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Designation of Renewable Acceleration Areas for Wind Power Using MCDM and GIS

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Abstract. The study presents a comprehensive methodology for designating Renewable Acceleration Areas (RAAs) using Multi-Criteria Decision Making (MCDM) and Geographic Information Systems (GIS) within a technical scenario. It integrates technical, environmental, and socio-economic criteria (or factors) to identify suitable locations for wind energy projects. The methodology emphasizes data collection, stakeholder consultation, and comprehensive spatial planning to ensure balanced and sustainable outcomes. The findings indicate that 31,031 km² of Hungary is suitable for wind energy development, which accounts for approximately one-thirds of the country's total area. The most optimal regions, which received the highest score, represent 9.7% of the country's area. The most appropriate locations, as determined by the technical scenario utilized, are those in proximity to the medium-voltage grid, as well as arable land, degraded areas, or industrial sites. Results show that high spatial resolution and reliable information can be provided for any selected region where the necessary data are available. Based on this foundation, the developed method is appropriate for analysing additional scenarios (e.g. environmental or socio-economical) and can also be utilized to evaluate the feasibility of other renewable energy sources, such as solar power plants.

Key words. wind energy, spatial planning, GIS, MCDM, suitability.

1. Introduction

The revised Renewable Energy Directive (RED - 2023/2413), adopted on 31 October 2023, mandates that Member States designate Renewable Acceleration Areas (RAAs) by 21 February 2026. RAAs are areas where renewable energy projects are not expected to have significant environmental impacts.

In Hungary, there have been no new wind farms constructed in the past 14 years due to a regulation that established a protection distance of 12 km around inhibited areas, effectively prohibiting the construction of wind farms within that zone. Due to the long-lasting legislative environment, no site suitability analyses have been carried out in the country so far. At the end of 2023, the government revised the regulations in order to expand wind power capacity. The protection distance of 12 km has been reduced to 700 m, which allows for the installation of wind farms in the country. The first permits have already started to be issued, making it important to carry out site suitability studies. This study is therefore timely, preparing for more investments soon.

A robust methodology for identifying low-conflict, low-sensitivity areas is crucial. Effective spatial planning must integrate diverse sectoral interests through continuous consultation with several stakeholders. This study aims to provide a science-based methodology for the integrated spatial planning of RAAs, focusing on wind energy projects.

2. Literature review

The literature review focuses on site suitability assessment for wind power plants within a European context. The research indicates that site selection follows multi-step processes that vary by methodology. These approaches include the use of exclusion criteria for environmentally sensitive areas (constraint mapping [1]), evaluation criteria (weighted indicators), and Geographic Information Systems (GIS) based Multi-Criteria Decision Making (MCDM) in the assessments.

The criteria identified in the research were categorized into technical, environmental-natural, and socio-economic factors. Technical factors encompass proximity to infrastructure or topographic aspects, while environmental considerations include land cover or protected areas [2]-[5]. Socio-economic aspects, such as distance to settlements, also play a significant role in these assessments [2]-[6]. The buffer distances applied in studies for exclusion vary depending on the factor; for instance, roads, railways, and transmission lines require protective zoning [7]. Wind farms typically necessitate larger buffers due to aviation safety concerns [8], [9]. Exclusion distances for protected sites are determined by national and international regulations [10], [11].

MCDM methods, such as the Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC), are widely utilized for spatial evaluations [2], [4], [5], [8], [12]-[14]. The cumulative impact of renewable projects is emphasized, with recommendations advocating for multipurpose land use and synergies in nature restoration [10], [15].

Though several studies have been published about site suitability for large-scale power plants using renewable energies, most of them either consider sub-national level evaluations or deal with only a small number of suitability factors [2], [4], [5], [8], [12], [14], [16]. The novelty of this study is that the proposed methodology can be applied at the national level (the study area is Hungary) and considers 24 factors, which makes it very complex and comprehensive.

3. Methods

A GIS-based MCDM assessment was used for the study. The following steps were carried out to prepare the analyses for the land suitability study:

A. Pre-processing the geodata
B. Defining buffer zones and suitability classes
C. Factor weighting
D. Raster operations in GIS
E. Evaluation of results

*A. Preprocessing the geodata***:** Collecting and preparing the necessary geospatial data as factors for the site suitability assessment.

Building a diverse geodatabase is the essence of the study. Unlike most methods suggested in the literature, ours is much more detailed, which presents a challenge to collect all the data but also provides reliable information from the study area. Geospatial datasets were gathered, verified for accuracy, and pre-processed using GIS tools. The factors considered in the assessment are summarized in *Table 1*, including technical, environmental, and socio-economic parameters.

In some cases, we combined several data sources to create a single layer that is very similar in properties, assumed importance, and expected impact on the results (e.g., nature conservation categories or creating bat habitats from forests and the 1000 m area around the entrance to the caves). We utilized the unemployment rate and the business tax income of the municipalities as socio-economic indicators.

The primary data sources included pan-European datasets such as Corine Land Cover, Natura 2000, and average wind speed, along with national spatial planning geospatial data related to infrastructure, as well as information from non-governmental organizations regarding bat and bird habitats.

Each aspect has been used differently. Some aspects were considered exclusion areas within their own territory (e.g., flood zones, bat or bird habitats, water bodies and wetlands, forests, protected areas, settlements, fruit orchards); others were given a buffer zone (e.g., infrastructural areas), and still others were assigned a gradual preference (grasslands or shrubbery, arable lands, degraded or industrial areas, and factors in *Tables 2-3*).

B. Defining Buffer Zones and Suitability Classes: Establishing buffer zones and classifying criteria based on distance or other parameters.

We defined the buffer distances and the widths of the gradual zones for areas that should be protected, as well as the criteria that are not distance-dependent factors, such as economic factors or wind speed. The proposed buffer distances are shown in *Table 1*. The criteria marked with X are excluded within their own area (these areas therefore have no suitability score). In this analysis, we present the technical scenario; therefore, we applied protection distances for technical parameters and infrastructure using GIS operations. This study does not fully comply with Hungarian legal requirements; however, it offers a more permissive scenario, focusing primarily on technical aspects.

Suitability scores were applied in cases where the suitability of areas varies as a function of distance in addition to the buffer distance (*Table 2*). In the case of the medium-voltage electricity grid, the closer the wind turbines are, the better. Therefore, no exclusion zone was defined, and suitability scores decrease with distance from the grid. On the other hand, it is advantageous to locate wind farms as far away from airports as possible for navigation purposes.

The whole area of grasslands and shrubbery is assigned a score of 3, as it is not excluded but is less eligible for investment. Arable lands and degraded or industrial areas (Preferable land-use areas), on the other hand, were assigned scores of 7 (arable) and 10 (degraded-industrial), as the installation in these areas is eligible for support unless there are other disqualifying factors. The higher the suitability score, the more favourable the area.

C. Factor Weighting: The factors are weighted by importance by using Analytic Hierarchy Process (AHP) [17], highlighting technical aspects.

AHP is one of the most widely utilized MCDM methods for facility site selection for various technologies, making it an effective tool for assessing locations for renewable energy sources such as wind turbines. AHP employs pairwise comparisons to assess the relative importance of various decision factors, thereby facilitating the analysis of complex decision-making scenarios. This method typically involves input from experts across various stakeholder groups, enabling a comprehensive consideration of diverse factors such as technical, environmental, and social-economical aspects.

The expert input determines the relative importance of criteria. The experts involved in the matrix are tasked with evaluating the relative importance of aspect X compared to aspect Y through a pairwise comparison, utilizing a scale from 1 to 9 based on their expertise.

Table I. – The criteria used in the analysis

Technical factors		Environmental factors		Social/Economical factors	
Criteria	**Exclusion**	**Criteria**	**Exclusion**	**Criteria**	**Exclusion**
Medium-voltage electricity grid	-	Bat habitats	X and B: 1000 m*	Inhabited areas	X
High-voltage electricity grid	B: 200 m	Bird habitats	X	Other built-up areas	
Hydrocarbon pipelines		Spatial density of birds	-	Vineyard and orchards	X
Roads, Railways	B: 200 m	Water bodies	X	Arable lands	-
Airports	B: 3000 m	Wetlands	X	Degraded, industrial areas	-
Average wind speed	-	Forest areas	X	Unemployment rate	-
Terrain slope	> 15°	Grasslands and shrubbery	-	Business tax income	-
Flood zones	X	Protected natural areas	X		

B: Buffer distance; S: Suitability score; X: Excluded within its own area
** The extent of the bat habitat was assumed to be the area of forest and 1000 m around the cave entrances.*

Table 2. – Suitability scores used for gradual zones in the analysis

Suitability score	Electricity grid (m)	Main roads (m)	Airports (m)	Average wind speed (m/s)	Terrain slope (°)	Spatial density of birds (%)	Unemployment rate (%)	Business tax income (€ /capita)
1	4500 <	4500 <	3000-3500	< 3		80 <		
2	4000-4500	4000-4500	3500-4000	3-4	13-15		> 1	499 <
3	3500-4000	3500-4000	4000-4500	4-5				
4	3000-3500	3000-3500	4500-5000	5-6	11-13	79-60	1.1-3	100-499
5	2500-3000	2500-3000	5000-5500	6-7				
6	2000-2500	2000-2500	5500-6000	7-8	9-11		3.1-5	50-99
7	1500-2000	1500-2000	6000-6500	8-9		59-40		
8	1000-1500	1000-1500	6500-7000	9-10	5-9		5.1-8	25-49
9	500-1000	500-1000	7000-7500	10-11				
10	0-500	200-500	7500 <	11 <	0-5	0-39	8 <	> 25

In this particular AHP application, criteria are assessed by professionals from architecture, landscape architecture, geoinformatics, regional planning, and electrical engineering. Although there may be varying perspectives on the importance of each criterion, the values presented in the AHP matrix were determined through their collaborative consensus, as shown in *Table 3*. The Consistency Ratio (CR < 0.1) ensures decision robustness.

Suitability scores are assigned based on distance classifications and weighted factors.

Table 3. – The weighting values based on AHP

Criteria	Weights
Medium-voltage electricity grid	0,272
Proximity to roads	0,065
Aviation	0,085
Average wind speed	0,174
Terrain slope	0,141
Spatial density of bird population	0,051
Grasslands and shrubbery	0,043
Preferable land-use areas	0,099
Socio-economic indicators	0,070

D. Raster Operations in GIS: Reclassifying raster layers and using tools like Euclidean Distance to fill gaps between data points.

All polygon vector layers that contain exclusion criteria solely within their own boundaries need to be converted to raster format. According to *Table 2,* it is essential to reclassify all raster layers in order to assign a corresponding value score. For raster layers such as average wind speed, which can exhibit a broad range of values, simplification is required.
The final site suitability score is computed using the Raster Calculator, integrating multiple criteria with weighted values for all individual raster cells. The overall suitability score can be calculated by multiplying the suitability score of each criterion by its corresponding weight obtained from the AHP results and then summing these values. The Map Algebra Expression (1) should follow the logic below:

$$\text{Suitability score} = C_1\,(\text{suitability score} \times \text{criteria weight}) + C_2\,(\text{suitability score} \times \text{criteria weight}) + C_n\,(\text{suitability score} \times \text{criteria weight}) \quad (1)$$

If a specific raster cell is characterized by a value of 0 in any of the area suitability criteria layers, this cell will be regarded as an excluded area in the final area suitability score due to the merging process. This consideration holds true regardless of how favourable the area may otherwise appear based on other suitability criteria.

E. Evaluation of Results: Using the Raster Calculator to determine final suitability scores and present results through maps and graphs.

Results are analysed through cartographic representations and statistical histograms, highlighting optimal RAA locations while identifying exclusion zones.

4. Results

Altogether, 31,031 km² of Hungary is suitable for wind energy developments to some extent, while two-thirds of the total 93,000 km² area is forbidden for such initiatives, according to the applied methodology and the restrictive factors. The gradual symbology used on the map (Figure 1) effectively illustrates the distinctions between the different areas, and the aggregation of the data layers is easily recognizable.

The spatial distribution of the suitable, i.e., the rated area, is very diverse. Apart from a few larger areas, a significant extent of the country is suitable for wind energy utilization, which shows a high contrast to the previously held belief that Hungary has unfavourable conditions in many related aspects.

Most of the no-go areas are attributed to land use (water bodies, wetlands, forest areas, inhabited areas, other built-up areas, vineyards, and orchards), protected natural areas, or infrastructural restrictions (high-voltage electricity grids, hydrocarbon pipelines, roads, railways). These factors overlap in many areas; for example, regions that are too steep for construction are often covered by forests, which are protected. Wind condition is not a limiting factor, since 91% of Hungary has an average wind speed of 6 m/s or faster at a height of 150 m.

The rated areas are diverse also in terms of suitability scores. As a supplement to the map, a suitability score distribution histogram is shown in Figure 2. Scores 1-3 and 10 are absent in the results, while most of the rated areas fall within category 8 (70.3%), meaning the conditions in this technical approach are very promising for future investments. The designation of RAAs is recommended based on this technical scenario. It is essential to emphasize that reducing environmental risks is a priority in the RAA designation. This study represents the first step in which both technical and, most importantly, environmental aspects have been examined. To ensure that the RAA designation achieves a fully risk-free status, it is crucial to incorporate the legal requirements in Hungary (such as the 700-meter buffer zone surrounding built-up areas), along with additional non-statutory buffer distances for environmental considerations. This latter approach aligns more closely with an environmental scenario.

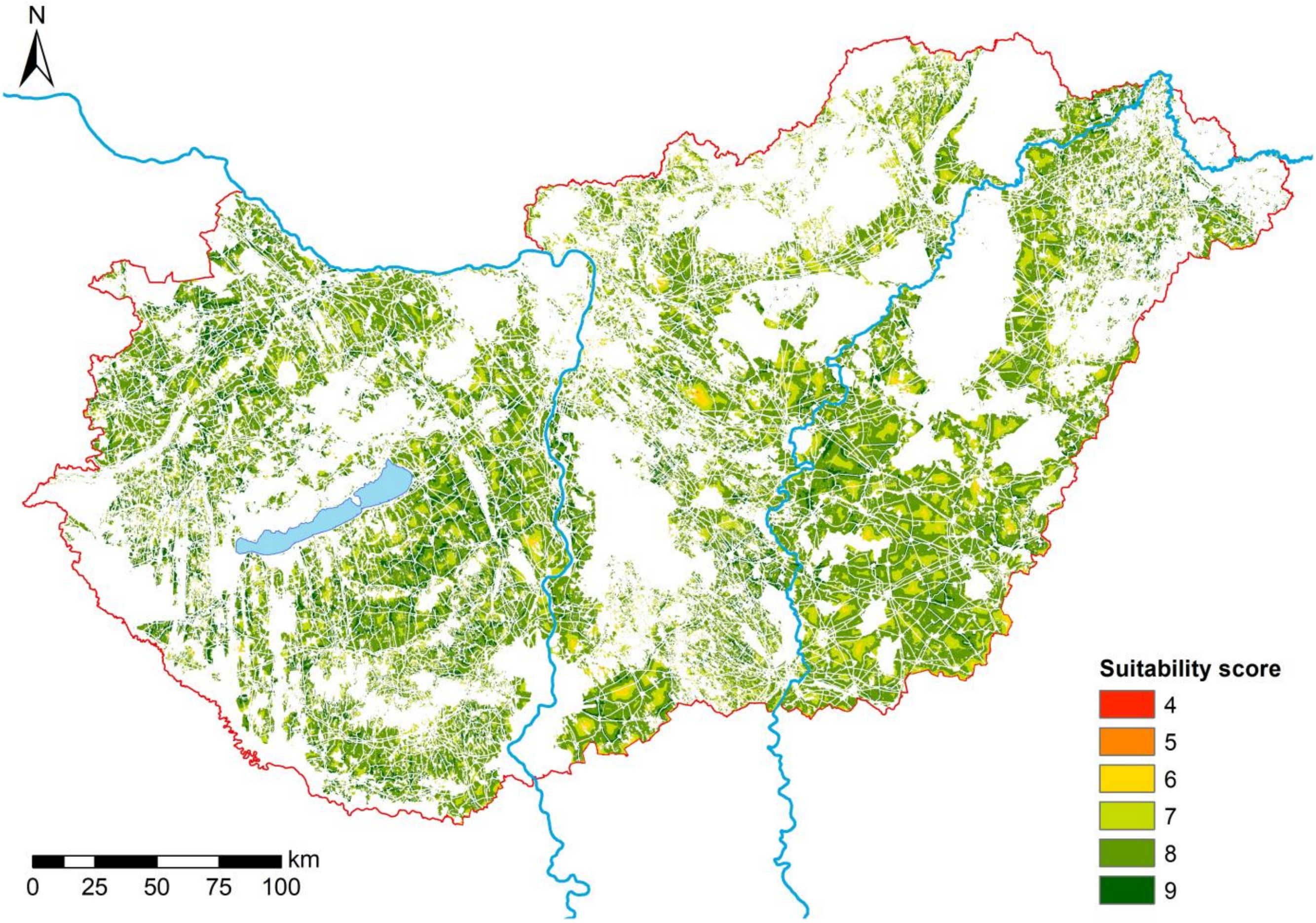

Fig. 1. Suitability of the area of Hungary for wind turbine developments.

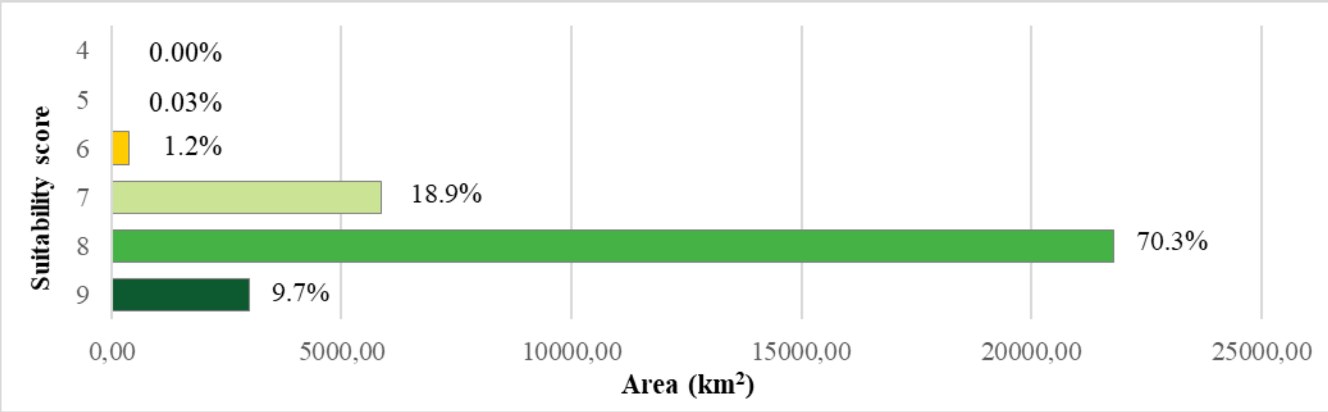

Fig. 2. Distribution histogram of the suitability scores in the rated area.

The areas considered the most suitable are located on arable and degraded lands and are near infrastructure lines. Results clearly show that proximity to the medium-voltage power network has a very strong effect due to its high factor weight in the AHP. Even if this criterion was considered crucial in such a technocratic approach, its role is probably overrated.

Considering the highest-rated areas (9), which reach almost 3,000 km² (9.7%), and applying a specific siting density of 20 MW/km² [18], nearly 60 GW of wind energy potential is available in the study area. For comparison, currently, only 330 MW of wind turbine capacity is installed in Hungary.

The GIS-based analysis, combined with Multi-Criteria Decision-Making (MCDM) tools, provides a robust framework for evaluating site suitability for renewable energy projects. The results offer a high level of accuracy and credibility in identifying the regions suitable for designation as Renewable Accelerated Areas. Thanks to its very high spatial resolution (Figure 3), the results can be used even at the local level.

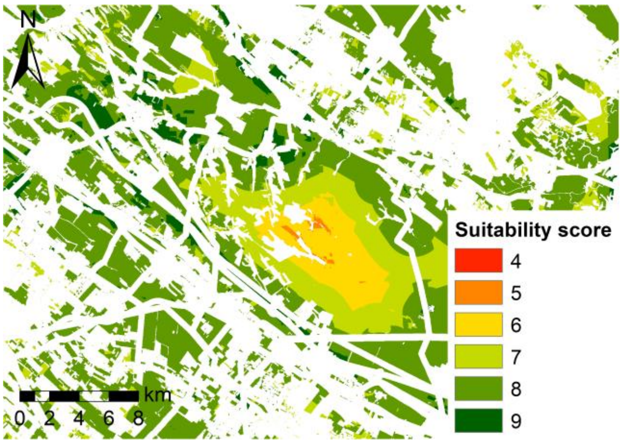

Fig. 3 Illustration of the fine details zoomed in of a random area.

5. Conclusion

Overall, the study demonstrates that the proposed methodology is effective in identifying suitable areas for renewable energy projects. By integrating technical, environmental, and socio-economic criteria and using advanced GIS and MCDM tools, the methodology provides a comprehensive and adaptable framework for the spatial planning of RAAs. The results support the achievement of renewable energy targets while promoting sustainable development and minimizing environmental impacts.

The developed methodological framework might be applied by other experts, while the results can be used by decision-makers for developing a regional or national wind energy strategy and for policymaking. Thus, the key findings include:

1. *Identification of No-Go Areas:* The analysis clearly identifies areas that are unsuitable for renewable energy development, such as protected natural areas and regions with high environmental sensitivity. These areas are marked as exclusion zones, ensuring that renewable energy projects do not negatively impact critical habitats and ecosystems.
2. *Suitability Scoring:* The methodology assigns suitability scores to different areas based on various criteria, including technical, environmental, and socio-economic factors. The final suitability scores help in ranking potential sites, with higher scores indicating more suitable locations for renewable energy projects.
3. *Visualization of Results:* The results are presented cartographically, with maps showing the suitability of different areas for renewable energy development. This visual representation helps in understanding the spatial distribution of suitable and unsuitable areas, making it easier to identify optimal locations for RAAs.
4. *Data Quality and Accuracy:* The accuracy of the results depends on the quality of the input data. High-quality, detailed, and up-to-date geospatial data are crucial for reliable analysis. The study emphasizes the importance of data harmonization and clustering to ensure consistency and accuracy.

5. *Stakeholder Involvement:* Continuous consultation with experts and stakeholders from different fields is essential for integrating diverse interests. This collaborative approach ensures that the methodology is comprehensive and considers all relevant factors.
6. *Legal and Regulatory Considerations:* The proposed buffer distances and exclusion zones should be compared with local legal conditions. The analysis can support the revision of overly strict legal constraints and propose amendments based on the results.
7. *Scenario Analysis:* As a follow-up to the research comparing different scenarios (environmental, technical, and socio-economic), the study provides a comprehensive analysis that considers various perspectives and priorities. This approach allows for a balanced evaluation of potential sites, taking into account the interests of various stakeholders.

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