Earth Science Informatics
https://doi.org/10.1007/s12145-024-01227-4

RESEARCH

Wind farm site selection using GIS-based multicriteria analysis with Life cycle assessment integration

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Received: 5 April 2023 / Accepted: 12 January 2024

Abstract

The sustainability of wind power plants depends on the selection of suitable installation locations, which should consider not only economic and technical factors including manufacturing and raw materials, but also issues pertaining to the environment. In the present study, a novel methodology is proposed to determine the suitable locations for wind turbine farms by analyzing from the environmental perspective. In the methodology, the life cycle assessment (LCA) of wind turbines is incorporated into the decision process. The criteria are ranked using analytical hierarchy process (AHP). The study area is chosen as the western region of Türkiye. The obtained suitability map reveals that wind speed is not the sole criterion for selecting a site for wind turbine farms; other factors, such as bird migration paths, distance from urban areas and land use, are also crucial. The results also reveal that constructing wind power plants in the vicinity of İzmir, Çanakkale, Istanbul, and Balıkesir in Türkiye can lead to a reduction in emissions. İzmir and its surrounding area show the best environmental performance with the lowest CO_2 per kilowatt-hour (7.14 g CO_2 eq/kWh), to install a wind turbine due to its proximity to the harbor and steel factory across the study area. Çanakkale and the northwest region of Türkiye, despite having high wind speeds, are less environmentally favorable than İzmir, Balıkesir, and Istanbul. The findings of LCA reveal that the nacelle and rotor components of the wind turbine contribute significantly (43–97%) to the environmental impact categories studied, while the tower component (0–36%) also has an impact.

Keywords Wind energy · Analytical hierarchy process · Sustainability · Life cycle assessment · SimaPro

Introduction

With the world's rapidly growing population and industrialization, the magnitude of energy consumption has increased unprecedentedly (Foster et al. 2009). The demand for this energy consumption, starting with especially the Industrial Revolution and continuing for years, caused greenhouse gases to accumulate in the atmosphere (Benti et al. 2023). Considering that these accumulated greenhouse gases may be responsible for global climate change, it has become imperative to put a stop to this deterioration. In response to global warming, climate change and air pollution, the European Commission plans to have zero greenhouse gas emissions by 2050 with the European Green Deal (Fetting 2020). It is aimed that this plan will be accepted not only by European member states, but also by lots of countries on an international scale. If only the European member states limit their carbon emissions under this plan, they may encounter challenges in competing with other countries in terms of trade and economy (Sahin et al. 2016). For this reason, it is believed that this Green Deal should be implemented by almost all countries of the world due to the establishment of fair competition in the commercial sense and the use of the Earth's atmosphere by the countries together. The first steps to ensure the international validity of all the regulations planned with the Green Deal were taken with the Paris

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Communicated by Gregorio Milani.

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Agreement (IRENA 2022) signed in 2016 (Falkner 2016). This agreement reflects the broad scope of the Green Deal, which goes beyond specific sectors and encompasses a wide range of areas. It addresses not only the supply of end-user products with potential climate impacts but also touches upon energy consumption in households and even agricultural policies. The Green Deal's application spans across various domains, emphasizing its comprehensive approach to tackling climate change. In addition, within the scope of this agreement, a series of measures, especially climate law and carbon limit tax, were also planned to be implemented within the countries (Sahin et al. 2016). With these measures taken, it is clear that investments will be integrated with renewable clean energy sources in a short time. In other words, production with zero greenhouse gases until 2050 will basically depend on accelerating the transition to renewable energy and even keeping the carbon emissions of this renewable energy at certain levels. Renewable energy also attracts the attention of humanity because it is clean, abundant, and cost-friendly (Krohn and Damborg 1999; Bell et al. 2005; Kann 2009; Konstantinos et al. 2019; Genç et al. 2021; Asadi et al. 2023; Raza et al. 2023). In order to pave the way for renewable energy sources, governments also offer considerable incentives to investors. For example, the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) in Germany has guaranteed priority procurement of renewable energy at a fixed tariff since 2000 (Höfer et al. 2016). Considering these incentives and even investments of states in energy, it is believed that renewable energy can soon replace fossil fuels. For example, developed countries such as Germany (Höfer et al. 2016) and China seek to meet more than 80% of their gross energy consumption from renewable energy with their goals for 2050 and beyond.

Wind turbines are known as cost-effective energy conversion systems thanks to corresponding technological developments in recent years (Karki and Billinton 2004; Höfer et al. 2016; Pryor and Barthelmie 2021; Guan 2023; Vallejo Díaz et al. 2023). This situation causes an increase in the interest in wind turbine facilities. In other words, wind turbines have taken their place in the literature as promising and clean renewable energy converters with their fast-growing technological infrastructure (Uyan 2013; Noorollahi et al. 2016; Shahid et al. 2019; Saraswat et al. 2021). With this concept, the rapid increase in the number of wind farm installations around the world demonstrates that the intense interest in wind turbines is also more than just rhetoric (Shorabeh et al. 2022; Çiftci et al. 2023).

The financial success of the operation of wind power plants primarily depends on the determination of suitable places for installation (Benti et al. 2023). The suitability of this location selection is related to not only the economic factors (e.g. wind speed profile and proximity to the transmission network), but also to the provision of some environmental (e.g. slope and height) and social (e.g. visual impact, noise pollution) criteria (Harding et al. 2008; Katsaprakakis 2012; Kokologos et al. 2014; Tabassum et al. 2014; Knopper et al. 2014; Freiberg et al. 2019; Manchado et al. 2019; Xu et al. 2021; Benti et al. 2023; Guan 2023). In other words, rather than placing the wind turbines in the windiest locations constantly, it may be more crucial to choose the location based on a variety of economic, ecological, and physical aspects (Jamshed et al. 2018). Studies in the literature dealing with the issue of effective site selection for wind turbines have generally utilized multi-criteria decision-making (MCDM) methods to evaluate the various aforementioned criteria together. These investigations have also shown several alternative analysis techniques while concentrating on various MCDM methodologies. For instance, ranking, weighted sum, weighted linear combination, Boolean overlay operation, order weighted average, trade-off analysis, analytical network process, and the analytic hierarchy process (AHP) are examples of analysis techniques (Elkadeem et al. 2021). Although it is not possible to specify which of these methods is the best, the AHP approach has grown in popularity for deciding the suitable sites for wind turbines (Dinçer et al. 2023). Because it is simple, user-friendly, and consistent in its decision-making (Höfer et al. 2016; Jamshed et al. 2018; Elkadeem et al. 2021; Manirambona et al. 2022; Benti et al. 2023; Rekik and El Alimi 2023; Demir et al. 2023). For example, Tegou et al. (2010) used the AHP method to determine the location of the wind power installation on the Greek island of Lesvos. Similarly, Chikoto et al. (2015) determined the relative importance of different site selection criteria for wind farms from a group of regional experts in their study and provided the integration of these criteria with each other using the AHP method. Additionally, by combining the AHP method with a geographic information system (GIS), these studies have also added visuality to their findings and given readers and investors the ability to assess them (Demir and Dinçer 2023; Yılmaz et al. 2023).

It is also important to consider the emissions that occur during the construction and operation of wind turbines (Sahin et al. 2016). Site selection plays a crucial role in reducing these emissions, as certain locations may require more transportation and infrastructure development, leading to higher emissions. Therefore, carefully analyzing the potential emissions of a wind turbine is essential to minimize its impact on the environment, because the environmental performance of wind turbines over their lifetime is a significant metric for assessing their sustainability. Life cycle assessment (LCA) is an efficient method for evaluating the environmental impacts of a product, process, or system throughout its life. LCA provides a comprehensive analysis of resource use, emissions, and potential impacts, helping to inform sustainable decision-making and reduce environmental and societal burdens.

In the field of wind energy, several LCA studies were conducted to evaluate the environmental impacts of wind turbine production (Guezuraga et al. 2012; Demir and Taşkin 2013; Vargas et al. 2015; Schreiber et al. 2019). Schreiber et al. (2019) conducted a comparative LCA study to evaluate the environmental impacts associated with the production of electricity from three different types of wind turbines that have a power class of 3 MW. They analyzed the environmental impacts by applying the method of ILCD/PEF recommendation version 1.09 and the Ecoinvent 3.3 database implemented into the GaBi 8.7 software. The CO_2 equivalents obtained were 7.25 g/kWh for doubly fed induction generator (DFIG) and direct drive permanent magnet synchronous generator (DDPMSG) and 12.43 g/kWh for direct driven synchronous generator (DDSG). Due to its heavier nacelle, the DDSG has greater impacts than the other wind turbines in 14 out of 15 categories. In a study conducted by Demir and Taskın (2013) in Kayseri, Türkiye, the environmental impacts of five wind turbines with different power outputs and hub heights were compared using LCA methodology. The results showed that the CO_2 emissions of the wind turbines ranged from 15.1 to 38.3 g/kWh, depending on their power and hub heights. The study found that wind turbines with higher hub heights, which can generate more electricity, have lower negative impacts on the environment. The wind turbine with a rated power of 2050 kW and a hub height of 100 m was identified as the best option for the region in terms of energy production, environmental considerations, and energy payback time. Vargas et al. (2015) also conducted a study to compare the environmental performance of two 2.0 MW wind turbines made of different materials and installed in Mexico, using LCA methodology. The study found that the turbine having a total weight of 1087.7 tons and blades made of glass fiber-reinforced plastic, had higher environmental impacts than the turbine having a total weight of 962.91 tons and blades made of fiberglass. The results were based on a 20-year lifespan of the turbines. In another study conducted by Guezuraga, Zauner, and Polz (2012), the environmental impact of two existing wind turbines - a 1.8 MW gearless turbine and a 2.0 MW gearbox turbine - was assessed using LCA. The study found that the average CO_2 emissions over the 20-year lifespan of the turbines was 9 gCO_2/kWh, as calculated using the Global Emission Model of Integrated System (GEMIS) software. The results showed that the manufacturing phase accounted for 84.4% of the turbines' entire life cycle, and that tower construction represented 55.0% of the total turbine production in terms of energy consumption. Despite previous studies that have utilized LCA methodology to assess the environmental impacts of wind turbines, LCA has not yet been employed as a tool for identifying suitable locations for wind turbine farms.

In summary, the AHP is recognized as a useful tool for the identification of suitable locations for wind turbine farms, as it takes into account several factors, including environmental impacts. However, while previous studies have explored this approach, there is still a gap in the literature when it comes to incorporating LCA in the site selection process of wind turbines. In response, the present study proposes a novel method that integrates AHP with LCA to determine suitable sites for wind turbines that consider their environmental impacts. The study area is selected to be the west side of Türkiye, and a specific procedure developed in Matlab is used to calculate the emissions due to transportation in each location across the area. GIS works are then implemented in ArcMAP to determine the most suitable locations for wind turbines. To the best of our knowledge, this is the first study that integrates AHP with LCA to identify suitable locations for wind turbines.

Methodology

The Analytical hierarchy process (AHP)

The AHP which is one of the most widely used MCDM methods, was developed by Saaty (Saaty 1980) to assist in the organization and analysis of complex decision-making problems. In the AHP, the first step involves defining the goal, which is the determination of suitable sites for wind farms in this study. Next, a hierarchical structure is established for the criteria, and a pairwise comparison matrix is developed. The comparison process involves using a scale to determine the dominance of one criterion over another (Saaty 2008). The elements in each column are then divided by the sum of that column, and the resulting values are summed up and divided by the total number of elements in the row. Finally, the consistency ratio (CR) is calculated using the following formulas.

$$CR = \frac{CI}{RI} \tag{1}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where CI is the consistency index, RI is the random consistency index and taken as 1.3952 for the case including 8 criteria (Golden and Wang 1989), λ_{max} is the principal eigenvalue and n is the number of criteria used in the AHP process. An AHP inconsistency is deemed acceptable if the consistency ratio value is less than 0.10.

Life cycle assessment (LCA)

In this study, the goal of LCA is to quantify the environmental impacts of wind turbines over their lifetime and analyze the effect of transportation distance from production site to construction location on its environmental performance. LCA is performed using the standards ISO 14,040 and ISO 14,044, and it consists of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The purpose of LCA is to evaluate the potential environmental impacts of a product, process, or service throughout its life-cycle, starting with the extraction of the raw material and completing with its disposal (ISO 2006). The functional unit is selected as 1 kWh of electricity delivered to the grid. The system boundaries of this study cover all life cycle stages of wind turbines from the acquisition of raw material to the disposal as called cradle to grave approach. The primary inventory data for the wind turbine (direct drive permanent magnet synchronous generator (DDPMSG)-3.2 MW) are retrieved from the literature (Schreiber et al. 2019) and the secondary data are collected from the Ecoinvent V3.7.1 database. The lifetime of a wind turbine is assessed as 20 years. SimaPro 9.2 PhD is used to perform the LCA analyses for this study. The CML-IA baseline V3.06 method, one of the most commonly used methods for LCA studies of wind turbines, is used to assess the turbine's environmental impacts (Martínez et al. 2009). The environmental impact categories of this method are listed as follows: abiotic depletion (AD, kg Sb eq), abiotic depletion-fossil fuels (AD-FF, MJ), global warming potential (GWP, kg CO_2 eq), ozone layer depletion (ODP, kg CFC-11 eq), human toxicity (HT, kg 1,4-DB eq), freshwater aquatic ecotoxicity (FAE, kg 1,4-DB eq), marine aquatic ecotoxicity (MAE, kg 1,4-DB eq), terrestrial ecotoxicity (TE, kg 1,4-DB eq), photochemical oxidation (PO, kg C_2H_4 eq), acidification potential (AP, kg SO_2 eq), eutrophication potential (EP, PO_4^{3-} eq).

Determination of emissions due to transportation

A wind turbine consists of several structural elements that can be procured from various locations. The rotor is procured from İzmir harbor, while the nacelle can be supplied from either İzmir or İstanbul harbor. Additionally, the tower, a cylindrical steel structural element, can be supplied from the iron and steel factories near the site. There are four tower producers located in Çanakkale, İzmir, İzmit, and Zonguldak cities within the study area.

The supplier of each element of the turbine should be determined based on the location where the wind turbine is being constructed, with sustainability as the main consideration. The emissions resulting from the transportation of each element of the wind turbine should be calculated for every site, as each element is carried by trucks from the supplier to the construction site. Once the emissions of a truck per ton per kilometer are obtained using the Ecoinvent database, the next step is to calculate the shortest route from the supplier to the construction site. This problem can be solved using swarm particle optimization.

In the proposed methodology, the swarm optimization process begins by generating a member on the global coordinates of the supplier using image processing techniques. The member can move in any direction (N, NE, E, SE, S, SW, W, NW) to an adjacent pixel. If there is more than one possible pixel to move, the member deletes itself and generates new members (carrying the mother's milestone) for every possible adjacent pixel. During each move, the swarm member checks the milestone of the arrival pixel. There are three possibilities at this stage. The first possibility is that there is no milestone at the arrival pixel. In this case, the swarm member moves to that pixel with its own milestone. This action is also valid when the milestone of the arrival pixel is greater than the member's own milestone. However, if the milestone of the arrival pixel is smaller than the member's milestone, the member deletes itself. This condition satisfies the optimality of the route. As a result, optimal milestones are assigned to every pixel of the road. The method is applied for every element of a wind turbine and the CO_2 emissions shown in Fig. 1 are achieved.

Site properties

In the present study, the possible locations for wind farms on the western side of Türkiye are investigated and shown in Fig. 2. The study area consists of the most densely populated areas in the country, and as a result, has a high electricity demand. The construction of wind power plants in these regions would help meet the growing demand for electricity while also reducing the country's dependence on fossil fuels. In addition, the region has well-developed infrastructure, including transportation networks and electricity grids. This infrastructure can be leveraged to support the construction and operation of wind power plants. Most importantly the Marmara, southeast Anatolian, and Aegean regions are identified as the most favorable locations for wind energy applications, owing to their high wind speeds, exceeding 3 m/s in most areas, making them highly suitable for wind power generation (Çam et al. 2005). Finally, due to the perpendicular orientation of the mountains with respect to the sea which is obvious in the digital elevation model shown

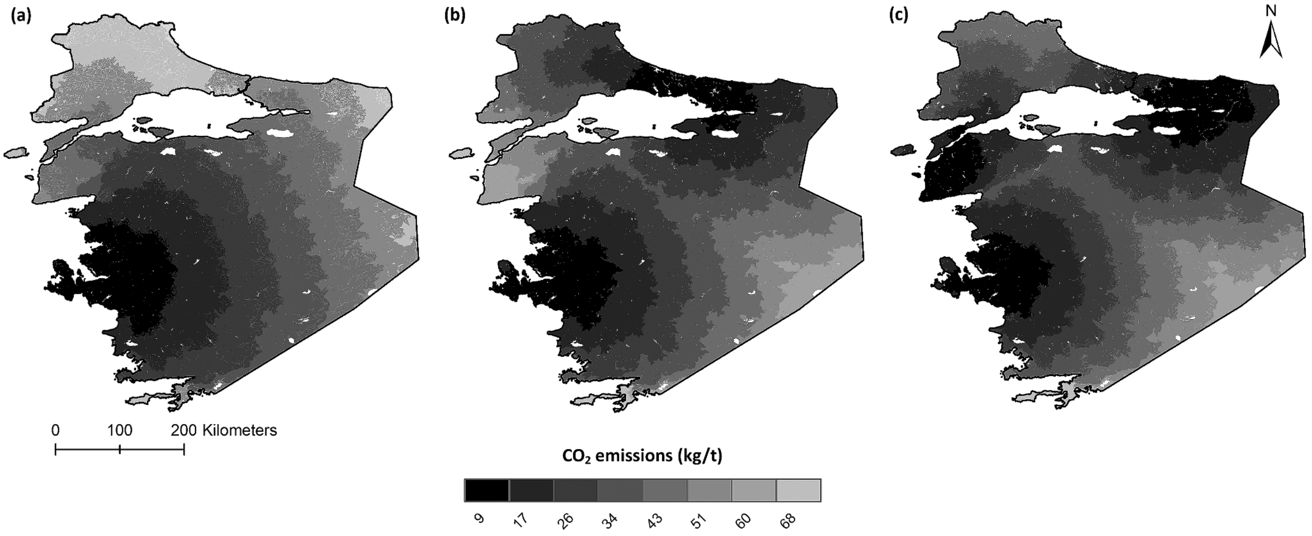

Fig. 1 CO_2 emissions for **a** rotor, **b** nacelle, and **c** tower of the wind turbine

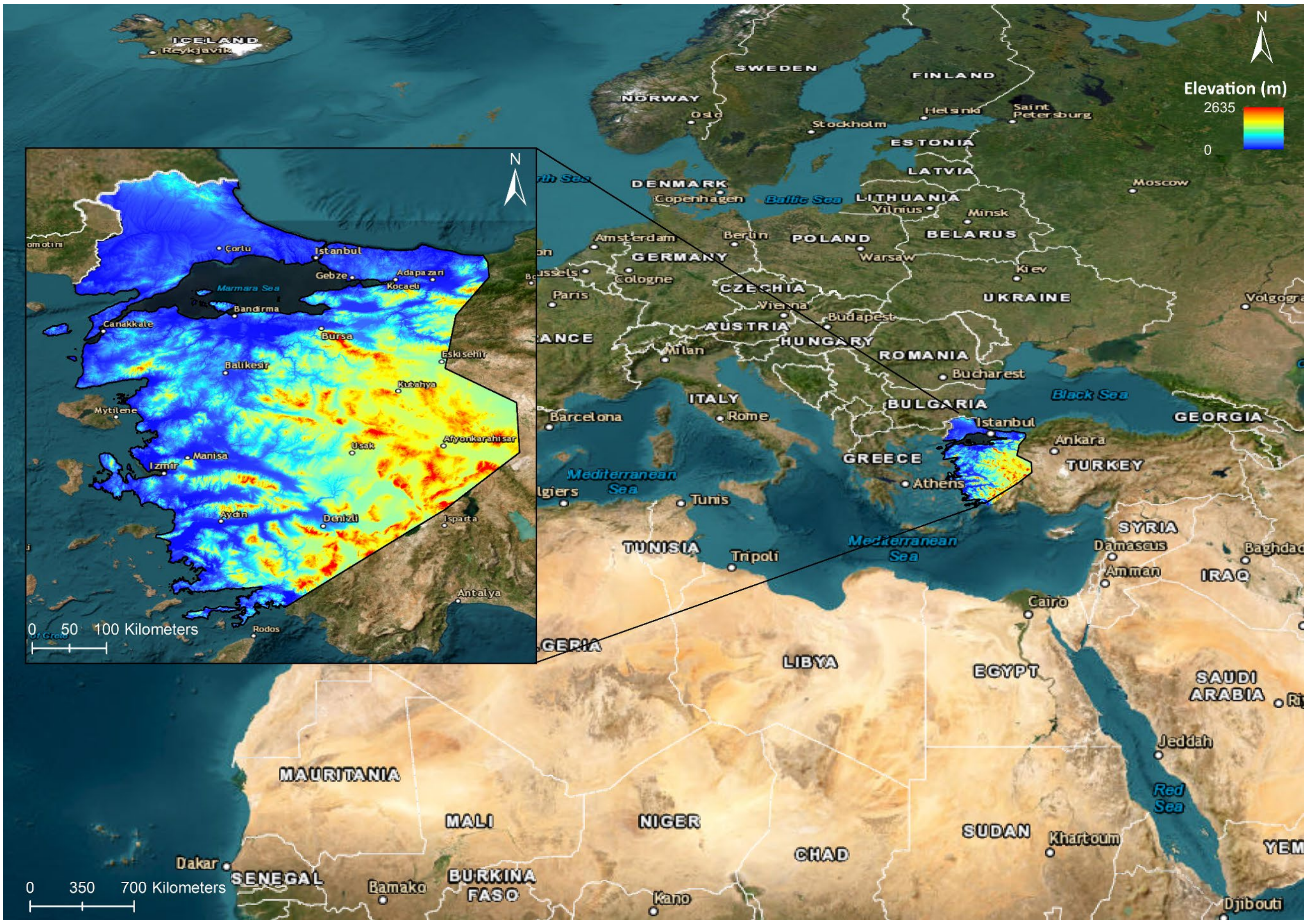

Fig. 2 The study area

in Fig. 2, the wind can penetrate deeper into the inland areas of the region, which has significant implications for wind power generation.

Constraints and classification

Wind energy potential

The wind energy potential of a site, as determined by the average wind speed in the area, is a critical criterion for evaluating the economic performance of a wind turbine. Sites with higher wind speeds have the potential to generate more electricity. As a result, this criterion is typically included in most studies and considered as one of the most crucial factors in the site selection process (Rodman and Meentemeyer 2006; Tegou et al. 2010; Gorsevski et al. 2013). Figure 3 presents the annual average wind speed distribution in the study area (Global Wind Atlas 2023). The regions proximate to the Aegean coasts demonstrate a comparatively higher distribution of the annual average wind speed, which ranges above 7 m/s. Conversely, only minor areas in the study region experience a wind speed below 3 m/s.

Land cover

Wind farm locations should be selected considering the land cover, so that the environmental impacts are minimized (Christie and Bradley 2012; Latinopoulos and Kechagia 2015). In addition, a proper consideration of land cover can lead to the development of sustainable wind power projects that benefit both the environment and economy. The installation of wind turbines requires open spaces, and areas with intensive agriculture or urban development are not suitable. Additionally, wind farms may impact the use of land for activities such as hunting, grazing, and recreation. The land cover obtained from Sentinel 2 satellite imagery is given in Fig. 3b (European Space Agency 2023). The sites for wind farms are only considered suitable if the area is classified as bare ground or rangeland.

Slope

The slope of land affects the access to the site for construction and maintenance activities. A steep slope can make it challenging to transport materials and equipment, leading to increased costs and safety risks. Additionally, maintenance of turbines installed on steep slopes can be difficult and costly, which can impact the long-term operation of the wind farm. Moreover, wind turbines are tall structures that are subjected to high wind loads. The slope of land affects the stability of foundation required to support the turbine (Obane et al. 2020). Installing a wind turbine on a steep slope requires additional foundation support, which can increase costs and impact on environment. Consequently, the proper slope of the land can have a positive impact on increasing the efficiency of wind turbine power generation (Huang et al. 2022). In the present study, the slope is categorized according to the scheme illustrated in Fig. 3c, wherein slopes with a gradient less than 3% are classified as highly favorable, while those exceeding 24% are considered restricted.

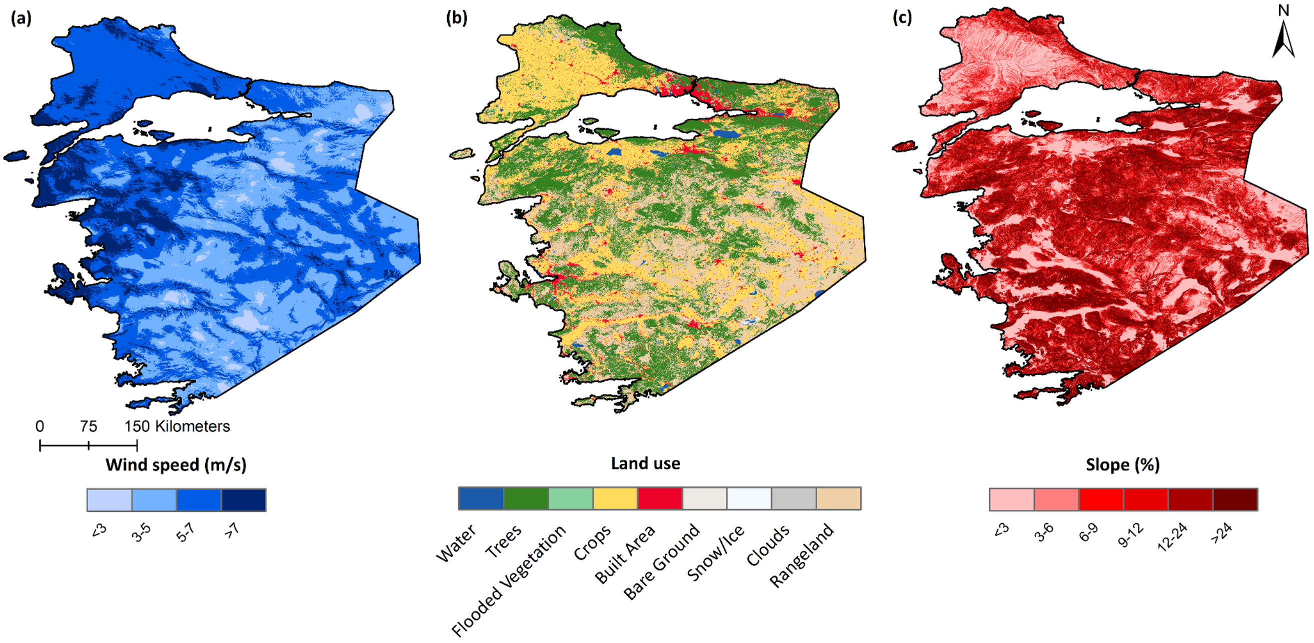

Fig. 3 The distribution of **a** annual average wind speed (m/s) **b** land use and **c** slope (%)

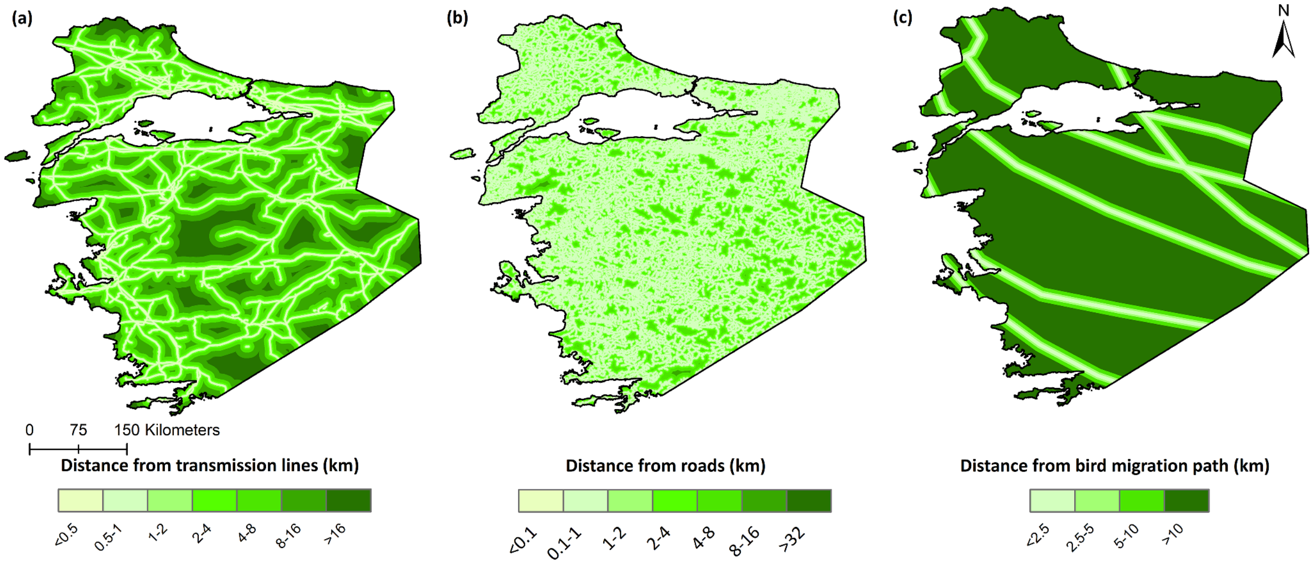

Fig. 4 The distance from **a** transmission lines, **b** roads, and **c** bird migration paths. The sources from which the data is obtained are listed in Table 1.

Table 1 Data sources for the study

Criterion	Source
Wind Potential (m/s)	Global Wind Atlas (2023)
Land Cover / Use	European Space Agency (2023)
DEM	Farr et al. (2007)
Slope (%)	Calculated using DEM
Distance from urban areas (km)	European Space Agency (2023)
Distance from transmission line (km)	Open Street Map (2023)
Distance from road (km)	Open Street Map (2023)
Bird migration paths (km)	Hacioglu (2017)

Distance from transmission lines

The cost of interconnecting a wind farm to a grid depends on the distance between the project site and the nearest transmission lines. Longer distances may require expensive equipment, such as higher voltage transformers and longer transmission lines, which can add significant costs to the project (Pamucar et al. 2017; Nasery et al. 2021). Moreover, longer transmission lines can result in higher line losses, reducing the amount of electricity that is delivered to customers. On the other hand, it is recommended that wind turbines be positioned at a safe distance from overhead power lines, taking into account both the height of the turbine and a safety distance that varies based on the voltage of the power lines (Nasery et al. 2021). In the present study, the minimum safety distance has been established as 500 m. Figure 4a shows the classification of distances from the power transmission lines (Open Street Map 2023).

Distance from urban areas

The placement of wind turbines near urban areas is restricted in order to prevent issues such as noise pollution, visual disturbance, and blade shadow effects (Noorollahi et al. 2016; Moradi et al. 2020). As a result, this study considers a buffer zone of 1 km. The most optimal locations are identified based on the criterion that the distance between urban areas and the site exceeds 2 km. The urban areas, labelled as built areas, are shown in Fig. 3b.

Distance from roads

Wind turbines can pose a safety risk to road users, especially if located close to roads (Baban and Parry 2001). On the other hand, they require access for construction, maintenance, and repairs. Access roads are necessary for transporting equipment, materials, and personnel to and from the site. Therefore, wind turbines are typically located at a sufficient distance from roads to allow for the construction of access roads (Al-Yahyai et al. 2012). The classification of the distance from roads is shown in Fig. 4b (Open Street Map 2023). Accordingly, wind farms are not allowed to be located within 100 m distance from roads.

Distance from bird migration paths

Bird strikes occur when birds collide to the rotating blades of wind turbines, which can result in injury or death of birds, as well as damage to the wind turbine. To minimize bird strikes, wind turbines are typically located away from bird migration routes (Taoufik and Fekri 2021), although some studies reported that the bird populations are not affected by

Table 2 The initial AHP matrix

Criterion	Wind Potential (m/s)	Bird migration paths (km)	Distance from urban areas (km)	CO_2 emission (kg/t)	Land Use	Distance from road (km)	Slope (%)
Wind Potential (m/s)	1.00	2.00	3.00	4.00	5.00	6.00	7.00
Bird migration paths (km)	0.50	1.00	2.00	3.00	4.00	5.00	6.00
Distance from urban areas (km)	0.33	0.50	1.00	2.00	3.00	4.00	5.00
CO_2emission (kg/t)	0.25	0.33	0.50	1.00	2.00	3.00	4.00
Land Use	0.20	0.25	0.33	0.50	1.00	2.00	3.00
Distance from transmission line (km)	0.17	0.20	0.25	0.33	0.50	1.00	1.00
Distance from road (km)	0.14	0.17	0.20	0.25	0.33	1.00	1.00
Slope (%)	0.13	0.14	0.17	0.20	0.25	0.50	0.50

Table 3 Summary of weights of constraints and indicators of their sub-criteria

Criterion	Weight	Sub-criteria	Indicators	Criteria	Weight	Sub-criteria	Indicators
Wind Potential (m/s)	33	< 3	1	Distance from urban areas (km)	16	0–1	restrained
		3–5	3			1–2	4
		5–7	6			> 2	9
		> 7	9				
Land Use	7	Water	restrained	Distance from transmission line (km)	4	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 (%)	3	0–3	9	Distance from road (km)	3	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			8–16	4
						> 16	2
CO_2 emission (kg/t)	11	< 8.5	9	Bird migration paths (km)	23	0-2.5	restrained
		8.5–17	8			2.5-5	3
		17-25.5	7			5–10	6
		25.5–34	6			> 10	9
		34-42.5	5				
		42.5–51	4				
		51-59.5	3				
		59.5–68	2				

the wind farms (Astiaso Garcia et al. 2015). As illustrated in Fig. 4c (Hacioglu et al. 2017), a 2.5 km buffer zone is established for the distance from the bird migration path, and locations beyond 10 km from the path are considered as the most suitable.

Determination of weights of constraints

The initial AHP matrix weights are determined by considering both expert opinions and the literature (Saaty 1980, 2008) and presented in Table 2. Since this study is among the first to introduce sustainability issues, particularly CO_2 emissions, there is limited information available in the literature to compare this criterion with others. Therefore, expert opinions are sought and utilized in the AHP calculations to determine the initial AHP matrix shown in Table 2. After determining the initial AHP matrix, the weights for each set of constraints are calculated by following the procedure explained in Section "The Analytical hierarchy process (AHP)" and presented in Table 3, along with the sub-criteria of each constraint and their respective indicators. The consistency ratio is calculated as 0.025, which is well below the acceptable limit of 0.10, indicating the calculated weights are consistent.

Results and discussions

Suitability map for wind turbines

In order to locate suitable areas for wind turbine installation, a combination of ArcMap 10.8.1 and Matlab is utilized. CO_2 emissions for each pixel are determined as described previously, utilizing a code that employs swarm optimization to follow the main roadways. These emissions data are incorporated into the AHP matrix, along with other criteria. The results of the AHP are then input into the ArcMap, where GIS operations are performed (Yılmaz et al. 2022), resulting in the final suitability map shown in Fig. 5. It is important to highlight that during the calculation process, all the data are gathered from reputable and well-known sources. This approach is adopted to ensure that the results remain unaffected by incomplete or inaccurate data. To ensure the accuracy of the data, information from one source is cross-verified with data from another source whenever possible, thus minimizing the likelihood of errors in the analysis.

The output composite map is divided into six categories, with the first category representing unsuitable regions and the remaining categories indicating suitability rank. The most favorable locations are found to be situated close to the Aegean coasts, in the northwestern region of Türkiye (near Edirne) and the central part of the country.

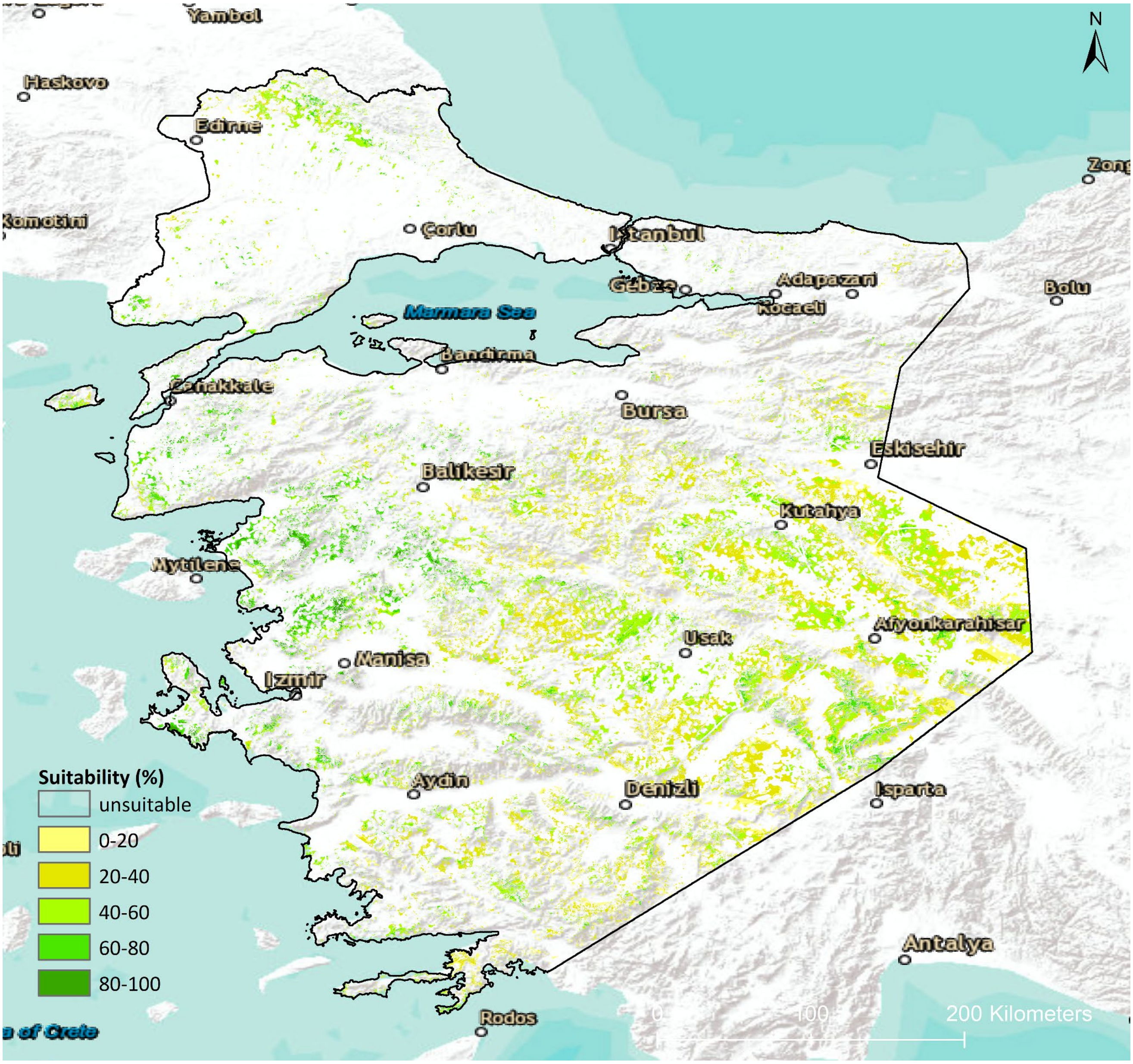

Fig. 5 Suitability map

Comparison of suitable sites with existing wind farms

The suitability map and the existing wind farms are shown in Fig. 6. Four regions with a high concentration of wind farms are highlighted. In the first region, located near the boundary of İzmir and Manisa, most of the existing wind farms are found to be located within suitable sites, as shown in Fig. 6-(1). In the second region, situated in the western region of Türkiye where wind potential is abundant, there exists a high density of wind farms. There are many suitable sites in the region and a vast majority of the existing wind farms are located in these regions. Nonetheless, there exists a wind farm situated on the northwest side of the region that is located within an unsuitable area. The reason for this is due to the proximity of the site to an urban area, which prohibits the construction of a wind farm. The third region under consideration is situated close to the boundary of Balıkesir and Manisa. The majority of wind farms situated in this region are found to be located outside of suitable areas. The primary reason for this is the unsuitability of these regions as indicated by satellite images of land cover, which reveal that the areas in question are densely populated with trees. The construction of wind farms in such areas is prohibited in this study. The examined fourth zone is located near the boundary of Afyonkarahisar and Isparta. Notably, nearly all the wind farms situated in this region fall within the boundaries of suitable zones. Particularly, a line of wind farms located near Dinar is accurately predicted by the study. It should be noted that there exists a wind farm located just north of region (4), situated along the bird migration path, which is considered a buffer zone within the context of this study.

Results of the LCA

The obtained environmental impacts of the wind turbine per kWh energy production from LCA analysis are presented in Table 4. AD impact category refers to mineral and resource consumption and therefore it is directly affected by the extraction rate of resources. The impact of this usage on their depletion is assessed based on their global availability stock. The AD impact category is divided into two subgroups, namely, materials and fossil fuels (Farinha et al. 2021). The AD value of a wind turbine per kWh is 7.14E-08 kg Sb eq,

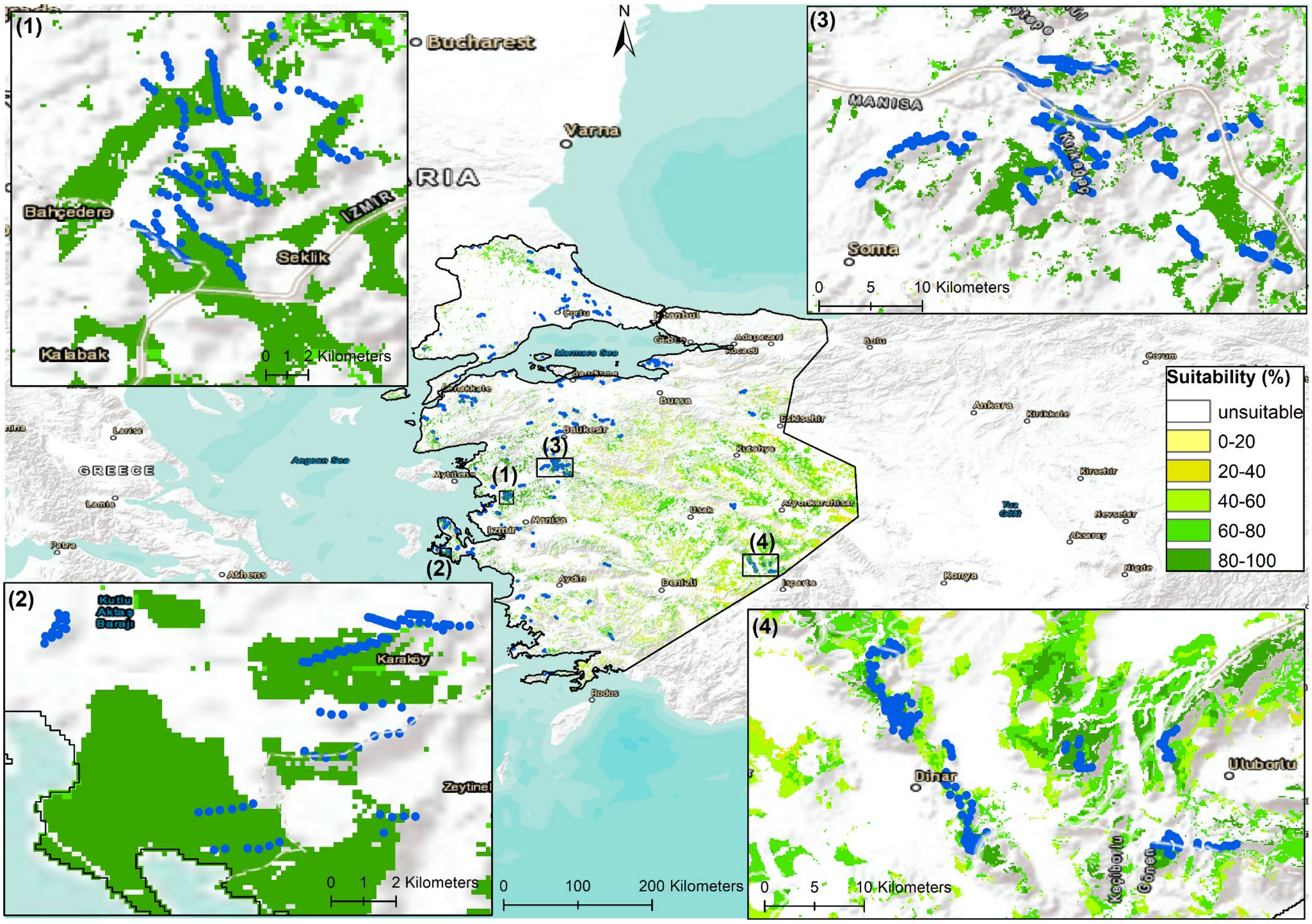

Fig. 6 Suitability map of wind farm locations, with existing wind farms marked (dark blue denotes existing wind farms)

Table 4 Environmental impact category values of wind turbine per kWh energy production (CML-IA baseline V3.06 method)

Impact category	Unit	Total	Nacelle and Rotor	Installation, Dismantling, and Maintenance	Foundation	Tower
AD	kg Sb eq	7.14E-08	6.92E-08	3.52E-10	1.50E-09	2.86E-10
AD-FF	MJ	7.88E-02	3.89E-02	1.06E-02	1.10E-02	1.83E-02
GWP	kg CO_2 eq	7.11E-03	3.05E-03	9.37E-04	1.33E-03	1.79E-03
ODP	kg CFC-11 eq	3.72E-10	1.76E-10	2.52E-11	7.64E-11	9.48E-11
HT	kg 1,4-DB eq	2.06E-02	1.76E-02	4.25E-05	7.53E-04	2.26E-03
FAE	kg 1,4-DB eq	1.18E-02	6.76E-03	2.00E-06	1.05E-03	3.94E-03
MAE	kg 1,4-DB eq	1.57E+01	9.44E+00	7.91E-03	1.47E+00	4.77E+00
TE	kg 1,4-DB eq	3.56E-05	3.31E-05	8.99E-08	1.49E-06	9.42E-07
PO	kg C_2H_4 eq	7.14E-08	6.92E-08	3.52E-10	1.50E-09	2.86E-10
AP	kg SO_2 eq	7.88E-02	3.89E-02	1.06E-02	1.10E-02	1.83E-02
EP	kg PO_4^{3-} eq	7.11E-03	3.05E-03	9.37E-04	1.33E-03	1.79E-03

and the nacelle and rotor have the most significant impact within this category due to their consumption of abiotic resources such as copper and steel. The AD-FF per kWh is calculated as 7.88E-02 MJ, and the nacelle and rotor also contribute the most to this category. GWP is one of the primary indicators of the environmental sustainability of the wind turbine, and its value for the wind turbine is 7.11 g CO_2 eq./kWh. The main source of GWP is the production and operation of the nacelle and rotor. The obtained GWP value for the wind turbine is consistent with the literature; GWP values of onshore wind turbines in previous studies range between 4 and 41 g CO_2 eq./kWh (Tremeac and Meunier 2009; Martínez et al. 2009; Guezuraga et al. 2012; Demir and Taşkin 2013; Siemens 2015; Schreiber et al. 2019). Turbine size and scale are significant factors affecting the efficiency of a wind turbine. In a study conducted by Demir and Taşkin(2013), the environmental performance of wind turbines with five different scales (330 kW, 500 kW, 810 kW, 2050 kW, 3020 kW) installed in Pınarbaşı-Kayseri were compared. They obtained 16.27 g CO_2 eq./kWh for the wind turbine (2050 kW) at 100 m hub height and 40.36 g CO_2 eq./kWh for the wind turbine (330 kW) at 50 m hub height. They revealed that the GWP can be reduced on a large scale by altering production processes of steel and concrete, the quantities of the materials used, or by employing alternative materials (Demir and Taşkin 2013). Although wind energy technology has a substantially lower impact on the environment than conventional technologies of power generation, the environmental impacts of various wind turbine technologies can vary significantly. Guezuraga et al. (2009) conducted an LCA in order to quantify the environmental impact of two wind turbines (1.8 MW gearless and 2.0 MW turbine with a gearbox). They found 8.82 g CO_2 eq./kWh for the wind turbine (1.8 MW gearless) and 9.73 g CO_2 eq./kWh for the wind turbine (2.0 MW turbine with a gearbox). It is revealed that gearless wind turbines offer better results in terms of GWP when compared with wind turbines with a gearbox (Guezuraga et al. 2012). Consequently, the GWP of wind turbines is affected by turbine size, scale, and employed technology due to the varying amounts of materials and production processes (Table 4).

The distribution of the environmental impact results based on the manufacturing processes for the turbine components, including the foundation, nacelle and rotor, tower and their installation, dismantling and maintenance are given in Fig. 7.

The nacelle and rotor are the primary contributors of the wind turbine's environmental impact, accounting for between 43% and 97% of the total impact throughout its service life. Additionally, the tower has a high impact on three environmental categories (MAE, FAE, and PO), representing over 30% of the total impact across the 11 categories. The foundation component's contribution to the turbine's environmental performance ranges from 2 to 21%. Finally, the installation, dismantling, and maintenance have relatively lower impact on most of the environmental impact categories.

The component that contributes the most to the GWP is the nacelle and rotor with a 43% share of the total, followed by the tower with a 25% contribution. Similarly, the nacelle and rotor are the dominant components that contribute to AD, with 97% of the total. The results are similar to the literature on the environmental performance of wind turbines. Using the LCA approach, Demir and Taşkin (2013) analyzed the environmental impacts of wind turbines. Their findings indicated that the share of nacelle and rotor in GWP is 43% for wind turbines of 2050 kW and 41% for wind turbines of 3020 kW. In addition, Vargas et al. (2015) applied the LCA methodology to conduct a study in which they examined the environmental performance of two wind turbines that were both 2.0 MW in capacity and were composed of different materials. They revealed that the share of nacelle and rotor in the AD is 86% and 89% depending on the type of material used in blades.

The distribution of CO_2 emissions by the location of wind farm on the map is indicated in Fig. 8. The results revealed that the turbines installed close to İzmir exhibit the lowest CO_2 per kilowatt-hour (7.14 g CO_2 eq/kWh). In contrast,

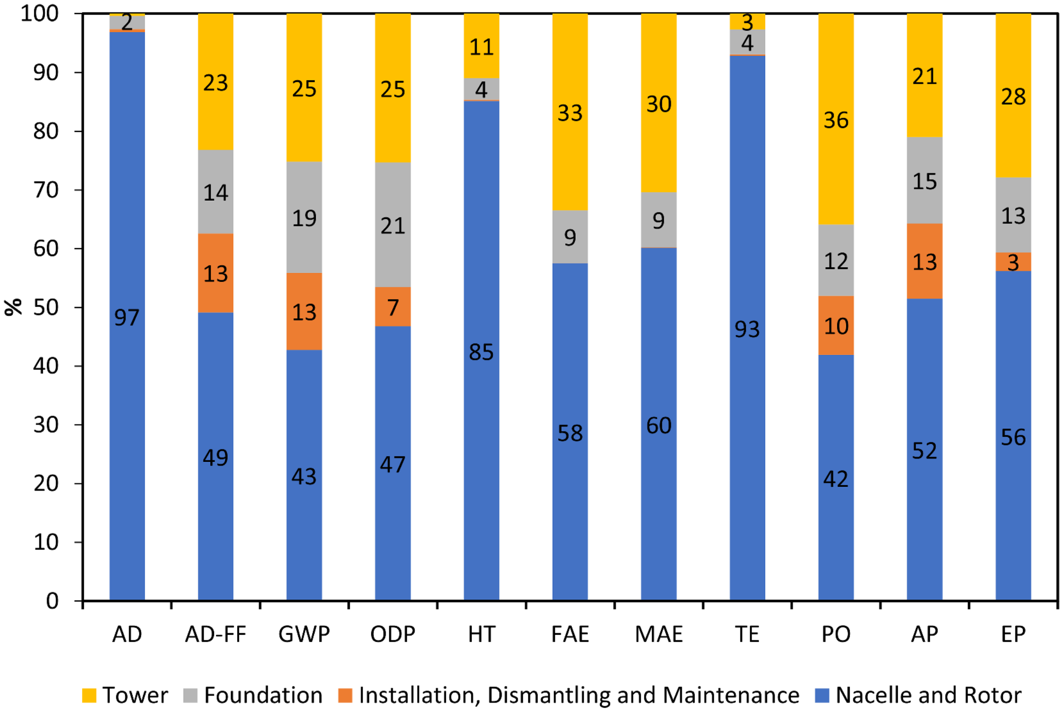

Fig. 7 The distribution of environmental impacts by components of wind turbine based on CML-IA baseline V3.06 method (AD: abiotic depletion, AD-FF: abiotic depletion (fossil fuels), GWP: global warming potential, ODP: ozone layer depletion, HT: human toxicity, FAE: freshwater aquatic ecotoxicity, MAE: marine aquatic ecotoxicity, TE: terrestrial ecotoxicity, PO: photochemical oxidation, AP: acidification potential, EP: eutrophication potential)

the overall CO_2 emissions of turbines installed near İstanbul and Çanakkale are slightly higher, at around 7.16 and 7.18 g CO_2 eq/kWh, respectively. The CO_2 emissions of the turbines installed along the border of Afyon and Isparta are significantly greater at around 7.26 g/kWh, ranking the highest in the research area. The differences in the overall CO_2 emissions between these locations can be attributed to several factors. The main factors are the distance from the production facilities of the rotor, steel factories (for the tower production) located in Türkiye, and the main harbors located in İzmir and İstanbul for the nacelle coming from abroad. The fuel consumption and emissions increase due to the longer distance.

The comparison of environmental impacts associated with constructing a wind turbine in four different locations (i.e., near İzmir, Istanbul, Çanakkale, and the boundary of Afyonkarahisar and Isparta) is depicted in Fig. 9. The specific locations are not indicated at this point; however, the calculations were based on building a wind farm within 15 km from the harbor of İzmir and İstanbul, within 15 km to a steel factory in Çanakkale, and close to the boundary of the study area near Afyonkarahisar and Isparta. From an environmental point of view, İzmir shows the best environmental performance to install a wind turbine due to its proximity to the harbor and steel factory across the study area. The results indicate that ODP is the most affected environmental impact category by transportation distance of the wind turbine with an increase of approximately 7%. Additionally, the GWP and AD-FF are influenced by 2% and 2.75% increase in their respective values due to the increased transportation distance. Due to their high wind power potential, the highest wind power production in Türkiye is in İzmir, Balıkesir, Çanakkale, and İstanbul. The findings of this study suggest that constructing wind power plants close to these locations can result in lower emissions compared to other regions in Türkiye. Particularly, İzmir and its surrounding region demonstrate strong potential as a favorable candidate for wind power plant construction, provided that all relevant criteria are considered. Although Çanakkale and the northwest region of Türkiye exhibit high annual average wind speeds, they are less favorable than İzmir, Balıkesir, or Istanbul in terms of environmental impacts.

Financial aspect

The levelized cost of energy for a land-based wind plant, as detailed in (Stehly and Duffy 2021), is presented in Fig. 10. This cost comprises various components, starting with turbine expenditures including rotor, nacelle, and tower costs accounting for 48% of the total expenses. These turbine-related costs are determined by the specific type of turbine

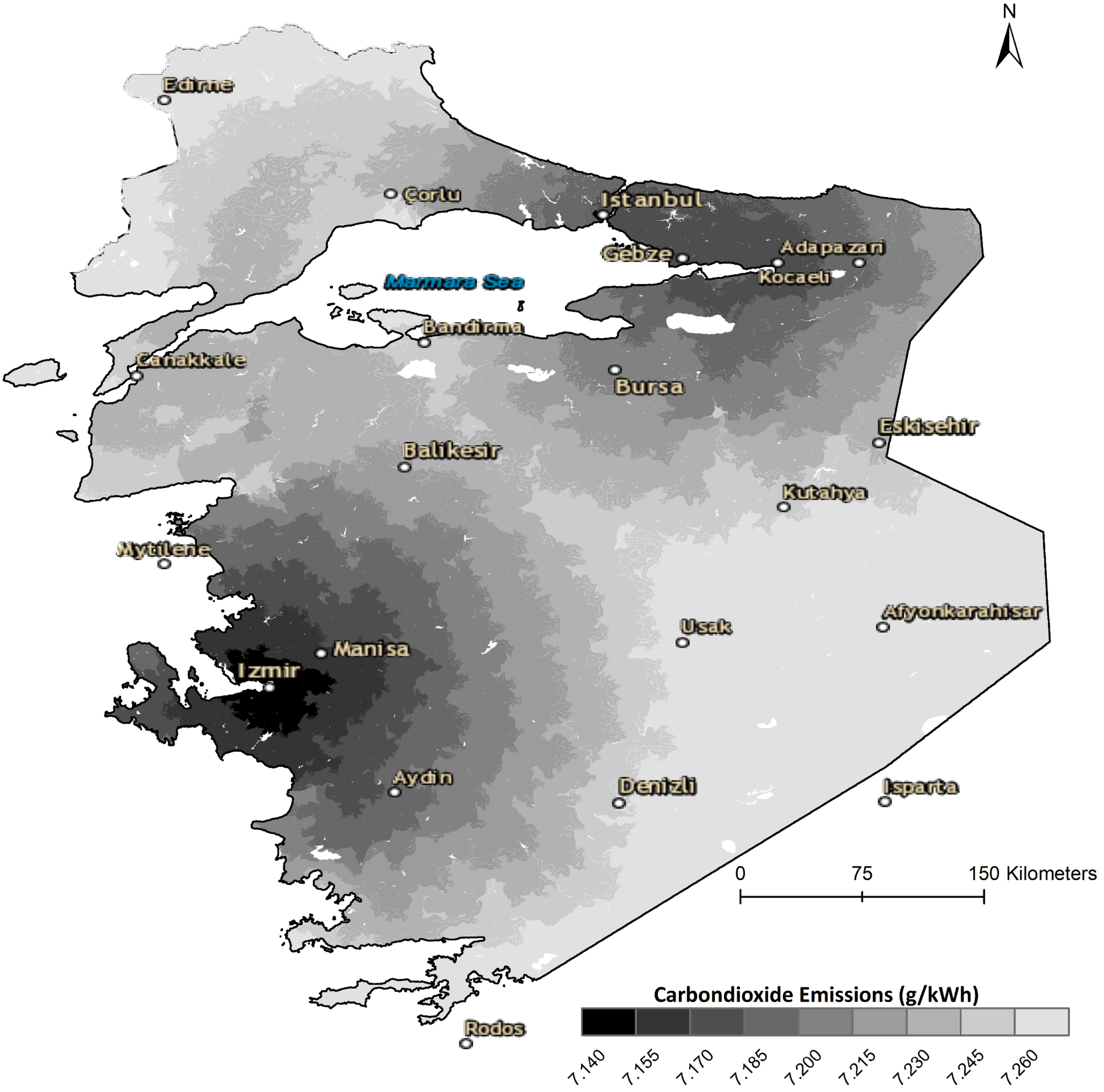

Fig. 8 The distribution of CO_2 emissions by the location of wind farms (g CO_2 eq/kWh)

selected and remain consistent regardless of the chosen wind turbine location.

System expenditures, accounting for 15%, encompass development, engineering, management, foundation construction, site access and staging, assembly and installation, and electrical infrastructure. In the study, the cost of site access and staging are indirectly factored in by considering criteria such as proximity to roads and urban areas. Assembly and installation costs are influenced by the terrain slope and are also integrated into the site selection process. The expense associated with electrical infrastructure is considered by evaluating the distance to transmission lines. The foundation cost may vary based on the soil characteristics of the site and the potential earthquake risk. In this study, the regions of İzmir, İstanbul, Çanakkale, and Balıkesir are considered among the most favorable areas. However, these regions also exhibit a higher risk of earthquakes, with İzmir and İstanbul facing a slightly elevated risk compared to the others. Consequently, due to this heightened earthquake risk, it may be necessary to employ larger foundations in these specific regions. Despite the foundation's contribution to the total cost being approximately 3.5%, it may be a

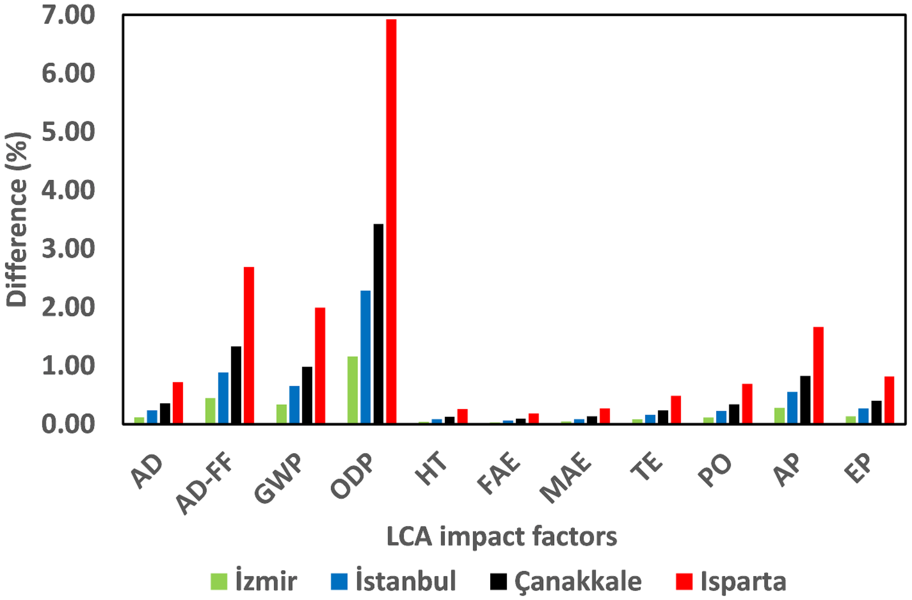

Fig. 9 The change in environmental impacts of the wind turbine by the location of wind farms

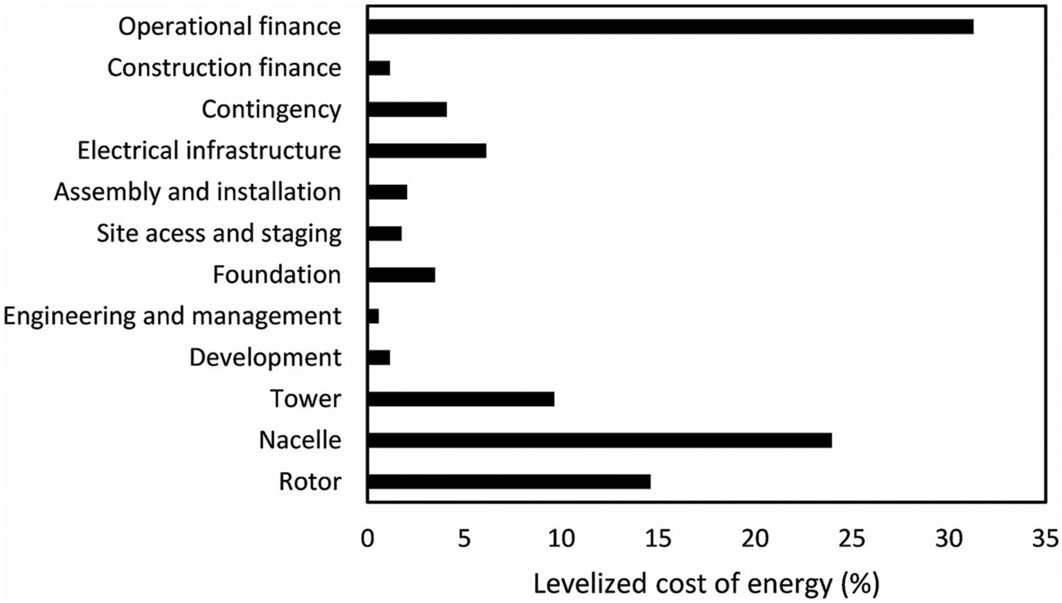

Fig. 10 Levelized cost for a land-based wind plant (Stehly and Duffy 2021)

factor worth considering in the site selection process, albeit not the most significant cost driver.

The financial expenditures, accounting for 5%, consist of contingency and construction finance costs, both of which are not site-dependent, assuming the wind plant is constructed in a unitary republic. Finally, operational expenditures, accounting for 32%, are influenced by the site's characteristics. For instance, worker travel costs to the wind power plant may increase with the distance from urban areas. However, in this study, a greater distance from urban areas is preferred to mitigate issues like noise pollution, visual disturbances, and blade shadow effects. Thus, in the interest of avoiding these issues, a slight increase in transportation costs for workers can be deemed acceptable.

Limitations

In the study, criteria are selected to account for various environmental, economic, and technical factors. These factors encompass wind potential, CO_2 emissions, slope, land cover, proximity to urban areas, transmission lines and roads, and consideration of bird migration paths. It's worth noting that the existing literature suggest other criteria, such as the impact on local flora (Sliz-Szkliniarz and Vogt 2011; Azizi et al. 2014), government support (Wu et al. 2019, 2020), and public acceptance (Yunna and Geng 2014; Rehman et al. 2019; Wu et al. 2020). For a comprehensive list of criteria, please refer to the study of Rediske et al. (2021).

It's important to emphasize that the selection of criteria should be tailored to the specific objectives of each study and the particular locations where the study is conducted. In the current study, the primary goal is to perform an LCA and incorporate it as a criterion for the wind turbine site selection process. As a result, due to the specificity of the focus, all the criteria proposed in the existing literature are unable to be incorporated into the site selection process.

Furthermore, the study primarily relies on average wind speed data, consistent with the conventional approach in previous wind farm site selection research. However, incorporating uncertainty considerations into wind speed predictions would be a valuable enhancement. Various techniques, such as ensemble forecasting, statistical modeling, Monte Carlo simulations, sensitivity analysis, and machine learning with probabilistic models, can address this concern. Since the adoption of these methods to address wind speed uncertainty could potentially alter the core focus of the study, exploring this aspect remains a prospect for future research.

Moreover, during the process of selecting a suitable site, it is possible to take into account the wake effect. While the wake effect has been considered in the optimization of wind turbine layouts in previous studies, there are only two instances where it was incorporated into the site selection process (Dinçer et al. 2023; 2024). In their research, they utilized Jensen's model to account for the wake effect. Nevertheless, it is worth noting that more advanced approaches, such as fluid-structure interaction methods (Dinçer 2019; Demir 2020) combined with computational fluid dynamics techniques (Anderson 1995; Velioglu et al. 2015; Demir et al. 2021) can offer a more detailed simulation of the wake effect. It may be worthwhile to consider including such a comprehensive wake effect simulation in future wind turbine site selection studies.

Finally, in this study, a 3.2 MW wind turbine with a direct drive permanent magnet synchronous generator is utilized. It's essential to recognize that changing the selected wind turbine model would result in variations in the outcomes of the LCA analysis, thereby impacting the suitability of the wind turbine sites. If different wind turbine models are to be considered, the site selection process needs to be adjusted to identify appropriate locations for each particular turbine. It's noteworthy that, for the sake of consistency, the turbine model remains unchanged throughout the analysis to ensure consistent results.

Conclusions

The study aims to determine the most suitable sites for constructing wind turbine farms in the western region of Türkiye. To achieve this goal, eight distinct criteria are established. The main novelty of this study is to include emissions determined from LCA as one of the criteria in the site selection process which is conducted using GIS-based AHP. For identifying the most favorable location for wind turbines, emissions data are incorporated into the AHP matrix and the results of the AHP are then input into ArcMap, where GIS operations are performed and as a result, the regions close to the Aegean coasts, in the northwestern region of Türkiye (near Edirne) are found to be situated as the most suitable ones. The resulting suitability map shows that, in addition to wind speed, other criteria such as bird migration paths, distance from urban areas and land use, are also important in selecting sites for wind turbine farms. It should also be noted that the identified suitable sites are in line with the pre-existing wind farms in the region.

In addition, the results of this study suggest that constructing wind power plants near İzmir, Çanakkale, İstanbul, and Balıkesir can lead to lower emissions compared to other regions in Türkiye. İzmir and its surrounding region are particularly suitable for wind power plant construction, provided that all relevant criteria are considered.

Furthermore, the environmental impacts of wind turbines are evaluated using the cradle-to-grave approach. The results indicate that the nacelle and rotor components of the wind turbine have the most significant environmental impacts with a share of 43–97%, while the tower component also has a high impact as 0–36%. Although Çanakkale and the northwest region of Türkiye exhibit high annual average wind speed, they are less favorable than İzmir and İstanbul in terms of the ODP, AD-FF, and GWP categories of environmental impacts. The results indicate that the ODP is the most affected environmental impact category by transportation distance of the wind turbine with an increase of approximately 7%. Additionally, the GWP and AD-FF are influenced by 2% and 2.75% increase in their respective values due to the increased transportation distance. The study's findings can be helpful in determining where to build future wind turbine farms in light of their potential environmental effects.

Author contributions A.E.D., S.G. and N.U. conducted life cycle assessment. A.E.D. and A.D. developed the method to determine spatial transportation emissions. A.E.D., A.D. and K.Y. performed GIS works. A.E.D., C.Ç., S.G. and N.U. wrote the manuscript. K.Y. prepared the data. A.E.D., A.D. C.Ç., N.U. and K.Y. performed the revisions.

Funding No funding was obtained for this study.
Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability Data will be provided upon request to Ali Ersin Dinçer.

Declarations

Competing interests The authors declare no competing interests.

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