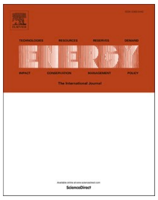
Energy 283 (2023) 129096

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Enhancing wind turbine site selection through a novel wake penalty criterion

A.Ersin Dinçer [a], A. Demir [b,*], K. Yılmaz [c]

[a] Dep. of Civil Eng., Hydraulics Laboratory, Abdullah Gül University, Kayseri, 38080, Turkey
[b] Dep. of Civil Eng., Structural Laboratory, Abdullah Gül University, Kayseri, 38080, Turkey
[c] Vortechs Engineering & Consultancy, Ankara, Turkey

ARTICLE INFO

Handling Editor: Jesse L. The

Keywords:
Wind power
Analytical hierarchy process (AHP)
Site selection
Wake effect
Suitability analysis
Geographic information system (GIS)

ABSTRACT

In this study, a novel approach that incorporates the wake effect as a penalty criterion within the Analytical Hierarchy Process (AHP) method is proposed. The research introduces the wake penalty criterion for the first time, considering both existing and newly located turbines. The results demonstrate the impact of the wake effect and identify areas with varying wake penalties. A comprehensive suitability analysis is conducted using AHP and Geographic Information System (GIS) techniques, resulting in a suitability map for wind turbine site selection. The analysis considers seven criteria, including the novel wake penalty criterion. The suitability map reveals a distribution of suitability ranges, with 73.8% of the total area excluded due to various constraints. Additionally, a comparative analysis is performed by excluding the wake penalty criterion, highlighting the contrasting effects of wake on turbine placement. Case studies in the Karaburun and Çeşme regions of İzmir further illustrate the influence of wake on turbine clusters and their alignment with prevailing wind directions. The findings indicate that the inclusion of wake effects provides a more precise and realistic depiction of viable wind turbine site selection. This is evident in the reduction of 55.5% and 18.6% in the most suitable region (80–100% suitability) and highly suitable region (60–80% suitability), respectively.

1. Introduction

Wind power has become a popular source of energy due to developing technology and increasing consciousness about the renewability of energy sources. Among the various renewable energy options, wind energy is preferred due to its minimal environmental impact [1]. Additionally, developed countries, which often have limited solar power potential in their terrains, tend to favor wind power over solar power. As a result, wind energy has gained popularity due to the increased investments made by developed countries in recent years [2].

When it comes to any energy conversion site, it is crucial to carefully choose the most suitable location, whether it's for a wind farm or a small wind turbine. Undoubtedly, the primary consideration is the energy source. However, there are additional criteria that must be taken into account for site selection beyond just the energy source. These criteria can be grouped into three categories: economic, environmental, and social [3]. It's worth noting that the total number of criteria across all classifications can exceed ten, making decision-making challenging. Consequently, numerous researchers have proposed various methods for multi-criterion decision-making (MCDM). Some of these methods [4] are Analytical Hierarchy Process (AHP) [5], ELECTRE [6], TOPSIS [7] and PROMETHEE [8]. Among these MCDM methods, the AHP method is widely considered the most preferred approach for spatial analysis of renewable energy sources [9–11]. AHP has been applied to the selection of wind power transformation sites worldwide: Brazil [12], China [13,14], Egypt [15], Germany [16], Ghana [17], Greece [11,18–20], India [21], Nigeria [22], Pakistan [23], Saudi Arabia [24], Sudan [25], Tunisia [26], Türkiye [27], UK [28] and USA [29].

During the implementation phase of the AHP method, it is crucial to define and select the criteria along with their weights. The determination of these criteria and their weights is typically accomplished through expert judgment [12,16,22,27] or by conducting surveys [15]. Not only for the AHP method but also for other MCDM methods, researchers establish the criteria based on the unique characteristics of the site. For on-land sites, commonly used criteria include wind speed, wind power density, distance from roads, distance from transmission lines, terrain slope, distance from urban areas, distance from airports, proximity to water bodies, land cover, presence of forests, elevation, and protected

---

* Corresponding author.
E-mail addresses: ersin.dincer@agu.edu.tr (A.Ersin Dinçer), abdullah.demir@agu.edu.tr (A. Demir).

https://doi.org/10.1016/j.energy.2023.129096
Received 6 July 2023; Received in revised form 19 August 2023; Accepted 12 September 2023

areas. Table 1 provides a summary of the criteria used for on-land wind turbine site selection. For offshore sites, frequently employed criteria include wind speed, bathymetry, wave height, accessibility to the electricity grid, ground distance, distance to ports, cost, fishing areas, shipping routes, protected areas, and the presence of submerged cables or pipes. Table 2 presents an overview of the criteria used for offshore wind turbine site selection.

Different criteria have been utilized depending on the specific circumstances of the site being considered, as indicated in Tables 1 and 2. The primary objective is to identify suitable and profitable locations for wind turbines. In this regard, the main source of income is derived from the wind speed and power density, which are natural factors that cannot be increased. However, the presence of turbines themselves can have a negative impact known as the wake effect, resulting in a decrease in downstream wind speed. The wake effect has been extensively studied and various theoretical definitions can be found in the literature [39–43]. When optimizing the layout of wind farm sites, these wake effects are taken into account, as they affect the downstream wind speed of the turbines [44–48]. The focus of these layout optimizations is not on the suitability of the region itself, but rather on mitigating the wake effect by strategically placing a cluster of wind turbines on the selected site.

In the context of wind turbine or wind farm site selection research, the wake effect plays a significant role in considering the impact of both existing turbines and the placement of new turbines on the existing ones. The presence of structures alters the downstream wind speed. Moreover, it is important to avoid placing a new turbine either downstream or upstream of an existing turbine.

To maximize the overall energy output of the site, a Euclidean distance from existing turbines can be used as a penalty criterion within the AHP method. However, this approach may penalize unnecessary regions around existing turbines because each existing turbine has a prevailing wind direction and crosswind regions are actually suitable for locating new turbines [48]. Instead of using Euclidean distance as a penalty criterion in the AHP method, upstream and downstream regions are defined based on Jensen's model [39] and a wake penalty criterion is applied to these defined regions. The amount of penalty is linearly related to the wake deficit as defined by Jensen's model.

Briefly, in this research, the novelty lies in the inclusion of the wake effect, which leads to a decrease in wind source, in the suitability analysis. This is achieved by introducing a wake penalty criterion, alongside other essential criteria within the AHP method. Notably, this study marks the first instance of incorporating the wake effect into the suitability analysis for wind turbines.

2. Methodology

In this research, the focus is on finding a suitable site for wind turbine allocation, taking into account multiple criteria. To handle the complexity of considering various criteria, the AHP is chosen as the preferred method, known for its popularity among MCDM methods. A key aspect of novelty in this article is the detailed definition and explanation of the wake penalty criterion, which is introduced alongside the other criteria used in the analysis.

2.1. The AHP method

The AHP is a MCDM method that is commonly utilized for determining the weights assigned to each criterion. In the AHP method [49,50], the relationships between criteria are established through expert input [11,16,17,51–54] or surveys [15,21]. By representing the pairwise relationships in matrix form, where each element is defined based on expert judgment, a constant matrix is obtained. This constant matrix is square, with its dimensions corresponding to the number of criteria being considered. To calculate the weights for each criterion, the constant matrix is normalized by dividing each element by the column-wise summation, and the row-wise means of the resulting matrix are computed. These row-wise means represent the weights assigned to each criterion. The sum of the weights for all criteria amounts to 100%, and these percentages are subsequently used in spatial analysis within a geographic information system (GIS).

Table 1
On land site selection criteria in literature.

	Wind speed	Wind power density	Distance to roads	Dist. to trans. lines	Terrain slope	Dist. to urban areas	Distance from airport	Proximity to water bodies	Land cover	Presence of forests	Elevation	Protected areas
Ali et al. [23]	✓	✓	✓	✓	✓	✓	×	×	✓	×	✓	×
Rekik et al. [26]	✓		✓	✓	✓	✓			✓	×		×
Asadi et al. [30]		✓	✓	✓	✓	✓						✓
Zalhaf et al. [25]	✓		✓	✓	✓	✓	✓				✓	
Amjad et al. [17]	✓		✓	✓	✓	✓	✓		✓			
Konstantinos et al. [11]	✓		✓	✓	✓	✓					✓	×
Baseer et al. [24]	✓	✓	✓	✓		✓	✓					
Höfer et al. [16]		✓	✓	✓	✓	✓		✓	✓	×		×
Jangid et al. [21]	✓		✓		✓				✓			
Noorollahi et al. [31]	✓		✓	✓	✓	✓	✓	✓				×
Watson et al. [32]	✓		✓	✓		✓						×
Latinopoulos et al. [18]	✓		✓		✓				✓			✓
Gorsevski et al. [29]	✓		✓	✓		✓			✓			✓
Tegou et al. [33]	✓		✓	✓	✓	✓	✓	×	✓	✓		✓

Note: ✓ for constraint type of criterion, × for restriction type of criterion.

Table 2
Offshore site selection criteria in literature.

	Wind speed	Bathymetry	Wave height	Acc. to electricity grid	Ground distance	Distance to ports	Cost	Fishing areas	Shipping routes	Protected areas	Presence of subm. cables and pipelines
Gil-Garcia et al. [34]	✓	✓	✓	✓	✓	✓	✓	×	×	×	×
Diaz et al. [35]	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
Vinhoza et al. [12]	✓	✓			✓	✓		×	×	×	×
Mahdy et al. [15]	✓	✓		✓	✓			×	×	×	×
Vagiona et al. [20]	✓	✓							×	×	
Vasileiou et al. [19]	✓	✓		✓	✓	✓			×	×	
Waewsak et al. [36]	✓	✓			✓	✓			×	×	×
Cavazzi et al. [28]	✓	✓		✓	✓	✓	✓	×	×	×	×
Wu et al. [13]	✓	✓	✓			✓		×	×		
Fetanat et al. [37]	✓	✓	✓	✓	✓		✓			×	
Wu et al. [14]	✓	✓	✓	✓	✓	✓	✓		×		
Kim et al. [38]	✓	✓	✓	✓	✓		✓	×	×	×	

Note: ✓ for constraint type of criterion, × for restriction type of criterion.

2.1.1. *Site properties*

In the present study, a specific peninsula of İzmir, encompassing the districts of Alaçatı, Urla and Karaburun districts, is selected as depicted in Fig. 1. This peninsula is widely recognized as the windiest region in Türkiye. Additionally, there are numerous operational wind turbines already present in this area (refer to Fig. 1). As a result, this peninsula is chosen as the application site for the proposed methodology, allowing for a tangible demonstration of the impact of wake effects from existing turbines on the allocation of new turbines. To facilitate this allocation, seven criteria are defined, namely: wake penalty, wind potential,

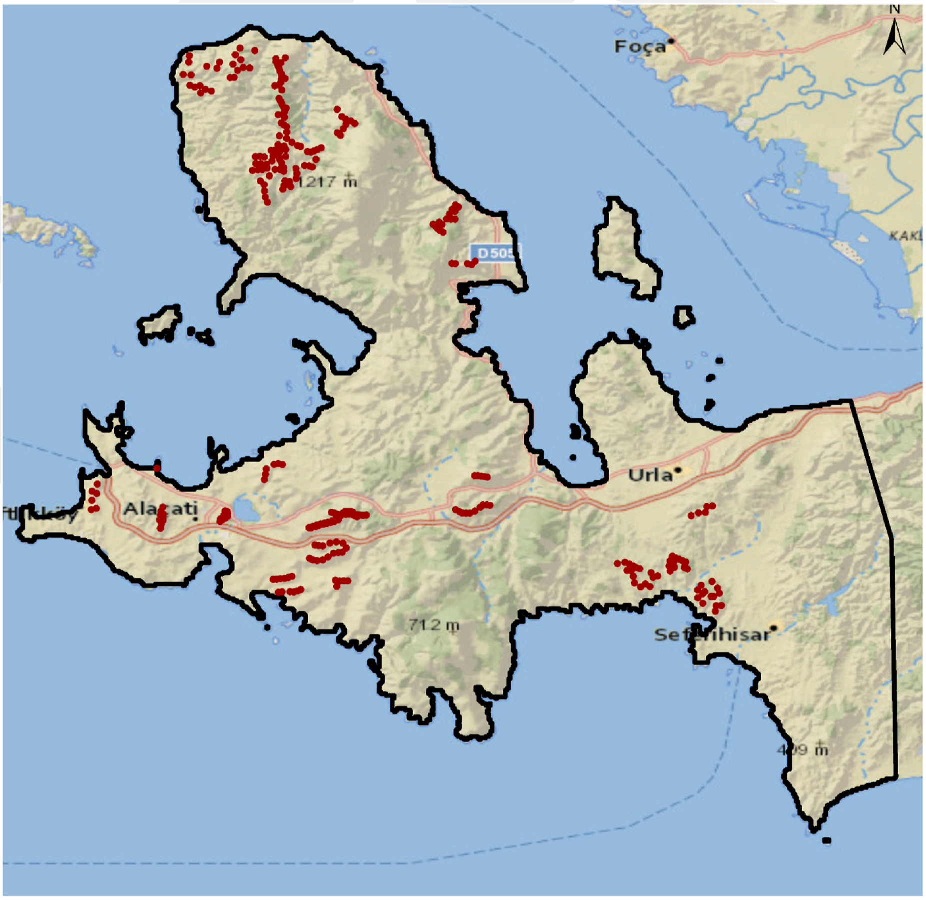


Fig. 1. Map of existing turbines.

distance to bird migration routes, land use, distance to transmission lines, distance to roads, and slope.

2.1.2. *Wake penalty*

The wake effect refers to the phenomenon occurring downstream of a turbine where the wind speed decreases due to change in dynamics of particles interacting with a structure [55,56]. This decrease in wind speed is commonly referred to as the wake effect and has been theoretically defined in numerous research studies [39–41]. In the context of optimizing wind farms on a particular site, the wake effect has been taken into consideration. Among the various wake models available, Jensen's model is often the preferred choice in these optimization studies [39].

Jensen's model provides a description of the wake effect using a function (eq. (1)), which establishes a constant wind speed at any given distance downstream. As depicted in Fig. 2, the wake effect impacts the wind speed experienced at a specific location, referred to as the actual wind speed u_x, rather than the speed at the location of the turbines. The wind speeds affected by the wake can be calculated using eq. (1).

$$v_x = u_x\left(1 - {}^2\!/_3\left(\frac{r_o}{r_o + \alpha x}\right)^2\right) \tag{1}$$

where v is the constant wind speed at distance x, u is the actual wind speed at distance x, r_o is the radius of the turbine, α is the wake angle which is taken as 0.1 and x is the distance from the turbine to a location in the downstream direction.

According to Jensen's model, the wind speed immediately after a turbine is approximately one-third of the wind speed that the turbine is facing. The impact of the wake effect diminishes as the distance from the turbine increases. In Ref. [48], the concept of wake decay is utilized within specific ranges. For the prevailing wind direction, it is assumed that the wake effect ceases beyond a downstream distance of 14 times the diameter of the turbine ($14D$). In Table 3, wind speeds are listed for distances of 14 times the turbine's diameter ($14D$) from the turbine's location.

In the literature, various ranges or constraints have been employed in optimization problems for the allocation of wind turbines within a cluster of turbines (wind farms). Minimum proximity distances between turbines have been defined as $2D$ [57], $4D$ [46,58–61] and $5D$ [62–72] in different studies. Alternatively, some research uses fixed distances such as $5D$ [73] or $8D$ [74] instead of defining limits.

In the context of this research, the aim is not to determine a specific range between neighboring turbines, but rather to define a wake region where penalties are applied for the allocation of new turbines. However, a limit is necessary to specify the extent of the wake effect. Therefore, it has been decided to use a distance of $15D$ as the limit for the wake effect. According to this assumption, approximately 95% of the wind speed is recovered after reaching the defined limit.

The wake penalty criterion is a novel concept, and for the first time, it is being introduced as a criterion in an MCDM method. As mentioned earlier, instead of using the Euclidean distance, the wake-affected range is preferred for applying penalties. This choice is motivated by the fact that, while a Euclidean definition constrains an area of $\pi 225D^2$, the wake effect definition only constrains an area of $30D^2 + \frac{0.4}{2\pi}\pi 225D^2$. The Euclidean definition encompasses both the crosswind region and the prevailing wind region, as depicted in Fig. 3. However, allocating a turbine in the prevailing wind region of an existing turbine leads to the wake effect, whereas there is no wake effect in the crosswind regions. Therefore, by applying the wake penalty only within the wake-affected range, land can be saved for the allocation of new turbines.

To establish a defined region around a turbine, the diameter of the turbine, denoted as D, needs to be determined. For this study, a turbine diameter of 100 m is assumed. When employing the Euclidean type of regional definition, it constrains an area of 7 km^2. On the other hand, by utilizing the wake effect type of regional definition, with an assumed wake effect limit of 15 D (equivalent to 1.5 km), the area constraint is reduced to 0.75 km^2. Consequently, using the wake effect type of regional definition (prevailing wind region) saves approximately 6.25 km^2 of land compared to the Euclidean type of regional definition.

The methodology of establishing the penalty region as a map is outlined in the appendix. In summary, the coordinates of existing turbines are extracted from the map displayed in Fig. 1. For each turbine, the surrounding area is categorized as delineated in Fig. 3 based on the prevailing wind direction derived from the wind direction map in Fig. 4. This classification is carried out on a pixel-by-pixel basis, with each pixel assumed to measure 50 m. By adhering to the steps outlined in the appendix, the wake penalty map, depicted in Fig. 5, is generated.

In addition to wake penalty region, to restrict the allocation of a new turbine around an existing turbine, a region is defined based on a Euclidean type of definition. The radius of this restricted region is set as $2D$ [57]. Additionally, the constraint region, defined by the wake penalty map, is scaled according to the distance from the existing turbine, as outlined in Table 5.

2.1.3. *Annual wind speed*

Wind potential is the only income for electricity production.

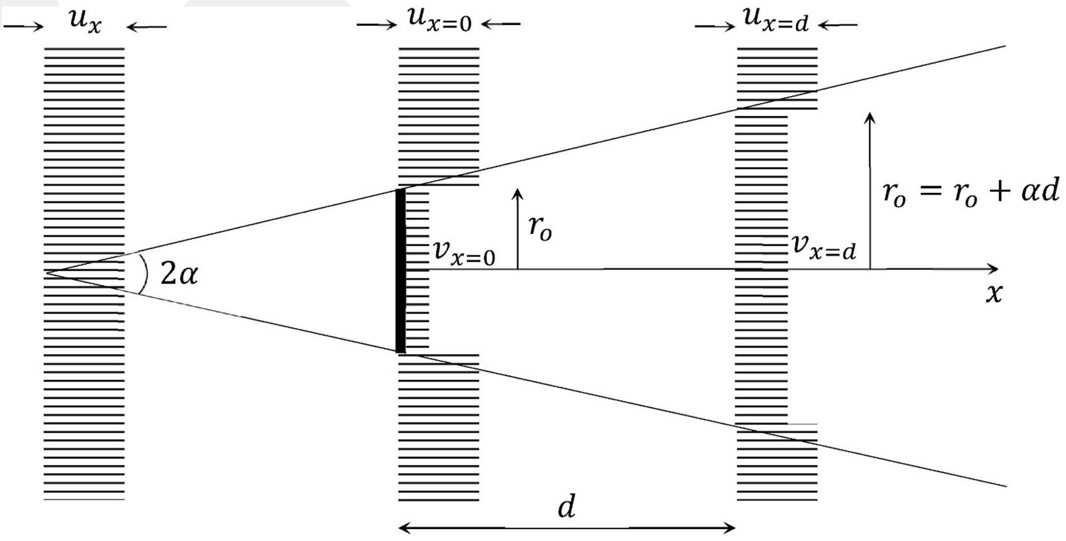


Fig. 2. Illustration of wake effect.

Table 3

Wake decay for downstream ranges based on Jensen's model [39].

x	0	*D*	2*D*	3*D*	4*D*	5*D*	6*D*	7*D*	8*D*	9*D*	10*D*	11*D*	12*D*	13*D*	14*D*
v	0.33	0.54	0.66	0.74	0.79	0.83	0.86	0.88	0.90	0.91	0.93	0.93	0.94	0.95	0.95

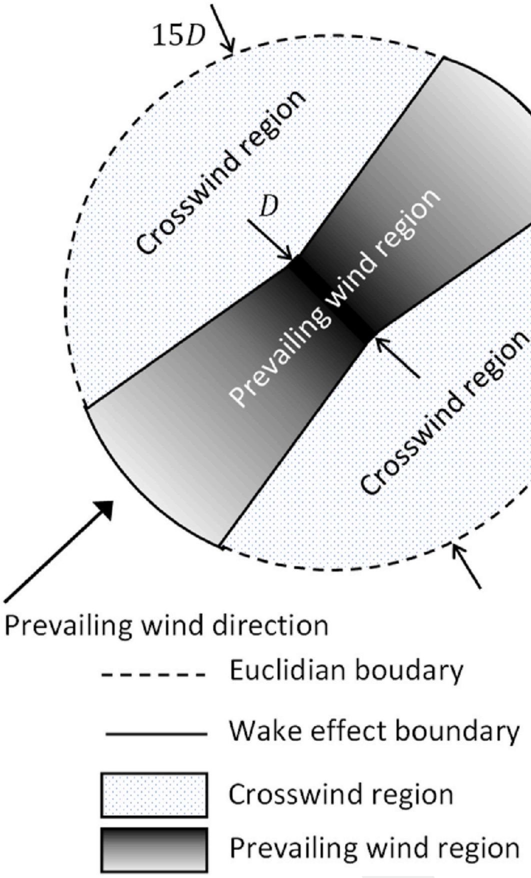


Fig. 3. Difference between Euclidean and wake type of definition of region around a turbine.

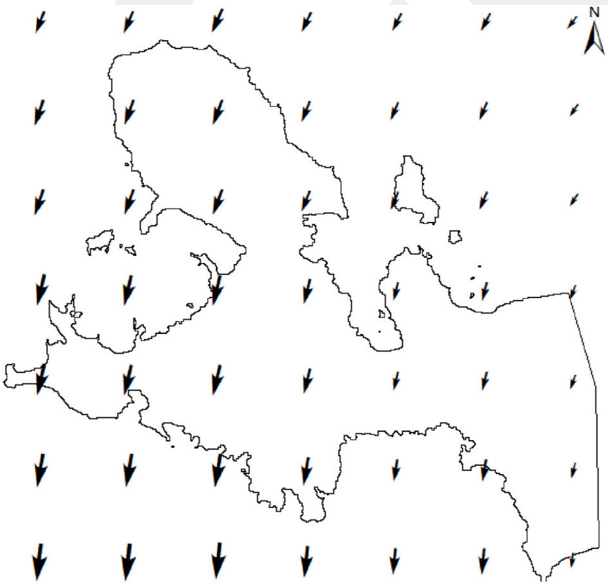


Fig. 4. Prevailing wind direction map.

Therefore, it is selected as a criterion for site allocation unexceptionally for every research in the literature. Two commonly used alternatives are employed to assess wind potential: wind speed and wind power density. While wind power density [16,30] is utilized in some studies, wind speed [11,12,15,17,18,20,21,25,28,29,31–34,36,75] is predominantly favored as an indicator of wind potential. Therefore, in this research, annual wind speed is employed to evaluate the potential of the wind at each site.

The wind speed map of the site is depicted in Fig. 6(a), providing a visual representation of the wind speed distribution across the area. The map showcases a maximum wind speed of approximately 14 m/s, while the minimum wind speed measures around 2 m/s. Sub-criteria pertaining to wind speed are outlined in Table 5, further detailing the specific factors considered in the evaluation process.

2.1.4. *Distance to bird migration patterns*

Birds pose potential risks to wind turbines and conversely, turbines can also pose risks to birds, so it is crucial to consider the impact on both the ecosystem and investment. Therefore, in this study, the criterion of proximity to bird migration routes is included in the site allocation process. Bird migration paths have been reconstructed based on data from Ref. [76] and visualized in Fig. 6(b). To ensure safety, a proximity range of 2.5 m is established for turbine site selection, and the constraint rate is defined to decrease linearly with increasing distance from the bird migration patterns, as outlined in Table 5.

2.1.5. *Land use*

While there may not be any specific governmental restrictions on wind turbine allocation, it is important to consider the preservation of nature even when utilizing renewable energy sources. In the selected region, the terrain is fertile and predominantly used for agricultural purposes. To protect the natural environment, restrictions are imposed, and wind turbines are only permitted to be allocated on bare grounds and rangelands. The land use map is given in Fig. 6(c).

2.1.6. *Distance to transmission lines*

The initial cost of a wind turbine is inversely related to the distance to the transmission line. Therefore, this criterion has been widely considered in previous research studies [16,33], including the present study. The sub-criteria for distance to the transmission line are provided in Table 5. Additionally, in order to ensure safety and avoid interference, turbines are not permitted to be allocated in close proximity to transmission lines. A limit of 500 m has been set, as depicted in Fig. 7(a), to maintain a safe distance between turbines and transmission lines.

2.1.7. *Distance to roads*

Having a wind turbine in close proximity to the road network offers several advantages. It reduces both the initial cost and maintenance cost of the turbine. Additionally, being near a road improves accessibility, enhancing safety during emergency situations. However, it is important to maintain a safe distance from the road to ensure the overall safety of the turbine. In this study, a constraint of 100 m is imposed to restrict turbine allocation near existing roads, as shown in Fig. 7(b). Further constraints related to road proximity are defined in Table 5.

2.1.8. *Slope*

The slope of the terrain is an important factor to consider for the safe operation of a wind turbine. To ensure safety, it is necessary to maintain a safe distance between the tips of the turbine blades and the ground. In this study, a constraint is imposed to restrict turbine allocation on slopes

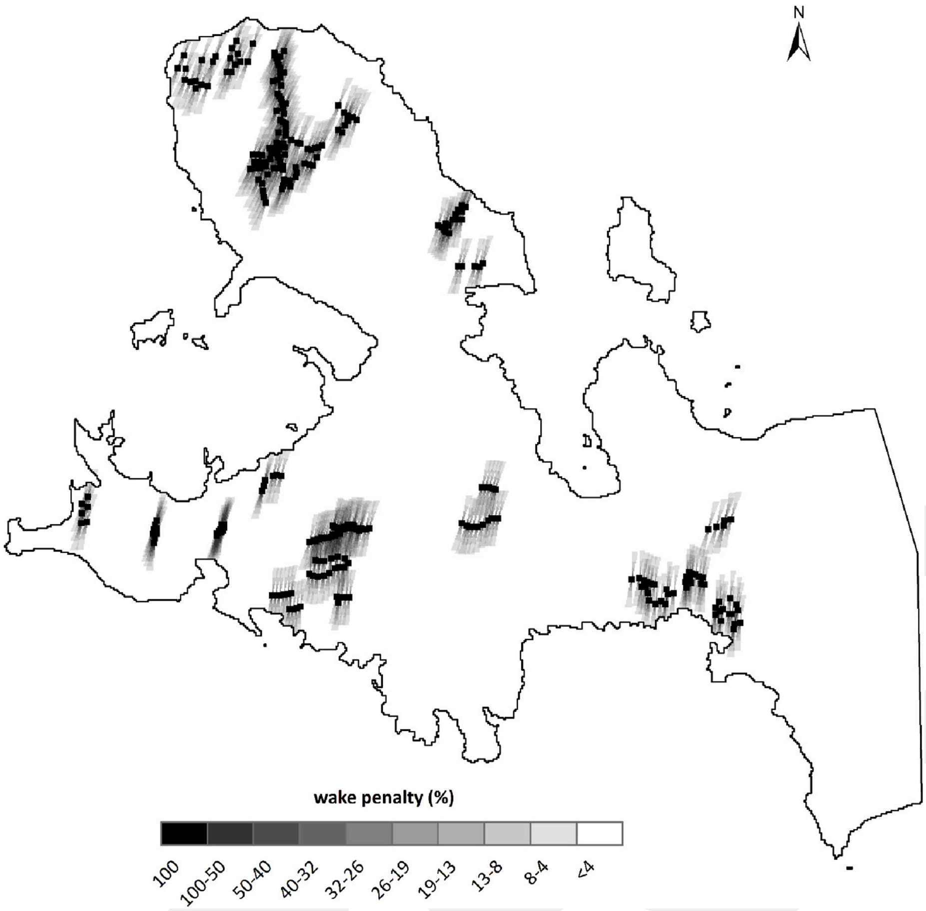


Fig. 5. Wake penalty map.

Table 4
Wake penalties and corresponding area of wind speed decrease.

Wake penalty (%)	Area (km^2)
restricted	53.2
100–50	1.8
50–40	4.3
40–32	7.9
32–26	12.5
26–19	17.6
19–13	28.0
13–8	44.0
8–4	49.8
<4	1541.8

steeper than 24%, as depicted in Fig. 7(c). Additional constraints are defined in Table 5 to enhance safety and reduce the initial construction cost of the turbine.

3. Results and discussions

Table 4 provides insights into the wake effects and their corresponding areas resulting from a decrease in wind speed at 100 m elevation also shown in Fig. 5. Jensen's model was employed to calculate these effects, and the wake penalty is expressed as a percentage.

The area around a turbine must be restricted due to some safety conditions. Accordingly, the radius of this restricted region is set as 2*D* resulting in a total restricted area of 53.2 km^2. Moving to the next category, where the wake penalty ranges from 100% to 50%, a smaller area of 1.8 km^2 experiencing this reduced wind speed is observed. Continuing down the table, a gradual decrease in the wake penalty percentages and an increase in the corresponding areas affected due to the Jensen's model. It is noteworthy that at lower wake penalty ranges, such as 13-8% and 8-4%, the affected areas are quite substantial.

A reliable AHP analysis involves three important steps. The first step is to identify and specify the criteria. Once the criteria are established, the next step is to calculate the weights of each criterion based on the interrelationships defined in a constant matrix. Finally, accurate definition of sub-criteria indicators for each criterion is necessary prior to conducting suitability analysis in GIS software. The weights of the criteria and the indicators of the sub-criteria are summarized in Table 5. By implementing these steps, a suitability map for wind turbine placement (Fig. 8) is generated through the analysis conducted in ArcGIS. For the classification process, Natural Breaks (Jenks) classification is utilized.

The analysis results reveal a distribution of the area covered by various suitability ranges, which exhibits a typical normal z distribution pattern, as shown in Table 6. Additionally, it is observed that 73.82% of the total area is restrained and excluded from consideration due to several factors, including land use restrictions, slope limitations, wake penalty constraints, distance to transmission lines, distance to roads, and proximity to bird migration paths.

The suitability map presented in Fig. 8 highlights the impact of wake effects. To further investigate and ascertain the definitive effect of wake, a repeated suitability analysis is conducted. In this second analysis, the wake penalty criterion is not excluded by assigning it a weight of zero. Instead, the indicators for each sub-criterion within the wake penalty are assigned a value of 9 (maximum value in suitability analysis), representing non-affected regions. As a result, the wake penalty criterion becomes insignificant due to its own weight, while the other criteria

Table 5
The AHP criteria.

Criterion	Weight	Sub-criteria	Indicators	Criteria	Weight	Sub-criteria	Indicators
Annual wind speed (m/s)	28	<3	1	Wake penalty (%)	28	100	restrained
		3–5	3			100–50	1
		5–7	6			50–40	2
		>7	9			40–32	3
						32–26	4
						26–19	5
						19–13	6
						13–8	7
						8–4	8
						4–0	9
Land Use	11	Water	restrained	Distance from transmission line (km)	8	0–0.5	restrained
		Trees	restrained			0.5–1	9
		Flooded veg.	restrained			1–2	8
		Crops	restrained			2–4	7
		Built area	restrained			4–8	6
		Bare ground	8			8–16	4
		Snow/ice	restrained			>16	2
		Rangeland	9				
Slope (%)	4	0–3	9	Distance from road (km)	4	0–0.1	restrained
		3–6	8			0.1–1	9
		6–9	7			1–2	8
		9–12	4			2–4	7
		12–24	2			4–8	6
		>24	restrained			>8	4
				Bird migration paths (km)	17	0–2.5	restrained
						2.5–5	3
						5–10	6
						>10	9

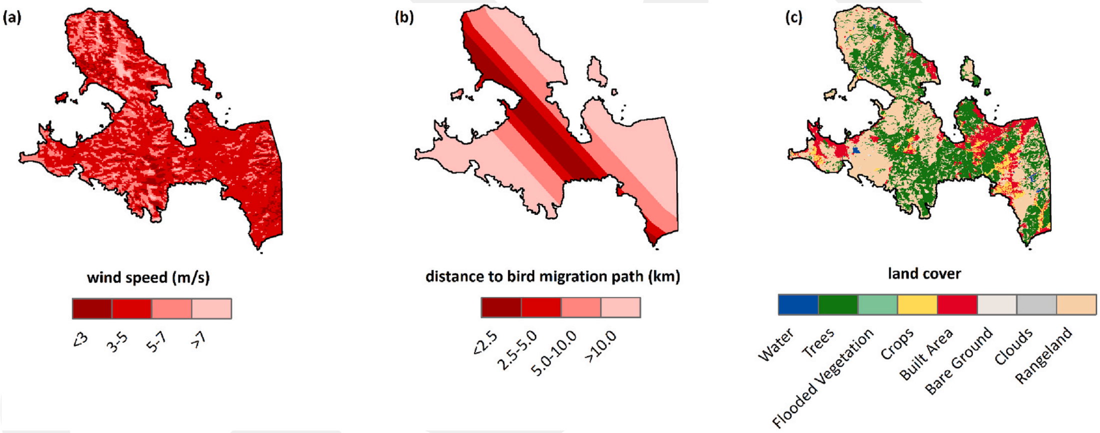


Fig. 6. Wind speed, Distance to bird migration and Land use maps.

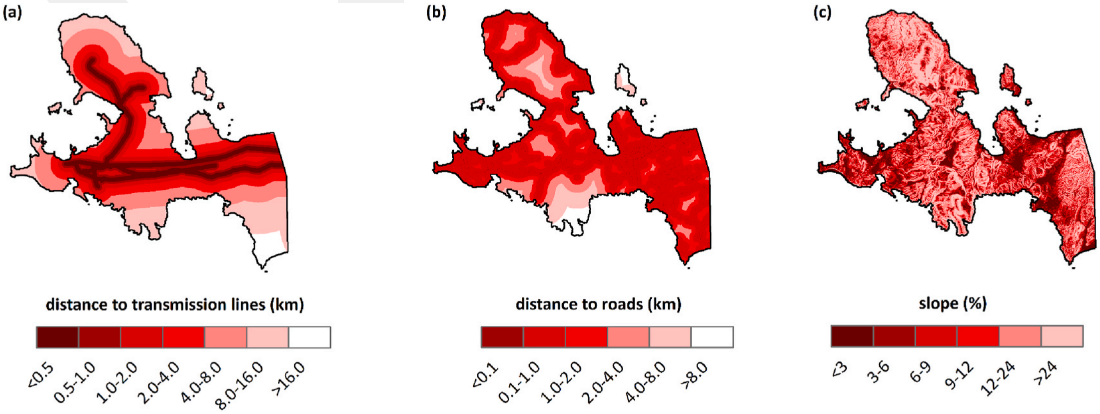


Fig. 7. Distance to transmission lines, distance to roads and slope.

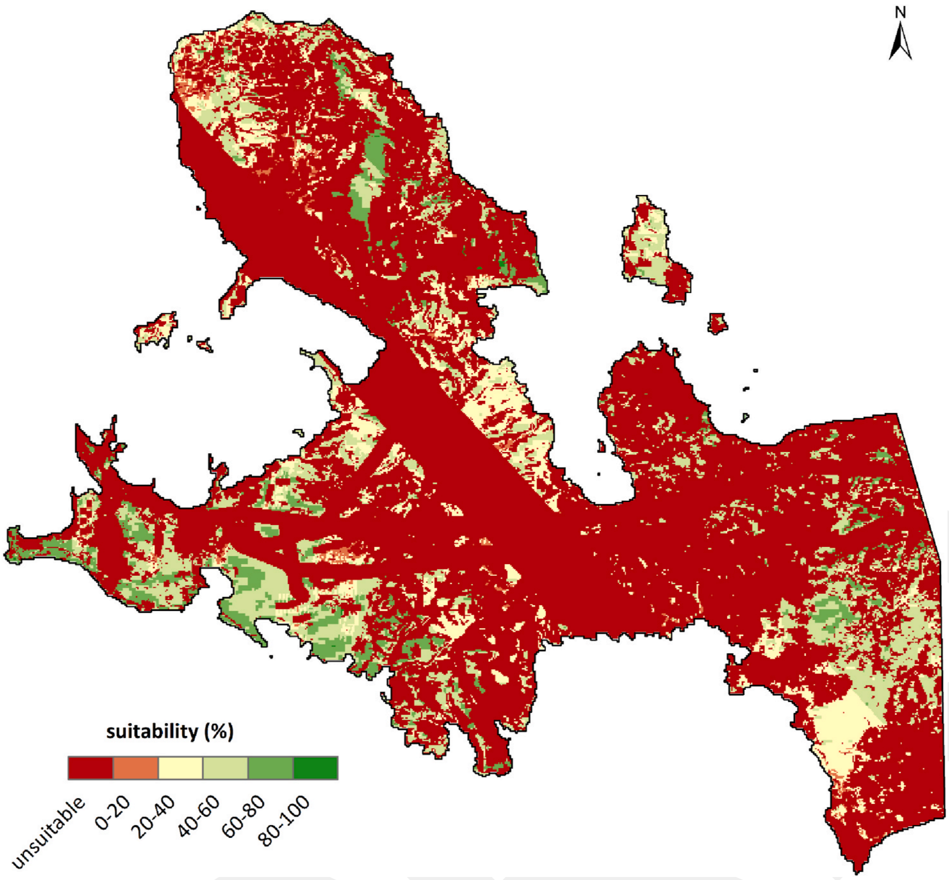


Fig. 8. Suitability map.

Table 6
Distribution of suitability ranges.

Suitability (%)	Distribution of area (%)
Unsuitable	73.82
0–20	0.93
20–40	8.01
40–60	12.83
60–80	4.37
80–100	0.04

remain influential.

The outcome of the suitability analysis conducted without considering the wake penalty criterion is displayed in Fig. 9(b), allowing for a comparison with the suitability analysis that includes the wake penalty criterion shown in Fig. 9(a). The contrasting effects of the wake penalty are depicted for better visualization. Two specific regions, Karaburun (Fig. 10) and Çeşme (Fig. 11), are given to showcase the impact of wake in more detail.

In the Karaburun region, there are two distinct clusters suitable for turbine placement. The first cluster is situated in the northwest, characterized by mountainous terrain with elevations ranging from 0 to 300 m. Due to the challenging topography, the turbines in this cluster are not evenly distributed and do not follow a regular pattern.

On the other hand, the second cluster is located in a linear formation, extending from the north to the south of the region (refer to Fig. 10). The turbines in this cluster effectively cover a significant portion of the surrounding suitable areas.

However, it is worth noting that there is a large expanse of suitable land in the south of Karaburun. This area has an elevation of 1113 m, making it the highest point within the site. Consequently, investors have been hesitant to utilize this region due to the higher initial cost associated with turbine installation in such challenging terrain.

In the Çeşme region, there are seven distinct clusters of turbines, as depicted in Fig. 11. The first cluster is situated in the western part of the region. Although the turbines in this cluster are individually placed, the overall allocation direction of the cluster does not align perpendicularly with the prevailing wind direction. Consequently, the turbines within this cluster are affected by each other, as observed in the second, third, and half of the fourth clusters.

The fourth cluster is particularly interesting as it consists of two groups of three turbines. The first group, located to the west within the cluster, is oriented in the north-south direction, while the second group, positioned to the north within the cluster, is oriented in the east-west direction. It should be noted that the prevailing wind direction for this cluster is north to south (as shown in Fig. 4). In this context, the alignment of the first group is not optimal, causing some turbines to be affected by wake. Conversely, the second group is perfectly aligned and perpendicular to the prevailing wind direction, resulting in no wake effect on any of the turbines. Instead, the regions to the north and south of the second group experience the wake effect, as implemented by the novel wake penalty criterion.

Similar effects of the wake penalty criterion are also observed in the fifth, sixth, and seventh clusters. The wake penalty criterion reduces the suitability rank of the affected regions within these clusters, highlighting the impact of wake on turbine site selection.

In addition, Table 7 presents a comprehensive comparison between the proposed method in which wake effects are considered and methods that do not incorporate such wake penalties. It is evident considering wake effects leads to notable changes in the distribution of suitable areas for wind turbine site selection. When wake penalties are included, regions previously deemed highly suitable experience reductions in

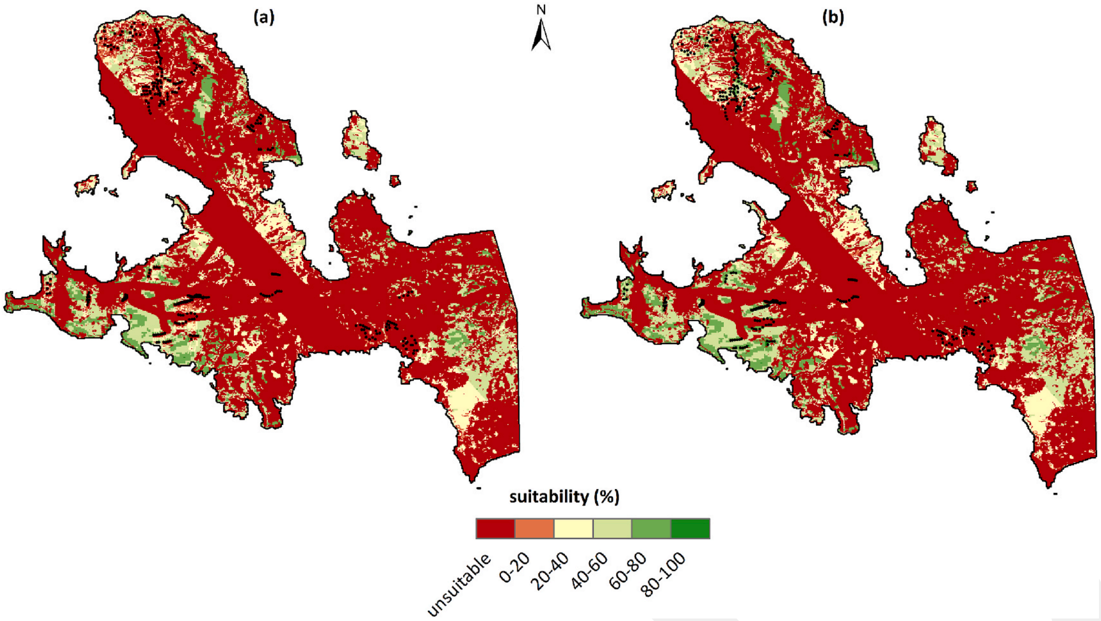


Fig. 9. Suitability maps (a) with wake penalty and (b) without wake penalty.

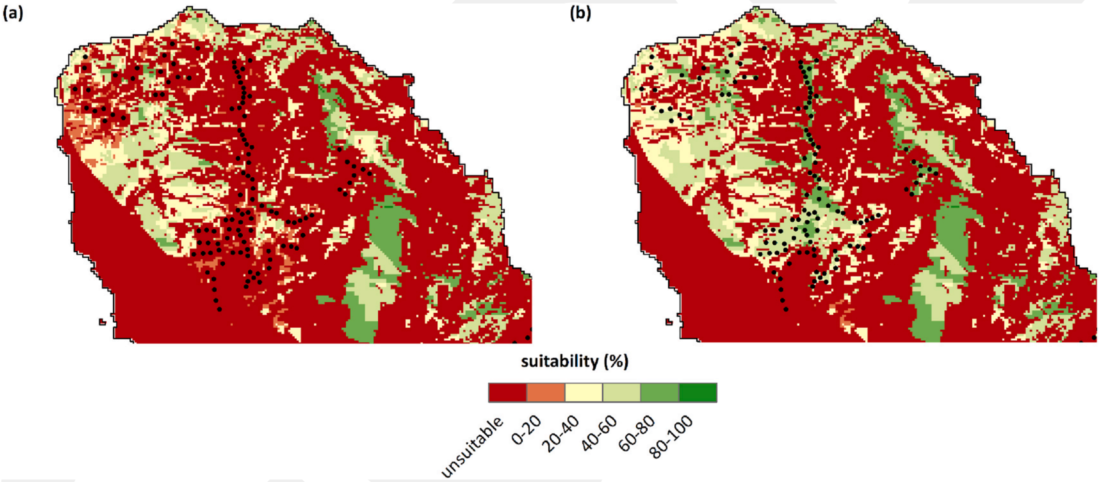


Fig. 10. Suitability maps of Karaburun (a) with wake penalty and (b) without wake penalty.

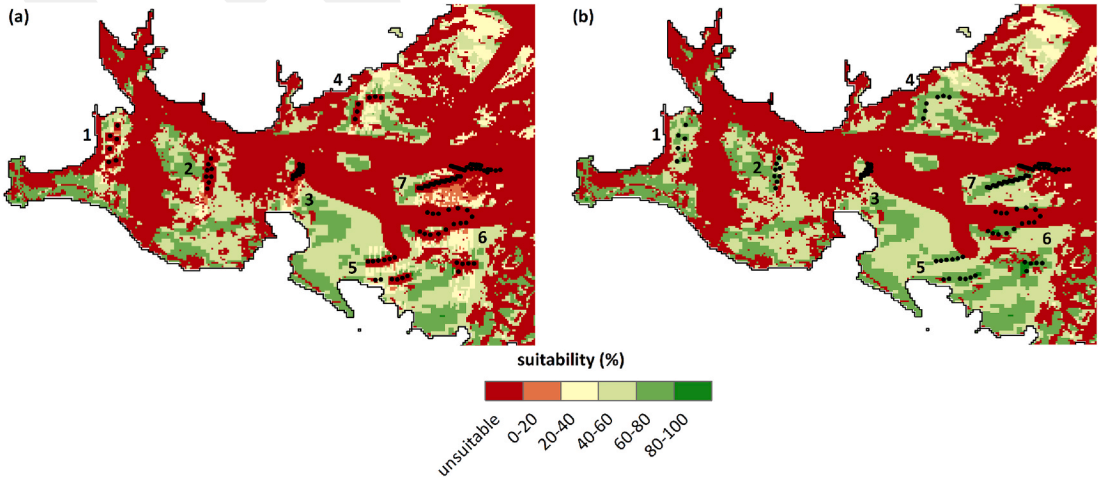


Fig. 11. Suitability maps of Çeşme (a) with wake penalty and (b) without wake penalty.

Table 7
Comparison of the areas with and without wake penalty criterion.

Suitability (%)	Area without wake penalty (km^2)	Area with wake penalty (km^2)	Change (%)
Unsuitable	1276.3	1300.0	1.9
0–20	4.9	16.4	236.6
20–40	132.5	141.1	6.5
40–60	251.4	225.9	−10.2
60–80	94.6	77.0	−18.6
80–100	1.3	0.6	−55.5

suitability. The regions categorized as "60–80%" and "80–100%" suitability, in particular, undergo significant decreases in the suitable area by −18.6% and −55.5%, respectively. These findings suggest that incorporating wake effects offers a more accurate and realistic representation of feasible wind turbine locations. In terms of the economic aspects of wind turbines, the inclusion of wake penalties holds implications for the overall financial feasibility of the chosen sites. While methods that exclude wake effects may identify larger areas as suitable, these findings might not accurately reflect the actual energy production potential of the turbines. Incorporating wake effects provides a more precise estimation of energy generation, as it considers the impact of existing turbines on the efficiency of new ones. Although including wake effects might lead to a reduction in the overall suitable area, it can potentially result in higher energy output from the selected sites, translating to improved economic returns in the long run. Thus, the consideration of wake effects aligns with a more economically prudent decision-making process for wind turbine site selection.

4. Conclusions

In the present study, a comprehensive analysis of wind turbine site selection by incorporating the wake effect into MCDM process is presented. The research focuses on both existing and newly located turbines, considering the impact of wake on the downstream wind speed and overall energy output of the site. This study marks the first instance of integrating the wake effect into the suitability analysis for wind turbines. The AHP method is utilized and seven criteria, including the novel wake penalty criterion, are selected to evaluate the suitability of potential wind turbine locations. These criteria encompass various economic, environmental, and social factors relevant to wind turbine site selection.

The results reveal the wake effects and their corresponding areas of reduced wind speed. Using Jensen's model, the wake penalty percentages, ranging from 67% to 4% and corresponding affected areas are calculated. After conducting AHP analysis, a suitability map for wind turbine placement is generated using ArcGIS. The map exhibits a distribution of suitability ranges, following a typical normal z distribution pattern. Furthermore, a repeated suitability analysis, excluding the wake penalty criterion, is performed to compare the impacts of considering and not considering the wake effect. The results demonstrate the contrasting impacts of wake on turbine site selection. Specific regions, such as Karaburun and Çeşme, are examined in detail, presenting the influence of wake on the allocation and orientation of wind turbine clusters.

In summary, the main contribution of this study is to introduce the wake effect as a criterion in the site selection process for wind farms. Including wake effects significantly shifts suitable areas, affecting initial high-suitability regions. While excluding wake effects might expand suitability, it undermines energy predictions and economic feasibility. Accounting for wake effects provides a more accurate energy estimate, enabling informed decisions and potential long-term economic gains. This integration bridges theoretical and practical wind energy considerations, creating a robust framework for economically sound turbine site selection.

CRediT authorship contribution statement

A.E. Dinçer: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **A. Demir:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **K. Yılmaz:** Resources, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix. Wake penalty

To initiate the procedure, the coordinates of the turbines, *turcoor*, and the wind direction (in angle), *wang*, are required. Additionally, certain limits and parameters need to be defined to establish the calculation algorithm, including the pixel dimension, *pd*, wake angle, α, the number of turbines, *not*, the maximum distance that the wake effect extends, *wed*, and the maximum number of affected pixels for a turbine, *mnoep*.

The coordinates of the existing turbines, *turcoor*, are obtained from the map shown in Fig. 1. Image processing techniques are employed to identify and locate the existing turbines, which are represented by red on the map.

```
Input ($pd, \alpha, not, wed, mnoep, turcoor_{not\times2}, wang$)
for i = 1 : $not$
        Step1 : Assign wake directions of turbine
                Input ( $\alpha, turcoor_{i\times2}, wang$)
                Output ($turang_{i\times3}$)
        Step2 : Determine tip coordinates of turbine
                Input ($turcoor_{i\times2}, turang_{i\times3}$)
                Output ($turtipcoor_{i\times4}$)
        Step3 : Specify neighbor pixels under wake effect
                Input ($pd, \alpha, wed, mnoep, turcoor_{i\times2},$
                 $turtipcoor_{i\times4}$)
                Output ($effnp_{i\times mnoep\times3}$)
end
Step4 : Apply wake effect to wind map (Figure 13)
        Input ($not, mnoep, turcoor_{not\times2}, effnp_{not\times mnoep\times3}$)
        Output ($wpm$)
```

Fig. 12. Algorithm of methodology

The calculations to determine the affected neighbor pixels, *effnp*, of turbines, *i*, begin by determining the wake direction of each turbine, *turang*, as depicted in Fig. 12. While wind direction can vary over time, it is assumed that wind turbines predominantly operate in the prevailing wind direction. Therefore, the wake direction of a turbine is assumed to align with the prevailing wind direction at its location. Wind directions are obtained as angles from the wind speed map presented in Fig. 4, utilizing image processing techniques.

The pixel dimension, *pd*, is set to 50 m which is assumed turbine radius. As a result, while the center of a turbine is represented by a single pixel, the turbine's tips should be represented by neighboring pixels. To determine the tip coordinates of a turbine, the prevailing wind direction at the turbine's location is taken into account. It is important to note that there may be an inherent error in the orientation of a turbine due to the pixel-based representation. For the assumed pixel dimension, the maximum error in turbine orientation is $\pm 22.5^\circ$.

In the final step of generating the wake penalty map, *wpm*, the ratio of the effect on neighbor pixels, $effnp(i, noefn, 3)$, is applied to a blank map (colored as white). Following the completion of the entire procedure outlined in Fig. 12, the region downstream of the turbine is determined. To define the region upstream of the turbine, the procedure needs to be repeated once more. As a result, regions are defined both upstream and downstream of the turbine, as shown in Fig. 3.

The procedure outlined in Fig. 13 is essential for accurately generating the wake penalty map. This is because there are cases where turbines are located downstream of other turbines, and it is necessary to map the wake effect of an upstream turbine before considering the downstream turbine. By following this procedure, the wake penalty map is obtained correctly.

```
Input ($not, mnoep, turcoor_{not\times2}, effnp_{not\times mnoep\times3}$)
$wpm(:,:,:) = 255$
while ($sum(effnp(:,:,:)) > 0$)
        for $i = 1{:}\, not$
                If ($sum(effnp(i,:,:)) \neq 0$)
                        $y = turcoor(i,1)$
                        $x = turcoor(i,2)$
                        $downstream = 0$
                        for $i = 1{:}\, not$
                                for $k = 4{:}\, mnoep$
                                        if ($y = effnp(j,k,1)$)
                                                if ($x = effnp(j,k,2)$)
                                                        $downstream = 1$
                                                end
                                        end
                                end
                        end
                        if ($downstream = 0$)
                                for $k = 1{:}\, mnoep$
                                        $yn = effnp(i,k,1)$
                                        $xn = effnp(i,k,2)$
                                        for $l = 1{:}\,3$
                                                $wpm(yn,xn,l) = wpm(yn,xn,l) * effnp(i,k,3)$
                                                $effnp(i,k,l) = 0$
                                        end
                                end
                        end
                end
        end
end
```

Fig. 13. Algorithm for wake penalty map

Based on the assumption of a wake loss limit of 15D, the wake effected distance, *wed,* is set as 30, which represents effected region around the turbine's location. Accordingly, the maximum number of effected pixels for a turbine, *mnoep*, is set to be smaller than $wed \times wed$.

References

[1] John CA, Tan LS, Tan J, Kiew PL, Shariff AM, Abdul Halim HN. Selection of renewable energy in rural area via life cycle assessment-analytical hierarchy process (LCA-AHP): a case study of tatau, sarawak. Sustainability 2021;13. https://doi.org/10.3390/su132111880.

[2] Kaldellis JK, Zafirakis D. The wind energy (r) evolution: a short review of a long history. Renew Energy 2011;36:1887–901.

[3] Sunak Y, Höfer T, Siddique H, Madlener R, De Doncker RW. A GIS-based decision support system for the optimal siting of wind farm projects. Germany: Universitätsbibliothek der RWTH Aachen Aachen; 2015.

[4] Aruldoss M, Lakshmi TM, Venkatesan VP. A survey on multi criteria decision making methods and its applications. American Journal of Information Systems 2013;1:31–43.

[5] de Fsm Russo R, Camanho R. Criteria in AHP: a systematic review of literature. Procedia Comput Sci 2015;55:1123–32.

[6] Govindan K, Jepsen MB. ELECTRE: a comprehensive literature review on methodologies and applications. Eur J Oper Res 2016;250:1–29.

[7] Behzadian M, Otaghsara SK, Yazdani M, Ignatius J. A state-of the-art survey of TOPSIS applications. Expert Syst Appl 2012;39:13051–69.

[8] Behzadian M, Kazemzadeh RB, Albadvi A, Aghdasi M. PROMETHEE: a comprehensive literature review on methodologies and applications. Eur J Oper Res 2010;200:198–215.

[9] Giamalaki M, Tsoutsos T. Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach. Renew Energy 2019;141:64–75.

[10] Rios R, Duarte S. Selection of ideal sites for the development of large-scale solar photovoltaic projects through Analytical Hierarchical Process–Geographic information systems (AHP-GIS) in Peru. Renew Sustain Energy Rev 2021;149:111310.

[11] Konstantinos I, Georgios T, Garyfalos A. A Decision Support System methodology for selecting wind farm installation locations using AHP and TOPSIS: case study in Eastern Macedonia and Thrace region, Greece. Energy Pol 2019;132:232–46. https://doi.org/10.1016/j.enpol.2019.05.020.

[12] Vinhoza A, Schaeffer R. Brazil's offshore wind energy potential assessment based on a Spatial Multi-Criteria Decision Analysis. Renew Sustain Energy Rev 2021;146. https://doi.org/10.1016/j.rser.2021.111185.

[13] Wu B, Yip TL, Xie L, Wang Y. A fuzzy-MADM based approach for site selection of offshore wind farm in busy waterways in China. Ocean Eng 2018;168:121–32.

[14] Wu Y, Zhang J, Yuan J, Geng S, Zhang H. Study of decision framework of offshore wind power station site selection based on ELECTRE-III under intuitionistic fuzzy environment: a case of China. Energy Convers Manag 2016;113:66–81.

[15] Mahdy M, Bahaj AS. Multi criteria decision analysis for offshore wind energy potential in Egypt. Renew Energy 2018;118:278–89.

[16] Höfer T, Sunak Y, Siddique H, Madlener R. Wind farm siting using a spatial Analytic Hierarchy Process approach: a case study of the Städteregion Aachen. Appl Energy 2016;163:222–43. https://doi.org/10.1016/j.apenergy.2015.10.138.

[17] Amjad F, Agyekum EB, Shah LA, Abbas A. Site location and allocation decision for onshore wind farms, using spatial multi-criteria analysis and density-based clustering. A techno-economic-environmental assessment, Ghana. Sustain Energy Technol Assessments 2021;47. https://doi.org/10.1016/j.seta.2021.101503.

[18] Latinopoulos D, Kechagia K. A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece. Renew Energy 2015;78:550–60. https://doi.org/10.1016/j.renene.2015.01.041.

[19] Vasileiou M, Loukogeorgaki E, Vagiona DG. GIS-based multi-criteria decision analysis for site selection of hybrid offshore wind and wave energy systems in Greece. Renew Sustain Energy Rev 2017;73:745–57.

[20] Vagiona DG, Kamilakis M. Sustainable site selection for offshore wind farms in the South Aegean—Greece. Sustainability 2018;10:749.

[21] Jangid J, Bera AK, Joseph M, Singh V, Singh TP, Pradhan BK, et al. Potential zones identification for harvesting wind energy resources in desert region of India – a multi criteria evaluation approach using remote sensing and GIS. Renew Sustain Energy Rev 2016;65:1–10. https://doi.org/10.1016/j.rser.2016.06.078.

[22] Ayodele TR, Ogunjuyigbe ASO, Odigie O, Munda JL. A multi-criteria GIS based model for wind farm site selection using interval type-2 fuzzy analytic hierarchy process: the case study of Nigeria. Appl Energy 2018;228:1853–69.

[23] Ali Y, Butt M, Sabir M, Mumtaz U, Salman A. Selection of suitable site in Pakistan for wind power plant installation using analytic hierarchy process (AHP). Journal of Control and Decision 2018;5:117–28.

[24] Baseer MA, Rehman S, Meyer JP, Alam MM. GIS-based site suitability analysis for wind farm development in Saudi Arabia. Energy 2017;141:1166–76. https://doi.org/10.1016/j.energy.2017.10.016.

[25] Zalhaf AS, Elboshy B, Kotb KM, Han Y, Almaliki AH, Aly RMH, et al. A high-resolution wind farms suitability mapping using gis and fuzzy ahp approach: a national-level case study in Sudan. Sustainability 2022;14. https://doi.org/10.3390/su14010358.

[26] Rekik S, El Alimi S. Optimal wind-solar site selection using a GIS-AHP based approach: a case of Tunisia. Energy Convers Manag X 2023:18. https://doi.org/10.1016/j.ecmx.2023.100355.

[27] Koc A, Turk S, Şahin G. Multi-criteria of wind-solar site selection problem using a GIS-AHP-based approach with an application in Igdir Province/Turkey. Environ Sci Pollut Control Ser 2019;26:32298–310.

[28] Cavazzi S, Dutton AG. An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential. Renew Energy 2016;87:212–28.

[29] Gorsevski PV, Cathcart SC, Mirzaei G, Jamali MM, Ye X, Gomezdelcampo E. A group-based spatial decision support system for wind farm site selection in Northwest Ohio. Energy Pol 2013;55:374–85. https://doi.org/10.1016/j.enpol.2012.12.013.

[30] Asadi M, Ramezanzade M, Pourhossein K. A global evaluation model applied to wind power plant site selection. Appl Energy 2023;336. https://doi.org/10.1016/j.apenergy.2023.120840.

[31] Noorollahi Y, Yousefi H, Mohammadi M. Multi-criteria decision support system for wind farm site selection using GIS. Sustain Energy Technol Assessments 2016;13:38–50. https://doi.org/10.1016/j.seta.2015.11.007.

[32] Watson JJW, Hudson MD. Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc Urban Plann 2015;138:20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001.

[33] Tegou LI, Polatidis H, Haralambopoulos DA. Environmental management framework for wind farm siting: methodology and case study. J Environ Manag 2010;91:2134–47. https://doi.org/10.1016/j.jenvman.2010.05.010.

[34] Gil-García IC, Ramos-Escudero A, García-Cascales MS, Dagher H, Molina-García A. Fuzzy GIS-based MCDM solution for the optimal offshore wind site selection: the Gulf of Maine case. Renew Energy 2022;183:130–47. https://doi.org/10.1016/j.renene.2021.10.058.

[35] Díaz H, Loughney S, Wang J, Guedes Soares C. Comparison of multicriteria analysis techniques for decision making on floating offshore wind farms site selection. Ocean Eng 2022;248. https://doi.org/10.1016/j.oceaneng.2022.110751.

[36] Waewsak J, Landry M, Gagnon Y. Offshore wind power potential of the Gulf of Thailand. Renew Energy 2015;81:609–26.

[37] Fetanat A, Khorasaninejad E. A novel hybrid MCDM approach for offshore wind farm site selection: a case study of Iran. Ocean Coast Manag 2015;109:17–28.

[38] Kim J-Y, Oh K-Y, Kang K-S, Lee J-S. Site selection of offshore wind farms around the Korean Peninsula through economic evaluation. Renew Energy 2013;54:189–95.

[39] Jensen NO. A note on wind generator interaction, vol. 2411. Citeseer; 1983.

[40] Katic I, Højstrup J, Jensen NO. A simple model for cluster efficiency. European wind energy association conference and exhibition 1986;1:407–10. A. Raguzzi Rome, Italy.

[41] Larsen GC, Højstrup J, Madsen HA. Wind fields in wakes. 1996.

[42] Mosetti G, Poloni C, Diviacco B. Optimization of wind turbine positioning in large windfarms by means of a genetic algorithm. J Wind Eng Ind Aerod 1994;51:105–16. https://doi.org/10.1016/0167-6105(94)90080-9.

[43] Frandsen S, Barthelmie R, Pryor S, Rathmann O, Larsen S, Højstrup J, et al. Analytical modelling of wind speed deficit in large offshore wind farms. Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology 2006;9:39–53.

[44] Grady SA, Hussaini MY, Abdullah MM. Placement of wind turbines using genetic algorithms. Renew Energy 2005;30:259–70. https://doi.org/10.1016/j.renene.2004.05.007.

[45] Elkinton CN, Manwell JF, McGowan JG. Algorithms for offshore wind farm layout optimization. Wind Eng 2008;32:67–84.

[46] Eroğlu Y, Seçkiner SU. Wind farm layout optimization using particle filtering approach. Renew Energy 2013;58:95–107. https://doi.org/10.1016/j.renene.2013.02.019.

[47] Pillai AC, Chick J, Khorasanchi M, Barbouchi S, Johanning L. Application of an offshore wind farm layout optimization methodology at Middelgrunden wind farm. Ocean Eng 2017;139:287–97.

[48] Ozturk U, Norman BA. Heuristic methods for wind energy conversion system positioning. Elec Power Syst Res 2004;70:179–85.

[49] Saaty TL. A scaling method for priorities in hierarchical structures. J Math Psychol 1977;15:234–81.

[50] Saaty TL. Group decision making and the AHP. The Analytic Hierarchy Process: Applications and Studies 1989:59–67.

[51] Raza MA, Yousif M, Hassan M, Numan M, Abbas Kazmi SA. Site suitability for solar and wind energy in developing countries using combination of GIS- AHP; a case study of Pakistan. Renew Energy 2023;206:180–91. https://doi.org/10.1016/j.renene.2023.02.010.

[52] Demir A, Dinçer AE, Yılmaz K. A novel method for the site selection of large-scale PV farms by using AHP and GIS: a case study in İzmir, Türkiye. Sol Energy 2023;259:235–45.

[53] Demir A, Dinçer AE. Efficient disaster waste management: identifying suitable temporary sites using an emission-aware approach after the Kahramanmaraş earthquakes. Int J Environ Sci Technol 2023:1–16.

[54] Yılmaz K, Dinçer AE, Ayhan EN. Exploring flood and erosion risk indices for optimal solar PV site selection and assessing the influence of topographic resolution. Renew Energy 2023:119056.

[55] Demir A. Hydro-elastic analysis of standing submerged structures under seismic excitations with sph-fem approach. Lat Am J Solid Struct 2020;17:1–14. https://doi.org/10.1590/1679-78256266.

[56] Demir A, Dinçer AE, Öztürk Ş, Kazaz I. Numerical and experimental investigation of sloshing in a water tank with a fully coupled fluid-structure interaction method. Progress in Computational Fluid Dynamics, an International Journal 2021;21:103–14.

[57] Song Z, Zhang Z, Chen X. The decision model of 3-dimensional wind farm layout design. Renew Energy 2016;85:248–58.

[58] Eroğlu Y, Seçkiner SU. Design of wind farm layout using ant colony algorithm. Renew Energy 2012;44:53–62.

[59] Kusiak A, Song Z. Design of wind farm layout for maximum wind energy capture. Renew Energy 2010;35:685–94. https://doi.org/10.1016/j.renene.2009.08.019.

[60] Hou P, Hu W, Chen C, Soltani M, Chen Z. Optimization of offshore wind farm layout in restricted zones. Energy 2016;113:487–96.

[61] Hou P, Hu W, Soltani M, Chen C, Chen Z. Combined optimization for offshore wind turbine micro siting. Appl Energy 2017;189:271–82.

[62] Huang H-S. Distributed genetic algorithm for optimization of wind farm annual profits. In: International conference on Intelligent systems applications to power systems. IEEE; 2007. p. 1–6.

[63] González JS, Rodriguez AGG, Mora JC, Santos JR, Payan MB. Optimization of wind farm turbines layout using an evolutive algorithm. Renew Energy 2010;35:1671–81.

[64] Emami A, Noghreh P. New approach on optimization in placement of wind turbines within wind farm by genetic algorithms. Renew Energy 2010;35:1559–64.

[65] Gao X, Yang H, Lu L. Optimization of wind turbine layout position in a wind farm using a newly-developed two-dimensional wake model. Appl Energy 2016;174:192–200.

[66] Marmidis G, Lazarou S, Pyrgioti E. Optimal placement of wind turbines in a wind park using Monte Carlo simulation. Renew Energy 2008;33:1455–60. https://doi.org/10.1016/j.renene.2007.09.004.

[67] Park J, Law K. Layout optimization for maximizing wind farm power production using sequential convex programming. Appl Energy 2015;151:320–34.

[68] Guirguis D, Romero D, Amon C. Toward efficient optimization of wind farm layouts: utilizing exact gradient information, vol. 179. Elsevier; 2016. p. 110–23.

[69] Parada L, Herrera C, Flores P, Parada V. Wind farm layout optimization using a Gaussian-based wake model. Renew Energy 2017;107:531–41.

[70] Sorkhabi SYD, Romero DA, Yan GK, Gu MD, Moran J, Morgenroth M, et al. The impact of land use constraints in multi-objective energy-noise wind farm layout optimization. Renew Energy 2016;85:359–70.

[71] Rivas RA, Clausen J, Hansen KS, Jensen LE. Solving the turbine positioning problem for large offshore wind farms by simulated annealing. Wind Eng 2009;33:287–98. https://doi.org/10.1260/0309-524X.33.3.287.

[72] DuPont BL, Cagan J. An extended pattern search approach to wind farm layout optimization. J Mech Des 2013;134:1–18. https://doi.org/10.1115/1.4006997.

[73] Lissaman PBS. Energy effectiveness of arbitrary arrays of wind turbines. J Energy 1979;3:323–8. https://doi.org/10.2514/3.62441.

[74] Fueyo N, Sanz Y, Rodrigues M, Montañés C, Dopazo C. High resolution modelling of the on-shore technical wind energy potential in Spain. Wind Energy 2010;13:717–26.

[75] Díaz H, Soares CG. A multi-criteria approach to evaluate floating offshore wind farms siting in the canary islands (Spain). Energies 2021;14. https://doi.org/10.3390/en14040865.

[76] Parklar Milli. Türkiyedeki kuş hareketliliği haritaları kitabı. Ankara: Orman ve su işleri bakanlığı; 2013.