DOI: Gelecek Vizyonlar Dergisi (fvj: Future Visions Journal) 9(1): 2025, 56-75

Submitted: 08.04.2025 **Revised:** 15.06.2025 **Accepted: 20.06.2025**

GIS-AHP BASED WIND POWER PLANT SITE SELECTION ANALYSIS: A CASE STUDY OF ŞARKÖY (TEKİRDAĞ)

CBS-AHS Tabanlı Rüzgar Enerji Santrali Yer Seçim Analizi: Şarköy (Tekirdağ) Örneği

Emre TUNALI[1]

Abstract

The population increase trend in Türkiye, unite with the rapidly growing urbanization process and economic development increases the demand for energy every passing day. The circumstance obligates the achievement of sustainability in energy production in Türkiye, a country poor in fossil fuel resources. Investments such as wind power plants to be held on a local scale are one of the steps that will be beneficial both in meeting energy demand and maintain continuity. In this regard, the main objective of the study is to determine suitable areas for the installation of wind power plants (WPP) in the Şarköy district of Tekirdağ and to offer a suggestion to investors and decision makers. In this research analytic hierarchy process (AHP) and Geographic Information Systems (GIS) has been used in an integrated manner. A pairwise comparison matrix table was prepared for the criteria determined in accordance with different experts opinons in the literature and criteria weightings were made. Additionally, suitable areas for wind farm installation in Şarköy were identified via the transfer and analysis of data obtained from various establishments and open sources into a GIS environment. The findings acquired from the study shows that the wind speed is the most affecting criteria in WPP site selection. Especially in the north and northeast of the district, wind speed averages reach the maximum level. Therefore, surface shapes such as hilltops and ridges, where criteria like slope and land use are also convenient, are highly suitable for WPP construction. Particularly the north of Ucmakdere, Güzelköy and Gaziköy neighborhoods are the areas with the most favorable potential. The "less suitable" and "suitable" areas for WPP installation show a heterogeneous distribution throughout the district. On the other hand, a three-dimensional turbine model was used in the study, and twelve wind turbines were placed on four sample sites determined to be "highly suitable" for WPP construction and their coordinates were given. The AHP method used in the study provides consistent results and its functionality in this type of analysis has also been revealed. The findings obtained from the study offers a guiding framework to investors and decisions makers. It will be possible to obtain expressive results by conducting appropriate technical and economic analyses.

Keywords: Energy Geography, Wind Energy, Site Selection, Multi-Criteria Decision-Making (MCDM), Spatial Suitability, Şarköy.

Öz

Ülkemizde artış eğilimi gösteren nüfus, hızla büyüyen şehirleşme süreci ve ekonomik kalkınmayla birleşerek enerjiye olan talebi her geçen gün artırmaktadır. Bu durum fosil yakıtlar bakımından fakir olan Türkiye'de enerji üretimindeki sürdürülebilirliğin sağlanmasını zorunlu kılmaktadır. Yerel ölçekte yapılacak rüzgâr santralleri gibi yatırımlar hem enerji talebin karşılanmasında hem de sürekliliğin sağlanmasında yarar sağlayacak adımlardan biridir. Bu bakımdan Tekirdağ'ın Şarköy ilçesinde rüzgâr enerji santrali (RES) kurulumuna uygun alanları belirlemek ve yatırımcılar ile karar alıcılara bir öneri sunmak çalışmanın temel hedefini oluşturmaktadır. Araştırmada analitik hiyerarşi süreci (AHS) ve Coğrafi Bilgi Sistemleri (CBS) entegre biçimde kullanılmıştır. Literatürdeki farklı uzman görüşleri doğrultusunda belirlenen kriterler için ikili karşılaştırma matrisi tablosu hazırlanmış ve kriter ağırlıklandırmaları yapılmıştır. Ayrıca, farklı kurum ve açık kaynaklardan elde edilen verilerin CBS ortamına aktarılması ve analiz edilmesiyle, Şarköy'de RES kurulumuna uygun alanlar tespit edilmiştir. Çalışmadan elde edilen bulgular, RES yer seçimini en fazla etkileyen kriterin rüzgâr hızı olduğunu göstermektedir. İlçenin özellikle kuzey ve kuzeydoğusunda rüzgâr hızı ortalamaları maksimum düzeye ulaşmaktadır. Dolayısıyla eğim ve arazi kullanımı gibi kriterlerin de elverişli olduğu tepe üstü ve sırt gibi yüzey şekilleri RES yapımına oldukça elverişlidir. Özellikle Uçmakdere, Güzelköy ve Gaziköy mahallelerinin kuzeyi potansiyelin en uygun olduğu alanlardır. RES kurulumu için "az uygun" ve "uygun" alanlar ise ilçe genelinde heterojen bir dağılış göstermektedir. Öte yandan çalışmada, üç boyutlu türbin modeli kullanılmış olup, RES yapımına "çok uygun" olarak belirlenen dört örnek saha üzerinde 12 adet rüzgâr türbini konuşlandırılmış ve koordinatları verilmiştir. Araştırmada kullanılan AHS yönteminin tutarlı sonuçlar verdiği ve bu tür analizlerdeki işlevselliği de ortaya konmuştur. Çalışmadan elde edilen bulgular, yatırımcılar ve karar alıcılara yönlendirici bir çerçeve sunmaktadır. Uygun teknik ve ekonomik analizler gerçekleştirilerek anlamlı sonuçlar elde etmek mümkün olacaktır.

Anahtar Kelimeler: Enerji Coğrafyası, Rüzgar Enerjisi, Yer Seçimi, Çok-Kriterli Karar-Verme (ÇKKV), Mekansal Uygunluk, Şarköy

[1] Arş. Gör. Marmara Üniversitesi, İnsan ve Toplum Fakültesi, ORCID No: 0000-0002-9808-3232, emre.tunalı@marmara.edu.tr.

INTRODUCTION

Since the onset of the industrialization process in the 18th century, there has been a tremendous increase in energy demand. Initially, industrial activities experienced rapid growth thanks to coal, but with the full integration of internal combustion engines and transformations in transportation in the 20th century, they began to be shaped by petroleum-derived resources. Moreover, the exponential increase in population over the past 250 years and successive technological advancements have significantly increased global energy dependency. This growing need for energy has paved the way for the utilization of alternative sources beyond fossil fuels. Especially since the second half of the 20th century, the widespread adoption of energy types referred to as alternative or renewable serves as an example of this trend. Nearly all renewable energy sources are directly or indirectly related to the sun. These sources include solar, wind, hydroelectric, geothermal, wave, and biomass energy, among others (Akova, 2016).

Renewable energy sources cause significantly less greenhouse gas impact compared to fossil fuels due to their low carbon emissions and thus contribute to energy efficiency (Diaz-Cuevas, 2018). Therefore, their advantageous position in combating global climate change has made them more attractive for countries. Indeed, agreements and targets such as the Paris Climate Agreement and the European Green Deal, to which European Union countries are signatories, hold significant importance in the fight against climate change (Demir et al., 2024). For example, within the framework of the European Green Deal, member states aim to reduce their dependence on fossil fuels. To achieve this, they are prioritizing investments in energy sources such as solar, wind, and hydroelectric power. In this way, Europe seeks to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030 and to become the first carbon-neutral continent by 2050 (Maris & Flouros, 2021). As a signatory to the Paris Climate Agreement, Türkiye, relatively poor in fossil fuel reserves, faces challenges in meeting domestic energy demand through indigenous sources. However, its proximity to the Basra Gulf and Caspian Basin – two regions that supply nearly 60% of the world oil and natural gas enables Türkiye to play a significant role as an energy transit corridor. Despite this, Türkiye imports billions of dollars' worth of oil, natural gas, and coal each year to meet its growing energy demand. This situation not only increases the current account deficit but also creates challenges in combating climate change. Given its goal of achieving net-zero emissions by 2053, it is essential for Türkiye to utilize its vast potential in alternative energy sources to reduce its dependence on imported energy (Atici et al., 2015).

Wind, which is the subject of this study, is essentially an indirect form of solar energy. It results from the differential heating of various regions of the Earth's surface, leading to the interaction between low- and high- pressure systems (Doğanay & Çoşkun, 2020). The kinetic energy obtained from wind is first converted into mechanical energy through turbines. Then, this mechanical energy is transformed into electrical energy by generators within the turbine. In recent years, the use of wind energy has increased due to advancements in the technical knowledge required for turbine installation and a reduction in costs (Rekik & El Alimi, 2023). Wind energy's low carbon emissions and environmental friendliness make it an attractive option for sustainable development. Additionally, its status as a domestic resource that reduces dependence on fossil fuels, along with its lower operation and maintenance costs compared to other energy sources, are key factors driving its widespread adoption (Arca & Keskin Citiroglu, 2020; Rekik & El Alimi, 2023). In this respect, the share of wind energy in total energy production has been steadily increasing in both developed and developing countries in recent years (Albraheem & AlAwlaqi, 2023). China is the undisputed global leader in both installed capacity and the commissioning of new turbines. According to 2023 data, China's wind energy installed capacity has reached 440 GW. This figure represents 43% of the world's total installed capacity, solely provided by China. In Europe, the leading countries in terms of installed capacity are Germany (69 GW), Spain (30 GW), the United Kingdom (29 GW), France (23 GW), Sweden (16 GW), and Türkiye (12 GW) (GWEC, 2024). Türkiye's first wind energy power plant, which began operations in 1998 in the Çeşme district of İzmir, has an installed capacity of 1.5 MW (Aydın, 2014). By 2012, the installed capacity had reached 2,312 MW (Şenel & Koç, 2015). Between 2012 and April 2025, the installed capacity increased by %475, surpassing 13,300 MW (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025). Accordingly, Türkiye has made significant progress in wind energy. However, to better harness this potential, it is essential to identify optimal locations for power plant installations. Determining the most suitable location is a complex decision-making process (Aydın, Kentel Erdoğan, & Duzgun, 2013). At this point, the selection of locations should not only consider economically cost-effective areas but also take into account a wide range of geographical, environmental, and social criteria (Arı & Gencer, 2020;

Rediske et al., 2021). Studies that integrate Multi-Criteria Decision Making (MCDM) and Geographic Information Systems (GIS) provide researchers, decision-makers, and investors with both detailed analysis capabilities and benefits in terms of visualization.

In the literature, there are many studies that jointly use MCDM methods and GIS (Özşahin & Kaymaz, 2014; Azizi et al., 2014; Sánchez-Lozano, García-Cascales, & Lamata, 2016; Ali, Lee, & Jang, 2017; Genç, M.S. et al., 2021; Konurhan & Başaran, 2023; Yaman, 2024). For instance, Koç et al. (2019) conducted a study in Iğdır province using the Analytical Hierarchy Process (AHP) and GIS together, based on a hybrid approach. First, they identified the optimal regions for wind and solar energy. Then, an analytical hierarchy structure was created for site selection using different criteria, and suitable locations were identified. In another study using the AHP, a method of MCDM, Youseffi et al. (2022) conducted a wind farm site selection analysis in the Semnan region of Iran. They evaluated the main criteria of the study through pairwise comparisons based on the opinions of different experts. After weighting the criteria using the AHP method, they determined that the most important criteria for wind farm installation were wind speed and slope. Site selection analyses using MCDM techniques are not limited to AHP alone. Mukhamediev et al. (2019) combined the AHP and Bayesian approaches in a site selection analysis for solar and wind power plants in Kazakhstan. The most significant feature of the study is the flexibility of the structure that processes spatial factors using fuzzy logic, as opposed to AHP, which does not handle uncertainties and provides more precise weights for criteria. When working with incomplete data, AHP alone may not yield reliable results. However, in this study, where the Bayesian Fuzzy Hierarchical Process was used, more consistent results were obtained even with incomplete data. In another study, Tercan (2021) used the Best-Worst Method (BWM), one of the MCDM techniques. Unlike other studies, the research included different criteria such as visual impact, noise impact, land fragmentation, etc., in determining the most suitable locations for wind farms in the Balıkesir province. The main difference between the BWM and AHP is that it involves comparing the best and worst criteria with the other criteria. This results in fewer pairwise comparisons, providing advantages in terms of speed and practicality for users (Tercan, 2021).

In this study, the Analytical Hierarchy Process (AHP) and GIS were used together to identify the most suitable areas for the installation of a wind power plant in the Şarköy district of Tekirdağ. The AHP method, which does not require complex calculations and ensures consistency in the calculation of criterion weights, is one of the most commonly used MCDM techniques in site selection analyses (Diaz-Cuevas, 2018). Indeed, due to its simple and understandable structure, the AHP method was preferred in this study as well. The reason for selecting the Şarköy district as the research area is primarily the region's significant wind energy potential. Previously, Akkaya (2019) conducted a GIS-based wind farm site selection analysis for Tekirdağ. A wind farm site selection analysis using the Best-Worst Method was also carried out by Özşahin and Kaya (2024). However, the distinguishing feature of this study from others is the use of the AHP method from MCDM techniques and the direct focus on the Şarköy district. In addition, there are seven wind power plants in the district that have received are in the pre-licensed project phase. Currently, the installed capacity of the three existing plants in the district is 54 MW. Once the projects are completed, an additional 443 MW will be added to the current installed capacity, thus positioning Şarköy as a key region in Türkiye's wind energy development. (Enerji Atlası, 2025). In summary, the main purpose of this study is to identify the areas suitable for wind power plant installation in Şarköy, whose WPP potential has been developing rapidly with the investments made in recent years, and to offer a recommendation to investors and decision makers.

Study Area

Located in the northwest of Türkiye, in the western part of the Marmara Region, Şarköy has an area of 487 km². The district lies between the latitudes of 40°32' and 40°50' North, and the longitudes of 26°54' and 27°24' East. To the north, it borders the Malkara district of Tekirdağ, to the northeast, the Süleymanpaşa district of Tekirdağ, to the west, the Gelibolu district of Çanakkale, and to the south, the Sea of Marmara (Figure 1).

Şarköy is the district of Tekirdağ with the most mountainous and rugged terrain (Kiper, Özyavuz, & Korkut, 2011). To the south of the district, particularly around the Şarköy town center and its surroundings, the elevation decreases to a minimum. As one moves north and northeast, the elevation increases rapidly. The peak of Ganos (Işıklar) Mountain, located in the northeast of the district, reaches an elevation of 924 meters. In terms of climate, the region is characterized by the Marmara Transition Climate. Summers are hot and dry, while winters are mild and rainy. The district does not have significant water resources. Most of the rivers in the area have seasonal flow and dry up during the summer. In the northwest of the district, at the point where it intersects with Malkara and Gelibolu, the Çokal Dam is located. The dam, built for irrigation and drinking water purposes, is situated on the Kocadere (Kavaklı) River. The vegetation in the district is diverse. In the north of the Ganos Mountains, some hygrophilous species characteristic of the Black Sea climate has spread due to increased precipitation (Kurtar, 2021). In the mountainous area located in the north and northeast, oak formations form the predominant vegetation type. Among these species, the most prominent is the sessile oak (Quercus petraea) (Özalp, 2019). Additionally, maquis formations are observed on the southern slopes of the mountains due to the influence of the Mediterranean climate (Kurtar, 2021).

Şarköy is a district where settlements have been established largely along the coastline from Süleymanpaşa, the central district of Tekirdağ in the east, to the Gelibolu district of Çanakkale in the west (Kurtar, 2021). Although narrow and deep valleys have affected settlement conditions in the northeast, the district has developed along the shores of the Marmara Sea. The population of Şarköy has increased significantly since the establishment of the republic. The district population, which was 3,263 in 1935, rose to 25,064 in 1985 and reached 34,091 as of 2024 (Başbakanlık İstatistik Genel Direktörlüğü , 1937; Devlet İstatistik Enstitüsü, 1993; TÜİK, 2025). In this respect, the district's population has shown an approximately 10-fold increase over a 90-year period. Economic activities in Şarköy exhibit a heterogeneous structure. In particular, wheat and corn are widely cultivated. It is also Tekirdağ's most important district in terms of grape and olive cultivation. Grapes grown on the southern slopes of the Ganos Mountains, which are exposed to marine influence, are used both as table olives and for wine production (Kurtar, 2021). In connection with this, the factories located in the district serve the food industry. During the summer months, Şarköy's population increases due to tourism activities. Secondary residences along the coastline are places where domestic tourists from neighboring provinces and districts spend their summer months and participate in recreational activities.

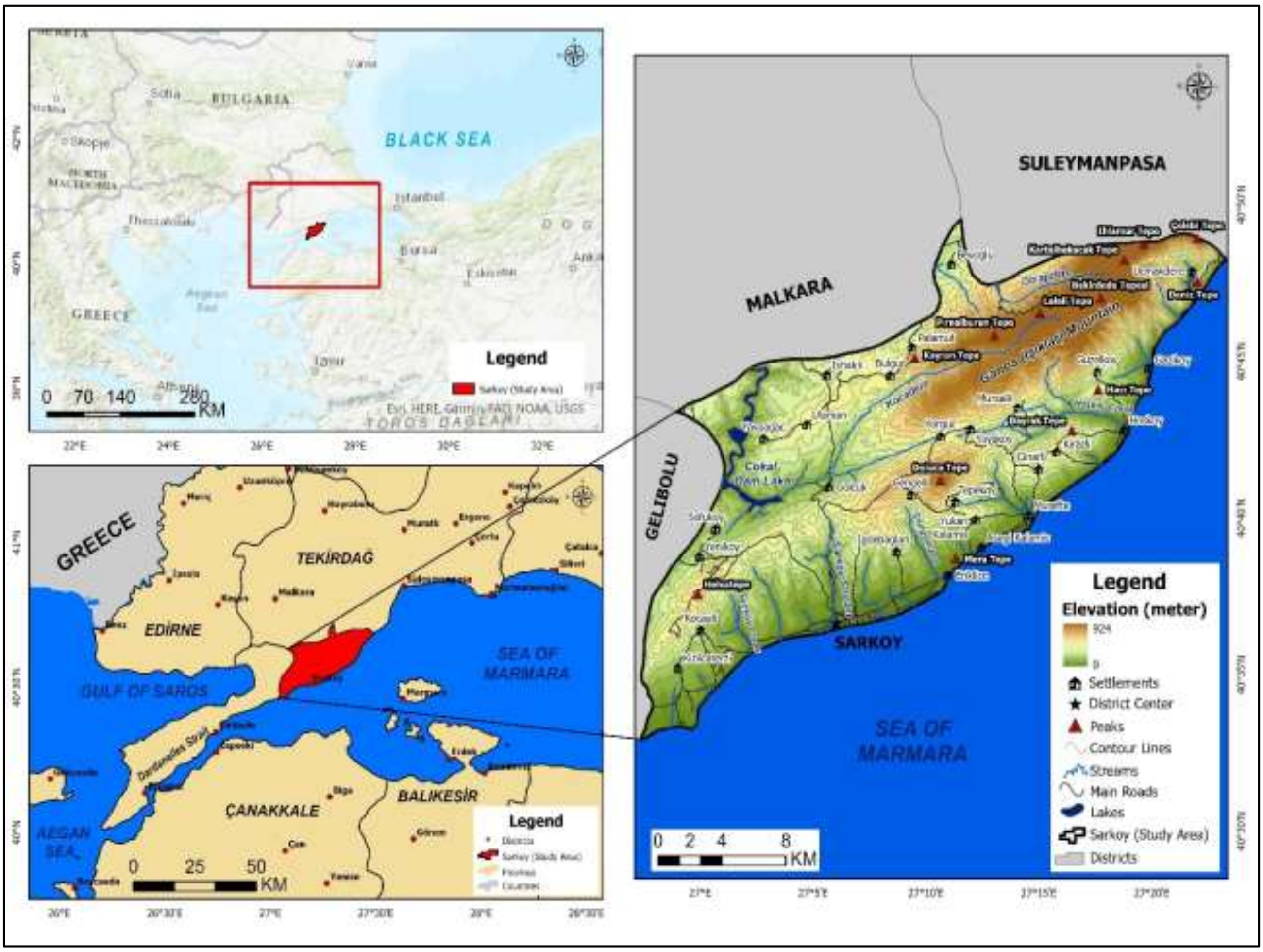

Figure 1: Location and Topographic Map of Sarkoy (Tekirdag)

MATERIAL AND METHOD

The data for the criteria used in the study were obtained from various institutions and online sources. Wind speed data at 100 meters above ground level was acquired from the Global Wind Atlas (GWA, 2024). The slope map obtained from surface analysis and stream network data derived from hydrological analysis were generated from the ALOS PALSAR digital elevation model (DEM) with 12.5-meter resolution (JAXA/METI, 2024). The geological formations in the lithology criterion and active fault data for the distance to fault lines criterion were obtained from the Earth Sciences Map Viewer portal on the website of the General Directorate of Mineral Research and Exploration (MTA) (Akbaş et al., 2011). Additionally, land use data was obtained from the Copernicus Land Monitoring Service (EEA, 2018). Other criteria used in the study (road network, power transmission line, and settlement areas) were acquired from Open Street Map (OSM) (OpenStreetMap, 2024). When creating the distance to settlement areas map, both OSM and Corine Land Cover 2018 data were combined. (Table 1).

Table 1. Criteria Data and their resources

Data	Data Type	Data Source
Wind Speed	Raster	Global Wind Atlas
Land Use	Polygon	CORINE Land Cover (2018)
Slope	Raster	JAXA / METI ASF DAAC (Alos Palsar)
Roads	Polyline	OpenStreetMap
Settlements	Polygon	CORINE Land Cover (2018) / OpenStreetMap
Energy Transmission Lines	Polyline	OpenStreetMap
Geology	Polygon	MTA (General Directorate of Mineral Research and Exploration)
Fault Lines	Polyline	MTA (General Directorate of Mineral Research and Exploration)
Rivers	Polyline	JAXA / METI ASF DAAC (Alos Palsar)

The first stage of the study consists of defining the problem and determining the research objective. The Şarköy district, located in the western part of the Marmara Region, has significant wind energy potential. However, proper evaluation of this potential requires providing recommendations to investors and decision-makers. In this regard, it was decided to conduct a wind power plant site selection analysis through an integrated AHP–GIS approach. The AHP method could process complex quantitative and qualitative data together. The fact that the criteria weights are determined based on expert opinions and can be tested makes it attractive to researchers. It was also preferred in this study because of its ease of integration into the GIS environment.

The second stage consists of selecting the criteria and determining their weights using the AHP method. The analytical hierarchy process, developed by Saaty (1980), creates a hierarchical network within the framework of goal (i.e., the problem), criteria (e.g., slope, wind speed, etc.), and alternatives (individual raster cells representing potential sites) for resolving the identified problem, and establishes a structure between these layers (Saaty R.W , 1987).

The third stage involved data collection and preprocessing steps for the criteria whose weights were calculated. The criteria for distance to settlement areas, roads, streams, fault lines, and power transmission lines, as well as geological data, are in vector format; whereas wind speed, land use, and slope data are in raster format. For the slope, wind speed, and land use criteria, were directly reclassified based on their inherent values without applying distance-based analysis. For data in vector format, multi-buffering analysis in ArcGIS Pro was used. The multi-buffering method was used to define spatial impact zones based on specific distance intervals. Subsequently, these data were converted to raster format and assigned suitability classes. For example, distances of 0-500 m from fault lines were classified as "not suitable," 500-1000 m as "less suitable," 1000-2000 m as "suitable," and places farther than 2000 meters as "very suitable." These raster layers were then uniformly categorized into four suitability classes using the reclassify tool. The suitability classes in the research were classified as: ‘Not Suitable’ (1), ‘Less Suitable’ (2), ‘Suitable’ (3), and ‘Highly Suitable’ (4).

In the fourth stage, limiting factors were identified, and areas unsuitable for the installation of wind power plants were determined. These limiting factors were categorized into four classes. The identification of these factors was based on studies in the literature. The limiting factors include areas with a slope greater than 30%, locations within 500 meters of a fault line, areas located less than 500 meters from settlement zones, and areas where the lithological structure is composed of alluvium.

In the fifth stage, after creating the pairwise comparison matrix and calculating the weight of each criterion, all the criteria were synthesized using the Weighted Sum method to create the final suitability map (Arca & Keskin Citiroglu, 2020). Then, the final suitability map and the constraints map were combined to identify the suitable areas for wind farm installation in Şarköy. The methodological workflow of the study is illustrated in Figure 2.

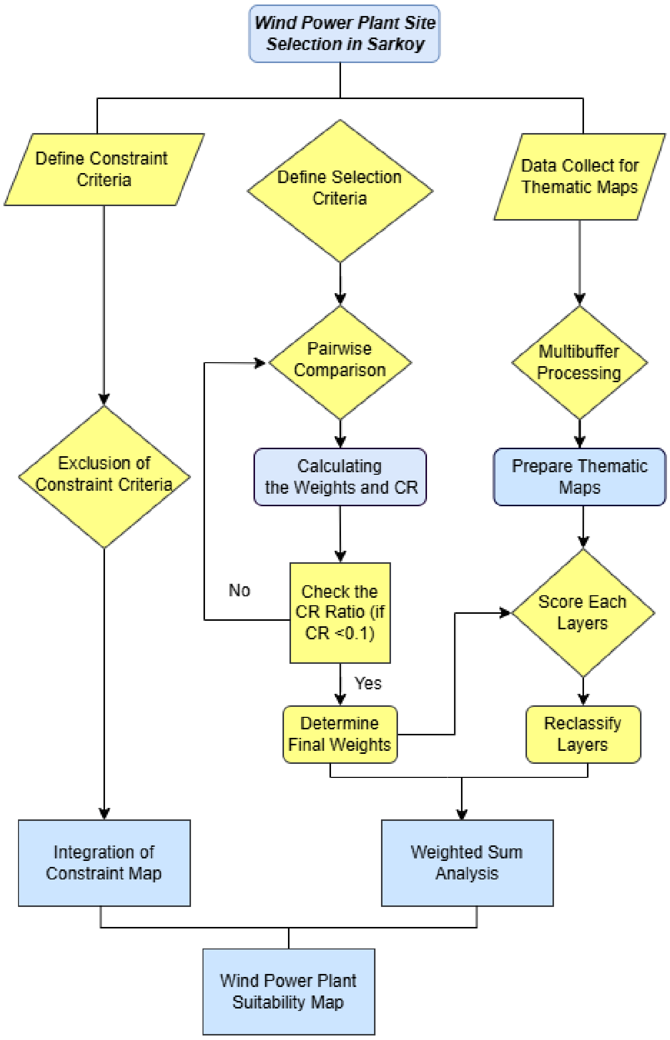

Figure 2. Methodology of the Study

Definition of Criteria

The criteria used in the analysis have been evaluated separately as explained below. Nine different criteria referenced in the literature were used in the study (Baseer et al., 2017; Shahid et al., 2019; Yildiz, 2024). These criteria include wind speed, land use, slope, distance to settlements, distance to roads, distance to energy transmission lines, distance to rivers, geology, and distance to fault lines.

Wind Speed

The primary source of energy utilized by wind power plants is wind speed. Additionally, wind speed is the most important factor in wind farm site selection analyses (Moltames et al., 2022; Rekik & El Alimi, 2023). In this regard, wind speed has been considered the most significant criterion in site selection analyses (Baseer et al., 2017). Wind turbines begin to operate at wind speeds of approximately 3 m/s, but this is not efficient. For turbines to operate with minimal efficiency, the wind speed must reach 6 m/s. On the other hand, to avoid damage from high wind speeds, wind turbines automatically shut down at a working speed of 25 m/s (Moltames et al., 2022; Benti et al., 2023). According to data from the Global Wind Atlas, the average wind speeds in Şarköy range from 4.2 to 10.8 m/s (Figure 3, Table 2). Especially the northern and northeastern parts of the district have highly favorable conditions for wind farm installation, as wind speeds reach their maximum levels in these areas.

Land Use

Another criterion used in the study is land use. Land use has an indirect impact on wind farm site selection. The existing land use conditions should be reviewed to position the turbines in the most suitable areas. In this regard, surfaces such as open spaces and pasturelands offer the best conditions for wind farm installation (Benti et al., 2023). Other land use types, such as artificial surfaces like cities and villages, areas very close to rivers, forested areas, etc., are not suitable for wind farm installation (Moltames et al., 2022). Indeed, in the relevant laws and regulations of some countries, energy facilities are only allowed to be installed on certain types of land cover. In areas such as natural conservation areas, national parks, and archaeological sites, construction is either not permitted, or the necessary permits must be obtained to confirm the land is suitable for construction (Orman Kanunu, 1956; Kültür ve Tabiat Varlıklarını Koruma Kanunu, 1983).

Slope

One of the criteria used in wind farm site selection is slope (Albraheem & AlAwlaqi, 2023). As the slope increases, both the installation and maintenance costs of the wind farm rise (Moltames et al., 2022). Relatively flat areas and terrains with mild slopes are highly suitable for wind power plant installation. Landforms such as mountains, steep slopes, and deep valleys are highly sloped and are unsuitable for turbine installation. The study site, particularly its northern and northeastern parts, has a mountainous structure. Additionally, to the north of Uçmakdere District, narrow and deep valleys form the topographic landscape. Therefore, the 30% slope, which has been accepted in previous studies, is considered the threshold value (Moradi et al., 2020). Consequently, areas with slopes exceeding this value are deemed unsuitable for wind farm installation in the study.

Distance to Roads

Another criterion used in the analysis is the road data obtained from Open Street Map (OSM). The distance to roads was analyzed by creating buffer zones at specific intervals. For instance, locations within 0-250 meters of a road were deemed unsuitable for wind farm installation due to safety risks (Figure 3). This safety risk can be attributed to the visual impact of turbine blades, which may distract drivers and cause mechanical noise (De Ceunynck et al., 2017). A distance between 250 and 1000 meters is considered quite suitable for installation (Table 2). Areas located too far from roads are not preferred, as they complicate installation conditions. Regions with easy and low-cost transportation opportunities stand out in power plant installations (Özşahin & Kaymaz, 2014). Additionally, areas close to roads facilitate power plant maintenance activities and labor access (Benti et al., 2023).

Distance to Settlements

Proximity to residential areas is considered in many studies in the literature (Urfalı & Eymen, 2021; Yaman, 2024). In this study, locations closer than 500 meters to residential areas were deemed unsuitable for power plant installation (Yildiz, 2024). The mechanical noise and acoustic effects caused by turbines, the potential future expansion of residential areas, and the fact that artificial structures increase surface roughness, thereby reducing wind speed, necessitate positioning power plants at a certain distance from settlements (Özşahin & Kaymaz, 2014; Moltames et al., 2022). On the other hand, having settlements sufficiently close to wind power plants (WPPs) facilitates energy supply-demand balance and helps minimize transmission losses.

Distance to Energy Transmission Lines

A certain amount of loss occurs during the transmission of electricity through high-voltage power lines. Therefore, the loss in wind-generated energy must be minimized before reaching consumers. To reduce both this transmission loss and connection costs, the distance between the power plant and the energy transmission line (ETL) should be kept to a minimum (in this study, a range of 250–1000 meters is considered the baseline) (Atici et al., 2015; Arı & Gencer, 2020; Rekik & El Alimi, 2023. However, placing wind power plants too close to transmission lines (within 250 meters) may lead to safety issues, particularly in case of blade detachment or tower collapse. A safe distance must be maintained between the ETL and the wind power plant due to turbine collapse height or blade detachment (Tercan, 2021; Albraheem & AlAwlaqi, 2023). Studies in the literature do not recommend the WPP installation in locations where the distance to the ETL exceeds 10,000 meters, as it becomes not economically viable (Baban & Parry, 2001; Yaman, 2024). In this study, taking into account the geographical conditions of the site, distances exceeding 8,000 meters were deemed unsuitable for power plant installation (Figure 3, Table 2).

Geology

Geological structure must also be considered in wind power plant site selection (Rediske et al., 2021). Soils composed of alluvium, which are weak and have low resistance, pose challenges during the construction of turbines (Azadeh, Ghaderi, & Nasrollahi, 2011). In particular, alluvial soils in the study site, which have a high risk of earthquakes, may undergo liquefaction during an earthquake, potentially causing damage to the wind plant. The foundation of the site where the plant is to be constructed must be durable, as this will significantly prevent issues such as tremors caused by natural and human factors (Özşahin & Kaymaz, 2014).

Distance to Fault Lines

In countries like Türkiye, where seismic risk is high, the distance to fault lines should be considered as a criterion in wind power plant site selection analyses (Yildiz, 2024). Located west of the Sea of Marmara, the Ganos Fault, a dextral strike-slip extension of the North Anatolian Fault Zone, runs approximately 45 km long, stretching from offshore Gaziköy into the Gulf of Saros. Comprising several parallel faults, the Ganos Fault became active in the late Miocene and led to the formation of the Ganos Mountains through transpressional movements (Janssen et al., 2009). On August 9, 1912, an earthquake occurring along this fault resulted in the loss of over 2,800 lives and left approximately 7,000 injured. The earthquake had its most severe impact along the coastal stretch between Mürefte and Şarköy, destroying thousands of homes. Consequently, the region's seismicity poses significant risks to both lives and property. To prevent damage to wind power plants during potential earthquakes, areas within 500 meters of the fault line are deemed unsuitable due to the heigh seismic risk and potential for ground rupture during earthquakes. (Moradi et al., 2020; Yildiz, 2024). Conversely, locations more than 2,000 meters away from the fault line are considered highly favorable for power plant construction (Figure 3, Table 2).

Distance to Rivers

The last criterion used in this study is the distance to rivers. Rivers can pose risks for wind farm installation due to their erosion effects, flood risks, and the loose materials that make up their beds (Moltames et al., 2022). Additionally, their capacity to shift over time can create various problems. Therefore, in this study, areas located less than 300 meters from rivers were deemed unsuitable for turbine installation (Figure 3). As the distance from rivers increases, the conditions for establishing a wind plant become more optimal.

Table 2. Suitability score for each criteria

	Not Suitable (1)	Less Suitable (2)	Suitable (3)	Highly Suitable (4)
Wind Speed (A)	4- 6 m/s	6 - 7 m/s	7-8 m/s	8-10,70 m/s
Land Use (B)	Artifical Surfaces, Water Bodies	Forest Areas, Agricultural Areas	Mixed Agricultural Areas	Grassland and Pastures
Slope (C)	> %30	%20-30	%10-20	%0-10
Distance to Roads (D)	0-250 m	2500-3500 m	1000-2500 m	250-1000 m
Distance to Settlements (E)	0-500 m	500-1000 m	1000-2000 m	> 2000 m
Distance to Energy Transmission Lines (F)	0-250 m, > 8000 m	4000-8000 m	2000-4000 m	250-2000 m
Geology (G)	Undifferentiated Quaternery	-	Upper and Middle Miocene Clastic Rocks, Middle and Upper Eocene Clastic and Carbonate Rocks	Upper Cretaceous Ophiolitic Melange, Middle-Upper Eocene Neritic Limestone
Distance to Fault Lines (H)	0-500 m	500-1000 m	1000-2000 m	> 2000 m
Distance to Rivers (I)	0-300 m	300-500 m	500-1000 m	> 1000 m

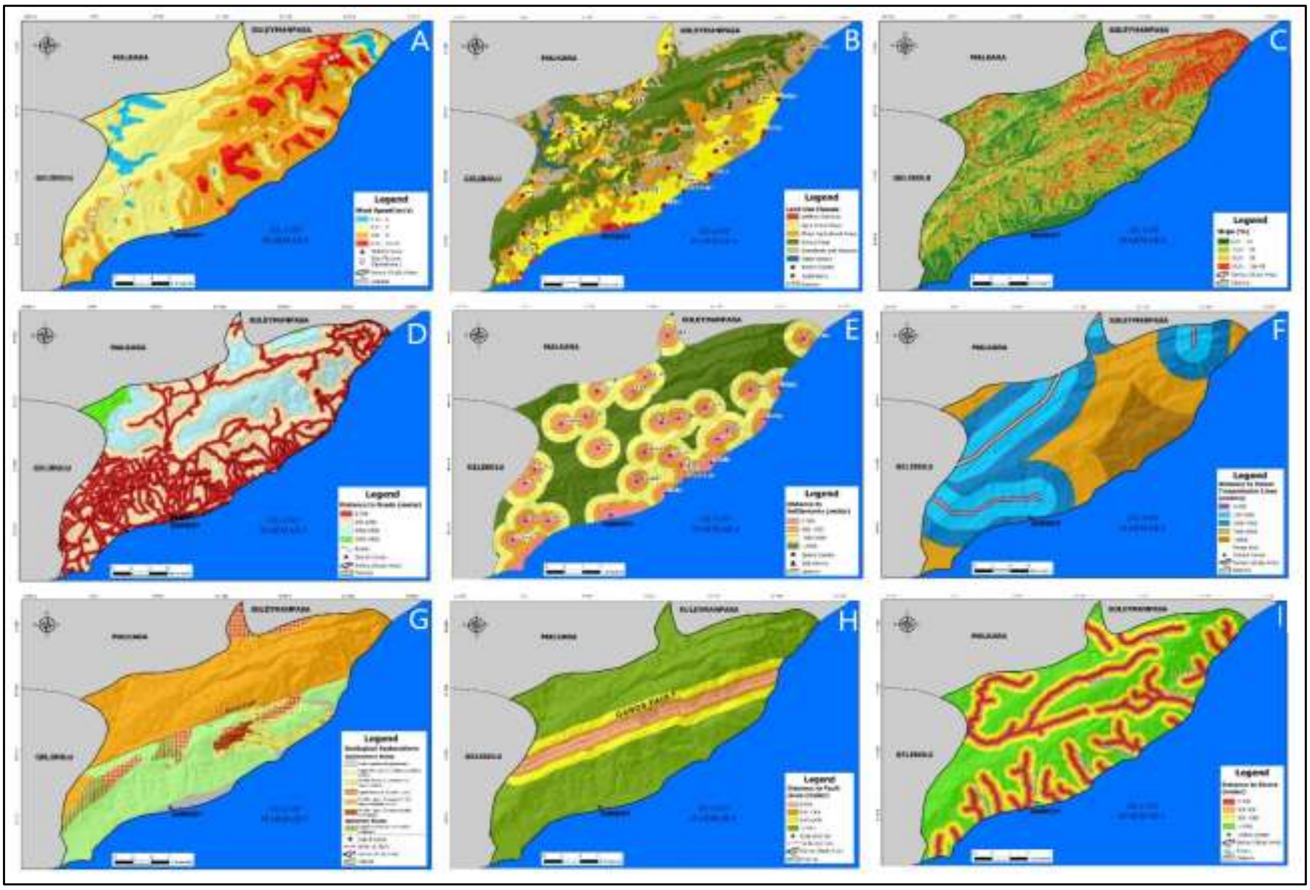

Figure 2. Criteria Maps: A) Wind Speed, B) Land Use, C) Slope, D) Roads, E) Settlements, F) Energy Transmission Lines, G) Geology, H) Fault Lines, I) Rivers

AHP Method

The criterion weights were determined using the Analytic Hierarchy Process (AHP) developed by Saaty (1980). Pairwise comparison scales from the literature and based on expert opinions were evaluated by taking into account the characteristics of the study area (Aitzhanov, 2016; Cunden et al., 2020; Ekiz, Şirin, & Erener, 2022; Yildiz, 2024; Yaman, 2024). The Analytic Hierarchy Process not only provides researchers with significant convenience in decision-making, but also ranks among the most frequently applied method in multi-criteria decision-making analysis thanks to its practical and manageable nature (Albraheem & AlAwlaqi, 2023; Rekik & El Alimi, 2023).

To perform pairwise comparisons, the 1-9 scale developed by Saaty is primarily used. Table 3 presents the nine-point scale employed for pairwise comparisons (Table 3). Through this scale, the quantitative superiority and relative importance of criteria are determined based on decision-makers' judgments or expert opinions (Saaty R.W., 1987). For instance, a value of 1 indicates that both criteria are equally important, while 9 signifies that one criterion is significantly more important than the other.

Table 3. The Fundamental Scale

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over the other	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another

7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compramise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

Source: Saaty. (1987)

Since expert opinion was not consulted in this study, pairwise comparison matrices from the literature were utilized. While incorporating these perspectives, a prioritization was established by carefully considering the geographical characteristics of the study area. The weights were determined through mathematical calculations performed on the matrices. Each matrix element is normalized by dividing it by the sum of its respective column (Saaty R.W , 1987). Subsequently, the average of each row is taken to calculate the relative weights of the criteria (Rekik & El Alimi, 2023; Albraheem & AlAwlaqi, 2023). The pairwise comparison scale used in the research is presented in Table 4. As shown in Table 4, wind speed emerges as the most influential criterion in wind power plant site selection, while proximity to rivers has the least impact.

Table 4. AHP Pairwise Comparison Matrix

	A	B	C	D	E	F	G	H	I
Wind Speed (A)	1	4	6	5	6	8	6	6	7
Land Use (B)		1	3	3	4	6	5	5	4
Slope (C)			1	1	3	6	4	4	3
Distance to Energy Transmission Lines (D)				1	2	6	3	4	3
Distance to Roads (E)					1	5	1	3	2
Distance to Streams (F)						1	1/5	1/3	1/3
Proximity to Settlements (G)							1	3	2
Lithology (H)								1	1
Proximity to Fault Lines (I)									1
Weights	0.38	0.19	0.11	0.11	0.06	0.02	0.06	0.03	0.04
(λmax) = 10.006 CI = 0.12 CR = 0.08 < 0.1									

Using the obtained weights, the eigenvector, maximum eigenvalue (λmax), and consistency index (CI) are calculated. The consistency index is a numerical value that indicates how consistent the pairwise comparisons are. When the consistency index approaches zero, it suggests that the criteria are logical and consistent; as it deviates from zero, inconsistencies between criteria become more apparent (Saaty R.W , 1987). The CI value is used to calculate the consistency ratio. The consistency ratio (CR) formula is shown below (Albraheem & AlAwlaqi, 2023):

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

The consistency ratio calculation also incorporates the random consistency index (RI). The random consistency index represents the average value of randomly filled pairwise comparison matrices. The RI value is constant and varies depending on the number of criteria (n). Since this study employed 9 criteria, an RI value of 1.45 was adopted (Saaty T. , 1980). The consistency index (CI) obtained through criterion weight calculations is divided by the random consistency index (RI) to determine the consistency ratio (CR). A CR value of less than 0.10 indicates that the study is consistent. If it exceeds 0.10, inconsistencies are present, and the values in the pairwise comparison matrix require reevaluation (Saaty R.W , 1987; Benti et al., 2023). In the study, the CR was calculated as 0.08. Since this value is below 0.10, the pairwise comparison matrix was accepted as consistent, and in the next stage, the weighted sum method was applied to create the final suitability map.

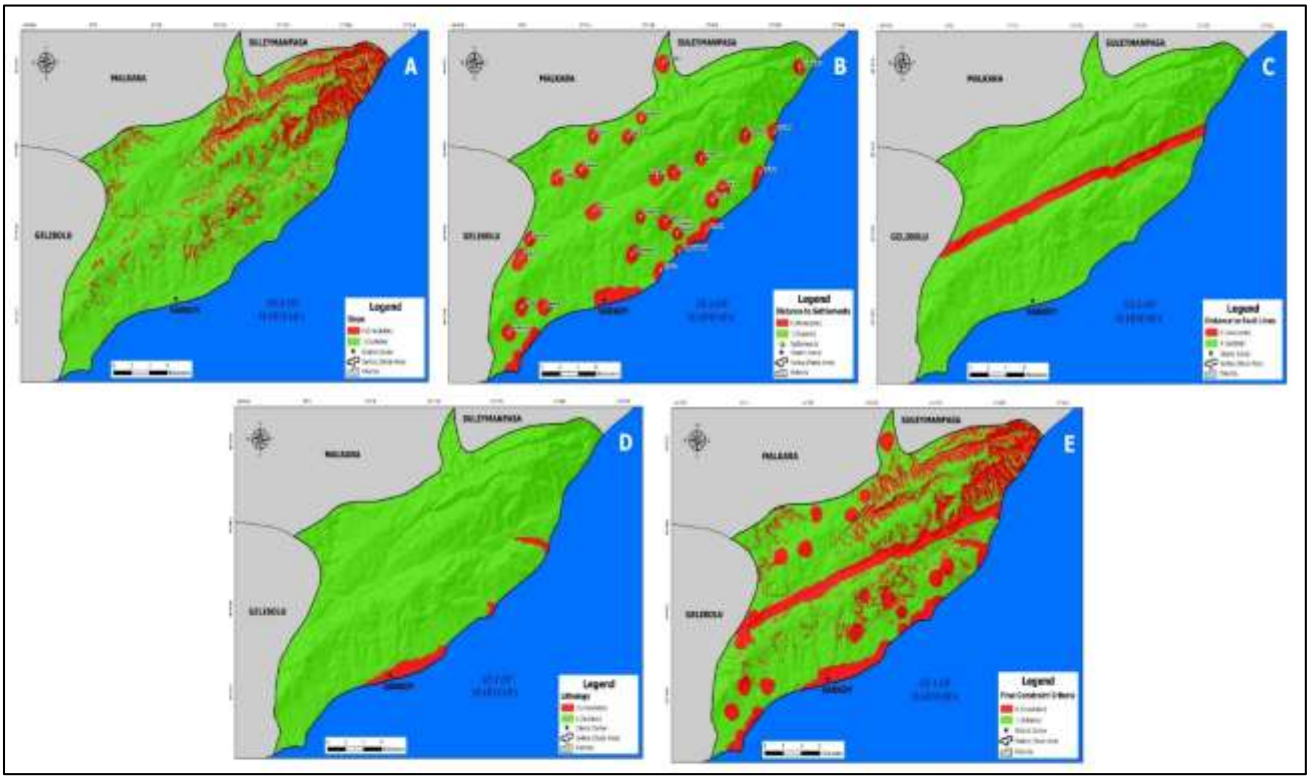

Figure 3. Constraint Criteria Maps: A) Slope, B) Distance to Settlements, C) Distance to Fault Lines, D) Lithology, E) Combined Constraint Criteria.

Constraint Criteria

Another critical stage of the study involves determining the constraint criteria (Table 5). When establishing these constraints, areas unsuitable for energy production due to physical and regulatory limitations are systematically eliminated (Yildiz, 2024). This research conducted an analysis based on restrictive factors identified in the literature. Using Boolean algebra, a masking process was employed in the methodology, assigning "0" to areas unsuitable for power plant installation and "1" to suitable locations. In the final stage, the 0 and 1 values are multiplied using the "Raster Calculator" tool in ArcGIS Pro. This process ultimately yields a map distinguishing between unsuitable (0) and suitable (1) areas for power plant installation (Figure 4). The constraint criterion maps are presented in Figure 4. The first constraint criterion used in the analysis is slope. Areas with slope values of 30% or higher were excluded from the analysis as they are unsuitable for turbine construction (Yildiz, 2024). Distance to fault lines was also included among the constraint criteria. The district, which has a high earthquake risk, also poses a risk for wind power plants. Therefore, areas located within 500 meters of fault lines are excluded from suitable areas for installation (Noorollahi, Yousefi, & Mohammadi, 2016). Another constraint criterion is the distance from settlement areas. Settlement areas should be located at a certain distance from wind power plants due to potential future expansion, visual-auditory effects, and security concerns. Accordingly, areas within 500 meters of settlement areas are considered unsuitable for construction (Noorollahi, Yousefi, & Mohammadi, 2016; Baseer et al., 2017). Finally, areas with lithological structures composed of alluvial deposits were included as constraint criteria due to their low stability and potential for liquefaction during earthquakes.

Table 5. Constraints in Site Selection

Constraint Layer	Exclusion Value	Reference
Slope	> %30	Yildiz. (2024)
Distance to Settlements	0-500 m	Baseer, et al. (2016); Noorollahi, Yousefi, & Mohammadi. (2016)

Distance to Fault Lines	0-500 m	Noorollahi, Yousefi, & Mohammadi. (2016)
Geology	Undifferentiated Quaternery	Azadeh, A., Ghaderi, S., & Nasrollahi, M. (2011); Özşahin & Kaymaz. (2014)

Weighted Sum Analysis

For the weighted sum analysis, the "Weighted Sum Function" tool in ArcGIS Pro was utilized. The weight of each criterion for wind power plant installation was previously calculated using the AHP method. The criterion weights determined through AHP were then integrated using the weighted sum method to generate the final suitability map (Benti et al., 2023). The weighted sum function calculates the total score for each raster cell by combining individual scores derived from criterion data with their respective weights (Yildiz, 2024). Constraint criteria were also incorporated using Boolean algebra. In the final stage, the weighted criterion data were merged with the constraint factor map, resulting in the final suitability map for power plant installation.

FINDINGS

This study conducted a wind power plant site selection analysis in Şarköy using nine different criterion scales. The evaluation resulted in four suitability classes: not suitable (unsuitable), less suitable, suitable and highly suitable. Before interpreting the findings, the study first examined which suitability classes the existing turbines fall into. The "Extract Multi Values to Point" tool available in ArcGIS Pro was used for the analysis. This tool was employed to determine which suitability classes (in raster format) correspond to the point format of the wind turbines. According to the analysis, out of the 23 existing wind turbines in the district, 3 are located in areas classified as less suitable, 16 are in suitable areas, and 4 are in highly suitable areas for wind power plant installation (Figure 5). The wind turbines classified as highly suitable are installed in the northeastern part of the district, while those categorized as suitable and less suitable are located in the southwestern area (Figure 6). Consequently, 86.95% of the operational turbines have been installed in optimal locations, points to a potentially favorable cost-benefit outcome. Moreover, this high percentage indicates that the AHP method produces successful results in WPP site selection analyses and aligns well with real-world conditions.

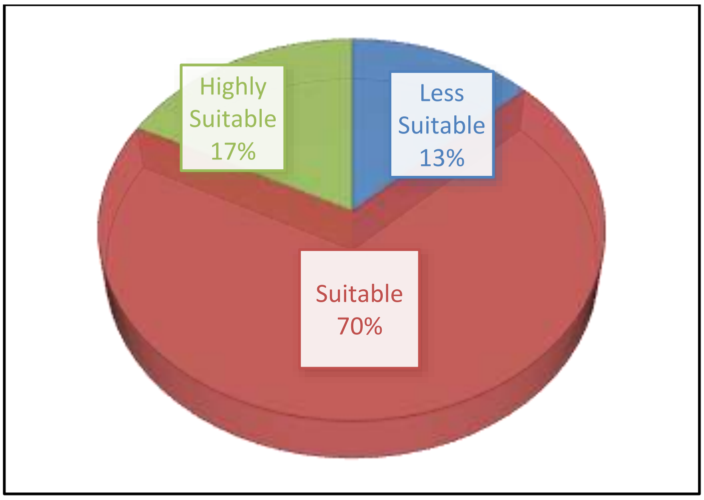

Figure 4. Suitability Class Assignment for Extracted Point Values

Although each criterion used in the analysis affects the study’s outcome, wind speed stands out as the most critical factor with a weight of 38%. The prevailing wind direction in the district is predominantly northeast and north, where northeastern wind (poyraz) plays a significant role. Additionally, during the winter and spring months, the frequency of southwestern wind (lodos) increases, though it is less efficient for wind energy generation compared to poyraz. While Şarköy has a high wind energy potential overall, this is not uniformly distributed across the entire area. For example, the eastern and northeastern parts of the district exhibit the highest average wind speeds, making them particularly favorable for wind power plant installations. In this region, the rapid increase in elevation from the coastline and the interaction between sea and valley breezes contribute to higher wind speeds. Additionally, the ridges act like towers, accelerating wind flow and enhancing the area's wind energy potential (Durak & Özer, 2012). Despite these favorable conditions, the steep slopes, distance from the road network, and the remoteness of energy transmission lines make the installation of wind power plants more challenging. Additionally, the terrain north of Uçmakdere and Gaziköy settlements consists of steep slopes and deep valleys. As a result, the topographical structure increases construction and maintenance costs, limiting the potential benefits of wind energy in the area. On the other hand, the northwestern part of the district was found unsuitable for WPP installation. There are two main reasons for this. The first is the low wind speed. The western part of Yayaağaç Neighborhood has the lowest wind energy potential in the district, with average wind speeds ranging between 4.15 and 6 m/s. The second reason is the proximity to water bodies. The presence of Kocadere and the Çokal Dam Lake built on this river creates challenges for wind farm installation. The flood risk in the river and dam surroundings, along with the lithological structure composed of alluvial deposits, negatively impacts site selection. Additionally, the flora and fauna around the water bodies would be adversely affected by WPP projects, posing sustainability risks. As a result, this northwestern area is classified as "not suitable" for wind farm installation based on the analysis. Overall, areas deemed unsuitable for WPP installation cover 209.35 km^2, accounting for 43% of the district's total land area (Table 6).

Table 6: Area Coverage per Suitability Classes

Suitability Score	Classes	Area (km^2)	Area Coverage (%)
Unsuitable	1	209,35	43
Less Suitable	2	131,29	26,96
Suitable	3	124,66	25,6
Highly Suitable	4	21,58	4,43
Total Area		486,88	100

The immediate vicinity of the Ganos Fault, which transects the district, poses significant seismic risks and is therefore unsuitable for wind turbine construction. Stretching approximately 40 km within Şarköy's boundaries, from Gaziköy neighborhood in the east to Sofuköy in the west, the Ganos Fault's 500-meter buffer zone was analyzed based on existing literature findings and deemed unsuitable for energy facilities. As shown in Figure 6, seven neighborhoods from Sofuköy to Gaziköy are not suitable for wind farm installation due to their proximity to fault lines and residential areas. Şarköy town center, Mürefte, and Hoşköy are the most populated settlements in the district. Land located within 500 meters of these settlements was categorized as "not suitable" for installation, considering their potential for urban expansion and acoustic impacts (Figure 6). Additionally, based on the analysis results, the surroundings of the remaining neighborhoods in the district are also unsuitable for WPP installation. Areas located more than 2000 meters away from residential zones were classified as 'highly suitable' locations for wind power plant installation.

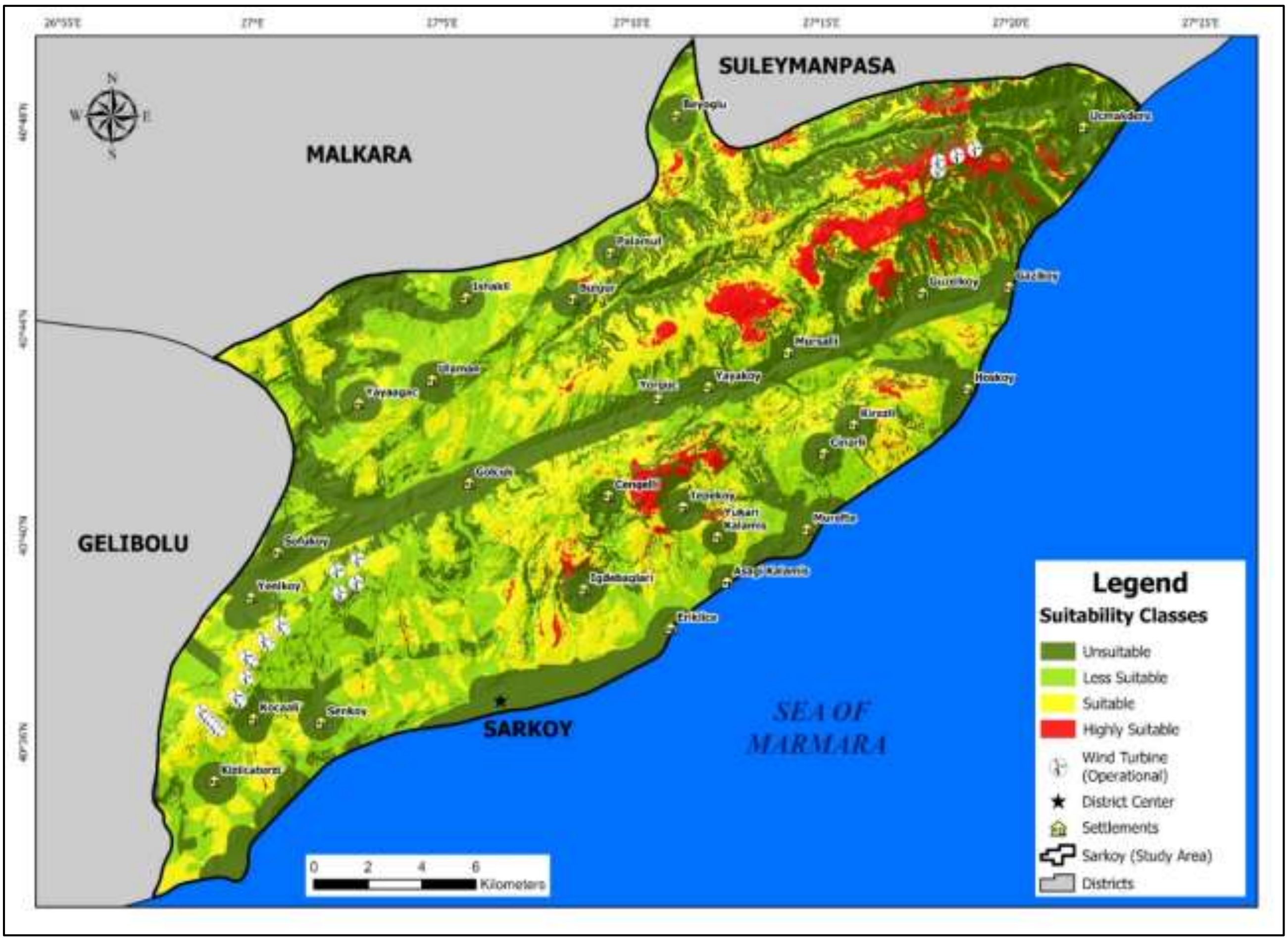

Figure 5. Wind Power Plant Suitability Map

In the site selection analysis, areas classified as less suitable and suitable exhibit a heterogeneous distribution (Figure 6). The analysis results indicate that areas categorized as less suitable for WPP installation cover 131.29 km², accounting for 26.96% of the district's total area. Meanwhile, suitable areas span 124.66 km², corresponding to 25.6% of the total area (Table 6). For example, during the reclassification stage of the study, areas with wind speeds between 6-7 m/s were categorized as less suitable, whereas areas with wind speeds ranging from 7-8 m/s were classified as suitable. Upon detailed examination of the map in Figure 6, it is observed that the areas most suitable for WPP installation are in parallel with the wind speed map. In this regard, areas with low scores on the wind speed criteria map are found to have low suitability in the analysis results as well. Similarly, in terms of land use, grassland and pasture areas are classified as very suitable, while heterogeneous agricultural areas are classified as suitable. Forest areas are evaluated as less suitable, and water bodies and artificial surfaces are deemed unsuitable for WPP installation. Another factor affecting WPP installation is the distance to roads. The effects of proximity to roads, either too close or too far, were already discussed in the materials and methods section. However, it is worth emphasizing that in this study, areas very close to busy roads (0-200 m) are deemed unsuitable for wind power plant installation, while areas more than 2000 meters away are considered less suitable. On the other hand, for wind turbines placed on terrain features such as hilltops and ridges, "turbine access roads" are constructed to facilitate access to the turbines. This improves access to the turbines, resulting in savings on operational and maintenance costs. Therefore, building such roads during the project phase will reduce the risk of problems arising from the distance to roads.

Areas classified as highly suitable for WPP installation cover 21.58 km², corresponding to 4.43% of the district's total area (Table 6). In Şarköy, the most optimal locations for power plant construction are concentrated in the northern and northeastern sectors where average wind speeds reach their maximum levels (Figure 6). Mean wind speeds range between 8-10 m/s in the northern parts of Güzelköy, Gaziköy, and Uçmakdere neighborhoods. Consequently, there is clear alignment between terrains with high average wind speeds and areas categorized as "highly suitable" in the analysis. Despite the high average wind speeds, the region's full potential remains underutilized. The main two reasons for this are the geographical formations and infrastructure deficiencies. The area's topography, characterized by steep valleys and rugged slopes, features gradient values exceeding 30%. In these sharply inclined valleys, both construction and operational costs become prohibitively expensive, making WPP development economically unviable. Moreover, projects implemented in such terrain the payback period is much longer. Areas that combine high wind speeds with optimal proximity to roads and power transmission lines present the most favorable conditions for WPP construction.

The wind energy potential is quite high on landforms such as hilltops and ridges that separate valleys. As a result of the analysis, areas in the very suitable class were found to be located on hilltops and ridgelines in the northern part of the district (Figure 6). The land north of Yayaköy, Mursallı, and Güzelköy is also highly suitable for WPP construction. Additionally, the area between Çengelli and Tepeköy, as well as the northern part of İğdebağları, is considered highly suitable for WPP construction according to the analysis findings (Figure 6).

Figure 7 shows areas classified as highly suitable for WPP installation across various sample sites. Four distinct zones were selected, with three turbine units positioned in each area for visualization purposes. Detailed information regarding the turbines' coordinates and elevation data is provided in Table 7. The 3D wind turbine model used in the study was sourced from Sketchfab user cesarkero (cesarkero, 2020). After obtaining the model from Sketchfab, it was transferred to the SketchUp application, where necessary adjustments related to the wind turbine were made. Subsequently, the model was exported to Google Earth Pro for visualization (Google, 2025; Triemble Inc., 2025). Some examples based on the analysis findings are presented below. These scenarios should be subject to further technical evaluation and investment feasibility studies before implementation.

Table 7. Sample Wind Turbine Coordinates

	ID	Latitude	Longitude	Height
A	WT 1	40.783353 N	27.281939 E	871 m
	WT 2	40.782719 N	27.287038 E	888 m
	WT 3	40.782600 N	27.291142 E	889 m
B	WT 4	40.764022 N	27.272320 E	709 m
	WT 5	40.763827 N	27.277213 E	731 m
	WT 6	40.764851 N	27.281805 E	762 m
C	WT 7	40.786554 N	27.351686 E	394 m
	WT 8	40.787365 N	27.348445 E	439 m
	WT 9	40.789799 N	27.346302 E	426 m
D	WT 10	40.654188 N	27.139931 E	304 m
	WT 11	40.657939 N	27.139768 E	364 m
	WT 12	40.661922 N	27.135925 E	389 m

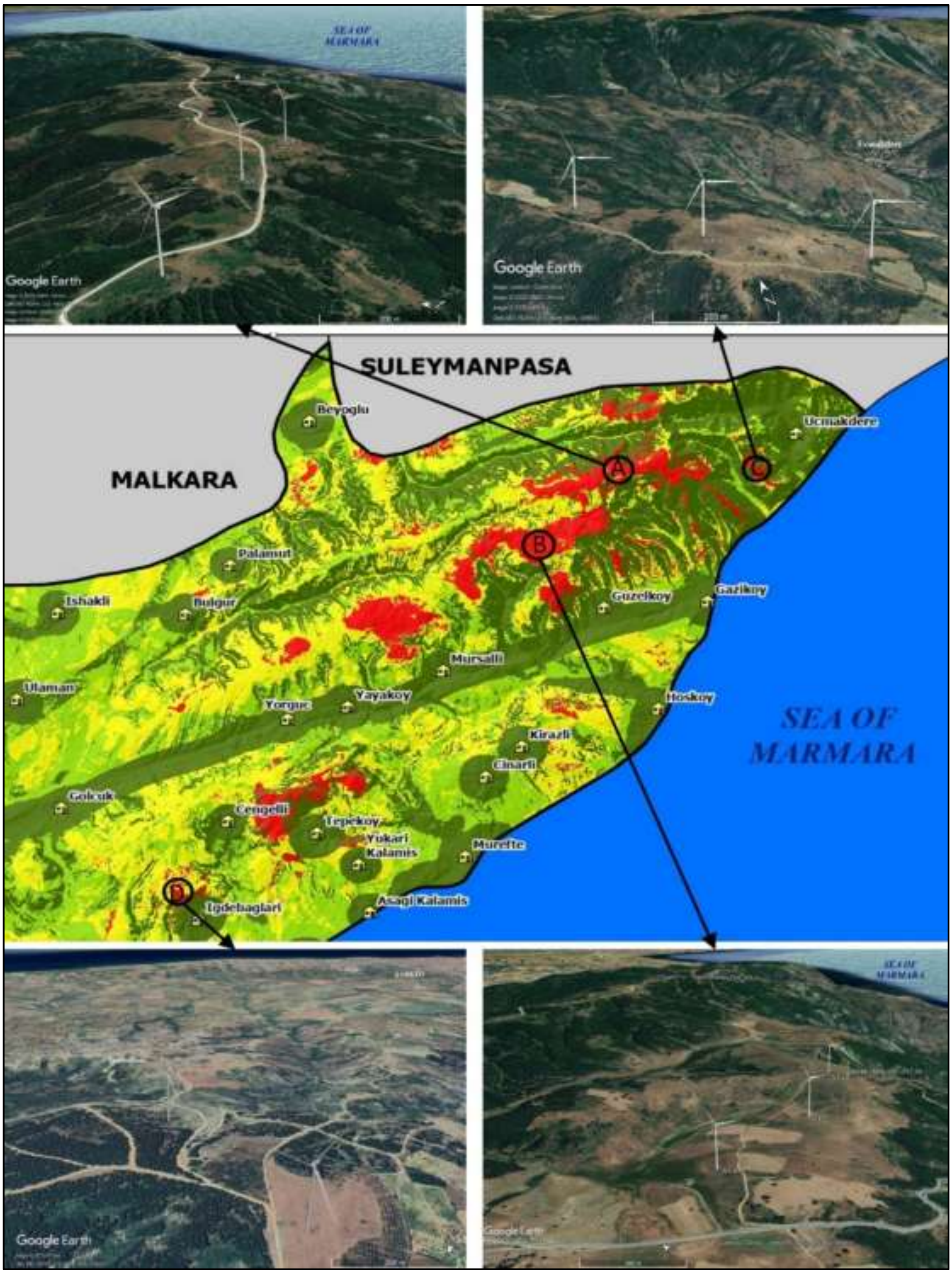

Figure 6. Wind Turbines Proposed for Highly Suitable Locations

DISCUSSION AND CONCLUSION

Wind energy, which is experiencing rapid growth today, stands as a prime candidate to replace fossil fuels alongside alternative energy sources like solar and hydroelectric power in the future. This necessitates conducting site selection analyses that incorporate numerous technical, environmental, and economic criteria, followed by presenting recommendations to decision-makers. The identification of optimal locations for power plants is achieved through various methodologies. In this Şarköy wind power plant site selection study, we employed multi-criteria decision-making methods, specifically AHP and GIS visualization tools, to identify the most suitable installation areas. The findings from the analysis, which consider both physical and human factors, demonstrate that the AHP method provides consistent results and has high functionality in site selection analyses. In determining this functionality, the current wind turbines' corresponding suitability classes were analyzed, and a high percentage of 86% was found. Consequently, by holistically evaluating findings from both literature and analysis, the applicability and validity of the AHP method was confirmed. The analysis revealed that the most suitable areas for WPP installation are concentrated in the northern and northeastern parts of the district. North of the Ganos Fault, transpressional movements have caused crustal compression, leading to the formation of the Ganos Mountains. Particularly, the summit areas of Işıklar (Ganos) Mountain were identified as very suitable for WPP. Specific areas to the north of Mursallı, Yayaköy and Güzelköy neighborhoods, and to the west of Uçmakdere village exhibit highly favorable conditions for wind turbine installations. When restrictive factors are incorporated into the analysis, areas with a slope value above 30%, those located less than 500 meters from fault lines, areas within 500 meters of settlements, and areas with alluvial lithological formations are deemed unsuitable for wind power plant installations. Furthermore, since wind speed carries the highest weight among the criteria, the terrain west of Yayaağaç and Ulaman neighborhoods, where average wind speeds decline, was deemed unsuitable for power plant installation.

There are two different WPP site selection studies in literature related to the study site. However, these two studies did not focus directly on Şarköy and instead analyzed the broader Tekirdağ province. Additionally, the methods used in those studies differ from the ones employed in this study. Although neither study provides specific information about Şarköy, there is a consistency in that some of the areas deemed suitable for wind power plants align with the Ganos Mountains region (Akkaya, 2019; Özşahin & Kaya, 2024). The study has two distinct aspects compared to other MCDM and GIS-based WPP site selection analyses. The first is the identification of which suitability classes correspond to the existing wind turbines. Very few studies in literature pay attention to which suitability classes the existing wind turbines correspond to (Tercan, 2021; Karamountzou & Vagiona, 2023; Demir et al., 2024). Another distinguishing feature of this study is the use of a 3D model for visualization. The 3D model was obtained from an independent user on the Sketchfab platform, and necessary adjustments to the turbine were made using the SketchUp application before being transferred to Google Earth Pro. Four different example areas corresponding to the "highly suitable" class were populated with 3D wind turbines, enriching the content through both textual and visual elements.

The study's limitations include the absence of field surveys and reliance on a single methodological approach. Since this research analyzed acquired data solely through the Analytic Hierarchy Process and weighted sum method without conducting field studies, some geographical factors may have been overlooked. Despite these constraints, the methodological validity and consistency with similar findings in other studies strengthen the research's credibility. For future studies in this field, we recommend either employing a different MCDM method or adopting an integrated approach combining multiple methodologies. In addition, since data could not be obtained for criteria such as distance to bird migration routes, distance to natural assets and cultural heritage, they could not be used in the study. The use of such data in wind farm site selection analyses will contribute to the study's more accurate results and the protection of biodiversity. The findings from this study provide geographically based recommendations for policymakers and investors. By supplementing these recommendations with detailed technical and cost analyses, more comprehensive and actionable results can be achieved.

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