



A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea

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Abstract Location selection for offshore wind farms is a major challenge for renewable energy policy, marine spatial planning, and environmental conservation. This selection constitutes a multi-criteria decision-making problem, through which parameters like wind velocity, water depth, shorelines, fishing areas, shipping routes,

environmental protection areas, transportation, and military zones should be jointly investigated. The aim of the present study was thus to develop an integrated methodology for assessing the siting of bottom-fixed offshore wind farms in two different countries (with different legal, political, and socio/economic characteristics). Our methodology combined multi-criteria decision-making methods and geographical information systems and was implemented in Cyclades (Greece) and in the sea area of İzmir region (Turkey). Experts used fuzzy sets and linguistic terms to achieve more consistent and independent rankings and results. In the Turkish region, the results showed that 519 km² (10.23%) of the study area is suitable for offshore wind farms, while in the Greek region, only 289 km² (3.22%) of the study area was found to be suitable. This spatial suitability analysis may contribute to provide some useful recommendations for the spatial marine planning at the regional scale, as well as for the preliminary assessment of new offshore wind farms in both countries.

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Introduction

The future challenge associated with the fossil fuel depletion and the concerns regarding climate change and its possible effects have persuaded governments to adopt a more sustainable energy model (Bartsch et al.

2000; Höök and Tang 2013; Tampakis et al. 2017). This shift to a more sustainable energy model is supported from investments and studies on renewable energy projects, such as hydro (Garegnani et al. 2018), solar (Tercan et al. 2020), wind (Uzar and Sener 2019; Enevoldsen et al. 2019), geothermal (Ghazvini et al. 2019), biomass (Ioannou et al. 2018), and wave (Vasileiou et al. 2017), in many developed and especially developing countries.

Wind power is one of the fastest-growing renewable energy technologies and offers a reliable, cost-efficient, and environmentally friendly way of producing energy. By the end of 2018, 11.7 GW of new wind energy has been installed in Europe, adding to the grid more capacity than any other form of power generation.. This growth is also supported by a new practice that allows wind energy power plants (WEPPs) to be installed within the marine space. The energy produced from offshore WEPPs in Europe was 2.7 GW and accounted for 23% of the gross annual installations' capacity during 2018 (Wind Europe 2018). The main reasons behind the growth of offshore WEPPs can be attributed to the high wind potential within marine areas, their minor environmental impact, and the lack of land space in some countries for the construction of onshore WEPPs (Esteban et al. 2011).

Offshore wind energy shares all the benefits of onshore wind energy in relation with conventional power sources but has also many advantages compared with its land-based counterpart. Winds in the marine space are usually stronger and more stable, resulting in higher energy generation per unit installed (Bilgili et al. 2011; Wu et al. 2018). Wind turbines at offshore WEPPs can also be greater due to the ease of transportation and the availability of vast areas that are suitable for major projects. On the contrary, onshore WEPPs are constrained to the ability to transport the wind farm parts, as well as the limited availability of space as a result of land-use conflicts. On the other hand, the construction of offshore WEPPs is more capital-intensive and involves higher risks and uncertainties that arise from the harsh conditions of the marine environment (Sun et al. 2012; Satir et al. 2018). The construction costs of offshore WEPPs increase significantly when they are installed in deep waters (e.g., deeper than 60 m) and far away from the coast due to foundation and cabling costs, respectively (Snyder and Kaiser 2009). Additionally, the operational and maintenance costs are higher when compared with their onshore counterparts

as a result of the logistical and safety issues, as well as the degradation of the wind farm materials (Staffell and Green 2014; Röckmann et al. 2017)

Choosing the optimal site for the construction and installation of WEPPs is an important and complex footstep in the planning process that is based on various economic, social, and environmental parameters and national regulation guidelines. The difference between onshore and offshore conditions plays an important role when considering the optimal site of WEPPs. Onshore WEPPs installation is usually restricted due to visual impacts (Bishop and Miller 2007), threats to bird life (Wang and Wang 2015), air traffic safety, noise impacts, and public acceptance (Mahdy and Bahaj 2018). Therefore, forests, agricultural areas (especially those of high productivity), tourism centers/attractions/landmarks, ecologically important areas (e.g., protected areas), protected landscapes, settlements and residential areas, major highways, railways and airports are excluded from the siting process. On the contrary, offshore WEPPs cause less environmental degradation and have less siting limitations (Kim et al. 2018). The areas that are excluded from siting offshore WEPPs are mainly offshore military forbidden zones, fishing areas, shipping routes, areas to be licensed for exploration and exploitation of hydrocarbons, special protected areas, and areas within the view of tourist/residence places in coastal areas (Vagiona and Karanikolas 2012; Chaouachi et al. 2017; Mahdy and Bahaj 2018).

Geographic information systems (GIS) are considered invaluable tools that allow decision-makers to evaluate the renewable energy potential regionally and determine the most suitable sites for onshore and offshore WEPPs (Pamučar et al. 2017). Several wind farm site selection studies combine multi-criteria decision-making (MCDM) methods and GIS applications to evaluate the economical, technical, and environmental applicable regions by visualizing and analyzing a big amount of spatial data related to the selected criteria (Latinopoulos and Kechagia 2015). In the literature, various studies have been undertaken to select suitable onshore WEPPs' location at different local, regional, and national scales using GIS and MCDM methods (Gorsevski et al. 2013; Azizi et al. 2014; Latinopoulos and Kechagia 2015; Sánchez-Lozano et al. 2016; Gigović et al. 2017; Ayodele et al. 2018; Díaz-Cuevas et al. 2018; Ioannou et al. 2019). Concerning the offshore wind farms, so far, various GIS-based explorations have been utilized to inspect the potential of offshore WEPPs

in different study regions (Martin et al. 2013; Wu et al. 2016; Cavazzi and Dutton 2016; Gadad and Deka 2016; Amirinia et al. 2017; Elsner 2019). However, there is limited literature about the site selection of offshore WEPPs by means of GIS-MCDM integration (Vasileiou et al. 2017; Mahdy and Bahaj 2018; Gavériaux et al. 2019; Stefanakou et al. 2019; Castro-Santos et al. 2020).

Among these studies, Vasileiou et al. (2017) have identified suitable locations for wave and wind energy plant investments in Greece and particularly in the Aegean Sea, using the analytic hierarchy process (AHP) and GIS. In this study, the criteria selected to determine the most suitable offshore WEPPs location included wind velocity, water depth, distance from shore, connectivity to local electrical network, number of people being served, ship traffic, and distance from ports. The results indicate that the potential areas for deploying offshore WEPPs in Greece are mainly located in the west and east of Crete, as well as in a lengthwise zone extended from north-central to central Aegean. Mahdy and Bahaj (2018) have identified appropriate sites for offshore WEPPs in Red Sea, Egypt, by using an integrated AHP-GIS approach. A few criteria, for example, shipping courses, ports, military zones, natural parks, links and pipe lines, angling zones, and oil and gas extraction zones, were utilized as prohibition criteria. Furthermore, in this study, bathymetry, soil properties, wind intensity, distance from shore, and distance from grid have been used as evaluation criteria for offshore WEPPs site selection. The exploration was directed at an enormous scale covering the entire of Egypt and its encompassing waters. The outcomes demonstrate that Egypt could possibly benefit from around 33 GW, which could be accomplished by just considering establishments at the high reasonableness seaward wind locales accessible. Gavériaux et al. (2019) present a combined cost analysis and a GIS-AHP-based methodological framework for offshore wind farm site selection in the Hong Kong bay. In this study, distance analysis (shorelines, flora and the fauna, recreation zones, ports, fishing areas, electrical grid in land), wind speed, and water depth have been used in order to evaluate the optimal marine sites for WEPPs.

The aim of the present study is to develop an integrated methodology for assessing the siting of offshore wind farms in two neighboring countries, Turkey and

Greece, with different legal, political, and socio/economic characteristics but with similar environmental characteristics. Within the framework of this methodology, multi-criteria decision-making (MCDM) methods and geographical information systems (GIS) will be used to determine suitable locations for offshore wind farms in the wider area of the Aegean Sea and specifically in the South Aegean region of Greece (Cyclades region unit) and in the sea area of İzmir region in Turkey. It should be also noted that the present study focuses in shallow water areas (< 70 m), offering economically and technologically feasible solutions in these areas.

A significant and unique aspect of the proposed study is the application of the same set of exclusion and evaluation criteria within two adjacent marine areas belonging to two countries, thus allowing a comparison between the offshore wind potential. Within each marine area (i.e., country), evaluation criteria were weighted by experts of each country, showcasing the importance each country places to each criterion. Hence, the proposed study is addressing an important issue that has not been fully examined in the existing literature, concerning the application of a common and holistic methodology for optimal utilization of renewable energy sources and optimal siting of offshore wind farms within adjacent marine areas, which takes into consideration economic, environmental, technical, land-use, societal, and aesthetical issues. Chaouachi et al. (2017) tried to address this issue for the case of three Baltic countries, but the relevant literature is still very limited. In addition, contrary to the three Baltic states examined by Chaouachi et al. (2017), in Aegean Sea, both Greece and Turkey have limited territorial waters and absence of an exclusive economic zone (EEZ) to deploy offshore renewable energy projects. Consequently, wind farms should be located quite close to beaches imposing thus several conflicts with pre-existing land uses. Our application can thus help (a) policy makers to enhance the legislative (marine spatial planning) instruments that determine the appropriate areas to place offshore WEPPs as well as (b) decision-makers to make more accurate decisions regarding investments in offshore wind projects. Additionally, it is an initial study on how countries with marine borders can exploit the offshore wind potential and share similar site selection processes, methodologies, and knowledge.

Study area

Turkey and Greece due to their geographical location and meteorological conditions are two countries with high offshore wind energy potential. This potential is situated in the Aegean Sea, which is a subdivision of the Mediterranean Sea among Turkey and Greece. Several studies that can be readily obtained in the literature highlight the potential of offshore wind energy in the Aegean Sea (Soukissian and Papadopoulos 2015; Soukissian et al. 2017; Vasileiou et al. 2017; Satir et al. 2018; Argin et al. 2019). Due to this, many researchers developed different methodological frameworks to evaluate the most suitable offshore wind farm locations (Vagiona and Karanikolas 2012; Argin and Yerci 2015; Vasileiou et al. 2017; Sourianos et al. 2017; Vagiona and Kamilakis 2018; Argin et al. 2019; Emeksiz and Demirci 2019; Stefanakou et al. 2019). However, there is a gap in the literature in regard to a framework that assesses the siting of offshore wind farms in both countries simultaneously. This endeavor requires primarily the analysis of the environmental characteristics of the Aegean Sea and then the exploration of the similarities and differences between the two countries' institutional frameworks (e.g., their marine spatial planning policy), as well as the different policy priorities.

The Aegean Sea is located in the northeastern Mediterranean. Turkey lies to the east and Greece to the north and west of the Aegean Sea, which covers an area of approximately 191,000 km² (Goksel et al. 2015). Aegean Sea is a shallow, elongate embayment (Yasar 2015) with hundreds of islands and thousands of islets and rocks. The Aegean Sea has very irregular coastlines and is an important center of world tourism (Besiktepe 2015). The delimitation of the regional waters in the Aegean Sea comprises a steady wellspring of contention and produces intermittent emergencies among Greece and Turkey. Both Greece and Turkey currently claim 6 nautical mile territorial seas in the Aegean. In Turkey, the total area of the study site is about 5078 km², while in Greece, the total area of the study site is 8969 km².

The wind climate of the Aegean is subject to winds associated with the cold outbreaks arriving from the north and cyclones arriving from the west as well as local and regional winds due to the influence of the orography (Besiktepe 2015). The proposed methodology is implemented in two areas. The sea area of İzmir region (Turkey) and the sea area between the islands of Mykonos, Naxos, and Paros (Greece) can be visualised

in (Fig. 1). It should be noted that the selected area in Greece is within the most appropriate marine regions for wind farm siting, as suggested by Vagiona and Kamilakis (2018).

Concerning the current energy situation, fossil fuels continue to dominate the national electricity mix in both countries. In 2018, 37.3% of Turkey's electricity production was obtained from coal, 29.8% from natural gas, 19.8% from hydropower, and 13.1% from renewable energy sources (MENR 2019). Respectively, in Greece, 19.9% of electricity was produced from lignite, 25% from natural gas, 9.2% from oil, 16.2% from hydropower, and 29.6% from renewable energy sources (HMEE 2018). Both countries are implementing policies to increase the penetration of renewable energy sources in their energy mix. The Turkish government is implementing an innovative policy based on renewable energy—particularly on wind and solar energy—to prevent risks arising from high-level fossil fuel use and to develop a sustainable energy model (MENR 2018). Similarly, the Greek government toward achieving the European binding target of at least 32% final energy consumption from renewable energy sources by 2030 is implementing a national renewable energy action plan to achieve the established target (HMEE 2018).

Regarding the institutional framework, Greece has already developed a legislative instrument for the spatial planning of renewable energy sources. Namely, the Special Framework for Spatial Planning for RES (SSPF-RES) is the main regulatory framework of Greece that determines the appropriate areas and the exclusion zones for the development of renewable energy projects (Baltas and Dervos 2012). On the contrary, in Turkey a corresponding legislative framework or regulation (about the spatial planning of RES) has not yet been established. So far, neither Turkey nor Greece has WEPPs in their marine space. Nevertheless, a number of offshore WEPPs are planned for development in Turkey. On the other hand, there are still no plans for offshore WEPPs in Greece, but several organizations have express strong interest in investing at the offshore wind sector.

Despite their diverse legal environment, a common goal of both countries is that their future investments on offshore WEPPs should maximize the potential benefits of wind power at the minimum (environmental) cost. Decision-makers should thus evaluate feasible sites for appropriate siting of offshore wind farms, i.e., sites that (a) minimize the associated environmental risks, (b)

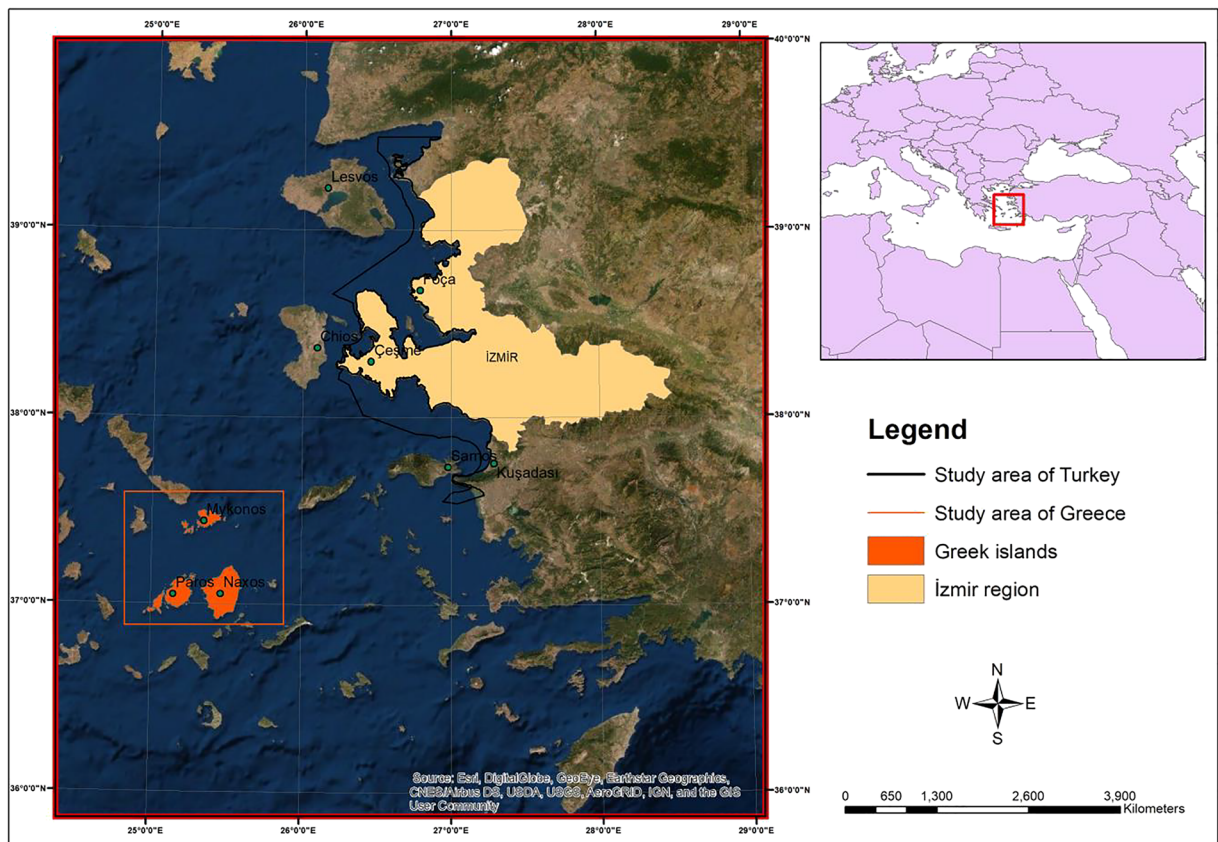


Fig. 1 Study regions

reduce local stakeholders’ opposition, and (c) increase the energy efficiency. In this context, a number of complex and usually conflicting criteria (economic, environmental, technical, social, political, etc.) should be taken into consideration in order to evaluate and select the most suitable and appropriate locations for siting offshore WEPPs in both countries (Fetanat and Khorasaninejad 2015; Wu et al. 2016; Chaouachi et al. 2017; Satir et al. 2018; Argin et al. 2019).

Material and methods

Data set

In İzmir region, for wind velocity layer, the Global Wind Atlas was used (WB. 2019). The World Bank and the International Finance Corporation have given this Wind Solar Atlas notwithstanding a progression of worldwide, territorial, and nation GIS information layers and blurb maps, to help the scale up of wind

control in every nation. In order to estimate the distances from shorelines, environmental protection areas and military forbidden zones, ports, fishing areas, and airports, the 1:100,000 scale İzmir-Manisa Environmental Plan was used. The water depth layer was prepared by digitizing the bathymetry sheet at a scale of 1:300,000. This bathymetry sheet was collected from the Department of Navigation, Hydrography and Oceanography in Turkey. Digitization, conversion, and analysis were performed using the ArcGIS commercial software (version 10.4.1).

The data sets and shapefiles used for the Greek study area were collected from a number of national and European official institutes/offices. The Hellenic Center for Marine Research (HCMR) provided the data layers for the wind velocity and the fishing areas. The Hellenic Nave Hydrographic Service (HNHS) provided the data layers for the Greek coastline, the water depth, and the areas that are forbidden zones due to military purposes. The shapefiles of the sub-cables, the airports, and the shipping routes were collected from the European

Marine Observation and Data Network and the existing renewable energy systems from the Greek Regulatory Authority for Energy (RAE). The data for the environmental protection areas (Natura 2000 areas) and the migration routes of birdlife were collected from the Greek open data catalogue (Geodata 2019) and the Hellenic Ornithological Society, respectively. The process, conversion, and analysis of the Greek data sets and shapefiles were also performed using the ArcGIS commercial software (version 10.2.2.)

Framework of land suitability decision-making

In this paper, the decision-making process for the identification of the optimal (bottom-fixed) offshore WEPPs sites includes four steps:

- (i) The first step is the exclusion of the areas that are incompatible with the development of offshore wind farms. International literature and the relevant national regulations were thoroughly examined, and several exclusion criteria were taken into consideration, such as wind velocity, sea depth, distance from shorelines, and distance from human activities and infrastructure.
- (ii) The second step is the evaluation of the potential areas, which resulted from the first step, using the selected multi-criteria method. Technical, economic, environmental and social criteria, such as visual effects, wind velocity, sea depth, distance from shorelines and distance from environmental protection areas, were used to evaluate the remaining areas. A group of experts was surveyed in each country (study area) in order to calculate the weights (i.e., the importance) of each criterion in the final site selection decision.
- (iii) The third step of the proposed methodology is the application of the MCDM model and the calculation of the suitability index (SI) for each study area.
- (iv) The fourth step is the presentation and discussion of the final results (i.e., of the offshore WEPPs suitability maps).

Evaluation and exclusion criteria descriptions

Several exclusion and evaluation criteria have been used in this analysis in order to develop the site selection

model for the future installation of offshore WEPPs. It should be noted that some of the criteria used to exclude the incompatible areas with the development of offshore wind farms were also used to evaluate the potential areas. More specifically, nine almost identical criteria were used in both study areas (countries). Two criteria were considered merely as evaluation criteria, one criterion only as exclusion criterion, and six criteria were used as both evaluation and exclusion criteria. The type of each criterion (evaluation and/or exclusion) and the buffer (exclusion) zones determined for each criterion are presented in Table 1. The reasoning for using each evaluation and exclusion criteria, which is determined by considering the relevant literature and expert opinions, is explained in detail in the following paragraphs. Criteria that are important but not relevant for the particular study areas (e.g., territories to be authorized for exploration and misuse of hydrocarbons) are not included in this analysis.

As already mentioned, the two countries differ on their coastal and marine (spatial) planning policy and legal framework. They also differ on their renewable energy (investment) policy. However, these differences are not so substantial as to require different evaluation and/or exclusion criteria. It should be also noted that the two study areas differ on their meteorological, environmental, and bathymetric conditions. These differences are important in the selection of the location of offshore WEPPs but do not affect the comparability of the study results. Therefore, the spatial evaluation of WEPPs at the regional scale of different countries enables a more accurate and case-specific decision. Most of the criteria presented in Table 1 are common among the two countries. However, there are some slight differences that can be attributed to different environmental characteristics (e.g., C_7 is deemed to be an evaluation criterion only in the Greek study area) or to data unavailability (e.g., there is no data availability for the criterion C_9 in the Turkish study area). All these details are explained in the following paragraphs.

C_1 (*wind velocity*) Wind velocity is directly linked with the energy production of WEPP and the financial return of the investment and therefore is one of the most important criteria in selecting the most suitable site (Cradden et al. 2016). The minimum average wind velocity determines the economic and technical feasibility of the WEPPs (Murali et al. 2014). According to several studies found in the literature, due to the high

Table 1 Criteria identification and buffer zones

A/a	Criteria	Type	Buffer zones (exclusion zones)
C ₁	Wind velocity	Evaluation and exclusion	< 6 m/sec
C ₂	Water depth	Evaluation and exclusion	> 70 m
C ₃	Distance from shorelines	Evaluation and exclusion	< 1.5 km, > 25 km
C ₄	Distance from shipping routes	Evaluation and exclusion	< 1 km
C ₅	Distance from environmental protection areas and military forbidden zones	Evaluation and exclusion	Only the boundaries of these areas (without buffer zone)
C ₆	Distance from ports	Evaluation	No buffer/exclusion zone
C ₇	Distance from important fishing areas	Evaluation and exclusion	Boundaries of important fishing areas
C ₈	Airports	Exclusion	< 2.5 km
C ₉	Sub-cables	Exclusion	< 250 m

costs of offshore WEPPS, areas with average wind velocity lower than 6 m/s should be deemed to be unsuitable and excluded from the evaluation (Vagiona and Karanikolas 2012; Cradden et al. 2016; Vasileiou et al. 2017; Sourianos et al. 2017).

C₂ (water depth) Water depth is associated with the offshore wind farm structure type and has significant techno-economic implications in the choice of the offshore wind farms’ location (Vasileiou et al. 2017). The greater the water depth, the higher the costs of construction, design, maintenance, control, and energy transmission (Chaouachi et al. 2017). Depending on the water depth of the installation area, the structure type can be fixed bottom or floating (Myhr et al. 2014). In the case of fixed-bottom offshore WEPPS, a quite limited water depth range (up to 60–70 m) is adequate for installations (Vasileiou et al. 2017). On the other hand, floating structures allow the development of offshore WEPPS in water depths greater than 200 m (Kausche et al. 2018). However, since the floating technologies are in the early stages of development and the costs associated are still significantly high, only the areas that the water depth is adequate for fixed-bottom structures will be taken into consideration. Therefore, offshore areas with water depth over 70 m are deemed to be unsuitable and thus excluded from further evaluation.

C₃ (distance from shorelines) Distance from shorelines is an important factor in determining suitable locations for offshore WEPPS. The shorter the distance, the lower the costs of submarine cables, maintenance, design, and construction (Snyder and Kaiser 2009). However, studies indicate that WEPPS are associated with negative

impacts on residential areas, such as mechanical and aerodynamic noise and visual effects (Wang and Wang 2015; Maslov et al. 2017). These negative impacts may cause deterioration of urban aesthetics, damage to habitats, and loss of real estate value (Sterzinger et al. 2003). The selected study areas are also well-developed (coastal) tourist destinations. Therefore, wind farms should be located away from the shoreline. In this framework, two buffer/exclusion zones are defined: (a) a minimum distance of 1500 m from the shoreline (to minimize residential/tourism impacts) and (b) a maximum distance of 25 km from the shoreline (to minimize the associated costs) (Mahdy and Bahaj 2018).

C₄ (distance from shipping routes) Shipping routes are deemed to be a competing use with the development of offshore WEPPS (Möller 2011; Caglayan et al. 2019). To ensure the safety of the maritime traffic and avoid land-use conflicts, offshore WEPPS should be sited at a safe distance (Murphy et al. 2011; Schillings et al. 2012). According to similar studies, areas that are closer than 1000 m from shipping routes should be excluded from the siting process (Möller 2011; Hong and Möller 2011; Kim et al. 2016).

C₅ (distance from environmental protection areas and military forbidden zones) Although WEPPS are generally regarded as environmentally friendly, there are environmental impacts associated with birds’ collisions and changes to benthic and pelagic habitats (Bailey et al. 2014; Wang and Wang 2015). Therefore, important birds and ecological areas should be taken into consideration during the selection process of offshore WEPPS locations. Such areas include NATURA 2000

areas, RAMSAR areas, wetlands, deltas, and region-specific coastal/marine environmental protection areas (e.g., *Monachus monachus* protection areas (Formigaro et al. 2017)).

In addition, military zones (i.e., zones of national defense interest and spaces of special military operations) should be also deemed to be exclusion zones in terms of (national) security. There has been always a conflict regarding the co-existence of offshore WEPPs and military zones, which usually include areas that are used for firing ranges, munitions dumping, military aviation exercises, and others (Schillings et al. 2012; Lindgren et al. 2013; Argin et al. 2019). In this study, military zones and environmental protection zones were taken as a single map layer (i.e., the boundaries of the exclusion zones are identical to the boundaries of military/environmental protection zones), while distance analysis was performed only as an evaluation criterion.

The most important wetland in the İzmir planning region is the Gediz Delta (the Bird Sanctuary of İzmir), which is the RAMSAR area of international importance. This RAMSAR area is also protected as a natural protected area and as a wildlife protection and development area (WPDA). The Gediz Delta creates a living space for wolves, foxes, jackals, martens, partridges, pigeons, and quails. At the same time, it is very rich in fish species and is a popular destination for migratory birds (EUM 2014). With an expected populace of < 700 people, the Mediterranean monk seal (*Monachus monachus*) has been classified by the International Union for the Conservation of Nature (IUCN) as imperilled (Karamanlidis and Dendrinis 2015) and is viewed as one of the most undermined marine warm-blooded creatures on the planet (Karamanlidis et al. 2016a, 2016b; Formigaro et al. 2017). Another important area in the Turkish region is Foça, which is a special environmental protection area known for its Mediterranean monk seal (*Monachus monachus*) (EUM 2014).

In Cyclades region, there are several areas that are part of the Natura 2000 network and recognized as Special Protection Areas (SPAs) and Sites of Community Importance (SCIs) (Regional Unit of South Aegean 2012). More specifically, there are 4 SPAs which cover approximately 112,209 ha of the sea and land area of the islands of Mykonos, Naxos, and Paros and 3 SCIs which cover more than 11,000 ha (European Environment Agency 2019). Of particular importance are those ecosystems which are sensitive with rich underwater life

and Posidonia beds. These ecosystems were found in two Natura sites in Cyclades: (a) Mikres Kyklades (GR4220013), which is situated south of Naxos island, and Nisoi Despotiko and Strongylo (GR4220017), which is situated southwest to the Paros island. All these areas were excluded from the WEPP site selection analysis¹.

C₆ (distance from ports) The distance from ports is used as a basis for assessing installation, construction, and ongoing plant operating costs (Cavazzi and Dutton 2016). Hence, offshore WEPPs should be located as close to ports as possible to minimize construction, maintenance, and rehabilitation costs. This criterion is used in this study only as an evaluation criterion because the zone restrictions are already imposed by means of *C₃* and *C₄*.

C₇ (distance from important fishing areas) The distance from important fishing areas is an important criterion that is used to minimize land-use conflicts (Yue and Yang 2009; Schillings et al. 2012). Fishing activities in Turkey are usually in the form of coastal fisheries. In this study, a minimum distance of 1.0 km buffer zone was well-defined from the coastlines (*C₃*), which also serves as an exclusion criterion that protects the coastal fishing activities². Contrary to the Turkish study area, in Greek offshore areas, *C₇* was used as both exclusion and evaluation criterion. Exclusion areas were determined according to maps of the most important fishing areas, which were provided by the Hellenic Center for Marine Research (HCMR)³.

C₈ (airports) Proximity to airports should be taken into consideration during the site selection process due to safety and visibility (Gigović et al. 2017). To minimize these adverse effects, offshore WEPPs should be located at a safety distance from airports (Argin and Yerci

¹ The newly established Cyclades Protected Areas Management Body (CPAMB), according to recent regulation (Law 419 of 20/2/2018), has full responsibility for the management of all these protected areas.

² It should be noted that the main fishing grounds in Turkish territorial waters in the Aegean Sea are located in Çandarlı Bay, İzmir Bay, Sığacık, and Kuşadası Bay (Kınacıgil and Ilkyaz 2012; Keskin et al. 2014). Angling exercises in this whole locale are spatially constrained because of the restricted mainland rack, the precarious slant, and its geomorphological qualities (Ismen et al. 2015).

³ In Cyclades, fishing is also a really important economic activity, which occupies a large number of employees (Tzanos et al. 2005; Payne et al. 2009). The main fishing grounds in the Greece territorial waters are located at the surrounding sea areas of Naxos and Paros.

2015). In this present study, areas within 2500 m from airports are considered unsuitable and are excluded from further assessment (Voivontas et al. 1998; Nguyen 2007).

C₉ (sub-cables) Underwater cables are a possible site obstruction that might cause accidents during the development and operation of offshore WEPPs (Saleous et al. 2016). In Cyclades region, telecommunication sub-cables are located at the sea area between the islands Paros, Naxos, and Mykonos, while electricity sub-cables connect the islands with Greek’s mainland. Areas within 250 m from sub-cables are excluded from the assessment (Saleous et al. 2016).

Representation of criteria as fuzzy sets

The chosen evaluation criteria are represented as fuzzy sets, utilizing the fuzzy sets hypothesis (Zadeh 1965). The membership functions of these fuzzy sets are utilized to estimate the individual fulfillment degree for a specific factor for every potential site (grid cell). These are actually functions characterizing the grade of membership of a factor *z* in the fuzzy set, by taking values between zero (0 = not fulfilled) and one (1 = fully fulfilled). Different types of membership functions can be utilized to portray these fuzzy sets. In this study, a linear function was utilized, with the goal that individual fulfillment degrees can be scientifically expressed by Eq. (1) (benefit criteria) or Eq. (2) (cost criteria). It ought to be noticed that for each factor, there is a lower threshold value (control point) *q* demonstrating its least suitable value and an upper edge esteem *p* showing that all values beyond this point are the most appropriate/suitable ones (Latinopoulos and Kechagia 2015).

Increasing fuzzy function: $\overline{MF}(z_i)$

$$= \begin{cases} 0 & \text{for } z_i < q_i \\ \frac{z_i - q_i}{p_i - q_i} & \text{for } q_i \leq z_i \leq p_i \\ 1 & \text{for } z_i > p_i \end{cases} \quad (1)$$

Decreasing fuzzy function: $MF_-(z_i)$

$$= \begin{cases} 1 & \text{for } z_i < p_i \\ \frac{z_i - q_i}{p_i - q_i} & \text{for } p_i \leq z_i \leq q_i \\ 0 & \text{for } z_i > q_i \end{cases} \quad (2)$$

Linear increasing functions were used for the factors of wind velocity (*C₁*), distance from shorelines (*C₃*),

distance from shipping routes (*C₄*), distance from environmental protection areas and military forbidden zones (*C₅*), and distance from important fishing areas (*C₇*). On the contrary, linear decreasing functions were used for water depth (*C₂*) and distance from ports (*C₆*). Table 2 systematically displays the fuzzy set memberships and membership functions, as well as the control points utilized for all factors determining the suitability of a WEPP. Moreover, the membership functions for the fuzzy representation of all evaluation criteria are outlined in Fig. 2a–f.

The selected range of the membership values is based on the different values assigned to the criteria in the existing literature (e.g., Yue and Yang 2009; Schillings et al. 2012; Vagiona and Karanikolas 2012; Cradden et al. 2016; Sourianos et al. 2017; Vasileiou et al. 2017). The maximum values to the linear increasing functions correspond to the conservative values found in the literature while the minimum values to the more lenient (less strict) ones. The same approach was adopted to assign the values to the linear decreasing functions⁴.

The following step in this examination was to transform the membership functions to thematic map layers, i.e., to suitability maps. In this context, the spatial information from each factor was represented as a fuzzy set by applying the membership functions in each grid cell, by utilizing the ArcGIS programming. The result of this strategy is to connect every grid cell with a “degree of fulfillment” for every evaluation criterion and afterward to map these values on a corresponding standardized map layer. Figures 3 and 4 illustrate the suitability maps, as generated in both countries.

Fuzzy AHP

AHP is a powerful decision-making approach to determine the priorities among various and contradictory factors (Saaty 1987; Torfi et al. 2010). This approach is a substantial essential strategy especially when subjectiveness exists what is more. Fuzzy set theory was presented to improve more simplistic

⁴ For example, in the literature, some studies require 5 km distance from environmental protection areas, while others 1 km (Yue and Yang 2009; Vagiona and Kamilakis 2018).

Table 2 Membership values/functions and control points

A/a	Criteria	Type	Membership function	q	p
C ₁	Wind velocity	Benefit	\overline{MF}	6.5 m/s	8 m/s
C ₂	Water depth	Cost	\underline{MF}	60 m	30 m
C ₃	Distance from shorelines	Benefit	\overline{MF}	2 km	5 km
C ₄	Distance from shipping routes	Benefit	\overline{MF}	2 km	3 km
C ₅	Distance from environmental protection areas and military forbidden zones	Benefit	\overline{MF}	1 km	5 km
C ₆	Distance from ports	Cost	\underline{MF}	25 km	1.5 km
C ₇	Distance from fishing areas (only applied in Cyclades study area)	Benefit	\overline{MF}	1 km	5 km

models and thus to evaluate the complex problems of the real world. Zadeh (1965) described a fuzzy set as follows: A fuzzy set of A; matching the real number between each point in X and $[0,1]$; and characterized by the function $\mu_A(x)$. Thus, fuzzy sets; existing sets only when they run with membership functions. The decision-making procedure involves uncertainty. This uncertainty may arise from verbal knowledge and subjective opinions. Producing analytical solutions with fuzzy logic enables more flexible decision-making. By applying fuzzy logic, some information presented verbally is converted into numerical equivalent data sets. Based on fuzzy theory, fuzzy AHP (FAHP) is one of the most commonly used MCDM methods (Yager 1978; Buckley 1985; Chang 1996). Buckley (1985) determines the fuzzy priorities of comparison rates whose membership functions are trapezoidal. In this study, Buckley FAHP method is preferred, and other methods are applied because of lack of information and important limitations such as irrational zero weight in criteria selection. Fuzzy numbers can better reflect expert judgment based on specific criteria based on actual values, and fuzzy numbers make it easier for decision-makers to evaluate to achieve the main goal. Buckley fuzzy weights are indicated by fuzzy trapezoid numbers and used geometric mean in their calculations. The stages of this approach are as follows (Buckley 1985):

Stage 1 Identification of comparison matrices. Pairwise comparison matrices are constructed with regard to the hierarchy system. The trapezium fuzzy number element

of each cell contained in the matrix is given in Eqs. (3) and (4).

$$M = \begin{bmatrix} 1 & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & 1 \end{bmatrix} = \begin{bmatrix} 1 & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \dots & 1 \end{bmatrix} \quad (3)$$

$$a_{ij} : \begin{cases} 1, 3, 5, 7, 9 & \text{comparison of criterion } (i, j) \\ 1, \frac{1}{3}, \frac{1}{5}, \frac{1}{7}, \frac{1}{9} & \text{comparison of criterion } (j, i) \end{cases} \quad (4)$$

Stage 2 Normalization and calculation of weight vector. For the calculation of the weight vector, the geometric mean of each row in the matrix is taken, and the normalization process is performed by dividing the sum of all rows. Fuzzy performance values are calculated with Eq. (5).

$$r_i = [a_{i1} \oplus a_{i2} \oplus a_{i3} \dots \oplus a_{in}]^{1/n} \quad (5)$$

\oplus symbol represents fuzzy collection.

Stage 3 Calculation of fuzzy weight and fuzzy performance values. Fuzzy performance values and fuzzy weight values are obtained by Eq. (6).

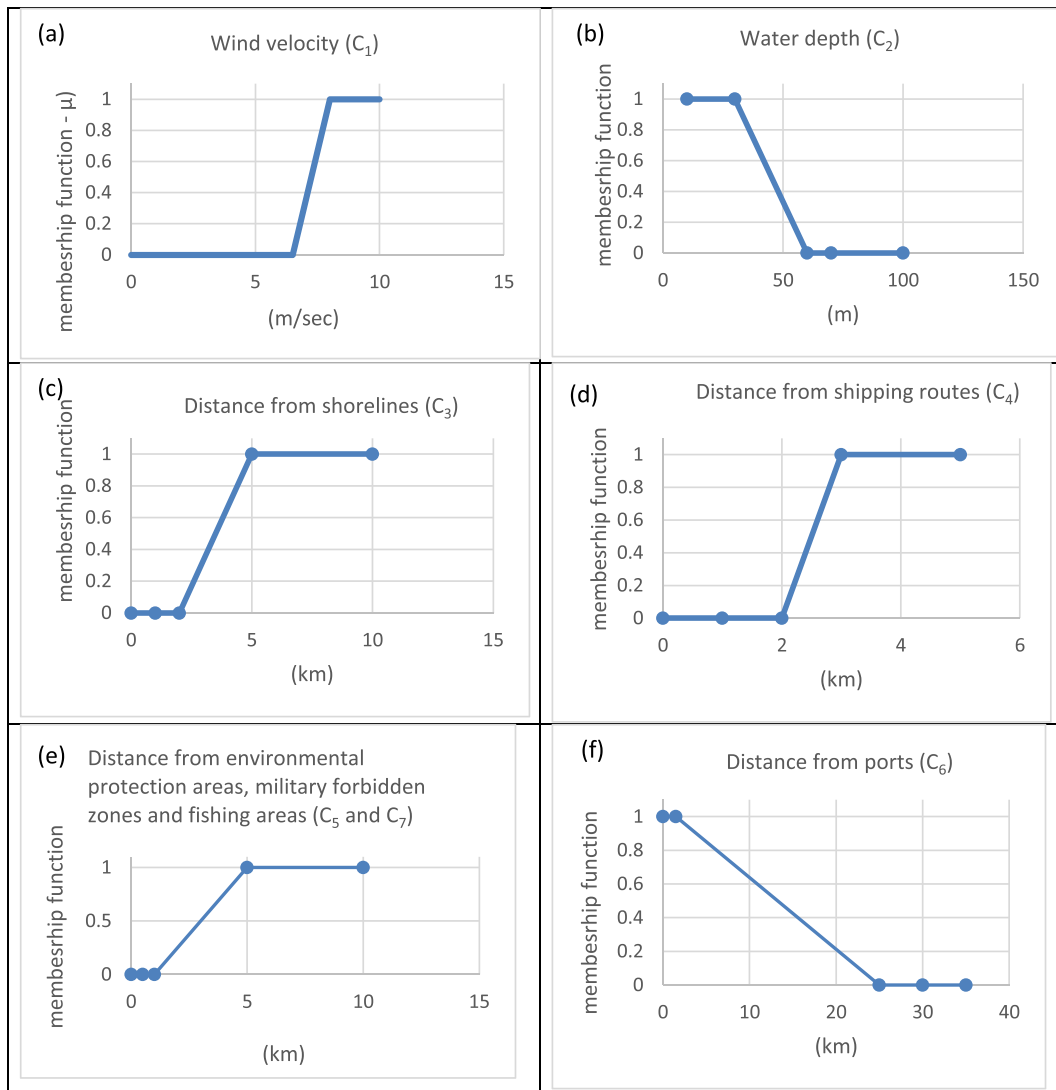


Fig. 2 Fuzzy sets for all evaluation criteria: (a) wind velocity (m/s); (b) water depth (m); (c) distance from shorelines (km); (d) distance from shipping routes (km); (e) distance from

environmental protection areas, military forbidden zones, and important fishing areas (km); and (f) distance from ports (km)

$$w_i = [r_1 \oplus (r_2 \oplus r_3 \dots \oplus r_n)^{-1}] \tag{6}$$

where w_i represents fuzzy weight of criterion i

In order to find out the best non-fuzzy performance, center of area (CoA) method is used as given in Eq. (7).

$$w_i = \frac{[(uw_i - lw_i) + [(mw_i - lw_i)]]}{3} + lw_i \tag{7}$$

where lw_i is the lower value of fuzzy weight of criterion i , mw_i is the middle value of fuzzy weight of criterion i , and uw_i is the upper value of fuzzy weight of criterion i .

Buckley’s FAHP method is applied to determine the importance weights of each parameter for offshore WEPPs location selection. Linguistic terms and corresponding fuzzy values for evaluation of criteria are used (Table 3) in order to evaluate the relative significance of the criteria.

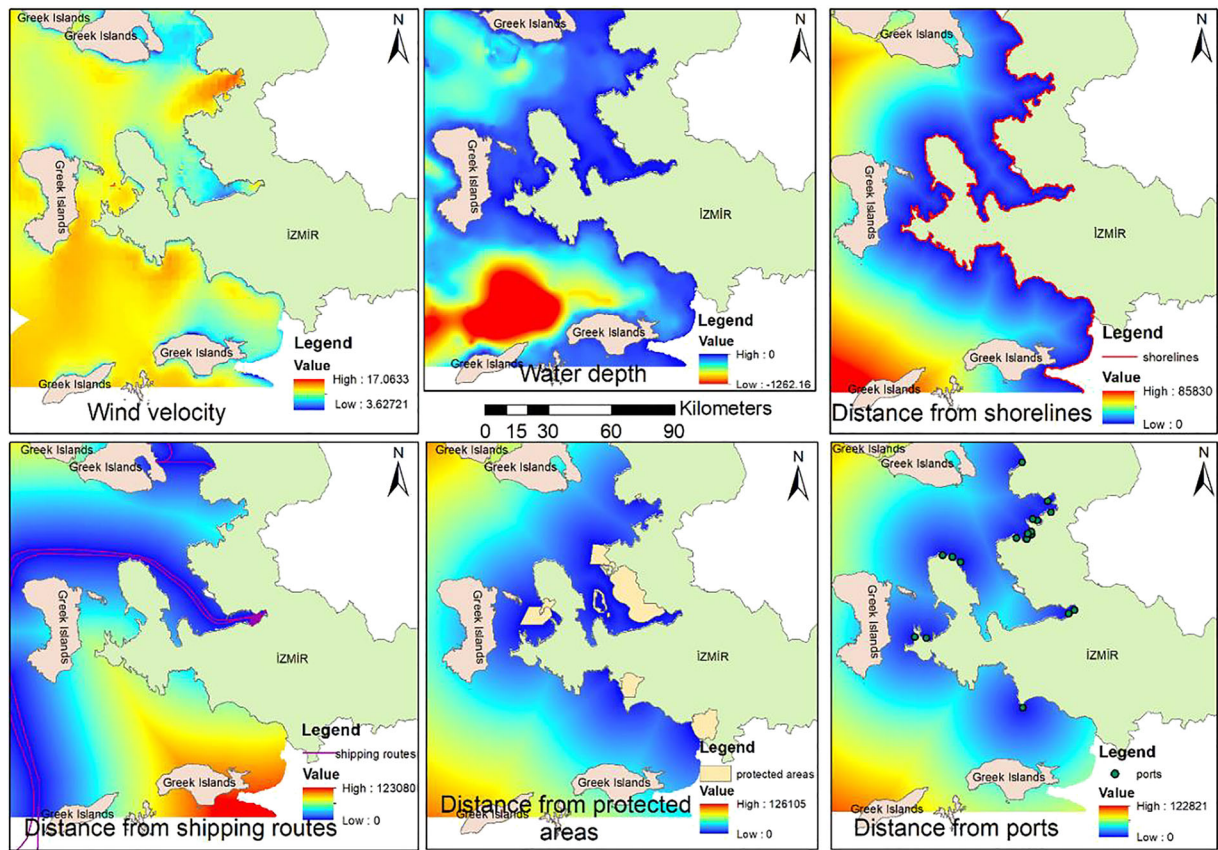


Fig. 3 Standardized suitability maps for the factors of: wind velocity, water depth, distance from shorelines, distance from shipping routes, distance from protected areas and military forbidden zones, and distance from ports in Turkish region

Weighted linear combination (WLC)

WLC approach was used for the multi-criteria location selection model. In this approach, each parameter (criterion) is multiplied by a certain weight, and the final results are summed—using map algebra—to obtain the result suitability index (Latinopoulos and Kechagia 2015). The WLC depends on joining the weighted averages of the selected parameters (criteria). Every parameter is characterized and duplicated together with its allotted weight and in a GIS overlay condition; weighted midpoints are added to get the final evaluation map. The total scores can be selected for suitability or sensitivity assessments for any study objective (Michael and Samanta 2016; Tercan et al. 2020). The higher the score, the better the site for a WEPP. In order to combine all evaluation criteria, Eq. (8) was used (adapted from Malczewski (2000)):

$$O_{WE}SI_i = \sum_{j=1}^n W_j x_{ij} \quad (8)$$

where $O_{WE}SI_i$ is the *offshore wind energy suitability index* for cell i , W_j is the relative importance weight of criteria j , x_{ij} is the standardized score of cell i for criteria j —as resulted from the standardized suitability maps (Figs. 3 and 4)—and n is the total number of criteria Malczewski (2000). In order to take also into consideration the exclusion criteria, it is necessary to include in Eq. (8) Boolean (true/false) constraints that may apply in each location. These constraints are actually included by assigning a zero value to any criterion, which for a given location, is not met (i.e., to any location which lies inside an exclusion zone/area). The estimation of the weight factors (W_j) is presented in the following section.

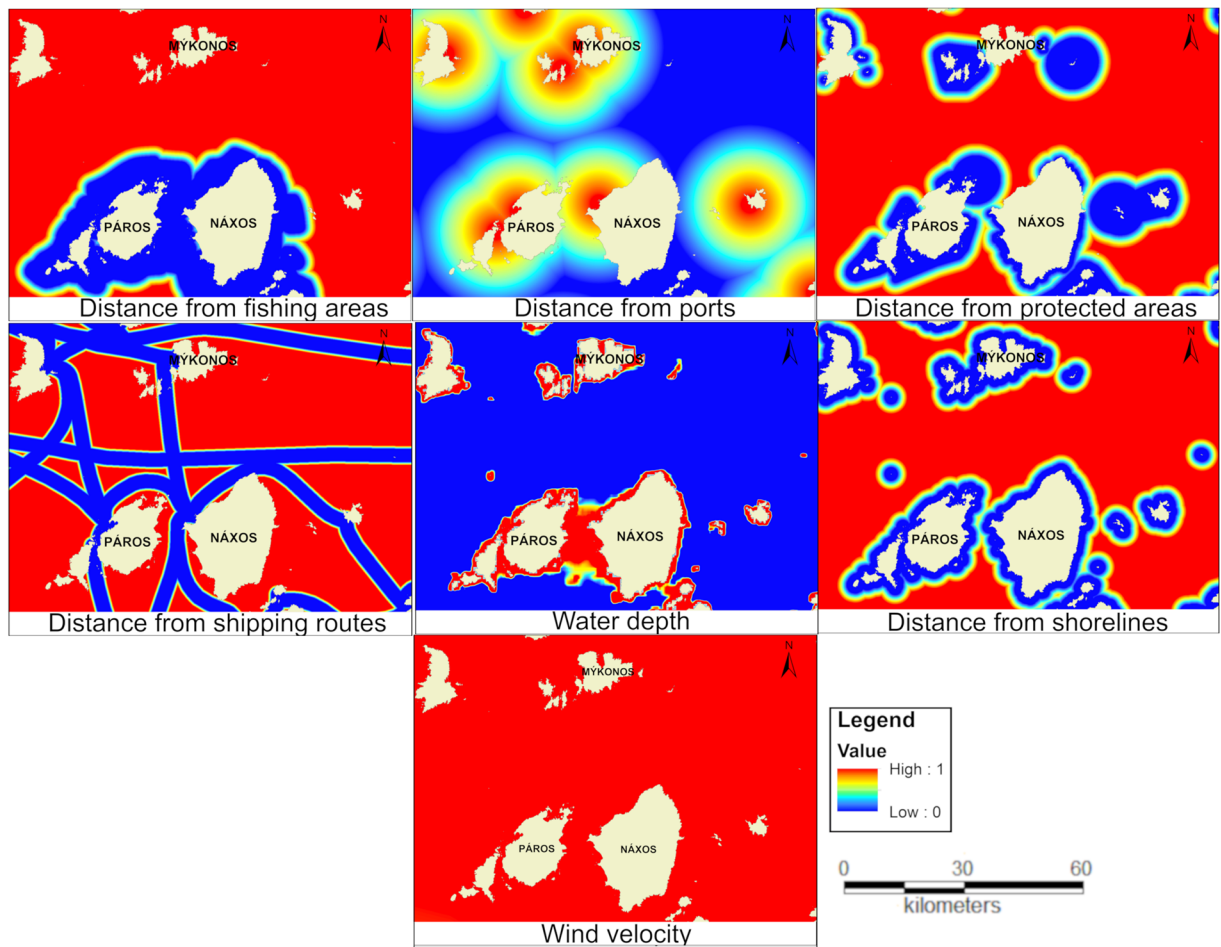


Fig. 4 Standardized suitability maps for the factors of: wind velocity, water depth, distance from shorelines, distance from shipping routes, distance from protected areas and military forbidden zones, distance from ports, and distance from fishing areas in Greek region

Results and discussion

Weighting results

In Turkey region, a decision model, consisting of 6 evaluation criteria, was used to select the relevant marine areas for offshore WEPPs. Simple pairwise comparisons were performed by using Buckley FAHP. The total number of pairwise comparisons is 15. City and regional planners, environmental engineers, and the authors have evaluated the selected criteria according to their expertise and experiences. After utilizing Buckley’s FAHP, the fuzzy evaluations of each criterion was done, and the evaluations of the experts in linguistic variables for the set of criteria were obtained. These

Table 3 Linguistic terms and corresponding fuzzy values

Linguistic terms	Fuzzy values
Absolutely strong	(2, 5/2, 3)
Very strong	(3/2, 2, 5/2)
Fairly strong	(1, 3/2, 2)
Slightly strong	(1, 1, 3/2)
Equal	(1, 1, 1)
Slightly weak	(2/3, 1, 1)
Fairly weak	(1/2, 2/3, 1)
Very weak	(2/5, 1/2, 2/3)
Absolutely weak	(1/3, 2/5, 1/2)

evaluations were subsequently converted into triangular fuzzy numbers. Then, the aggregated fuzzy ratings of each criteria types are calculated to determine the fuzzy decision matrix. The aggregated evaluations in fuzzy form and fuzzy weights of parameters are presented in Table 4. In particular, the third column in Table 4 shows the corresponding eigenvectors (i.e., relative weights). In this study, FAHP application and pairwise comparison matrices can be considered appropriate since the consistency ratio was lower than 0.1.

In the Greek region, the decision model consists of 7 evaluation criteria. Twenty-six experts in the field of offshore wind farms and marine spatial planning, including academics, scholars, and researches (from Greek and European institutions), were selected. A short-structured questionnaire was designed and administered in order to rate the most important criteria for offshore wind farm site selection. A 9-level Likert scale was used to rate the importance of each criterion (1 = no significant; 9, extremely important). The median value of the score distribution was used as the weighing factor of each criterion. These factors are then normalized in order to estimate the final weights. The results of this procedure are depicted in the fourth column of Table 4, while the last column estimates the differences in weights assigned to the selected criteria by the two countries' groups of experts.

In the Turkish region, the criteria affecting the offshore WEPPs location selection have the following ranking order $C_1, C_2, C_6, C_5, C_3, C_4$. Namely, the most important one is the wind velocity, followed by the water depth and the distance from ports. Therefore, it can be concluded that Turkish experts are highly prioritizing the cost/feasibility criteria. On the other hand, in the Greek region, the ranking order of criteria is as

follows: $C_3, C_1, C_2, [C_4, C_5, C_6], C_7$ (the brackets indicate that those three criteria are equally important). So, the main difference between the two group of experts (i.e., between the two countries) is the higher priority given by the Greek experts to the distance from shorelines criterion, which indicates a higher importance on minimizing the visual impacts on the well-developed tourist areas of the selected Islands. The rest of the evaluation criteria weights have slight differences, while the C_7 criterion, which used only in the Greek study area, was found to be the least important by the Greek experts.

Offshore WEPPs suitability maps

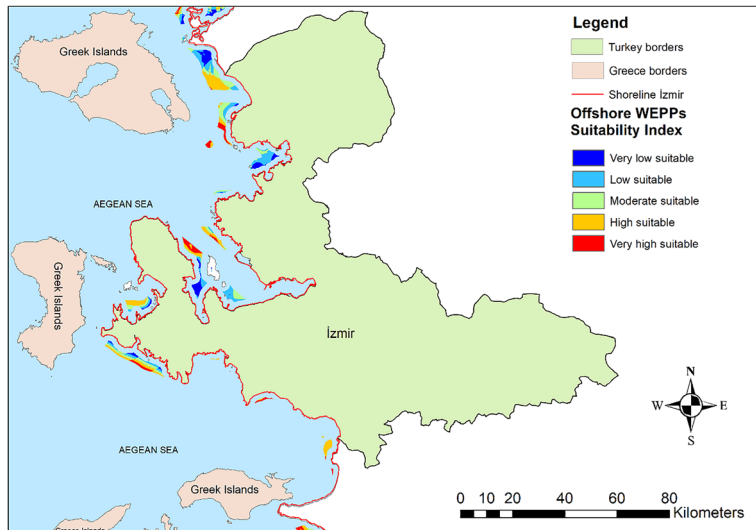
The WLC method was then performed with the weighted overlay function available in the ArcGIS spatial data analysis tool in both study areas. Figure 5 presents the final suitability maps of GIS-based fuzzy MCDM method in Turkey region, and Fig. 6 presents the final suitability maps in the Greek region. Suitable sites of the study area are graded between high and low potential. In the Turkish study area, after excluding all the above-mentioned limiting factors (exclusion zones) from the study area, 519.2 km² (corresponding to about 10.23% of the study area) was determined as suitable. In Greece, due to the greater water depth, the suitable area is relatively smaller, as only 289 km² (corresponding to about 3.22% of the study area) is found as appropriate for offshore wind energy power plants.

In both countries, tourism infrastructures and activities in the coastal areas were considered very important, so it was proven to be more than necessary to preserve the regional/local tourism potential and the urban/coastal aesthetics. In order to protect these tourist

Table 4 Criteria weights used in the GIS model

A/ a	Criteria	W_{Turkey}	W_{Greece}	Differences ($W_{\text{Turkey}} - W_{\text{Greece}}$)
C_1	Wind velocity	0.2531	0.1667	0.0864
C_2	Water depth	0.1986	0.1429	0.0557
C_3	Distance from shorelines	0.1314	0.2380	- 0.1066
C_4	Distance from shipping routes	0.0911	0.1190	- 0.0279
C_5	Distance from environmental protection areas and military forbidden zones	0.1500	0.1190	0.0310
C_6	Distance from ports	0.1759	0.1190	0.0569
C_7	Distance from fishing areas	0 (not included)	0.0950	- 0.0950

Fig. 5 Offshore WEPPs suitability maps in the Turkish region

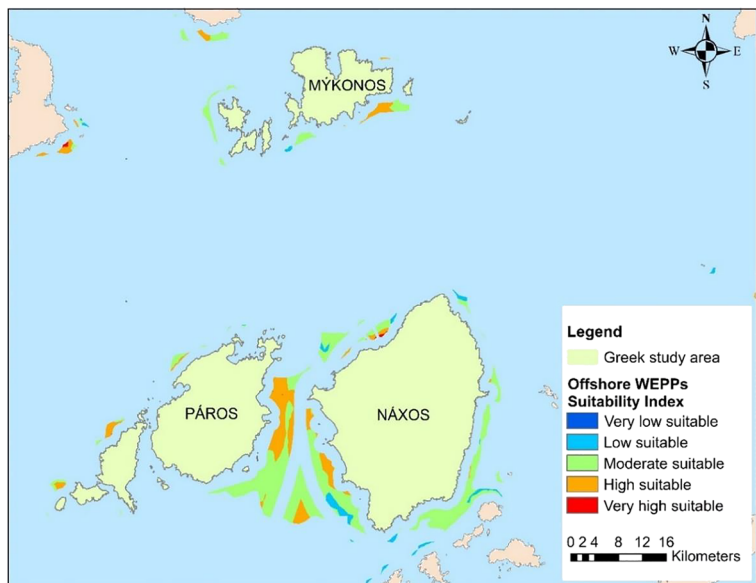


attractions and to sustain regional tourism development, the exclusion of marine areas within a certain distance (1.5 km) from the shore seems to be one of the most important parameters (exclusion criterion). In Izmir region (Turkey), the distance from shores criterion limited considerably the number and the total area of suitable sites. Likewise, in the Greek study area, following the water depth criterion, distance from shore was the second most important exclusion criterion, which reduced the potential areas for offshore WEPPs development. Other important limiting factors in both regions/

countries are the narrow territorial waters and the extensive marine areas which are designated to protect the marine flora and fauna (e.g., the Mediterranean monk seals in Izmir region).

Concerning the evaluation criteria, the minimum water depth is considered (due to physical constraints but also due to experts' ranking) as the most important criterion in the Turkish region, in order to reduce construction, maintenance, repair, and transportation costs. On the contrary, in the Greek islands under study, the most important evaluation criterion was the distance

Fig. 6 Offshore WEPPs suitability maps in the Greek region



from the shore (in order to preserve the landscape and to minimize impacts on local tourism). However, it should be noted that these two criteria are somehow interrelated but also conflicted criteria in both areas because, as moving away from the shore, the water depth is increasing. So, it is crucial to find a satisfactory balance between these two criteria in the search of the optimal location/siting of offshore WEPPs.

It should be also noted that in both study sites, the less restrictive criterion is the wind power (wind velocity), which is deemed to be very important from both countries' groups of experts. Nevertheless, despite this high wind speed potential (not only in our study areas but throughout the Aegean Sea), investments in offshore wind farms have not yet been made in either country. Specifically, in Turkey, offshore WEPPs support policies are not yet sufficient, and the relevant regulation should change in order to support/promote future investments in offshore wind energy. Financial motivations and open market, which are generally utilized in the EU nations, ought to be acquainted by the legislature with the help of offshore wind power ventures (Satir et al. 2018). On the other hand, despite the fact that these incentives are present in Greece (i.e., there is a satisfactory financial support mechanism for the promotion of renewable energy systems), there are still several barriers for investing in offshore wind energy. The most important (and commonly reported) one is the lengthy and complicated licensing procedure in wind energy (a simplification and redesign of the licensing process are necessary). Another issue, which poses significant economic constraints (problems), is the poor connection of the Aegean islands to the mainland grid. Finally, the development of offshore wind farms is a capital-intensive activity/investment which necessitates a stable investment and institutional environment, which was not the case in Greece during the last decade, due to the economic crisis that the country has experienced.

Conclusions and future recommendations

The high wind speed potential in the Aegean Sea will be the focus of attention for many local, national, and international investors in the near future. So, the aim of this study was to organize and make use of a systematic GIS-MCDM-based integrated approach on both regional and international scale to determine the optimal regions for the selection of offshore WEPPs. Thus, the

main contribution/strength of this study is the development of an integrated methodology for evaluating the siting of offshore wind farms using the same exclusion and assessment criteria within two adjacent marine areas belonging to two countries with high wind energy potential. Specifically, we applied our method in Cyclades (Greece) and in the sea area of İzmir region (Turkey). By using this approach, a number of complex and contradictory factors/criteria have been considered in order to find the optimal locations for offshore WEPPs. A number of marine sites/regions were first excluded, as unsuitable, based on a large number of factors selected for both areas (i.e., fishing areas, water depth, wind velocity, military forbidden zones, environmental protection areas, natural habitat, sub-cables, shipping routes, important bird areas, tourism activities, transportation costs). The most important exclusion criteria for each study area (country) were then detected. Subsequently, a number of evaluation criteria were jointly used in both countries to generate a suitability map for each region. Both physical constraints and experts' views were found quite similar in both study areas (countries), showing that both countries are facing common challenges and common problems related to the investment in offshore wind energy.

Our results indicate that, despite all the limiting factors, several marine areas have excellent potential for offshore WEPPs. Consequently, offshore WEPPs investments may be economically feasible and technically viable by exploiting existing technologies regarding offshore installations. Another strength of this study is that the offshore WEPPs' spatial suitability analysis adopted and discussed herein may provide some useful recommendations for the preliminary assessment of new offshore WEPPs, as well as for spatial marine plans and zoning for RES at the national and/or the regional scale in both countries. This approach can also provide a common/transnational decision support system that will be able to investigate complex spatial (marine) location problems and to produce a marine spatial planning strategy for decision-makers. After all, unlike fossil fuel exploitation/exploration (oil and gas), joint research and sharing on knowledge on the use/installation of renewable energy sources are opportunities for trustful and sustainable cooperation in the maritime space of the two countries.

A number of extensions to the present methodology could be considered for future studies in order to address the weakness of the present manuscript. These

extensions could be in terms of spatial level of analysis, energy production, weighting factors, and offshore wind farm structure/foundation type. For example, future studies could incorporate more criteria which were omitted from this study, such as seismic fault zones, rocky areas, areas with extreme meteorological conditions, ecological corridors, and radar corridors. In addition, an integrated future study could be carried out: (a) in a common cross-border marine area (as our two study areas are not adjacent), (b) by using the exact same weighting factors to allow better comparison of the marine areas, and/or (c) by taking into account the floating wind power plants' technologies which are now becoming cost-effective (i.e., by evaluating higher water depths, excluded in the present exploration).

In order to improve the performance of our results, it would be also useful to make more detailed (i.e., small-scale) feasibility analysis at appropriate offshore WEPPs regions. The proposed (WEPPs) investments should be also further evaluated at both regional and national level, according to their potential to cover the energy demands of the two study areas, as well as to contribute to the Greek and Turkish energy grid, respectively.

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Compliance with Ethical Standards

Conflict of interest All authors states that there is no conflict of interest.

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