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An integrated Bayesian Best-Worst Method and GIS-based approach for offshore wind power plant site selection: A case study in North Aegean and Marmara Sea (Türkiye)

Açık deniz rüzgar enerjisi santrali saha seçimi için entegre bir Bayesian En İyi-En Kötü Yöntemi ve CBS tabanlı yaklaşım: Kuzey Ege ve Marmara Denizi'nde (Türkiye) bir vaka çalışması

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ABSTRACT / ÖZ

In today's world, renewable energy sources are in great demand due to the negative effects of fossil fuels on the environment. Wind power plants are an important renewable energy source alternative to fossil fuel consumption. Offshore wind farms established in coastal areas and seas are used effectively in many parts of the world. The wind power plants, especially in the Northwest region of Turkey and the Aegean coasts, constitute an important potential. This study selects suitable sites for offshore wind farms in the Marmara Sea and North Aegean Coasts of Turkey by integrating the Bayesian Best-Worst method (BWM) and GIS. Bayesian BWM improves the traditional BWM integrating the preferences of multiple experts. In the study, 17 sub-criteria were determined under four main criteria of "technical", "socio-economic", "environment," and "location". Experts' judgments through the filled enabled the criterion weights to be obtained. The criteria weights found using the Bayesian-BWM model were integrated into the GIS, and suitable locations for the offshore wind farm were determined. Accordingly, the study area off the coasts of Aliağa, Bozcaada, and Gökçeada on the North Aegean coast, and the part south of the Marmara Sea and the area around Kapıdağ Peninsula are suggested as suitable areas for wind power plants.

Günümüz dünyasında fosil yakıtların çevreye olan olumsuz etkilerinden dolayı yenilenebilir enerji kaynakları büyük talep görmektedir. Rüzgâr santralleri, fosil yakıt tüketimine alternatif önemli bir yenilenebilir enerji kaynağıdır. Kıyı bölgelerinde ve denizlerde kurulan offshore rüzgâr santralleri dünyanın birçok yerinde etkin bir şekilde kullanılmaktadır. Rüzgâr santralleri dikkate alındığında özellikle Türkiye'nin Kuzeybatı bölgesi ve Ege kıyıları önemli bir potansiyel oluşturmaktadır. Bu çalışmanın amacı, Bayesian Best-Worst yöntemini (BWM) CBS'ye entegre ederek Türkiye'nin Marmara Denizi ve Kuzey Ege Kıyılarında açık deniz rüzgâr santralleri için uygun yer seçimini belirlemektir. Bayesian BWM, birden çok uzmanın tercihlerini etkili bir şekilde entegre ederek orijinal BWM'yi optimize eder. Çalışmada BWM modeli kullanılarak "teknik", "sosyo-ekonomik", "çevre" ve "konum" olmak üzere dört ana kriter altında 17 kriter belirlenmiş, kriterleri içeren anketler uzmanlar tarafından doldurulmuş ve son ağırlıkları verilmiştir. Bayesian-BWM modeli kullanılarak bulunan kriter ağırlıkları CBS'ye entegre edilmiş ve açık deniz rüzgâr çiftliği için uygun yerler bulunmuştur. Buna göre, Kuzey Ege kıyılarındaki Aliağa, Bozcaada ve Gökçeada açıklarındaki çalışma alanı ile Marmara Denizi'nin kısmen güneyi ve Kapıdağ Yarımadası çevresi rüzgâr santrali için uygun alanlar olarak önerilmektedir.

1. Introduction

The interest in renewable energy sources has increased in recent years due to fossil fuels, environmental effects, and being a non-renewable resource (Gao et al., 2020). Wind energy, a renewable energy source, is important among energy sources. First, many facilities were established on land to benefit from wind energy. Developing technology has allowed wind power plants to be installed in the seas after the land (Caceoğlu et al., 2022; Ayodele & Ogunjuyigbe, 2016; Zhao & Ren, 2015). Offshore wind power plants have become popular in recent years due to the uncertainty of wind resources, the difficulty and cost of energy transfer, and the distance from energy demand centers to increase prices (Fan et al., 2016; Markard & Petersen, 2009). The offshore wind speed ratio is higher than on shore. Therefore, more energy can be produced from offshore systems. Today, more investment is made in offshore systems (Díaz & Soares, 2020).

Offshore wind power plants, the smoothness of the seas, their unobstructed nature, and the fact that they are open in many places allow them to receive more and faster winds. Offshore wind power plants can be installed in a much larger area, and the visual and sound effects are deficient (Vasileioua et al., 2017; Salvador et al., 2022). These criteria are important advantages of offshore wind farms. So, installing offshore wind farms have become very common in recent years.

In the last 20 years, electricity generation applications from wind energy have increased significantly. According to the Global Wind Energy Council (GWEC) 2019 report, while the total installed power of wind energy was 24 GW on land and 0 GW in open seas in 2001, it increased to 621 GW on land and 29 GW in open seas in 2019. Accordingly, the installed power of wind farms has increased approximately 30 times worldwide. It will increase to 94 GW in 2021. According to the GWEC scenarios, it is estimated that there will be 1200 GW by 2030. While the rate of offshore wind turbines in this installed capacity was 0% in 2001, it increased to 5% in 2019 (Fig.1) (GWEC, 2019-2022). In Europe, offshore wind farms' installed power is approximately 28 GW today. European countries have decided to increase the installed capacity of offshore wind power plants up to 160 GW by 2030 (Wind Europe, 2022). As of 2022, Turkey has no significant offshore wind farms (OWF) installations. A major shortcoming is the absence of offshore wind farms in a peninsula like Turkey, surrounded by seas on three sides.

Turkey is a country that imports 75% of the energy it needs. Most of the energy sources in the country are produced from fossil fuels, and only 15% is formed from renewable energy sources. So, the diversity of renewable energy sources should be increased to reduce external energy dependence. Electricity production is mainly produced from hydroelectric power plants, followed by wind energy. According to the Turkish Wind Energy Association (TWEA) 2022 report, the total installed capacity of onshore wind has reached 11101 MWm. According to the latest data, there are 3983 turbines in a total of 273 active power plants, and the electricity produced from these power plants is approximately 30,900 GWh (TWEA, 2022).

Since offshore wind farm location selection is a long-term investment, this problem should be considered a strategic multicriteria decision-making problem since the selection criteria conflict with each other (Deveci et al.2021). Using GIS-based models to solve the offshore wind farm problem can solve the problems related to sea area demands. While the profitability of the investment can be maximized, the negative effects of the power plant can be minimized (Kim et al. 2016). In the literature, there are various studies that make site selection analyses using MCDM methods for both inland and offshore areas. Table 1 shows the MCDM methods and working areas used for wind energy site selection. Accordingly, in wind energy site selection, such as Best–Worst Method (BWM), Analytic Hierarchy Process (AHP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), various MCDM meth-

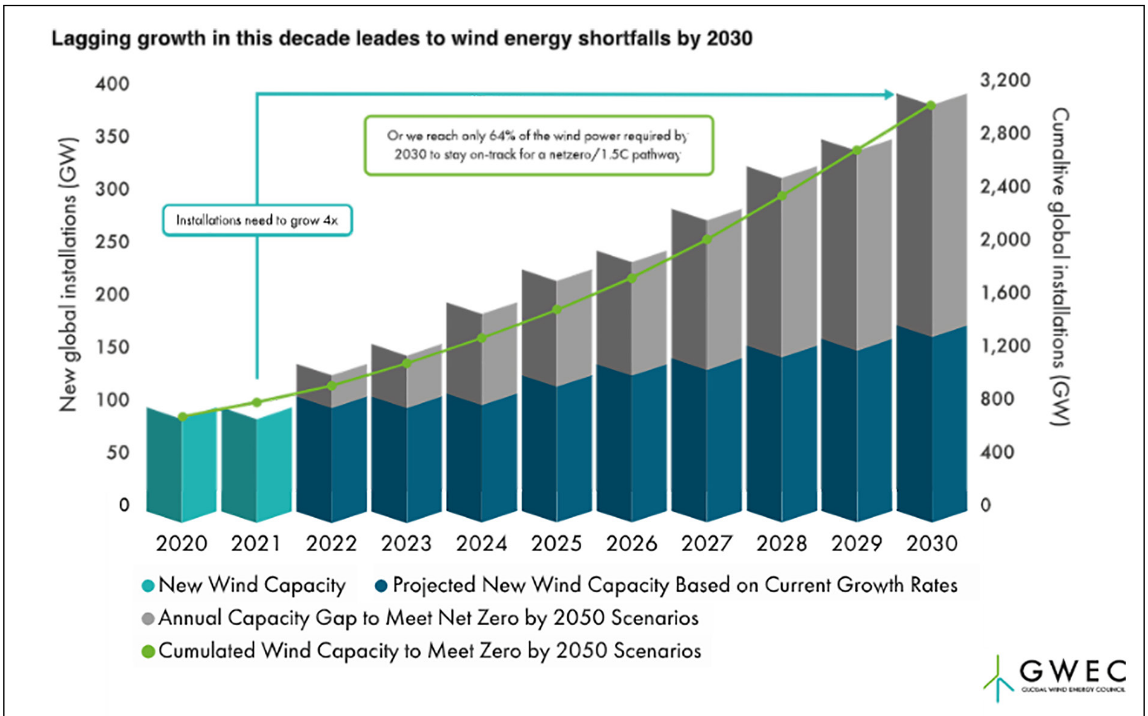

Figure 1. *Installed power scenarios of wind power plants in the world till 2030 (GWEC,2022)*

ods have been used. Among the MCDM methods used, the AHP methodology was used the most. The AHP method uses pairwise comparison matrices and synthesizes the judgments given by the experts.

Moreover, such methods have been used with other MCDM methods such as TOPSIS, PROMETHEE, and ELECTRE III (Roy, 1978; Brans et al., 1984; Hwang & Yoon, 1981). Various techniques have been used for MCDM in offshore site selection problems. Gil-Garcia et al. Fuzzy-AHP method is integrated with GIS to select the most suitable wind farm located in the Gulf of Maine and its surroundings in the USA. Likewise, Taoufik and Fekri used the Fuzzy-AHP method integrated with GIS and searched for suitable places for a wind power plant on the coast of Morocco. Salvador et al. In this study, by using the Bayes-BWM method, which is the method in this study, suitable locations for a wind power plant on the coast of Australia were investigated.

There are studies on various MCDM methods in Turkey (Özşahin & Kaymaz, 2013; Akalın, 2018; Genç et al., 2021; Caceoğlu et al., 2021). However, these studies generally remained within the framework of a conclusion evaluated within the authors' knowledge and drawn accordingly. In addition, the issue of site selection has not typically been addressed from a geographical perspective.

This study aims to conclude by taking experts' opinions from different fields (geography, geology, disaster science, renewable energy, GIS modeling, etc.) for OWF's location selection. It includes a Bayesian BWM and GIS-based integrated model for OWFs location selection. Bayesian Network (BN) makes comparisons under uncertainty and is a mathematical model with significant pros for modeling qualitative and quantitative variables (Salvador et al.,2022). It has also been used to solve decision-making problems (Bhandari et al., 2015; Yazdi, 2019; Pui et al., 2017, 2016; Carriger et al., 2019). Site selection problem with BN has been handled in various fields such as logistics, security, communication, border security, and traffic regulation (Nedjati et al., 2017; Yazdi et al., 2019b; Lessin et al., 2018; Kim & O'Kelly, 2009; Gonzalez et al., 2019). Within the scope of the study, its integration with BWM and GIS, and the comprehensive evaluation of the criteria determined by the literature and the field of study, including experts in different areas, is considered an innovation. In addition, thanks to the Bayesian BWM, which is used in the weighting of the criteria which has an impact on the selection of the location, it is possible to make more consistent evaluations with less data and to aggregate the assessment of more than one expert with a probabilistic perspective (Mohammadi and Rezaei, 2020; Rezaei, 2015).

2. Materials and methods

2.1. Study Area

The study area consists of the Marmara Sea, Turkey's 4th largest sea and an inland sea, and the North Aegean Coasts (Fig. 2). The Sea of Marmara within the study area is located between latitudes 40°- 20' and 41°- 10' and longitudes 27° and 29°- 30'. The Sea of Marmara is connected to the Aegean by the Dardanelles and the Black Sea by the Bosporus. The widest part of the sea in the north-south direction is 80 km, and the longest in the east-west direction is 280 km. Its area is 11,352 square kilometers. In addition, the Sea of Marmara is an internationally important waterway due to the straits.

There are important islands and peninsulas in the Marmara Sea. The Armutlu and Kapıdağ peninsulas are two significant peninsulas, and the Izmit, Gemlik, Bandırma, and Erdek gulfs on both sides constitute the most important natural harbors. The Sea of Marmara can be morphologically divided into two in the east-west direction. These are the deep part with pits at a depth of about 1335 meters in the north and the shallow part with a depth of 100 meters in the south. Especially areas with deep holes are not suitable for installing wind panels. These two parts are separated along the line of Armutlu Peninsula and Marmara Island. The largest island in the Sea of Marmara is Marmara Island. There are also the Avşa archipelagos (Ekinlik Island, Avşa Island, Paşalimanı Island, etc.) and

Table 1. *Summary of studies combining GIS/MCDM methods and fuzzy logic in the selection of suitable locations for wind energy sources.*

Author(s)	Study area	Year	MCDM Methods
Lee, 2010	Taiwan	2010	AHP
Özşahin and Kaymaz, 2013	Turkey	2013	AHP
Fetanat et al., 2015	Iran	2015	AHP
Sánchez-Lozano et al., 2016	Spain	2016	TOPSIS- AHP
Wu et al., 2016	China	2016	ELECTRE
Sajid et al., 2017	S. Korea	2017	AHP
Pamuar et al., 2017	Serbia	2017	MAIRCA- BWM
Vasileioua et al., 2017	Greece	2017	AHP
Lotfi et al. 2018	Iran	2018	TOPSIS
Uzar and Ener, 2019	Turkey	2019	AHP
Deveci et al. 2020	Turkey	2020	TOPSIS
Reza et al. 2020	Iran	2020	ANP-VIKOR
Taoufik and Fekri, 2021	Morocco	2021	Fuzzy-AHP
Caceoğlu et al., 2021	Turkey	2021	AHP
Salvador et al., 2022	Australia	2022	Bayesian-BWM
Sánchez-Lozano et al., 2022	USA	2022	TOPSIS- AHP

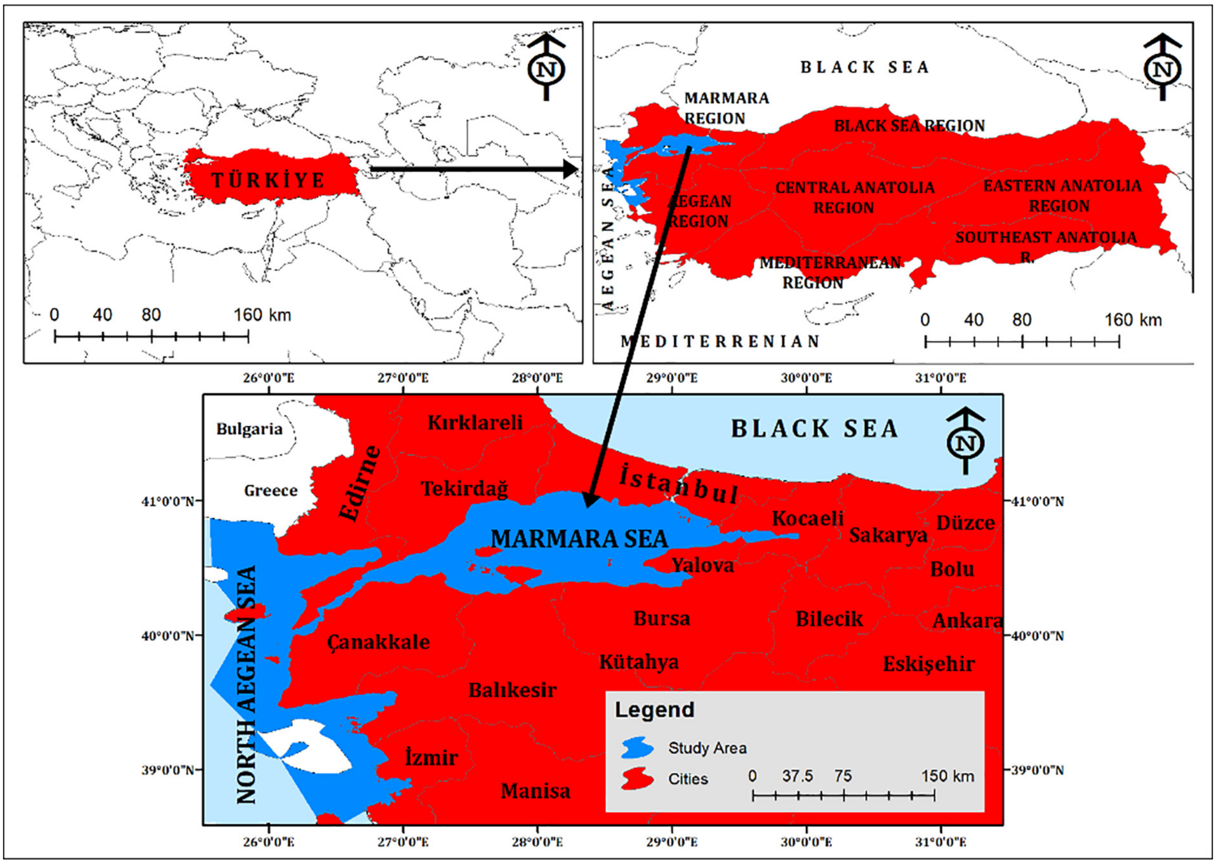

Figure 2. *Study area location map.*

Prince archipelagos (Büyük, Kınalı, Heybeliada and Burgaz) (Barka & Kadinsky-Cade, 1988) Especially the coastal areas close to the islands create a significant potential for wind panel installation. Islands located on the shores of the Marmara Sea and the North Aegean Sea are an advantage for wind farm installation.

The Sea of Marmara and its surroundings have a temperate climate, and four seasons are experienced in the region. The speed of the currents in the Sea of Marmara varies between 750 and 2.5 km per hour (21-70 cm/s). The speed of the tides in the Sea of Marmara is also too small to be noticed. On the other hand, because of the strong winds pushing the water, there are some level changes on the north and south coasts. Especially Lodos, Kıble and Keşişleme winds contribute to these level changes (Barka & Kadinsky-Cade, 1988). These local winds in the study area are also very important for Wind Power Plants. Areas with intense winds will be suitable for wind panel installation.

The coasts of the North Aegean Sea within the study area start from the north of İzmir and extend to Greece in the north. The study area was determined as the areas close to the Turkish coasts, but the Exclusive Economic Zone (EEZ) boundaries were not considered (Fig. 2).

The Aegean Sea, which was a land mass in the Pliocene period, took its present appearance with the formation of uplifts, collapses, and faulting due to tectonism in specific periods (Atalay, 1982). The area covered by the Aegean Sea is mostly shallower than 600 meters. The Aegean Sea has a north-south length of 660 km, while its east-west width is 270 km in the north, 150 km in the middle, and 400 km in the south. The Aegean Sea is between the Mediterranean, which has tropical and mid-latitude climate characteristics, and Europe and the Black Sea, which has temperate and cold climate characteristics. Etesian winds blow in the North Aegean Sea and its coasts during summer. Bora-type winds influence the region in the autumn and winter (Oran, 1994). These winds, effective both in summer and winter in the working area, are very important for wind panels and are the most significant factor in increasing efficiency.

The study area constitutes the areas with the highest wind speed on the Turkish coasts (URL-2). The continental shelf is comprehensive in many coastal regions, with many islands. The places where the continental area is large, and the island coasts are suitable for wind panels (Fetanat and Khorasaninejad, 2015; Caceoğlu et al., 2022; Salvador et al., 2022). In addition, when the vicinity of the study area is evaluated in terms of population, it has a large population. The size of the population also increases the energy supply. It is necessary to create alternative energy sources to meet the energy demand in the region (Havan, 2017). An OWF to be established on the North Aegean coasts and the Marmara Sea is vital for diversifying energy resources. Therefore, this region was chosen as the study area. Finally, the Dardanelles Strait, where wind power plant installation will not be possible, has been included in the study area to ensure the integrity of the study area.

3. Research Methodology and Data

The primary purpose of this study is to find suitable places for OWFs. In this context, the Bayesian best-worst method, one of the multi-criteria decision-making methods (MCDM), has been used by integrating it into GIS.

3.1. Bayesian Best-Worst Method

BWM is widely used because it uses less data than methods such as AHP, and because it has two vectors, it allows for consistency calculation (Rezaei, 2015; 2016). Although BWM has many advantages, it cannot solve group MCDM problems. Due to the uncertainty and complexity of real-world issues, more than one decision-maker is often needed. To eliminate this limitation, Bayesian BWM has been proposed (Mohammadi & Rezaei, 2020). Bayesian BWM only needs integers like traditional BWM. These are pairwise comparison matrices. These matrices are modeled using the multinomial distribution. The outputs of Bayesian BWM are final weights containing the evaluations of all decision-makers and credal graphs showing the superiority level of the criteria. The Bayesian BWM solution has four steps (Mohammadi & Rezaei, 2020; Munim et al. 2022; Gul & Yucesan 2022; Saner et al. 2022).

Step 1: Determine the criteria to be evaluated.
At this stage, the main and sub-criteria to be evaluated are determined in line with the literature research and the opinions of expert groups.

Step 2: Determination of the Best and Worst criteria.
Based on the hierarchy determined at this stage, the Best (Most important, most desirable) and Worst (least important, least desirable) criteria are determined.

Step 3: Creating the best-to-others and others-to-worst vectors.
The best criterion determined in the previous step is compared with the other criteria. A scale of 1-9 is used for comparisons. One indicates that the two criteria are equally important, and nine indicates that the best criterion is more important than the compared criterion. With these comparisons, the Best-to-others vector is obtained $A_B^k = \left(a_{B1}^k, a_{B2}^k, \dots, a_{Bn}^k\right), A_W^k \;\; k = 1,2,\dots,K$.

Similarly, the worst criterion is compared with the other criteria, and the Others-to-worst vector is obtained $\left(a_{1W}^k, a_{2W}^k, \dots, a_{nW}^k\right)^T \; k = 1,2,\dots,K$.

Step 4: Determination of aggregated final weights and credal ranking
At this stage, thanks to the multinomial and Dirichlet distribution presented, final weights and credal graphs are obtained. Credal ranking graphs show at which confidence level the criteria are superior to each other. The JASGs and MATLAB codes required for the solution were taken from (URL-1) and adapted to the study.

3.2. GIS Method

The study identified ten experts from different disciplines (geography, geology, disaster science, renewable energy, GIS modeling, etc.) to evaluate the questionnaires. Afterward, 17 criteria were determined under four main headings (technical, socio-economic, environment, and location). Detailed information about the criteria (scale, data type, etc.) is given in Table 2 in detail. These criteria were chosen considering the study area characteristics and the relevant literature. In line with the determined criteria, a questionnaire was prepared by the best-worst method. The questionnaire was used to find the weight values of each criterion in line with the experts' opinions.

Each criterion used in the study should be adequately transferred to the GIS environment. For example, the criteria such as wind speed, water depth, pipe, and cable line below the technical main criteria should be both suitable for the work area and their classification should be done correctly. Therefore, all the criteria prepared were cut according to the study area and their classification was made by considering their values. On the other hand, the weight values within themselves must also be calculated to use the criteria, cut and classified according to the study area in the Weight Sum analysis. For example, wind speed data is divided into six classes. Each class of this criterion, divided into six classes, should be weighted according to the degree of importance. For this purpose, a questionnaire by the best-worst method was prepared for each criterion, and each criterion's weight values were calculated using these questionnaires. While the weight values of the criteria were found according to the determined classes, they were calculated according to the procedure suggested by Rezaei (2015). The data whose weight values were calculated were finally reclassified according to their weight values using the "Reclassify" method and made ready for analysis. Weight Sum analysis was applied using these weight values and the general weight values filled and found by the experts.

3.2.1. Selection of the criteria

It is a very important issue that the power plants to be established for solar, wind, or wave energy in any place should be installed in suitable areas. For this reason, there are many studies conducted with MCDM and GIS aiming to find suitable locations for solar, wind, or wave power plant installation (Caceoglu et al., 2022; Taoufik & Fekri, 2021; Castro-Santos et al., 2020; Satir et al., 2018; Aydın et al., 2013; Tercan, 2021; Vasileiou et al., 2017; Castro-Santos et al., 2020). In these studies, various criteria (wind speed, wind power density, pipe, cable lines, etc.) were used to find the installation of power plants in suitable places. This study aims to find appropriate locations for OWFs. For this purpose, 17 criteria have been determined under four main criteria. These, within the technical main criterion, wind speed, water depth, pipe, cable line, capacity factor distribution and submarine geomorphology. Within the socio-economic main criterion, tourism density, beach areas and sea traffic, within the environment main criterion, sea sunken areas, bird migration routes, visual impact and seismicity, within the location main criterion, distance to power lines, distance to ports, distance to coastline, distance to islands and distance to airports (Fig. 3). While selecting these criteria, the literature on the subject was examined in detail, and the physical and human characteristics of the study area were considered. Among the many criteria used in the literature, the criteria deemed appropriate by the authors were selected according to the features of the study area.

Technical main criteria (wind speed, water depth, pipe and cable line, capacity factor distribution and submarine geomorphology) are explained in detail according to their situation in the study area and depending on the literature:

Wind Speed (A1): Wind speed is one of the most critical criteria used in OWF studies and has a high weight value. The wind speed criterion was the primary criterion in almost all the studies examined (Van-Haaren & Fthenakis, 2011; Özşahin &

Table 2. *Offshore criteria and their classes, source, type, and resolution.*

Main Classification	Criteria	Data Source	Data Type	Resolution (Scale)
Technical	Wind speed	Global Wind Atlas, 2022	Grid	100 m
	Water depth	GEBCO, 2022	Grid	30 m
	Pipe and cable line	Interagency Ocean Observation Committee (IOOC), 2022; BOTAŞ, 2022	Shapefile - Line	1:100,000
	Capacity factor distribu-tion	Global Wind Atlas, 2022	Grid	100 m
	Submarine geomorpho-logy	GEBCO, 2022	Grid	30 m
Socio-economic	Tourism density and beach areas	OpenStreetMap, 2022	Shapefile - Polygon	1:100,000
	Cost	OpenStreetMap, 2022	Shapefile - Line	1:100,000
	Sea traffic	Marine Traffic, 2022	Shapefile - Line	1:100,000
Environment	Sea sunken areas	Akkoç, 2013	Shapefile - Point	1:25,000
	Bird migration routes	Kiziroğlu and Erdogan, 2015	Shapefile - Line	1:100,000
	Visual impact	Authors created it based on coastal distance.	Shapefile - Line	1:100,000
	Seismicity	MTA, 2022	Shapefile - Line	1:100,000
Location	Distance to power lines	OpenStreetMap, 2022	Shapefile - Line	1:50,000
	Distance to ports	OpenStreetMap, 2022	Shapefile - Point	1:25,000
	Distance to coastline	OpenStreetMap, 2022	Shapefile - Line	1:100,000
	Distance to islands	OpenStreetMap, 2022	Shapefile - Point	1:100,000
	Distance to airports	OpenStreetMap, 2022	Shapefile - Point	1:25,000

Kaymaz, 2013; Höfer et al., 2016; Ayodelea et al., 2018; Shorabeh et al., 2021). Wind speed directly affects the workability of the power plant. The energy produced from wind power plants is directly proportional to the cube of the wind speed. According to this ratio, while the wind speed increases the efficiency by 150% in terrestrial areas, it increases by 40% in the open seas due to the stability of the wind speed (Caceoğlu et al., 2022). The minimum wind speed required for wind farms differs in most studies. For instance, Gorsevski et al. (2013) reported wind speed from zero to 7.5 m/s, Ali et al. (2019) minimum 4 m/s for wind farms in different locations, Shorabeh et al. (2022) values of 5 m/s for large wind farms and 4 m/s and less for small wind farms, Saraswat et al. (2021) determined wind speeds between 5-6 m/s as suitable areas. In addition, wind speeds above 15 m/s can cause damage to wind turbines (Taoufik & Fekri, 2021). Finally, recent developments in wind power plants show that large turbines with 87–100 m hub height and 8–10 MW capacity will be preferred soon (Caceoğlu et al., 2022). Wind speeds in the study area range from 6 to 9.5 m/s on average (Fig. 4-A1). In this study, the wind speed at 100 m was used and the areas with a minimum wind speed of 7 to 9 m/s were determined as suitable areas.

Water Depth (A2): Water depth is an important criterion as it directly affects the type and cost of the wind farm to be built. It is also frequently used in OWF studies (Murali et al., 2014; Vasileioua et al., 2017; Deveci et al., 2020). In the studies, it was stated that 50 m or less depths would be suitable for wind farm installation, while it was noted that the power plant could be installed at water depths varying between 50 and 100 m (Taoufik & Fekri, 2021). Another study stated that power plants built at water depths exceeding 75 m would be difficult to construct, and the cost will increase (Murali et al., 2014). In many parts of the study area shores, the first 50 m of the shoreline is very narrow. After a few kilometers, depths of 50 m can be reached. Between 50 and 100 m is a large area. After 100 m, the slope increases after the depth, and the depths can change in short distances (Fig. 4-A2). Therefore, the coasts of the study area with a depth of 75 to 100 m have been determined as the priority areas.

Another important issue regarding water depth for OWFs is landslides under the sea. High seafloor slopes can cause submarine landslides. It is known that seafloor landslides occur in many parts of the Marmara Sea (Sivri, 2013). In addition, in steep places where the sea depth increases, it is difficult for

Technical	Socio-economic	Environment	Location
• Wind speed • Water depth • Pipe and cable line • Capacity factor distribution • Submarine geomorphology	• Tourism density and beach areas • Cost • Sea traffic	• Sea sunken areas • Bird migration routes • Visual impact • Seismicity	• Distance to power lines • Distance to ports • Distance to coastline • Distance to ıslands • Distance to airports

Figure 3. *Criteria for site selection of offshore wind farms (OWFs).*

the power plant to anchor to the seabed. Considering these criteria in the study, the experts who filled out the questionnaire were given the necessary information.

Pipelines and Cables in the Seabed (A3): Pipe and cable lines under the sea are vital due to factors such as wind farms' effect on fixing the seabed and the difficulties during installation, and the difficulty of energy transfer. Submarine cable lines start from the North Aegean coast within the study area, pass through the Çannakkale Strait, and then through the Sea of Marmara and the Bosporus. Pipelines (natural gas) pass through the Marmara Sea (Fig. 4-A3). In addition, there are telecommunication cables around the Sea of Marmara and the Bosporus. However, these cables could not be transferred to the map. Therefore, such small cable lines could not be used in the study. Buffer analysis determined the distances to the pipes and cable lines selected in the study. Accordingly, 100 m perimeter of pipe and cable lines were defined as unsuitable areas and low weight values were given to these areas.

Capacity Factor Distribution (A4): Capacity factor distribution is an important criterion in wind power plants built at sea or on land. The capacity factor is the expected wind power generation ratio to the wind power at the wind turbine's rated power over a given time (Siyal et al. 2015). The capacity factor is one of the most influential parameters showing the wind energy generator's electricity generation efficiency and directly impacts the electricity cost. It is an indicator of the economic viability of a wind energy project (Nedaei et al., 2014). The capacity factor value of today's wind turbines is up to 50%. The approach of the capacity factor to the ideal weight means an increase in energy production (Tortumluoğlu & Doğan, 2021). For a wind turbine or a wind farm, a capacity factor of 20-40% is ideal (Snyder & Kaiser, 2009). According to the average capacity factor distribution determined by the General Directorate of Renewable Energy in the study area, the capacity factor distribution of especially the North Aegean coasts (around Çanakkale - Bozcaada) is between 50-60%. Around the Marmara Sea, this rate is around 25-40%[1] (Fig. 4-A4). Accordingly, the study area and its surroundings provide ideal conditions for capacity factor distribution. A wind farm to be established is likely to provide sufficient efficiency.

Submarine Geomorphology (A5): Submarine geomorphology is very important in determining the seafloor's diversity, the seabed topography's movements, and scanning the area for power plant installation. High-risk events such as slope fractures, landslides, underwater cave collapses, and collapses that may occur under the sea can cause severe damage to the turbines. Ground scans and extensive geotechnical analysis are required for reliable turbine foundations. The study area and its surroundings (especially the Sea of Marmara) have unique and complex features and active tectonics. The North Anatolian Fault Line is one of the most influential factors forming the study area. The shelf area covers about half of the Marmara Sea and is quite wide in the south and southwest. It narrows entirely in front of the Ganos and Samanlı mountains. Near Uçmakdere, the coast completely disappears to the west of Tekirdağ, and the shelf area in front of the sea almost disappears. In addition, there are deep depression areas and many sea valleys in the Marmara Sea (Akyüz, 2007). On the other hand, the North Aegean Coasts of the study area were selected especially close to the coast and the continental shelf is wide, although the depths increase in some places in these areas (Fig. 4-A5). A wide continental shelf is very important for OWFs.

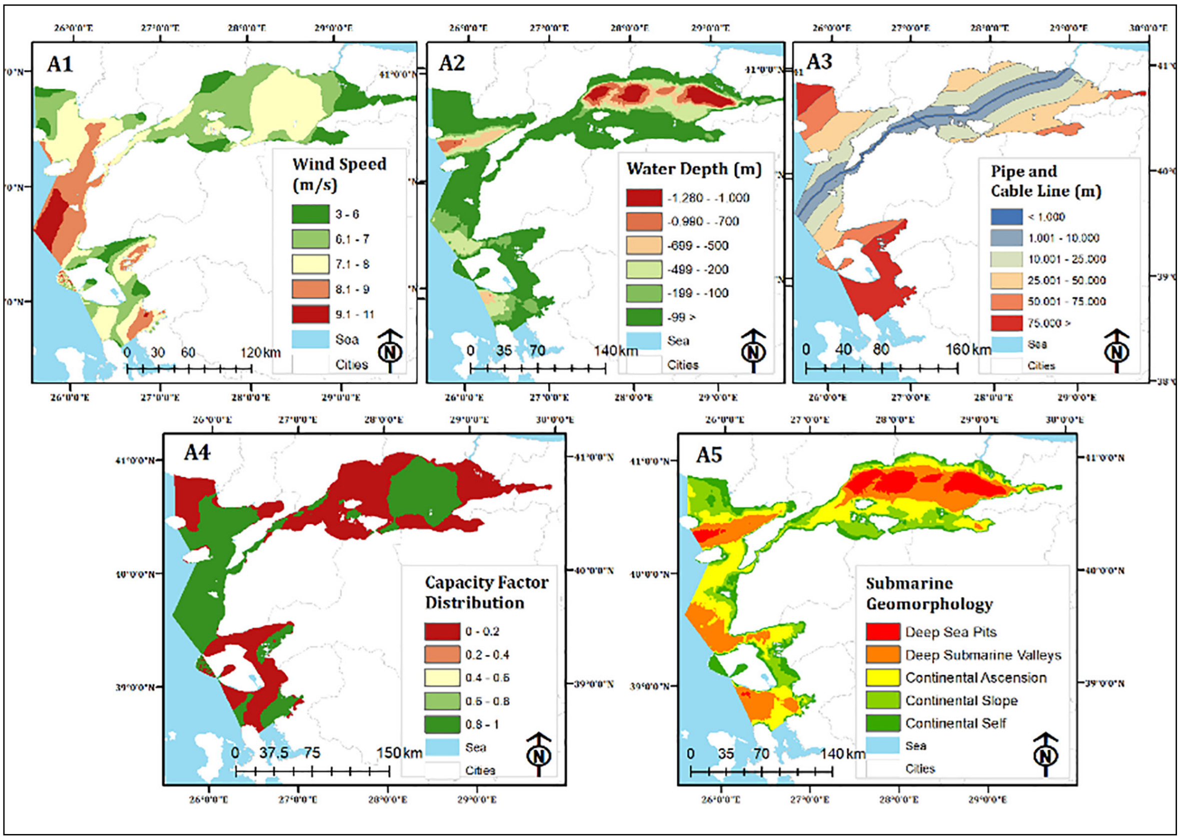

Figure 4. Technical criteria for offshore wind farm site selection: Wind speed (A1), Water depth (A2), Pipelines and cables in the seabed (A3), Capacity factor distribution (A4) and Submarine geomorphology (A5).

[2] These values have been prepared by considering the technical values of a 3 MW wind turbine.

Socio-economic main criteria (tourism density, beach areas and sea traffic) are explained in detail according to their situation in the study area and depending on the literature:

Tourism Density and Beach Areas (B1): Tourism Density Beach Areas: Tourist attractions may be affected by wind turbines in some cases. These touristic activities on the coasts are beach areas, yacht and daily boat tours, and diving activities. Especially wind power plants established on the shores where such tourism activities occur can negatively affect tourist attractiveness due to visual and noise pollution. According to their studies on tourists, Lilley et al. (2010) stated that they can be adversely affected by a wind farm being established in the open sea in any touristic destination area. In the same study, considering that the avoidance effect decreases with distance from the shore, it was concluded that this result would be reduced by placing offshore wind turbines further away from the sea. In this study, coastal areas with intense tourism were determined and distance analysis (buffer) was applied (Fig. 5-B1). Accordingly, low weight values are given to coastal areas close to tourism areas.

Cost to Install OWFs (B2): The depth of the water, the distance to the shore, the rugged submarine geomorphology, the length of the cable for electricity transmission, the high wave height and speed (more robust structures need to be made, which increases the cost) are the factors that increase the installation cost of OWFs (Caceoğlu et al., 2022; Gil-García et al., 2022; Taoufik & Fekri, 2021). As you move away from the coast, the sea's depth increases and the underwater topography becomes more complex. In addition, the farther from the shore, the longer the cable line for electricity transmission will increase. Therefore, OWFs should be installed close to the coasts, in areas with low depth and where possible underwater topography is suitable.

In this study, to create the cost map of the study area, the criteria (water depth, distance to the shore, etc.) that affect the cost were determined in the literature. The weight values of these criteria need to be determined. For this, the authors created a BWM questionnaire, and the weight values of each criterion were found. Finding weight values and criteria were reclassified within themselves using ArcGIS software. As a result, these criteria overlapped with the Weight Sum analysis method and the areas where the high cost was found. The study used this map as a cost map (Fig. 5-B2).

Sea Traffic (B3): Ship traffic is an essential issue for OWFs. OWFs can be dangerous to install in areas with heavy ship traffic. Turkey acts as a bridge between Asia and Europe. The only way for a ship departing from the Black Sea to sail to the Aegean and Mediterranean Seas and from there to the world is to use the Bosporus and Dardanelles (this is also true vice versa). Therefore, the ship traffic between north and south and east and west is intense (Marine Traffic, 2022). Due to the intensity experienced in the Straits, the Republic of Turkey has determined the passageways to the characteristics of the ships (length, load, etc.) by bringing a series of rules for the safe and regular flow of ship traffic (Turkish Straits Marine Traffic Regulation, 2019). Consideration of these ship routes is essential for the installation of OWFs. The study applied a buffer analysis considering the ship routes in the study area (Fig. 5-B3). Low weight values are given to areas close to shipways.

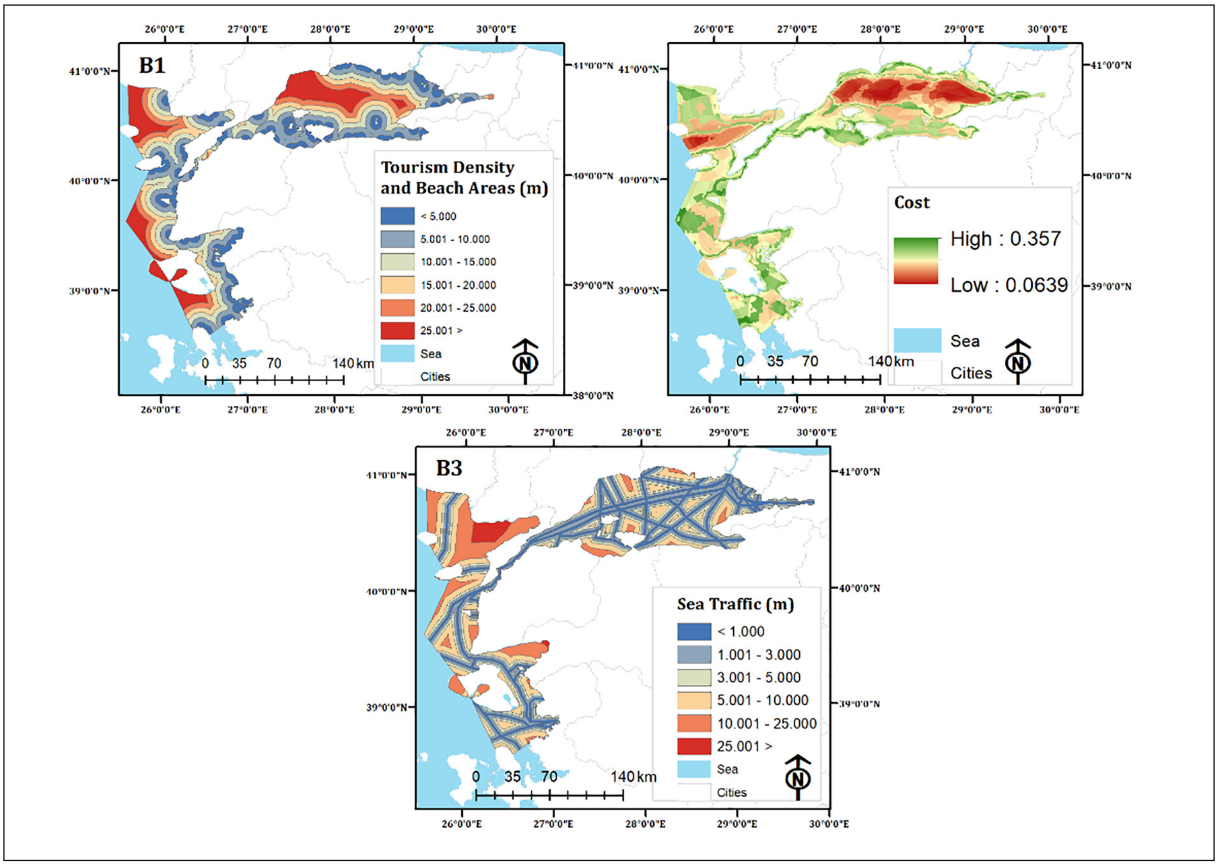

Figure 5. *Sosyo-economic criteria for offshore wind farm site selection: Tourism density and beach areas (B1), Cost (B2) and Sea traffic (B3).*

Environment main criteria (underwater wrecks, bird migration routes, visual impact, and seismicity) are explained in detail according to their situation in the study area and depending on the literature:

Underwater Wrecks (C1): Underwater Wrecks have an important historical value and are frequently used in underwater diving tourism. In addition, vehicles such as old planes and tanks are sunk in the name of diving tourism development. This underwater debris can sometimes be found near the shore. This may affect the site selection of OWFs. Therefore, this criterion was considered important and added to the study. Within the scope of the study, each wreck was determined, and buffer analysis was applied to determine the distances to these wrecks (Fig. 6-C1).

Bird Migration Routes (C2): The effect of birds on OWFs is quite limited, according to the literature. However, birds can physically strike turbines' wind blades, towers, engine rooms or related infrastructure elements. This can partially damage the turbines (Moriguchi et al.2019). The important thing here is the lives of the wildlife, namely the birds. Turbines installed on bird migration routes can harm the lives of birds. For this reason, this issue is important in the turbine installation site selection and has been added as a criterion to the study.

Due to its location, Turkey is on bird migration routes that migrate in both north-south and east-west directions. In particular, the study area is located on the migration routes of many birds that periodically migrate from Europe to Africa or Africa to Europe (Kiziroğlu & Erdogan, 2015; Bird Map, 2022). The study applied a buffer analysis considering the bird migration routes passing through the study area (Fig. 6-C2). These regions are restricted by giving low weight values to the areas close to the bird migration routes.

Visual Effect (C3): Wind farms near shore or tourist destinations can be problematic for locals and tourists. Ladenburg (2009) found that whether the public has positive thoughts about the existing wind turbines and the proximity of the turbines to the coastal areas is related. On the other hand, it has been stated that wind turbines close to the coasts will be a focus of attention (Sullivan et al., 2013). Considering these issues, buffer analysis was applied by giving high weight values to places with a certain distance to touristic places and coasts (approximately 15-20 km) (Fig. 6-C3).

Seismicity (C4): Wind turbines and turbine infrastructures (cable, concrete block, transformer station, etc.) can be damaged directly due to the shaking caused by the earthquake or as an indirect effect of the earthquake, because of liquefaction, landslides and tsunamis (Genç et al., 2021; Caceoğlu et al., 2022). The presence of intense fault lines in Turkey increases the potential for earthquakes. Since 1900, 19 earthquakes of magnitude 7.0 have occurred (BOUN KOERI Regional Earthquake-Tsunami Monitoring Center, 2022). In particular, the North Anatolian Fault line, Turkey's most important fault line, passes through the northern and southern borders of the study area. A buffer analysis was applied to the study area using the fault lines data produced by the General Directorate of Mineral Research and Exploration (MTA). According to the analysis results, the distances close to the fault lines are limited by giving low weight values (Fig. 6-C4).

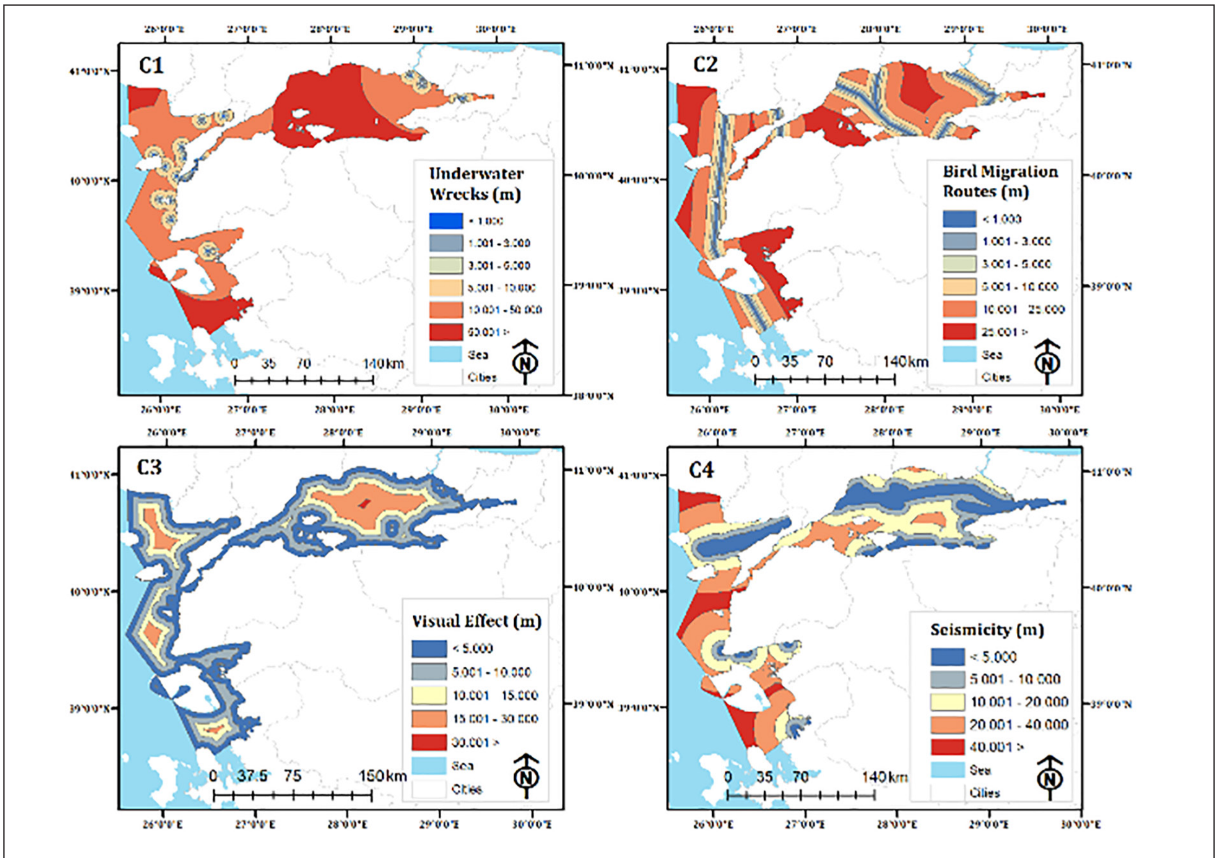

Figure 6. *Environment criteria for offshore wind farm site selection: Underwater wrecks (C1), Bird migration routes (C2), Visual effect (C3) and Seismicity (C4).*

Location main criteria (Distance to power lines, distance to ports, distance to the coastline, distance to islands, distance to airports) are explained in detail according to their situation in the study area and depending on the literature:

Distance to Power Lines (D1): The electricity produced from wind power plants must be transmitted to the nearest power lines and areas with energy demand. The cost of laying electrical transmission cables from wind farms to coastal areas increases tremendously as the distance to the shore increases (Kim et al., 2018). Therefore, it is very important to know the exact location of the substations for the economic feasibility analysis. High-voltage power lines located in the coastal area of the study area have been identified. Buffer analysis was applied to these lines within the scope of the study, and the distances in the open sea were determined. Weights suitable for the criteria were given according to the results of this analysis (Fig. 7-D1).

Distance to the Coast and Ports (D2,3): The distance to the shore and ports is an important criterion in the OWF installation. Pay attention to the distance to the coast to supply the necessary construction materials during the installation and transfer the electrical energy produced. The cost may increase as the distance to the shore increases. Accordingly, regions close to the coast are more advantageous for OWF installation. The study classified these regions from near to far by giving higher weight values (Fig. 7-D2-3).

Distance to Islands (D4): Important islands (Bozcaada, Gökçeada, Avşa island, etc.) settled around the study area. Especially Bozcaada and Gökçeada surroundings are places where wind speed is very high. So, OWF installation around the Island can be important in supply and electricity transmission and use. All island regions in the study area were determined, and distances to these islands were calculated. A gradual classification was made towards distant parts by giving high-weight values to areas close to the islands (Fig. 7-D4).

Distance to Airports (D5): Sounds emanating from the wind blades of offshore wind farms in the take-off and landing areas of aircraft may disrupt the communication signals of the plane, depending on the landing and take-off times. Offshore wind farms need to be 3 km away from airports (Pantaleo et al., 2005). So, a buffer analysis was applied by determining the airports and aircraft routes near the study area. Accordingly, classification was made from near to far, and the necessary weight values were given (Fig. 7-D5).

4. Application Study and Results

The Bayesian BWM method was used to determine the criterion weights. First, the criteria weights were evaluated by experts. Criteria selections were made according to the characteristics of the specialist and the field of study. Considering the hierarchy of criteria, vectors from best to worst and from others to the worst were transferred to the MATLAB program, and aggregated final weight values were obtained. The weights of the main criteria were multiplied by the weights of the relevant criteria. The global weight values to be transferred to GIS are presented in Table 3. Accreditation charts, another feature of Bayesian BWM, are shown in Figure 8.

Credal ranking graphs express at what level the criterion at the starting point of the arrow is superior to the criterion at

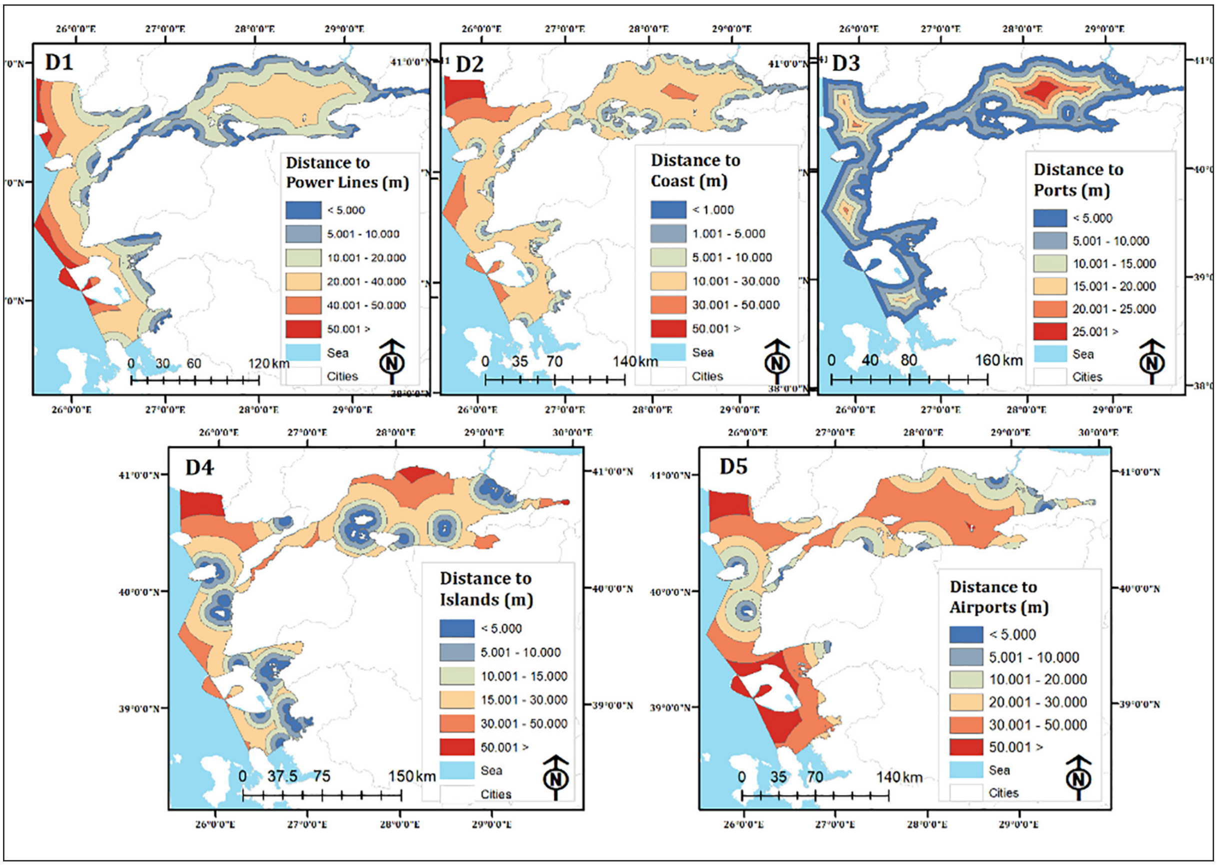

Figure 7. *Location criteria for offshore wind farm site selection: Distance to power lines (D1), Distance to coast (D2), Distance to and ports (D3), Distance to islands (D4) and Distance to airports (D5).*

Table 3. *Weights of the criteria using Bayesian-BWM.*

Code	Criteria	Global Weights	Code	Criteria	Global Weights
A1	Wind Speed	0.120	C2	Bird Migration Routes	0.032
A2	Water Depth	0.059	C3	Visual Impact	0.021
A3	Pipe and Cable Line	0.050	C4	Seismicity	0.065
A4	Capacity Factor Distribution	0.111	D1	Distance to Power Lines	0.108
A5	Submarine Geomorphology	0.037	D2	Distance to Ports	0.057
B1	Tourism Density and Beach Areas	0.039	D3	Distance to Coastline	0.058
B2	Cost	0.045	D4	Distance to Islands	0.032
B3	Sea Traffic	0.049	D5	Distance to Airports	0.068
C1	Sea Sunken Areas	0.047			

the point where the arrow reaches. These values can take between 0.5 and 1. If this value is "1", the relevant criterion is superior to the other criterion at 100% confidence level. As this value decreases, the importance level of the two criteria being compared approaches each other.

4.1. Production of a Conformity Map for a Wind Power Plant

The OWFs setup in the workspace is analyzed in five classes, as shown in Figure 8; "extremely suitable", "very suitable", "suitable", "less suitable," and "not suitable". "Extremely suitable" and "very suitable" classes indicate the most suitable areas for a wind farm. These regions constitute approximately 4,030 square meters to 16% of the study area (Table 4). According to the result, the most suitable places for the wind farm correspond to a small place compared to the total size of the study area. Therefore, it is seen that there are limited areas for wind panel installation in the study area (Fig. 9).

According to the analysis results, the Aegean Sea coasts of the study area have more suitable places for power plant installation. Particularly in the north of the Aegean Sea, the partly northern and southern surroundings of Gökçeada and the southern shores of Enez district, and in the south, the region starting from the offshores of Erenköy and Kumkale on the west side of Çanakkale and up to the surroundings of Bozcaada are among the most suitable areas for power plant installation. Bozcaada's western and southwestern parts also form appropriate areas for power plant installation. Further south, Burhaniye and Ayvalık offshore and İncirlik, Aliağa, and Yenifoça offshore, located on the southern border of the study area, are other important suitable areas for power plant installation (Fig. 9).

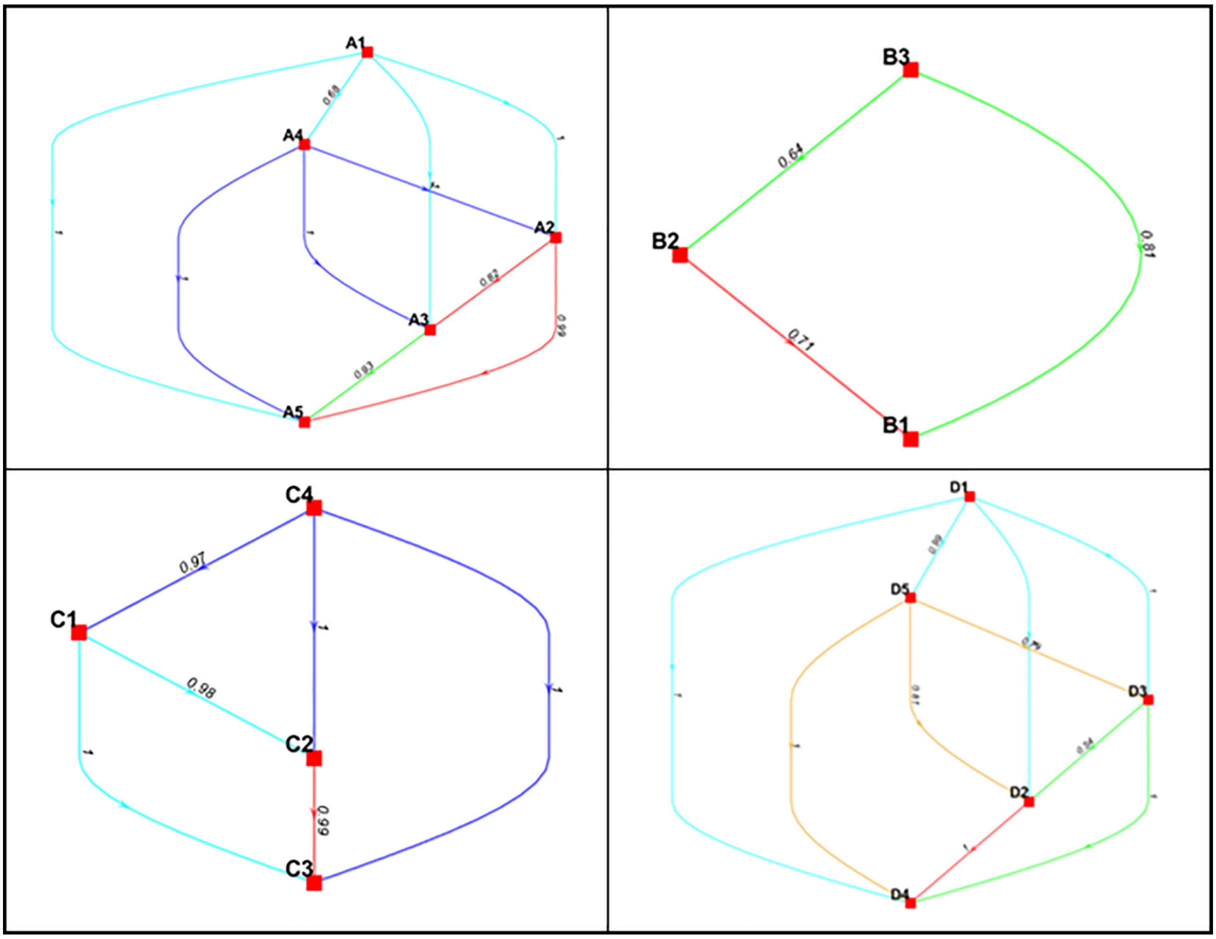

Figure 8. *Credal Ranking Graph*

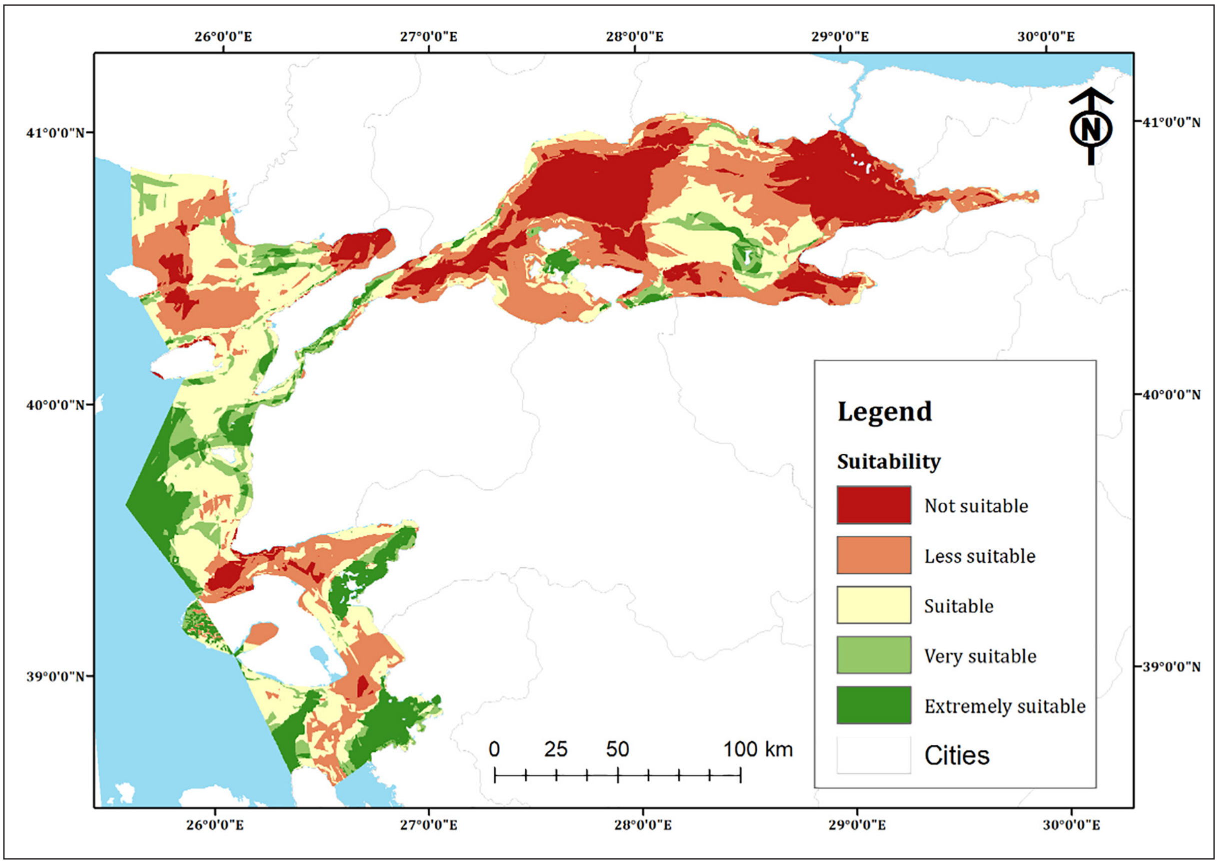

Figure 9. *Final suitability map for offshore wind farms in the Sea of Marmara and the North Aegean Coasts.*

Table 4. *Wind power plant classes and spatial distribution*

Suitability Classes	Suitability Values	Area	
		%	km2
Not Suitable	< 0.19	23.83	5.646
Less Suitable	0.19-0.21	22.61	5.358
Suitable	0.21-0-24	36.53	8.656
Very Suitable	0.24-0.25	6.04	1.433
Extremely Suitable	0.25 >	10.96	2.598
Sum		100	23.693

The North Aegean Sea coast of the study area has approximately 75% more suitable locations for wind farm installation than the appropriate regions. The main reason is the high wind speed and wind capacity factor. In particular, the wind speed criterion came to the forefront as the most important criterion in the weighting results and thus affected the outcome. The northern parts of the Gallipoli Peninsula, the surroundings of Gökçeada, and the region starting from the Çanakkale Strait offshore to Bozcaada (Photo. 1). The western parts of Bozcaada have the highest wind speed values in the study area. The wind speed in the region is up to 9-10 m/s. These values are suitable values for the wind power plant. Therefore, it is true that the coasts of the North Aegean Sea appear as appropriate areas for power plant installation.

According to the analysis results, some regions of the Dardanelles Strait seem suitable for installing wind power plants due to high-weighted criteria such as proximity to the coast, power lines, and city centers (Fig. 9). However, these areas are unsuitable for power plant installation due to narrow and sea traffic. Therefore, the suitability of these areas should be ignored.

According to the study outputs, many of the Marmara Sea are classified as “ unsuitable” and “less suitable” areas. Especially the great Marmara Trench, located near the northern coastal parts of the Marmara Sea and collapsed under the control of a fault, is an unsuitable area for power plant installation. The fact that this region has a lot of depth, the national and international ship traffic is very intense, and it is relatively far from the coast and city centers is effective in this result. On the other hand, Istanbul’s Asian shores, off Gebze and Kocaeli Bay are the least suitable areas for power plant installation. It has been classified as the least right area for installing the power plant due to the high sea traffic, low wind speed and capacity factor value.

According to the study results, the most suitable areas for wind power plant installation in the Marmara Sea are. It is off the northwest of Armutlu, off Bandırma, northwest of Kapıdağ

Photo 1. *West offshore of Bozcaada and existing Bozcaada windmills*

Peninsula and north of Paşalimanı Island and northwest of Marmara Island. Most of these areas are classified as suitable due to factors such as high wind speed, low sea traffic, low sea depth, proximity to the city center and power lines due to the islands. In addition, starting from the shores of Tekirdağ to the offshore areas of Şarköy are partially suitable. Especially Marmara Island and the surrounding island community are the most suitable areas for a wind power plant. The power plants to be established in these areas must have the opportunity both to meet the needs during the installation phase from the islands and to provide the use of the energy to be produced to the islands or to transmit it through the islands.

According to the study outputs, some remote areas from the coastal regions were suitable areas for OWF installation. Some western parts of the Aegean Sea, shown as "extremely suitable areas" in Figure 9, fall within the area in question. These areas have the highest wind speed, wind capacity factor distribution, and density. Therefore, the fact that these criteria have a high weight value in the study has affected the result in this direction. However, these areas are disadvantageous in terms of cost. It should be considered that the OWF planned to be established here may be costly.

5. Conclusion

This study integrated the Bayesian BWM method with GIS to determine suitable areas for wind power plants. For this purpose, 17 criteria and experts from different disciplines were chosen under four main criteria. Literature review and study area characteristics were considered in determining the criteria. The criteria include wind speed, sea depth, submarine geomorphology, distance to power lines, and seismicity. These criteria were weighted in line with the experts' opinions. The output of Bayesian BWM was entered into the relevant criterion. The resulting map was created by applying the Weight Sum analysis method, one of the overlay tools in ArcGIS 10.8.

The framework of the study area has been divided into five classes to determine the suitable locations for the wind farm. "Extremely suitable" and "very suitable" classes suit wind power plant installation. The appropriate areas of the results of the conformity map produced in line with the determined criteria have come to the forefront as the areas that are affordable in terms of cost, accessible in terms of supply, high efficiency and partially close to energy consumption centers. As a matter of fact, at the stage of obtaining results, these outputs were compared with both existing resources and the characteristics of the study area, and this conclusion was reached. Therefore, according to the data of this study, these areas constitute ideal areas for wind power plant installation. On the other hand, the regions determined as "suitable" classes have the most significant part in the study area. These areas are not very suitable for cost and efficiency comparison. Finally, "less suitable" and "not suitable" classes are inappropriate for wind power plants.

Although the study contributes to the literature with GIS-based Bayesian-BMW integration, it has some limitations. By adding more criteria to the criteria determined in the study, the study can be enriched, and more precise results can be obtained. There are various types of wind turbines in wind power plants. Such technical information was not included in the study. Researching wind turbine types and getting technical knowledge will help determine the ideal wind turbine for suitable areas. This was another limitation of the study.

Declaration of competing interest:

The authors declare that they have no competing financial interests or personal relationships that affect the work in this article.

Author contribution: Z.K. contributed to data analysis, drawing of some maps and figures; Z.K., M.Y., M.G. contributed to introduction, application of the method, literature review, interpretation of results and production of figures.

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