vegetation; Protected deposit areas, exploration areas and geopark areas.

This logically implies the requirement to identify those areas that are determined by the limits mentioned above. The priority limits were primarily large protected areas and national parks, but also small protected areas and protected bird areas. This implies the elimination of the areas shown in Figures 1 and 2 (the area of the Slovak Republic is 37.49% covered by protected areas).

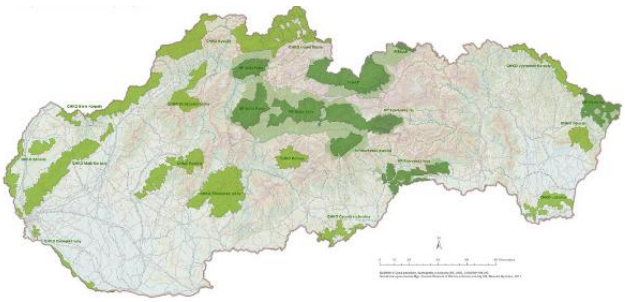


Figure 1 Map of large protected areas, source: [24]

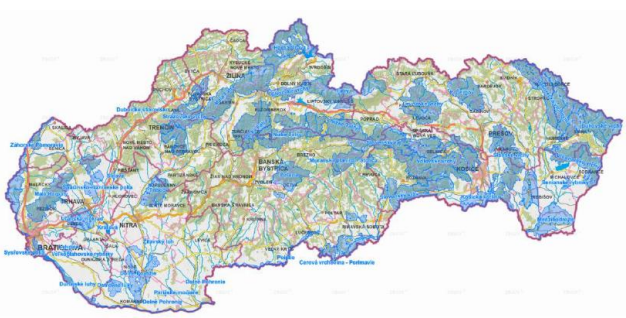


Figure 2 Map of bird protected areas, source: [25]

CC BY NC

Geographical conditions, i.e. mountains and forests, can be considered as other important boundary conditions for the location of wind parks, as they represent a serious obstacle to air flow. These thermal boundary conditions are shown in Figures 3 and 4.

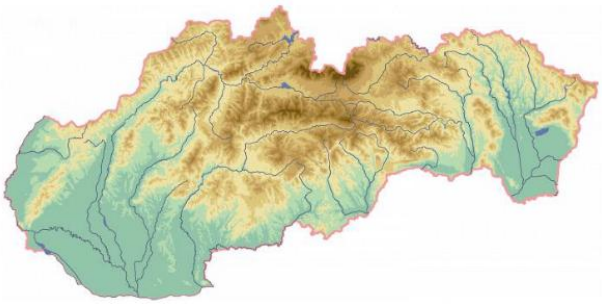


Figure 3 Map of mountain ranges, source: [26]

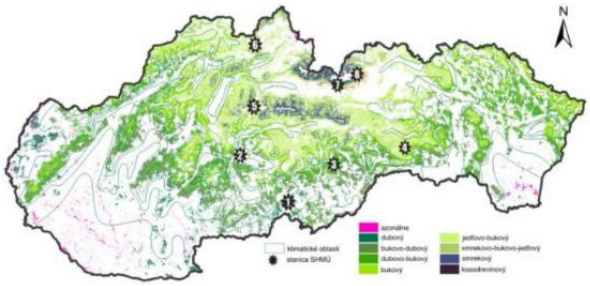


Figure 4 Map of forests, source: [27]

By intersecting the boundaries from Figures 1 to 4, Figure 5 determines a map of suitable areas based on geographical conditions, on which the locations where the legislation allows wind farms to be built are marked.

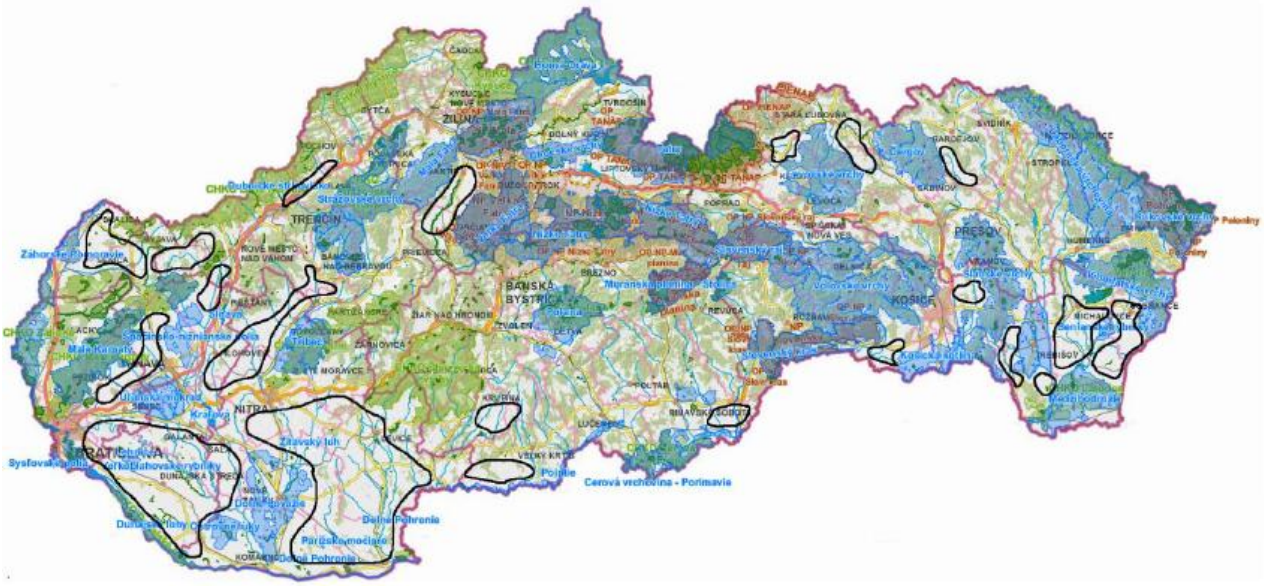


Figure 5 Map of suitable areas based on geographical conditions, source: [26]

3.1.2 Wind location requirements

One of the most important determinants of wind farm location is the average annual air velocity. This is because the output of wind turbines is directly proportional to the third power of the wind speed, with the result that even a small increase in wind speed significantly increases electricity production. Ideal locations are those where the airflow is stable and values between 4 and 25 m/s are usually measured. At lower wind speeds, wind turbines may be switched off or produce less power, at extremely high wind speeds (e.g. above 25 m/s) the turbines may be switched off for protection (depending on the type of turbine installed). A minimum wind speed of 4 m/s is required for efficient operation of a wind turbine, with economic viability being achieved at wind speeds of around 6 m/s. Figure 6 illustrates the different wind speed levels within the Slovak Republic. Figure 6 shows that the strongest airflow can be observed in western and eastern Slovakia and also on the tops of the mountains. These regions have the most stable wind conditions with the highest measured airflow values, which allows wind turbines to operate more efficiently. Although the flow in the northern mountain areas is very strong, the measured values are often too high or irregular, which can limit their suitability for wind turbines.

Another important determinant of wind farm siting is the average wind energy density; this physical quantity is used to describe the energy available in the wind per unit area and is closely related to air density, as air density affects power density. A key characteristic of power density is that it is very sensitive to wind speed, as power increases with the third power of the wind speed, i.e. if the wind speed doubles, power density increases eightfold. A map of the average power density within the Slovak Republic is shown in Figure 7.

CC BY NC

Based on the geographical and wind requirements for the location of wind farms, areas can be created that meet all conditions.

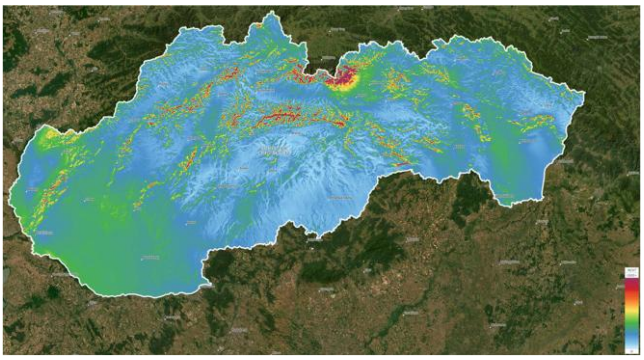


Figure 6 Wind speed map, source: [28]

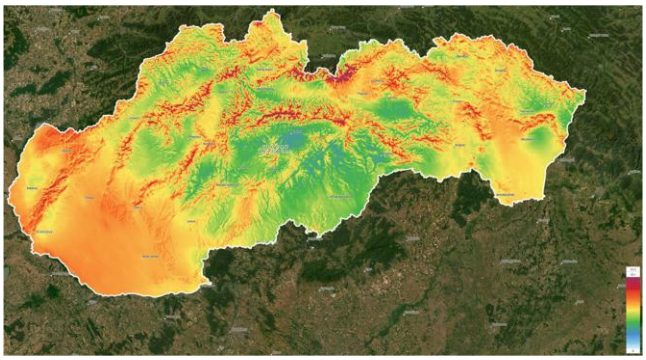


Figure 7 Map of average wind energy density, source: [28]

3.2 Criteria for determining the suitability of sites for the construction of wind parks

The selection of suitable sites for wind farms is based on geographical and socio-economic factors. Optimal siting of wind farms has an impact on the efficiency of generation, minimising the cost of electricity generation and transport and reducing the environmental impact of electricity generation and transport. Wind turbines are designed for wind speeds between 3 and 30 m/s, as higher wind speeds could damage the turbine. Therefore, the areas with the greatest potential for the efficient use of wind energy have been identified.

The following decision criteria can then be considered for the identified areas:

1. Wind speed (m/s): Wind speed is a key factor in the selection of sites for wind turbines because it directly affects the amount of energy generated, i.e. because higher average wind speeds increase the efficiency of electricity generation, thus improving the economic return on the project. Meanwhile, the IEC Standards for Wind Turbines distinguish 4 classes of turbines based on this factor:
    a) High Wind Class for areas with high average wind speeds up to 10 m/s,
    b) Medium Wind Class for areas with medium wind speeds up to 8.5 m/s,
    c) Low Wind Class for areas with low average wind speeds up to 7.5 m/s
    d) Very Low Wind Class for areas with extremely low wind conditions below 6 m/s.
2. Average wind energy density (W/m^2): This variable is dependent on the wind speed variable, and if only wind densities greater than 300 W/m^2 are considered for efficiency reasons, the wind strength classification is given as excellent for wind strengths between 6.89 and 7.35 m/s with an average wind power density of 287.19 - 344.62 W/m^2, as excellent for wind strengths in the range 7.35 - 8.04 m/s with an average wind power density of 344.62 - 459.50 W/m^2, and as great for wind strengths in the range 8.04 - 10.80 m/s with an average wind power density of 459.50 - 1148.75 W/m^2.
3. Terrain shape - elevation (m) and slope (degrees): The roughness or height of the terrain also influences turbulence and wind direction, and the construction of wind farms and the economic costs of their operation are lower in the lowlands.
4. Distance from protected areas - NP, SPA, Natura2000, protected bird areas (km): proximity to protected areas is an important environmental aspect.
5. Distance of other limiting elements - surface water, airstrips, power lines (km): other environmental and technical elements can also be included in the limiting factors.
6. Population density (population/km^2): at higher densities, more residents experience the negative impacts of wind farms, such as noise or visual disturbance.
7. Proximity to populated areas (km): Greater distance from populated areas minimises potential negative impacts and reduces the risk of disapproval from local residents. According to the EIA (Environmental Impact Assessment), the design of wind farms must comply with the minimum spacing between wind turbines and residential areas as defined by legislation and technical standards (for wind turbine heights between 25 m and 50 m, a minimum distance of 1000 m; for heights between 50 m and 100 m, a minimum distance of 1500 m; for heights between 100 m and 150 m, a minimum distance of 2000 m; for heights above 150 m, a minimum distance of 3000 m).
8. Environmental burden: The construction of a wind farm may have an impact on local ecosystems and biodiversity, and may require serious interference with nature, such as the necessary felling of trees.
9. Proximity to the transmission grid (km): Shorter distance to the existing transmission system reduces connection costs and minimises electricity transmission losses.
10. Energy potential of an area (MWh): the estimated amount of electricity that can be generated at a given location affects the overall efficiency and return on investment.

CC BY NC

11. Construction costs (EUR million/MW): Includes capital expenditure for the installation of the wind park, with lower costs contributing to faster payback.
12. Noise pollution (dB): the level of noise generated by turbines can affect the quality of life in nearby communities.
13. Other indicators: cost of land, cost of labour, visual impact, soil erosion, labour availability, impact on bird migration routes, seismic activity, runoff, safety requirements, flood threat, and others.

3.3 Multi-Criteria Decision Making (PROMETHEE II)

It is evident that when assessing alternatives for the location of wind farms, a greater number of criteria must be taken into account. Therefore, multi-criteria decision-making methods or multi-criteria evaluation of variants (alternatives) appear to be a suitable tool for deciding on their location. Multi-Criteria Decision Making (MCDM) is a field of decision theory that deals with the selection of an alternative from a set of alternatives according to a number of often conflicting criteria. Currently, a large number of methods have been developed for solving alternative evaluation problems (e.g., Decision Matrix Method - DMM, Forced Decision Matrix Method - FDMM, Analytic Hierarchy Process - AHP, Weighted Sum Approach - WSA, Elimination and Choice Translating algorithm - ELECTRE, Technique for Order of Preference by Similarity to Ideal Solution - TOPSIS, Preference Ranking Organisation Method for Enrichment Evaluations - PROMETHEE, etc.), which are covered in a number of publications, with a relatively comprehensive overview provided by [10-14].

The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) class of methods also belongs to that area of decision theory. PROMETHEE class methods are by their nature based on pairwise comparison of variants. From this class, PROMETHEE I and PROMETHEE II are among the most widely used methods (e.g., [29, 30]), but other modifications have also been developed, such as PROMETHEE V and PROMETHEE VI. Further analyses will use the PROMETHEE II method, which allows for a comprehensive evaluation and comparison of alternatives based on different criteria. The PROMETHEE II method was developed by Brans and Vincke [29] in the 1980s and has since established itself as one of the most widely used methods in the field of decision analysis.

The conceptual strength of these methods lies in their ease of interpretation and flexibility in taking into account both quantitative and qualitative factors. These characteristics are the main reasons for their wide application in areas such as environmental management, real estate assessment and contractor selection. Behzadian, et al. [20] highlight the ability of the PROMETHEE family of methods to adapt to decision situations in which uncertainty plays an important role. They also describe their extension with preference functions based on fuzzy logic, which allow efficient evaluation of alternatives under conditions of imprecision and complexity. In more recent applications, as reported by Sarwar, et al. [31], PROMETHEE methods confirm their ability to generate Pareto-efficient and intuitively ranked alternatives, which represents a significant advantage over other approaches such as AHP or TOPSIS that are based on more rigid forms of aggregation. All these attributes have consolidated the position of PROMETHEE as an integral part of modern decision making.

The PROMETHEE II method aims to produce a complete ranking of alternatives based on the decision maker's preferences. Its main steps include:

1. Normalisation of the decision matrix.
2. Calculation of preference functions.
3. Aggregation of preferences.
4. Calculation of input flows, output flows and net flows.
5. Determination of the final ranking.

This approach allows decision makers to take into account different criteria and preferences when evaluating alternatives.

The PROMETHEE II method is applied in the evaluation of the optimal location of wind parks in the Slovak Republic because it is relatively easy to implement and offers a simple evaluation process. Its shortcomings are negligible and can be overcome by using hybrid and integrated models [19].

The application of the PROMETHEE II method is based on the assumption that there is a set of n alternatives $A = \{a_1, a_2, \ldots, a_n\}$ and a set of k criteria $Y = (y_1, y_2, \ldots, y_k)$, where each criterion $y_{(i)}$ (i = 1, 2, ..., k) is assigned a weight $w_{(i)}$ (i = 1, 2,..., k). Let the matrix **V** (nxk) represent the values of the n alternatives for the k criteria. For each criterion y_i, (i = 1, 2,..., k), a preference function $F_{(i)}(a_j, a_l) \rightarrow \langle 0,1 \rangle$ is defined that expresses the strength of preference of alternative $a_j$over $a_l$in terms of *the i-th* criterion.

The assumption is that each preference function of the corresponding criterion F_i, i = 1, 2, ..., k, is a non-decreasing function of the value of the difference of the corresponding criterion values $d_i = v_{ji} - v_{li}$, i = 1, 2, ..., k. In general, the preference function F_i and its waveform are shown in Figure 8.

CC BY NC

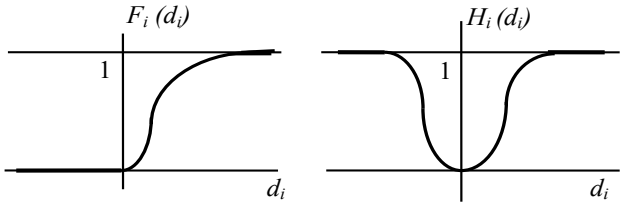


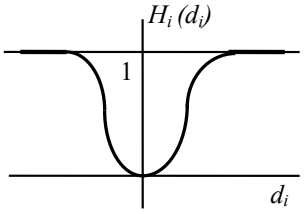
Figure 8 Function flow $F_i(d_i)$ *and* $H_i(d_i)$

For each $i = 1, 2, ..., k$, the function $H_i(d_i)$ is computed as (1)

$$H_i(d_i) = \begin{cases} F_i(a_j, a_l), & d_i \geq 0 \\ F_i(a_l, a_j), & d_i \leq 0 \end{cases} \tag{1}$$

a expresses the preferences of alternative a_j, $j = 1, 2, ..., n$, with respect to alternative a_l, $l = 1, 2, ..., n$, and the preferences of alternative a_l with respect to alternative a_j, as well as the indifferences of the two alternatives. The ordered pair $\{y_i, H_i(d_i)\}, i = 1, 2, \ldots, k$, is called the *generalised criterion* (Figure 1). The type of generalized criterion applied is shown in Table 1. The parameter standard deviation of the normal distribution σ is defined for that type of criterion.

Table 1 Type of generalized criteria applied

Type	Definition	The course of the function
VI.	$H_i(d_i) = 1 - e^{-\frac{d_i^2}{2\sigma^2}}$	

For each pair of variants a_j, a_l, a multi-criteria preference index $\pi(a_j, a_l)$ is defined, which is a weighted average of the k values of the preference functions considered. This index expresses the intensity of the decision maker's preference for the variant a_j, $j = 1,2,\ldots,n$, with respect to the variant a_l, $l = 1,2,\ldots,n$, considering all criteria (2):

$$\pi(a_j, a_l) = \frac{\sum_{i=1}^{k} w_i F_i(a_j, a_l)}{\sum_{i=1}^{k} w_i} \qquad w_i \geq 0, i = 1,2,\ldots,k \tag{2}$$

For the comprehensive evaluation of alternatives using the PROMETHEE II method, the so-called net flow is used, which is calculated from the input and output flows. The output flow values the intensity of preference of the alternative $a_j \in A$ with respect to all other alternatives compared. Conversely, the input flow values the preference intensity of all other alternatives relative to the alternative $a_j, j = 1,2,\ldots,n$

Output flow (positive outranking flow) for the alternative (3): $a_j, j = 1,2,\ldots,n$

$$\Phi^+(a_j) = \frac{1}{n-1} \sum_{l=1}^{n} \pi(a_j, a_l) \tag{3}$$

Input flow (negative outranking flow) for the alternative (4): $a_j, j = 1,2,\ldots,n$

$$\Phi^-(a_j) = \frac{1}{n-1} \sum_{l=1}^{n} \pi(a_l, a_j) \tag{4}$$

Net flow for the alternative (5): $a_j, j = 1,2,..,.n$

$$\Phi(a_j) = \Phi^+(a_j) - \Phi^-(a_j) \tag{5}$$

The PROMETHEE II method results in an overall ranking of alternatives based on net flow. The alternatives are ranked in descending order according to the calculated values $\Phi(a_j)$. A higher value indicates a better alternative in terms of preferences.

CC BY NC

4 Optimisation of wind park locations in Slovakia based on PROMETHEE II

Based on the elimination of unsuitable areas for the location of wind farms (geographical and wind requirements), areas with the greatest potential for their construction were identified. The Python programming language and the QGIS geographic information system were used for the analysis as a multi-platform open-source geographic information system that allows viewing, creating, editing and analysing spatial data and producing map outputs [32]. The criteria listed in Table 2 were considered in identifying potential wind farm development sites.

A questionnaire-based communication with selected respondents was used to select the criteria. The results of the communication were reflected in the final set of criteria. The main task of the respondents was to identify those criteria that they considered important in the decision-making process for wind farm siting. The criteria identified primarily included average wind speed (100% of respondents), wind variability (92.9%), impact on birds and bats 92.9%, elevation and terrain profile 64.3%. Other criteria, such as land cost, risk of extreme precipitation, earthquake risk, noise pollution, and total MW power were no longer assessed as particularly important, although they could be used in further analyses.

Thus, the conditions of the criteria for determining the suitability of sites for the construction of wind farms were then formulated in Table 2, taking into account the implemented elimination of unsuitable areas, based on the implemented questionnaire method.

Table 2 Criteria conditions for determining the suitability of sites for wind farms Source: own elaboration

***Criterio*n**	***Most suitable* (1)**	***Suitabl*e (2)**	***Average* (3)**	***Less suitable* (4)**	***Least appropriate* (5)**
Wind speed	>6	6-5	5-4	4-3	<3
Wind energy density	>300	300-250	250-150	150-100	<100
Altitude	<500	500-1000	1000-1500	1500-200	>2000
***Slop*e**	<5	5-10	10-20	20-30	>30
Distance from NP, MPA and Natura2000	>5000	5000-4000	4000-3000	3000-2500	<2500
Distance from bird territories	>5000	5000-4000	4000-3000	3000-2500	<2500
Distance from surface waters	>3000	3000-2000	2000-1000	1000-500	<500
Distance from the airport zone	>10000	10000-8000	8000-7000	7000-5000	<5000
Distance from power lines	<2000	2000-3000	3000-4000	4000-5000	>5000
Population density	<10	10-50	50-90	90-110	>110
Distance from residential zone	>1500	1500-1000	1000-700	700-500	<500

Based on the above, suitable locations for wind farms have been generated and are represented by the suitability map in Figure 9. Suitable areas are highlighted in blue and identify areas that are mainly located in the lowlands with stable wind conditions.

From the suitable areas, the territories of the municipalities Tešedíkovo, Radošovce, Komárovce, Svodín, Vrakúň and Černochov (marked in red in Figure 9) were identified as the most suitable based on the established criteria and further analysed using the PROMETHEE II method.

Only some of the criteria that were used to plot the suitability map were applied in the PROMETHEE II analysis, namely: wind speed, wind energy density, elevation, slope and population density. Table 3 presents the values of each criterion considered for each identified area (*L1, L2, ..., L6*) and the weights assigned to each criterion regarding its importance (*k1, k2, ..., k5*). The weights were determined based on a questionnaire completed by experts on the subject. As already mentioned in section four, the analysis was carried out in the selection of the preference function (Table 1), due to the impossibility of quantifying the indifference and preference thresholds based on the qualitative data obtained from the questionnaires. The required parameters (standard deviation) for the above preference function were obtained based on the values presented in Table 3.

The wind speed and wind energy density criteria were maximised, while the others were minimised.

Based on the values shown in Table 3, the values of the preference functions can be calculated for each criterion *k1* to *k5*, each site *L1* to *L6* and compared against all other sites. In this way, 6 different tables with preference values for each criterion were created. Then a weighted sum was made from the calculated values using defined weights (multi-criteria preference index - key 4 values in rows and columns in *L1* to *L6*).

CC BY NC

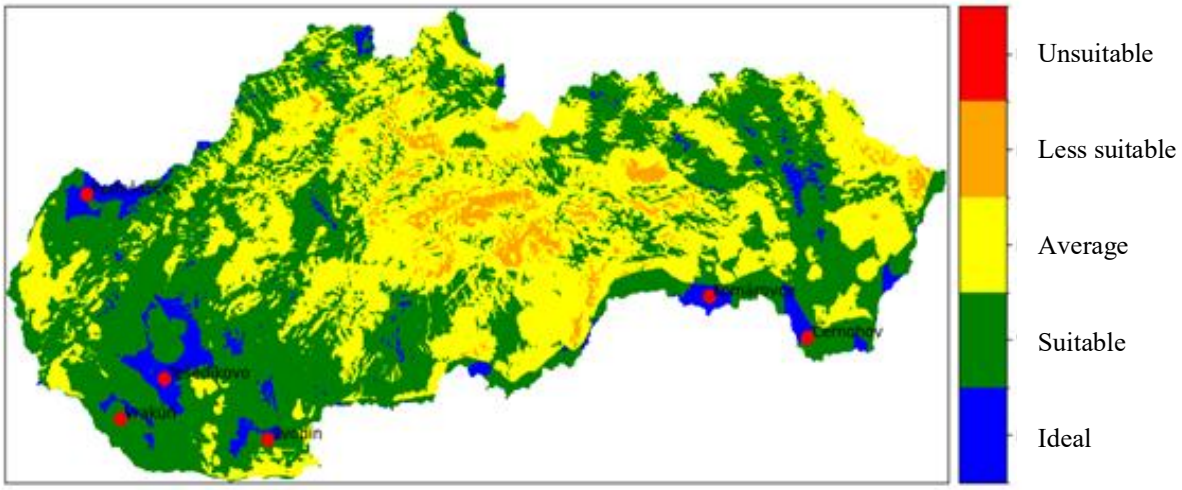


Figure 9 Map of the suitability of wind farm locations, source: own elaboration based on [26]

Table 3 Values of criteria in the calculation of PROMETHEE II Source: own elaboration

			L1	*L2*	*L3*	*L4*	*L5*	*L6*	Parameters	
***Criterio*n**		***Max/Min***	***Tešedíkovo***	***Radošovc*e**	***Komárovce***	***Svodín***	***Vrakúň***	***Černochov***	***Weights***	σ
Wind speed	*k1*	***Max***	6.38	6.77	4.76	6.15	6.56	5.29	0.25	0.72
Wind energy density	*k2*	***Max***	302.51	375.94	207.51	268.39	324.92	219.97	0.35	58.68
Altitude	*k3*	***Min***	112.98	189.58	213.80	193.74	112.70	102.23	0.1	45.62
***Slop*e**	*k4*	***Min***	6.46°	9.5°	12.06°	11.00°	6.42°	5.83°	0.05	2.43
Population density	*k5*	***Mi*n**	163	68	48	44	75	39	0.25	42.33

Table 4 presents the aggregated values of the preference functions from which the corresponding output and input flows can be calculated (Table 4). The output (positive) flow Φ^+ expresses how strong the preference of one location is relative to the others. The input (negative) flow Φ^-, on the other hand, values the strength of the preference of all other locations with respect to a given location. For the PROMETHEE II method, however, the net flow Φ (Table 4) can be calculated as the difference of the output and input flows.

Table 4 Preference function values and calculation of flows, source: own elaboration

	L1	*L2*	*L3*	*L4*	*L5*	*L6*	Φ^+	Φ
L1	0	0.0244	0.0680	0.0680	0	0.0436	0.2040	-0.1811
L2	0.0934	0	0.0680	0.0680	0.0934	0.0436	0.3664	0.1437
L3	0.0498	0.0498	0	0	0.0498	0	0.1494	-0.2902
L4	0.0498	0.0498	0.1178	0	0.0498	0.0436	0.3108	0.0325
L5	0.1178	0.0244	0.0680	0.0680	0	0.0436	0.3218	0.0545
L6	0.0743	0.0743	0.1178	0.0743	0.0743	0	0.4150	**0.2406**
Φ^-	0.3851	0.2227	0.4396	0.2783	0.2673	0.1744		

The calculated net flow values Φ allow the alternatives to be ranked from most preferred to least preferred site. Since the higher the net flow value Φ , the better the alternative, the highest net flow value Φ is 0.2406 for site *L6* indicating that in terms of the defined criteria the best location for the wind park can be considered to be the area of the municipality of Černochov. The ranking of the analysed areas *L1, L2, ..., L6* is given in Table 5.

Table 5 Resulting ordering of alternatives using the PROMETHEE II method, source: own elaboration

Order	Φ	**Location**	**Village**
1.	0.2406	*L6*	Černochov
2.	0.1437	*L2*	Radošovce
3.	0.0545	*L5*	Vrakúň
4.	0.0325	*L4*	Svodín
5.	-0.1811	*L1*	Tešedíkovo
6.	-0.2902	*L3*	Komárovce

5 Discussion

Recently, the use of renewable energy sources has become an important issue in the context of global warming and the resulting concept of sustainability (sustainable development aims to meet the needs of the present generation without compromising the ability of future generations to meet their own needs, and must reconcile the three key elements of economic growth, social inclusion and environmental protection). In the field of renewable energies, wind energy is one of the promising solutions to reduce dependence on fossil fuels and improve the environmental balance of countries. However, its use in the Slovak Republic is still very limited compared to other European countries.According to the data of the Office for Regulation of Network Industries, wind energy in 2016 produced an annual amount of generated electricity of only about 6 MWh, while neighbouring countries had wind sources with a total installed capacity of: the Czech Republic - 217 MWh, Poland 1 616 MWh, Austria - 1 084 MWh, Hungary - 329 MWh and Germany 29. These figures also indicate a great potential for further development, as according to various estimates, up to approximately 20% of the territory of Slovakia is suitable for the construction of wind power plants (https://www.iusaegis.sk/uncategorized/veterne-elektrarne-v-podmienkach-slovenskej-republiky/).

This is why the issue of the location of wind farms in Slovakia is currently a very topical problem in the context of sustainable development policy. Still, this issue represents a very complex system of decision-making, which requires detailed analysis in many areas. A large number of geological and socio-legal factors have to be considered in the construction of a wind park, which may include suitable climatic conditions, terrain profile, availability of infrastructure, as well as the impact on the local population and various economic and environmental factors. In the Slovak Republic, these conditions are defined in the Directive of the Ministry of the Environment of the Slovak Republic of 21 April 2010 No 3/2010 'Standards and limits for the siting of wind power plants and wind parks in the Slovak Republic' and in Act 309/2009 Coll. on the promotion of renewable energy sources and high-efficiency combined production In 2019, the Government of the Slovak Republic approved the National Energy and Climate Plan (NECP) until 2030, which aims to achieve a level of installed capacity of wind power plants of 500 MWh by 2030 in the field of wind energy use in Slovakia (in 2020 it was only 4 MWh).

When determining the suitable location of the wind park, it is necessary to examine primarily suitable geological conditions for its construction, but this group can also include the availability of the site for construction machinery, the distance of high and low voltage power lines from the planned location. The overall safety of operation, including sufficient distance from populated areas, must be emphasised in the impact of its construction. Furthermore, economic criteria are also important, e.g. the cost of construction, including the cost of land, the cost of transporting materials, etc., but also the cost of operation, which is again the cost of transport, or the average wages in the area. In addition to the above criteria, a prerequisite for the selection of a site for the construction of a wind park is the preparation of an Environmental Impact Assessment (EIA) study, the cost of which is relatively high and affects the overall investment intensity of the construction of the wind park under consideration.

In the presented analysis, the criteria used were those that were considered important for the selection of the optimal location for wind parks in Slovakia based on the survey. Based on the criteria considered, a map of the suitability of wind park locations was generated, which divided the territory of Slovakia into areas that are not suitable for construction at all (e.g. for nature protection reasons) to the most suitable areas. From these areas, 6 areas were identified, which formed the basis for their comparison with each other by means of the chosen PROMETHEE II method.

As a result of the solution, the wind park locations in each area are ranked based on the calculated values of net flows in Table 6. The calculated ranking for the six identified areas is Černochov, Radošovce, Vrakúň, Svodín, Tešedíkovo, Komárovce, with net flux values of 0.2406, 0.1437, 0.0545, 0.0325, -0.1811, -0.2902, while allowing to interpret the preferences of the individual territories. Based on the performed calculations, it is possible to prefer the territory of the village Černochov, which is located in the south-east of Slovakia in the Košice region, among the identified areas.

Based on the research conducted, the implemented procedure can be summarised in the following steps:

1. Elimination areas
    - 1.1. Geographical location requirements
        - 1.1.1. Areas suitable for construction
        - 1.1.2. Areas conditionally suitable for construction
        - 1.1.3. Areas unsuitable for construction
    - 1.2. Wind location requirements
        - 1.2.1. Wind speed
        - 1.2.2. Average wind energy density
2. Formulation of criteria for determining the suitability of sites
    - 2.1. Wind speed
    - 2.2. Average wind energy density
    - 2.3. Landform
    - 2.4. Distance from protected areas
    - 2.5. Distance of other limiting elements

CC BY NC

2.6. Population density
2.7. Proximity to populated areas
2.8. Environmental burden
2.9. Proximity to the transmission network
2.10. Energy potential of the area
2.11. Construction costs
2.12. Noise pollution
2.13. Other indicators

3. Choice of multi-criteria variant evaluation method (DMM, FDMM, AHP, WSA, ELECTRE, TOPSIS, PROMETHEE, etc.)
4. Calculation of the best location of wind farms based on the selected method of multi-criteria evaluation of variants

This generalised procedure can serve as a useful tool for solving wind farm siting decision-making problems. However, when the requirements are modified based on legislative regulations (elimination of areas) and specified criteria are applied (determination of site suitability), it can also serve as a general guide for siting any facility.

6 Conclusion

The transition to renewable energy is a vital component of sustainable development, and wind energy plays a central role in reducing reliance on fossil fuels. However, Slovakia's utilisation of this resource remains far below that of neighbouring EU countries. This study addressed the challenge of siting wind parks by combining spatial analysis with multi-criteria decision-making using the PROMETHEE II method.

Through a structured elimination of unsuitable areas and a GIS-supported identification of technically feasible zones, six candidate sites were selected and evaluated. The PROMETHEE II method provided a transparent and quantitative framework for ranking these sites based on expert-weighted criteria, including wind speed, wind energy density, elevation, slope, and population density. Among them, Černochov emerged as the most suitable location.

The methodology developed in this study can serve as a generalised decision-support tool for policymakers and investors. Moreover, it demonstrates that, despite regulatory and spatial limitations, Slovakia has viable opportunities to expand wind energy infrastructure, thereby contributing to national and EU climate goals.

Future research should focus on extending the analysis with more detailed datasets, incorporating dynamic environmental assessments, and exploring alternative MCDM approaches to validate or compare results. Doing so will enhance the robustness and applicability of the framework for future renewable energy investments.

Acknowledgements
This work was supported by the Grant Agency of Slovak Republic - VEGA grant no. 1/0120/23 "Environmental models as a tool for ecological and economic decision making ".

References

[1] OKTE: *Národný energetický mix,* Available: https://www.okte.sk/sk/zaruky-povodu/narodny-energeticky-mix/2023/ [07 May 2025], 2023. (Original in Slovak)
[2] ABDULLAH, L., CHAN, W., AFSHARI, A.: Application of PROMETHEE method for green supplier selection: a comparative result based on preference functions, *Journal of Industrial Engineering International,* Vol. 15, pp. 271-285, 2019. https://doi.org/10.1007/s40092-018-0289-z
[3] ADEYEYE, K., IJUMBA, N., COLTON, J.: Exploring the environmental and economic impacts of wind energy: A cost-benefit perspective, *International Journal of Sustainable Development & World Ecology,* Vol. 27, No. 8, pp. 718-731, 2020. https://doi.org/10.1080/13504509.2020.1768171
[4] HDIDOUAN, D., STAFFELL, I.: The impact of climate change on the levelised cost of wind energy, *Renewable energy,* Vol. 101, pp. 575-592, 2017. https://doi.org/10.1016/j.renene.2016.09.003
[5] NAZIR, M.S., ALI, N., BILAL, M., IQBAL, H.M.N.: Potential environmental impacts of wind energy development: A global perspective, *Current Opinion in Environmental Science & Health,* Vol. 13, pp. 85-90, 2020. https://doi.org/10.1016/j.coesh.2020.01.002
[6] SOTIROPOULOU, K.F., VAVATSIKOS, A.P., BOTSARIS, P.N.: A hybrid AHP-PROMETHEE II onshore wind farms multicriteria suitability analysis using kNN and SVM regression models in northeastern Greece, *Renewable Energy,* Vol. 221, 119795, pp. 1-13, 2024. https://doi.org/10.1016/j.renene.2023.119795
[7] JOSIMOVIĆ, B., SRNIĆ, D., MANIĆ, B., KNEŽEVIĆ, I.: Multi-criteria evaluation of spatial aspects in the selection of wind farm locations: Integrating the GIS and PROMETHEE methods, *Applied Sciences,* Vol. 13, No. 9, 5332, pp. 1-21, 2023. https://doi.org/10.3390/app13095332

CC BY NC

[8] LATINOPOULOS, D., KECHAGIA, K.: A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece, *Renewable Energy,* Vol. 78, pp. 550-560, 2015. https://doi.org/10.1016/j.renene.2015.01.041
[9] AL-YAHYAI, S., CHARABI, Y., GASTLI, A.: Review of the use of Numerical Weather Prediction (NWP) Models for wind energy assessment, *Renewable and Sustainable Energy Reviews,* Vol. 14, No. 9, pp. 3192-3198, 2010. https://doi.org/10.1016/j.rser.2010.07.001
[10] KUMAR, A., SAH, B., SINGH, A.R., DENG, Y., HE, X., KUMAR, P., BANSAL, R.C.: A review of multi criteria decision making (MCDM) towards sustainable renewable energy development, *Renewable and Sustainable Energy Reviews,* Vol. 69, pp. 596-609, 2017. https://doi.org/10.1016/j.rser.2016.11.191
[11] LAK KAMARI, M., ISVAND, H., ALHUYI NAZARI, M.: Applications of multi-criteria decision-making (MCDM) methods in renewable energy development: A review, *Renewable Energy Research and Applications,* Vol. 1, No. 1, pp. 47-54, 2020. https://doi.org/10.22044/rera.2020.8541.1006
[12] NAMIN, F.S., GHADI, A., SAKI, F.: A literature review of Multi Criteria Decision-Making (MCDM) towards mining method selection (MMS), *Resources Policy,* Vol. 77, 102676, pp. 1-13, 2022. https://doi.org/10.1016/j.resourpol.2022.102676
[13] QU, Z., WAN, C., YANG, Z., LEE, P.T.-W.: *A Discourse of Multi-criteria Decision Making (MCDM) Approaches*, In: Multi-Criteria Decision Making in Maritime Studies and Logistics: Applications and Cases, P. T.-W. Lee and Z. Yang, Eds, Cham: Springer International Publishing, pp. 7-29, 2018.
[14] SANTOSO, I., DARSONO, S.: Review of criteria on multi criteria decision making (Mcdm) construction of dams, *GEOMATE Journal,* Vol. 16, No. 55, pp. 184-194, 2019. https://doi.org/10.21660/2019.55.87673
[15] BERTONCINI, M., BOGGIO, A., DELL'ANNA, F., BECCHIO, C., BOTTERO, M.: An application of the PROMETHEE II method for the comparison of energy requalification strategies to design Post-Carbon Cities, *Aims Energy,* Vol. 10, No. 4, pp. 553-581, 2022. https://doi.org/10.3934/energy.2022028
[16] COQUELET, B., DEJAEGERE, G., DE SMET, Y.: Analysis of third alternatives' impact on PROMETHEE II ranking, *Journal of Multi-Criteria Decision Analysis,* Vol. 31, No. 1-2, e1823, pp. 1-14, 2024. https://doi.org/10.1002/mcda.1823
[17] KUNCOVA, M., SEKNICKOVA, J.: Two-stage weighted PROMETHEE II with results' visualization, *Central European Journal of Operations Research,* Vol. 30, No. 2, pp. 547-571, 2022. https://doi.org/10.1007/s10100-021-00788-9
[18] MISZCZYŃSKA, K.: Improving managerial decisions in health care sector: application of Promethee II method in public hospitals, *Operations Research and Decisions,* Vol. 30, No. 4, pp. 65-79, 2020. https://doi.org/10.37190/ord200405
[19] MACHARIS, C., SPRINGAEL, J., DE BRUCKER, K., VERBEKE, A.: PROMETHEE and AHP: The design of operational synergies in multicriteria analysis.: Strengthening PROMETHEE with ideas of AHP, *European journal of operational research,* Vol. 153, No. 2, pp. 307-317, 2004. https://doi.org/10.1016/S0377-2217(03)00153-X
[20] BEHZADIAN, M., KAZEMZADEH, R.B., ALBADVI, A., AGHDASI, M.: PROMETHEE: A comprehensive literature review on methodologies and applications, *European journal of Operational research,* Vol. 200, No. 1, pp. 198-215, 2010. https://doi.org/10.1016/j.ejor.2009.01.021
[21] BRANS, J.-P., MARESCHAL, B.: The PROMCALC & GAIA decision support system for multicriteria decision aid, *Decision support systems,* Vol. 12, No. 4-5, pp. 297-310, 1994. https://doi.org/10.1016/0167-9236(94)90048-5
[22] GOURAIZIM, M., MAKAN, A., EL OUARGHI, H.: A CAR-PROMETHEE-based multi-criteria decision-making framework for sustainability assessment of renewable energy technologies in Morocco, *Operations Management Research,* Vol. 16, No. 3, pp. 1343-1358, 2023. https://doi.org/10.1007/s12063-023-00361-4
[23] RASHID, N.R.M., HUZA, D.R.N.M., NAEM, A.M., FAUZAN, F.A.S.: Efficiency Measurement and Ranking of Water Supply Service Malaysia by Using Hybrid DEA and PROMETHEE II Method, *4th International Conference on the Future of Asean 2022 (ICoFA 2023),* pp. 41-49, 2023. https://doi.org/10.2991/978-2-38476-076-3_5
[24] MIHÁĽ, F.: *Európsky deň národných parkov: Naše prírodné bohatstvo,* [Online], Available: https://www.sopsr.sk/web/?cl=20499 [12 Dec 2024], 2019. (Original in Slovak)
[25] Map Portal KIMS: [Online], Available: https://webgis.biomonitoring.sk/ [17 Feb 2025], 2025. (Original in Slovak)
[26] Map Portal: *Geological Map of Slovak Republic,* [Online], Available: https://apl.geology.sk/mapportal [15 Feb 2025], 2025.
[27] Forest Portal: *Climate change,* [Online], Available: https://www.forestportal.sk/odborna-sekcia-i/ekologia-a-monitoring/klimaticke-zmeny/ [09 Jan 2025], 2025. (Original in Slovak)
[28] Global Wind Atlas: *Slovakia,* [Online], Available: https://globalwindatlas.info/en/area/Slovakia [10 Feb 2025], 2025.
[29] BRANS, J.-P., VINCKE, P.: Note—A Preference Ranking Organisation Method: (The PROMETHEE Method for Multiple Criteria Decision-Making), *Management science,* Vol. 31, No. 6, pp. 647-656, 1985. https://doi.org/10.1287/mnsc.31.6.647

[30] DEJAEGERE, G.: Comparing with Promethee: some new theoretical contributions, *4OR,* Vol. 22, No. 4, pp. 543-544, 2024. https://doi.org/10.1007/s10288-024-00570-y
[31] SARWAR, M., ZAFAR, F., MAJEED, I.A., JAVED, S.: Selection of suppliers in industrial manufacturing: A fuzzy rough PROMETHEE approach, *Mathematical Problems in Engineering,* Vol. 2022, No. 1, 6141225, pp. 1-19, 2022. https://doi.org/10.1155/2022/6141225
[32] ALRIOLS, M.G., CAMPOS-CELADOR, A., ULAZIA, A., URRESTI, A., IBARRA-BERASTEGI, G., ANTXUSTEGI, M.: *Use of QGIS open software to define the local renewable energy resources. a project based learning experience*, In: INTED2018 Proceedings, pp. 2577-2583, IATED, 2018.

Review process
Single-blind peer review process.