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Marine Suitability Assessment for Offshore Wind Farms' Deployment in Thrace, Greece

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Abstract: The exploitation of renewable energy resources is an effective option to respond to climate change challenges. Wind energy can be exploited more efficiently and effectively than any other renewable energy source. By switching from onshore wind energy projects to offshore, the positive aspects of onshore wind energy remain and, at the same time, no valuable onshore area is occupied, while their efficiency (e.g., capacity factor) is increased. Greece has a rich wind potential and the maritime region of Thrace is one of Greece's maritime regions with the greatest potential for the development of offshore wind energy. The aim of the present paper is to identify the most appropriate sites for the deployment of offshore wind farms in the region of Thrace. The methodology includes (i) the delineation of the study area and the definition of the support structure of the wind turbine, (ii) the identification of seven (7) exclusion and fifteen (15) assessment criteria, (iii) the suitability analysis under five different zoning scenarios (equal weight, environmental, social, techno-economic, and researchers' subjective), and (iv) the micro siting and qualitative assessment of the most suitable sites based on energy, environmental, social, and economic criteria. The methodology is based on the combined use of Geographical Information Systems (GISs), specifically ArcGIS Desktop version 10.8.1, wind assessment software tools (WaSPs), specifically WaSP version 12.8, and multi-criteria decision-making methods. The results of the paper illustrate that the optimal suitability area that is proposed for offshore wind farm deployment is located at the easternmost end of the Greek part of the Thracian Sea. The planning and the deployment of offshore wind farm projects should follow a holistic and environmentally driven approach to ensure the integrity of all habitats and species affected.

Keywords: offshore wind farms; environmental impact; exclusion criteria; assessment criteria; economic criteria; social criteria; energy analysis; site selection process; suitability assessment

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1. Introduction

The utilization of wind energy is gradually but steadily shifting towards the marine area, where there is access to stronger and more stable winds [1]. While the production of clean energy is increasing, some technical, environmental, and social challenges arise, especially those with long term effects, and are yet to be sufficiently researched.

There are two types of technologies currently available in marine areas—fixed-bottom offshore and floating offshore. The main difference is that the first one is economically profitable in marine areas with depths of up to 60 m and the second one is profitable at depths between 60 and 1000 m [2].

The overall impact of such a project, economically, socially, and environmentally, depends on its final size. The cumulative effects from the higher number of WTs of an offshore wind farm (OWF) or that of a dozen smaller OWFs in close proximity to each other, are a major cause of negative impacts [3]. A 20-turbine OWF will have a lower cumulative impact than a 100-turbine OWF, in all aspects concerned.

The utmost attention should be concentrated on the numerous effects of such a project. Findings of high scientific importance can be drawn from the sequencing of the impacts. Even a smaller-scale pilot level implementation will have a major footprint on the three fundamental pillars—environment, economy, and community.

For OWFs, the negative impacts are divided into two main categories, those with significant effects on marine biodiversity and those with significant effects on avifauna. For marine biodiversity, severe impacts occur during the construction and decommissioning phases of the project, due to anthropogenic noise, habitat loss, and fragmentation. Regarding the avifauna, the most notable environmental impacts happen during the operational phase and are associated with the potential for birds to collide with turbine blades or towers. Therefore, it is only logical that the best possible practices and mitigation techniques should be adopted, to reduce negative impacts. For the optimal siting of future OWFs in Greece's territorial waters, the first pilot projects ought to be equipped with extensive monitoring and evaluation programs, so as to gain experience, which should be presented in the form of guidelines and instructions, avoiding general undesirable impacts and providing help in assessing environmental impacts in the long term.

On an economic level, the administrative region will benefit and new jobs will be created in different fields, such as technical/maintenance, safety, and monitoring of bird and marine fauna behavior. Regarding the community, on a social level, issues could arise which affect local people, such as fishermen, and tourism activities. Moreover, other issues may emerge such as the change of the vessels' routes and the visual/acoustic disturbances caused to the inhabitants of the areas where the OWF will be installed.

There are several studies found in the international literature that investigate suitable or even the most sustainable sites for offshore wind farm (OWF) deployment (e.g., [4–21]), using various exclusion and assessment criteria. Geographic Information Systems (GISs) and multi-criteria decision-making (MCDM) are the most widespread tools and techniques used in the above analysis. Important and noteworthy research regarding OWF siting has been performed in Greece [4,10,14,15,21].

Vagiona and Karanikolas [4] explore Greece's offshore wind farm siting problem using a methodological approach that integrates GISs and MCDM approaches to determine the most efficient sites. Using Geographic Information Systems (GISs), all coastal areas that do not meet a set of requirements such as wind velocity, protected areas, and water depth are found during the first level of analysis and are not included in the next phase. During the assessment phase, the Analytical Hierarchy Process (AHP) is used to identify the most suitable areas for OWF siting.

The results indicate the ten most appropriate sites for offshore wind farm siting in the country. Christoforaki and Tsoutsos [10] provide a methodological framework for OWF siting based on legal restrictions, with a specific interest in biological and financial assets, using the island of Chania (Crete) as a case study. The methodology includes the following three steps: (i) exclusion of inappropriate sites based on geological, environmental, visual, and acoustic restrictions; (ii) assessment of natural impacts on birdlife, as well as on Special Protection Areas (SPAs) and Sites of Community Importance (SCI); and (iii) evaluation of wind potential and electricity needs in the regional unit of Chania. The results indicated two potential areas where two hypothetical siting scenarios of a wind farm deployment are applied. Vagiona and Kamilakis [14] applied various siting criteria (technical, spatial, economic, social, and environmental) found either in the national legal framework or proposed in case studies found in the international literature, to detect the most suitable areas for OWF deployment in the South Aegean region (Greece). GISs and a combination of MCDM methods (AHP and TOPSIS) were used in the analysis. Two sites are proven to be eligible for OWF siting and are further evaluated. Stefanakou et al. [15] provide a decision support model that assesses OWF suitability for floating installations in the Aegean Sea, using MCDM analysis and GISs.

It is obvious that there are several studies investigating wind farm siting issues worldwide, as well as in the country under study (Greece). They use several exclusion and assessment criteria and apply different multi-criteria methods combined with GISs to conclude the appropriate or the most appropriate wind farm siting areas. The ranking of the appropriate areas may vary depending on the data and the multi-criteria methods used. Therefore, a further analysis of the most appropriate areas and a comparative analysis among them could help in the selection of the most sustainable area.

The methodological approach includes the following four stages: (i) the identification of areas that are inappropriate for wind farm siting based on legal constraints are initially excluded, (ii) definition of a set of evaluation criteria that are used to provide the most suitable areas, (iii) an economic evaluation of the highest-scored sites is performed, and (iv) a sensitivity analysis on the weights of the criteria is conducted. Results indicated that only a small percentage of the case study are characterized as being appropriate as a floating wind turbine siting, although wind potential is considered efficient in more sites. Gkeka-Serpetsidaki and Tsoutsos [21] applied a methodology to determine a sustainable siting of OWFs in the island of Crete (Greece). In total, 14 exclusion and 16 evaluation criteria were applied, using the AHP and GISs. This study incorporates the views of numerous local experts and stakeholders, while considering the insular features of the island of Crete. Seven distinct commercially available models are used to evaluate the energy capacity of the highly suitable marine areas.

The main objective of the present study is to identify the most suitable areas in Thrace, Greece for the siting of an offshore wind farm and then analyze them according to their suitability in different aspects—environmental, technical, economical, and social.

The focus of this study is the methodological framework used for the selection and assessment process of the suitability analysis. The methodology includes (i) the delineation of the study area and the definition of the support structure of the wind turbine, (ii) the identification of seven (7) exclusion and fifteen (15) assessment criteria, (iii) the suitability analysis under five different zoning scenarios (equal weight, environmental, social, techno-economic, and researchers' subjective), and (iv) the micro siting and qualitative assessment of the most suitable sites based on energy, environmental, social, and economic criteria.

In this study, the focal point is to determine the most suitable areas, not simply based on distance from objects, but to offer a precise methodology and a concrete definition of the value changes, depending on the different variables used. For this reason, equations are introduced where grey areas are emerging and where qualitative methods are not the optimal solution. Afterwards, these values will be used in the ArcGIS application that will help determine the most suitable areas.

The methodology framework, supplemented by the correct GIS and wind assessment applications, is a working mechanism for selecting offshore wind farm locations of either technology—fixed-bottom or floating. This tool can be applied on a national scale as well, but the following qualitative analysis should account for the differences and particularities between each administrative region. With its correct implementation, it helps to avoid planning and strategic mistakes that induce adverse effects on an environmental or social level, while, at the same time, retaining a positive value on a techno-economical scale, as part of the total investment. By tweaking the exclusion criteria, which are dependent on each country's legislative framework, this methodology can be applied to any other country. In other cases, it can be used as a tool to assess the suitability values of existing OWFs.

The main contributions and significant aspects of the present research can be summarized by the following: (i) the paper focuses on a specific oriented marine area, enhancing the precision and correctness of results; (ii) the proposed methodology includes a wide number of criteria (22 criteria—7 exclusion, and 15 assessment); (iii) the most suitable solutions for two offshore wind technologies (fixed-bottom and floating) are proposed for the examined area; (iii) the paper strongly considers environmental protection, as it incorporates four environmental criteria in the analysis; (iv) for certain criteria (depth, distance from grid, distance from port, and distance from shore), this paper provides a precise methodology and concrete definition of the value changes, depending on the different variables used and not simply based on the distance of the proposed area from the examined criterion. Therefore, appropriate equations and computations in GISs are introduced for each of the aforementioned criteria; (v) the most suitable sites are selected based on quantitative and qualitative analysis; (vi) the most suitable sites are selected based on the following five different scenarios: equal weight, environmental, techno-economic, social, and researchers' subjective scenario; (vii) the micro siting of the selected sites is performed to achieve maximum exploitation of the wind potential; and (viii) an initial after-assessment analysis follows to hierarchically rank the selected sites, regarding energy, environmental, economic, and social aspects.

The present paper proposes a robust methodological framework for OWF deployment, with respect to the characteristics of the insular area and the available technology, and can be applied to any study area and various spatial scales.

The structure of the paper is as follows: Section 2 outlines the methodology and materials used. The exclusion and assessment criteria are presented, with a description for each, and its function in the selection is explained. For the applicable criteria, equations are introduced to help quantify them based on distance. This section concludes with the application of multi-criteria method, AHP. Section 3 includes the scenarios and the results, which offer a detailed view of the process and a comparison between them. The paper concludes with Section 4, where the final selection of the four most suitable areas for OWFs' exploitation is presented and analyzed comparatively between them.

2. Materials and Methods

The methodology starts with the delineation of the study area and the selection of a suitable offshore wind turbine. Seven (7) exclusion criteria and fifteen (15) assessment criteria are selected. The Analytical Hierarchical Process (AHP) is used to provide weights on each criterion, under five different siting scenarios (equal weight, environmental, social, techno-economic, and researchers' subjective). The results are inserted into the ArcGIS software, specifically ArcGIS Desktop version 10.8.1, to identify areas with the greatest suitability values. The final step includes the use of WAsP software, specifically WaSP version 12.8, for micro siting in the most suitable areas.

The selection of the administrative region of Thrace for this analysis is due to the fact that the marine area of Thrace provides fertile ground for the implementation of the first pilot OWF in Greece. Firstly, the North Aegean is a relatively shallow sea, encompassing many areas with a depth of less than 60 m, thus making a fixed-bottom OWF application possible. Other favorable aspects include technical-related matters such as the existence of the port of the city of Alexandroupolis being in close vicinity, which can cope with the requirements of such a project, the proximity of the high-voltage grid to the shoreline, and the overall great wind potential of the region.

Evros is expected to become an important energy hub for the eastern Mediterranean, while the recent legislation (Article 174/Bulletin No. 4964, Government Gazette A 150/30.7.2022) on offshore wind farms demarcates the potential OWF Organized Development Areas (OWFODAs); Thrace is considered as a pilot area for the development of OWFs. These areas are also confirmed as being suitable for the first pilot OWF project in Greece [22].

The marine area of Thrace and the Evros and Nestos deltas are among the most important biodiversity zones at the European level, both for birds and marine mammals and reptiles, so any planning should be conducted with respect to the environment and its ecosystems. The environmental impacts of OWFs are numerous and each stage of the project life cycle affects different species.

The Evros Delta has been greatly disturbed in recent years, reducing its importance for birds, but it remains one of the most important wetlands in Greece and Europe and one of the most important migratory passages in our country. It maintains a variety of habitats in a small area and continues to host a diverse avifauna, serving not only as a wintering/stopover site for migratory species, but also as a breeding site for rare and endangered avifauna species. One of the biggest issues is the protection of vulnerable and endangered birds, as they face dangers during the project's operation, which is the longest period of the life cycle, with a duration of up to 25 years. In order to mitigate this phenomenon, an automatic collision avoidance system should be installed and it is considered necessary to have observers during the migratory periods, in order to avoid bird collisions to the maximum extent possible.

During the construction phase of the life cycle, the main pollutants are the drilling and general disturbance of the seabed. The impact on marine mammals and reptiles that use these areas for feeding and breeding needs to be studied further. The work should be carried out in such a timeframe that these species are affected as little as possible. It is considered necessary to apply the most stringent/strict methods of mitigating noise disturbance, in order to avoid the complete displacement of species. Noise reduction applications, such as double bubble curtains and other innovative techniques and methods, are considered obligatory.

The whole methodological process and framework is briefly presented in Figure 1.

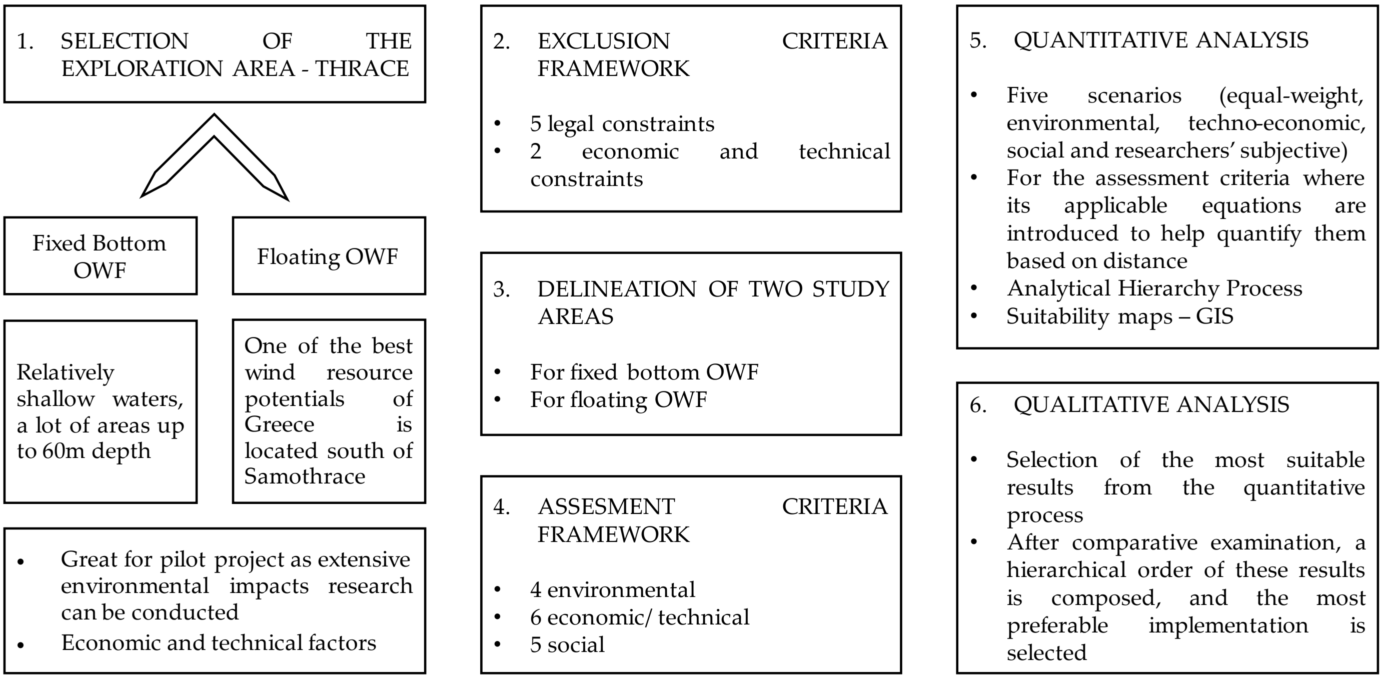

Figure 1. Methodological framework of this study.

Geographical Information Systems and Analytical Hierarchical Process were used to convert the acquired data into exclusion and assessment criteria and then into thematic maps for the identification of suitable areas. In total, 7 exclusion criteria, with main source being the legislative framework, specifically Article 6 par. 1 and 2 of the Special Spatial Planning Framework for RES (Government Gazette 2464B/2008), and 15 assessment criteria were selected, based on the recent literature as well as European and international experience (e.g., [4–21]). The criteria are divided into three (3) categories—environmental, techno-economic, and social. Out of those categories, four (4) scenarios were deployed, three (3) sharing the same name as the category, as well as the equal weight scenario in which all criteria were treated equally. The fifth and final scenario was the researchers' subjective scenario, which was based on the judgements and expertise of the authors. With the help of the Analytical Hierarchical Process, the weights of each criterion are derived and, using GIS applications, an analysis is performed to visualize the results, using thematic maps at the study area level.

2.1. Exclusion Criteria

The spatial suitability of both currently available offshore wind technologies is examined. While the legal constraints remain the same, for the determination of the study area, a different category of depth is used, thus creating two non-overlapping, interlocked study areas. For the determination of the initial study area, a buffer of 6 nautical miles (current extent of territorial waters of Greece) was created from the coastline of the administrative region of Thrace, which is composed of the following three (3) regional units: Evros, Rhodope, and Xanthi.

In Table 1, all the exclusion criteria that were considered in the present study are presented. All the legal constraints applicable to offshore wind that are included in the Specific Framework for Spatial Planning and Sustainable Development for Renewable Energy Sources (SFSPSD-RES) [23] are implemented in the form of exclusion criteria.

Table 1. Exclusion criteria used in this study.

EC No.	Exclusion Criterion	Description	Buffer Zone	Category of Constraint	Data Source
1	Inside territorial waters	The study area was limited within the territorial waters of Greece in the North Aegean, therefore within 6 nautical miles, or approximately 11.1 km, from the coastline.	11.1 km (6 n.m.)	Legal	[24]
2	Depth	Essential for the separation into two study areas. For depths of up to 60 m, fixed-bottom technology was preferred and for depths from 60 to 1000 m, floating technology was deemed befitting.	-	Technical	[25]
3	Average wind speed at 150 m	Areas with wind speeds below 5 m/s were excluded, because they were not considered efficient for a project of this scale in the long term.	-	Economical	[26]
4	Protected areas—Ramsar and NATURA 2000 Special Protected Areas	For the configuration of the study area, the boundaries of the International Wetlands Convention—Ramsar and priority habitats that have been classified as Sites of Community Importance (SCI) (or Special Areas of Conservation—SAC) in the NATURA 2000 network, in accordance with the Council Directive 92/43/EEC, were used. They are the most crucial for the consideration of the study area, since their main protective objects are avifauna species. The territory within a 2 km radius of the mentioned boundaries were excluded.	2 km	Legal	[27,28]
5	Monuments of archaeological heritage	For the configuration of the study area, the boundaries of the archaeological sites were used, based on the official archaeological cadaster of Greece. Based on Article 6 par. 1 and 2 of the Special Spatial Planning Framework Planning for RES—Government Gazette 2464B/2008 in a radius of 7D (which equals to 1.22 km, based on the WT-V174—9.5 MW) from the boundaries of archaeological and cultural heritage sites, any RES construction is prohibited.	1.22 km	Legal	[29]
6	Urban fabric/Settlements	For the configuration of the study area, the boundaries of the settlements were used, based on the Corine Land Cover cartographic background 2018 (codes 111: Continuous Urban Fabric and 112: Discontinuous Urban Fabric) and on personal observation of the limits of the settlements. This was subsequently verified with the official census of the locations of settlements in Greece. Based on Article 6 par. 1 and 2 of the Special Spatial Planning Framework Planning for RES—Government Gazette 2464 B/2008, in a radius of 1 km from the settlement boundaries, any RES construction is prohibited.	1 km	Legal	[30]
7	Bathing shores	For the configuration of the study area, the bathing shores, which are included in the quality monitoring program of bathing waters coordinated by the Ministry of Environment and Energy, (YPEN) were used. Based on Article 6 par. 1 and 2 of the Special Spatial Planning Framework Planning for RES—Government Gazette 2464B/2008, around the bathing sites, a buffer of 1.5 km was created, which prohibits any RES construction.	1.5 km	Legal	[31]

A visual representation of the exclusion criteria is shown in the two maps below (Figures 2 and 3).

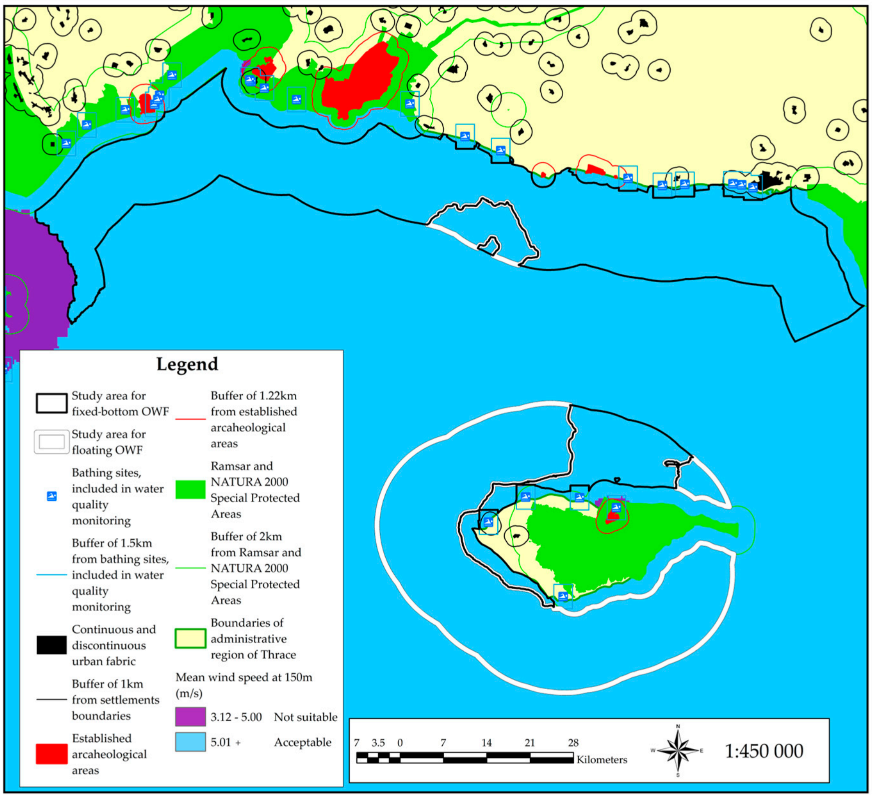

Figure 2. Land-related exclusion criteria.

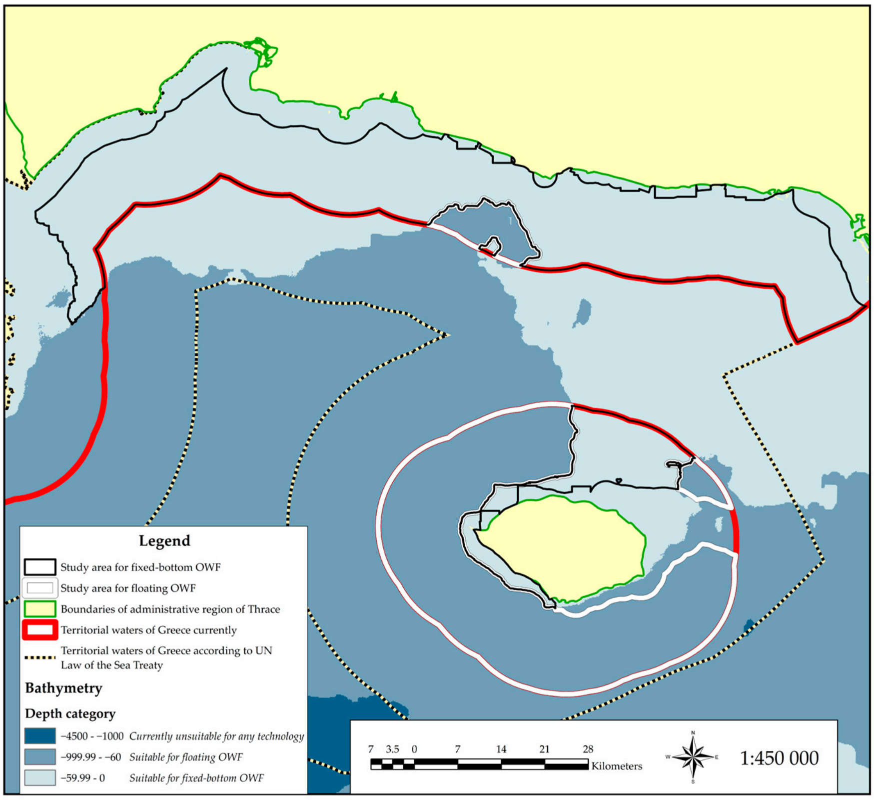

Figure 3. Sea-related exclusion criteria.

2.2. Assessment Criteria

The next step in the methodology is the determination of the assessment criteria that will be used for the calculation of the suitability values inside the selected areas. In total, fifteen (15) criteria were chosen. They were divided into the following three categories: environmental, economic/technical, and Social.

1. Protected areas (Natura 2000, IBA)

The nationally and internationally protected areas are of the utmost importance for the consideration of the sustainability of the OWF and are considered in almost all offshore wind farm suitability studies (e.g., [4,5,10,14,21]). Fixed-bottom applications are expected to cause more environmental impacts compared to floating structures. Depending on the fixed-bottom technology, the interaction with the seabed can vary from causing severe damage to it, e.g., monopiles that require drilling, to less damage, e.g., suction- or gravity-based foundations. During the construction and decommissioning phase, negative impacts occur for fish, sea mammals, and mainly marine biodiversity. Throughout the operational phase, mainly avifauna species can be injured, killed, and/or displaced. Recently, it has been proven that OWFs affect marine sediment quality and microbial communities [32].

Inside both study areas, the Natura 2000 Site of Community Importance (SCI) GR1110013, Thalassia Periochi Thrakis, is present with flagship species the Green turtle—*Chelonia mydas* and the Loggerhead Turtle—*Caretta caretta*. Inside the study area for fixed-bottom installations, the Natura 2000 Special Protection Area (SPA) GR1110012, Samothraki: Oros Fengari kai Paraktia Zoni is also located, with notable avifauna species such as the Turtle Dove—*Streptopelia turtur*; the Buzzard—*Buteo buteo*, which is also endemic to the island; and another 40 avifauna species. The study area for floating platforms shares the same border with the Important Bird Area (IBA) GR007 and the Natura 2000 site Special Protection Area (SPA) GR1110012, Samothraki: Oros Fengari kai Paraktia Zoni. These two protected areas exclusively include avifauna species under their protection scheme.

2. Migratory bird routes

Impacts on avifauna do not differ between the two different platforms, if the wind turbines stay the same. The administrative region of Thrace, especially its two river deltas, those of Evros and Nestos, constitutes vital stopover sites on the migratory Mediterranean/Black Sea flyway for birds [33]. Since areas with high wind power potential and bird migratory routes coincide frequently [34], it is critically important to pick an area where the risk of bird collisions is minimized, in order to avoid putting the nature conservation in danger [35]. Studies have shown that measures such as increasing visibility of rotor blades or implementing radar systems to automatically detect and track birds, accompanied with scientists monitoring birds' movements close to OWFs, minimize potential collisions or can even eliminate them [36].

3. Distribution of *Posidonia oceanica*

Posidonia oceanica is a crucial habitat for all Mediterranean Sea marine species and can be found in depths up to 50 m. These meadows are declining at alarming rates due to climate change and human activities [37]. In the last two decades, *P. oceanica* has become one of the main targets of the protection and management of the Mediterranean marine environment, as it is an important habitat for a vast number of Mediterranean marine fauna and also an important source of oxygen production. The mapping of these habitats has not yet happened on a governmental/national level and all data used are drawn from research works and studies [38,39]. Unfortunately, they favor similar habitats as those required for the construction of OWFs, exposing the *P. oceanica* beds to risk from direct physical destruction, sedimentation occurring from the drilling of the seabed, and changes in hydrographic regimes [40]. Only fixed-bottom foundations affect this habitat, completely destroying it where the wind turbines are placed, regardless of the type of foundation technology, though each foundation type has a different 'destruction' footprint. The cable laying, which is needed for both technologies, also dislocates meadows, accounting for 22.86% of the total area disturbed [41].

Depending on the foundation technology, with monopiles causing the largest area of seabed disturbance (a median value of 63.62 m^2 per foundation—the maximum extent of temporary and permanent seabed disturbance is 12.124 square meters for monopile foundations [42]), it is projected that meadows in radius of up to 150 m from the foundation will be severely damaged, if not completely removed.

Conversely, OWFs can prevent local trawling and decrease the amount of fishing methods that reduces *P. oceanica* coverage [43]. Any plans for OWFs in the Aegean Sea will have to be carefully prepared with respect to *P. oceanica* seabed coverage, to ensure the correct conservation practices for this endemic, priority species [40].

4. Important marine mammals' area

The marine region of Thrace is home to rich and unique marine fauna. Any construction work occurring in this area will seriously affect sea mammals and should be carried out with strict measures of amplifying the sound effects, especially during the construction phase of the project. Current studies [36,44] show that during the operational phase, the behavior of the animals is mostly not negatively affected. After installation, habitat gain and fisheries exclusion are major contributors that enhance local species abundance, which can have mixed impacts on biodiversity and conservation values. More valuable insights are expected in the coming years, as more research programs will closely monitor the effects on the biological processes of OWFs on animals in the long term. Fixed-bottom applications have major detrimental impacts on marine mammals in the construction phase [45]. Floating OWFs, throughout their whole life cycle, are considered to have slightly negative to neutral effects, depending on the area of their implementation. The most impactful environmental effects are structural impediments [46]. In the marine area of Thrace, the delineated region of the important marine mammals' area is approximately the isobathic contour of 70 m depth [36].

5. Mean wind speed at 150 m

One of the most important indicators in the selection of the final area is the wind velocity, as it is the main factor affecting the total electricity yield during the operational stage of the life cycle of an OWF. It is crucial to conduct extensive anemological research before choosing the exact location, since even small changes in wind speeds can have considerable effects on electricity production and the industries and populations that depend on it [47].

6. Mean wind power density at 150 m

Wind power derives from the wind speed of a location. It increases with the cube of the wind speed, as per Equation (1) [48].

$$P_{wind} = \frac{E_{kin,wind}}{\Delta t} = \frac{\rho A v^3}{2}, \tag{1}$$

where

ρ is air density,
A is swept area,
v is wind speed.

To put that into perspective, if the wind speed is doubled, the wind power increases eightfold. When the wind power is divided by the area of interest, wind power density emerges, as shown in Equation (2) [49].

$$WPD_{wind} = \frac{P}{A} = \frac{\rho v^3}{2}, \tag{2}$$

where

ρ is air density,
v is wind speed.

Wind power density helps compare wind resources independent of the wind turbine, since it does not have a dependence on the radius of a wind turbine swept area. This makes wind power density the foundation for classifying the wind resource [49]. Mean wind power density is preferred over mean wind speed when comparing sites with different probability distribution skewness (k), due to the cubic nonlinear dependence of wind power on wind speed [50]. In the marine region of Thrace, and specifically in the study areas, the fluctuation between the upper and lower values of k is less than 0.5; therefore, the areas do not differ much in distribution skewness. The values of probability distribution skewness (k) were calculated using the software WaSP, version 12.8.

7. Depth

Apart from being the criterion that delineates the two selected study areas, depth plays a major role in the economic feasibility of an OWF. Increasing economic costs due to depth affect fixed-bottom applications more severely after the certain threshold of 60 m, making them economically unfeasible [51]. Their floating counterparts have a standardized increase in costs up to 1000 m in depth [2]. These costs include investment and other maintenance costs related to depth and how they are affected by its increase. Since the North Aegean is relatively shallow, this allows great maneuverability between selecting either of the offshore wind technologies.

8. Distance from the grid

The distance of an OWF from the national electricity grid (in particular the high-voltage grid) is a significant criterion for both technical and economic reasons [52]. A connection to the high-voltage grid is preferred because a connection to lower-voltage grids could potentially lead to a risk of cable destruction from electricity grid overloading [53]. There are multiple factors influencing the cost of submarine transmission cables. Generally, for large offshore projects, Alternating Current (AC) transmission lines are apt up to a certain transmission distance threshold, after which the electrical losses will constrain the project to the usage of high-voltage direct current (HVDC) transmission, for economic feasibility [54]. The Hellenic national electricity grid connecting Alexandroupoli with Kavala spans parallel to the Thrace's shoreline, so the distance at all given points of the study areas to the grid is less than 70 km.

9. Distance from port

Ports play a key role in all the phases of the life cycle of an OWF, as an economic factor. The most important and restricting phases are the construction and decommissioning phases, since only certain ports are considered suitable for undertaking such a project due to the nature of the materials used and their size [55]. Proximity to ports also insures faster and less costly maintenance trips during the operational phase of the project. Naturally, cumulative investment costs increase the further away an OWF installation is from a port [56]. The administrative region of Thrace has two ports with cargo turnover—the Alexandroupolis port, which is the primary and well-maintained port of the region, and the Porto Lagos port. However, neither of the two are considered to be capable of supporting such a project at this stage.

10. LNG station, subsea pipeline, and other technical structures

In the gulf of Alexandroupolis, a liquefied natural gas (LNG) storage terminal is scheduled to be completed by 2025. It will be connected via a pipeline to the National Natural Gas Transmission System on land. Other technical structures that could pose an obstacle are electricity transmission lines. A buffer of 500 m radius around the terminal and 250 m for the subsea pipelines was created.

11. Density of vessel routes (2022)

An OWF should ensure safe navigation and not interfere with confirmed vessel routes [14,21]. With this criterion, shipping, passenger, and fishing vessels routes are considered, without a hierarchical order of importance. Inside the study areas, there are two ports handling shipping vessels and their cargo—Alexandroupolis and Porto Lagos. Two ports with passenger vessels routes exist, connecting Alexandroupolis and Samothrace. Moreover, the North Aegean has plenty of fishing activities and small fishing vessels are recorded nearshore. The density of routes is calculated as the number of vessel routes per square km per year.

12. Fish farming

The official fish farming areas or Organized Aquaculture Development Areas (OADAs) allocated by the Greek government are an obligation that stems from a European directive aiming to regulate the marine spatial framework of aquaculture in Greece [57]. Some cases show that fishing inside OWFs is possible, but only on a small-scale level [58]. Many scientific works have shown that an OWF has a positive influence on the abundance of the fish population of the regions where they are installed [59–61]. Inside those delineated areas, the installation of an OWF is prohibited but the OADA inside the study area is not yet legislatively confirmed, hence it is used as an assessment and not an exclusion criterion.

13. Military training areas

In order to secure national security, some marine areas are used by the Hellenic Navy, Air Force, and Army for naval military training or as military firing practice areas [52]. At present, these areas cannot be altered for the installation of the OWF to be deemed possible, but, as happened with the LNG—Gastrade terminal, some concessions could be made if the project receives support on a governmental/national level.

14. Distance from shore

Distance from shore, from a social point of view, includes both visual and acoustic disturbance. Acoustic disturbance can be identified quantitatively using mathematical equations. The noise generated by wind turbines is considered a significant nuisance [62]. The legal obligation to noise nuisance thresholds, according to Presidential Decree 1180/1981, is that the maximum permissible noise limit for installations close to residential buildings is set at 45 dB(A), irrespective of the area in which the installation is located, measured within the occupied building with the door and windows open. If visualized on a map, this is the first buffer where every passerby is considered to be affected, usually spanning from 0.5 km to 1.5 km depending on the wind turbine used. Visual disturbance is identified qualitatively. It is determined by the extent to which a person on the shore will be aggravated by the visual interference of the OWF while looking at the horizon [63].

15. Distance from airports

Wind turbines can interfere with aviation and other radar signals and require a minimum distance from airports, as per the Greek Spatial Plan. Based on similar studies [21,64] and international experience regarding the nearest in proximity wind farm installations to major radar systems or an international airport [65,66], three impact zones were created depending on the distance from the one aviation infrastructure of national importance found in Thrace, the Democritus Airport in Alexandroupoli.

2.3. Defining the Values of Each Criterion

All the criteria had a minimum and maximum value. Depending on whether the criterion had a constant value, there was an inside/outside of the study area restriction. In the areas where the criterion area overlapped with the study area, the value assigned was 1, if not it was 0. If the value of the criterion was not constant, then, depending on the data, a variable value was assigned. Since there are two separate study areas, the minimum/maximum values for the variable in value criteria differ in each study area. Table 2 presents all the assessment criteria used, their category, the minimum and maximum value in their range, and whether they are a cost or a benefit criterion.

The main observation is that four criteria, namely AC3—Distribution of *Posidonia oceanica*, AC10—LNG station and subsea pipeline, AC12—Fish farming areas, and AC15—Distance from airports, are not affecting the floating offshore technology in this particular area.

Table 2. Assessment criteria used in this study.

AC No.	Assessment Criterion	Category	Minimum Value		Maximum Value		Benefit/Cost	Data Source
			Fixed	Floating	Fixed	Floating		
AC1	Protected areas (Natura 2000, IBA)	Environmental	Outside study area		Inside study area		Cost	[28,67]
AC2	Migratory bird routes	Environmental	Outside study area		Inside study area		Cost	[68]
AC3	Distribution of *Posidonia oceanica*	Environmental	0% (Chance of existence)		92%	0%	Cost	[38,39]
AC4	Important marine mammals' area	Environmental	Outside study area		Inside study area		Cost	[69]
AC5	Average wind speed at 150 m	Economic/Technical	5.1 m/s		9.2 m/s	9.5 m/s	Benefit	[26]
AC6	Average power density at 150 m	Economic/Technical	279 W/m^2	431 W/m^2	1090 W/m^2	1291 W/m^2	Benefit	[26]
AC7	Depth	Economic/Technical	0 m	−60 m	−60 m	−1000 m	Cost	[25]
AC8	Distance from the grid	Economic/Technical	0–10 km		50–60 km	70–80 km	Cost	[70]
AC9	Distance from port	Economic/Technical	0–10 km		40–50 km	70–80 km	Cost	[71]
AC10	LNG station, subsea pipeline and other technical structures	Economic/Technical	Outside study area		Inside study area	Outside study area	Cost	[72]
AC11	Density of vessel routes (2022)	Social	0 (routes per sq. km per year)		802	754	Cost	[73]
AC12	Fish farming	Social	Outside study area		Inside study area	Outside study area	Cost	[57]
AC13	Military training areas	Social	Outside study area		Inside study area		Cost	[74]
AC14	Distance from shore	Social	0–1.5 km		11–12 km		Cost	[75]
AC15	Distance from airports	Social	>20 km		1.75–2 km	>20 km	Cost	[30]

There are two (2) categories of criteria depending on the calculation of their valuation. The first one includes criteria that have a predetermined calculated value, either on Outside/Inside condition or directly assigned by the data source, such as wind speed or density of ship routes, namely the criteria AC3, AC5, AC6, and AC11. For the techno-economic criteria AC7, AC8, and AC9 and social criterion AC14, an equation was introduced to determine their value, based on the distance of the object under investigation to various points in the study area.

AC7. Depth:

Depth plays a major role in the change of the overall costs of the project. Different technologies have different costs; thus, different equations are used [54,76]. Functions for both technologies are generalized, since there are different foundation types with varied costs. In both methods, all costs apart from operational and maintenance costs are incorporated from every stage of the life cycle of an OWF.

For fixed-bottom technologies [54], Equations (3) and (4) are used to determine the value for each 1 m isobathic contour. From 0 to 25 m depth, monopile foundations are considered the most economically viable, while from 25 to 60 m depth, jacket foundations are considered the most economically viable. Equation (3) is used to determine the total value of the foundation costs for monopiles in USD/MW.

$$y = 201x^2 + 612.93x + 411464, \quad (3)$$

where x is the absolute value of depth in meters.

Equation (4) is used to determine the total value of the foundation costs for jackets in USD/MW.

$$y = 114.24x^2 - 2270x + 531738, \quad (4)$$

where x is the absolute value of depth in meters

For floating technologies [76], Equation (5) is used, which determines the value of the foundation costs for tension leg buoys in USD/MW for each 1 m isobathic contour.

$$y = 773.85x + 680651, \quad (5)$$

where x is the absolute value of depth in meters.

AC8. Distance from the grid:

In the table below, the overall change of costs, as a function of the distance to a high-voltage grid, is presented. The two Equations (6) and (7) calculate the ascending costs with increasing distance from the high-voltage grid [54].

The component costs in the equation account for all the necessary switchgear, transformer, and substation costs. According to Bosch et al. [54], for OWF installations of several hundred MW, HVAC transmission is the cheaper option until the distance of the OWF reaches 56 km from the grid, while HVDC transmission becomes the most economically profitable option from 56 km and upwards. Transmission costs in this paper adapt to the lowest cost technology option in relation to the distance from the grid.

From 0 km up to 56 km, HVAC transmission will be used with the following equation:

$$y = 0.0085x + 0.0568, \quad (6)$$

where x is the distance in kilometers.

From 56 km and upwards, HVDC transmission will be used with the following equation:

$$y = 0.0022x + 0.3878, \quad (7)$$

where x is the distance in kilometers.

AC9. Distance from port:

The costs for fixed-bottom and for floating OWFs differ due to the different technologies and subsequently different operational and maintenance costs; thus, two different calculation methods are used [54,77]. For fixed-bottom applications, the calculation is based on a factor which increases every ten kilometers (Table 3). Both methods calculate the operation and maintenance costs of an OWF, but in fixed-bottom technologies, other relevant costs are also incorporated [77].

Table 3. Scale factors in relation to ascending distance from ports, used to calculate the values in fixed-bottom applications. The factors are modified from the original source to fit the current study's parameters.

Distance from Port (km)	Scale Factor	Value (EUR/kW)
0–10	1	79.2
10–20	1.007	79.8
20–30	1.028	81.5
30–40	1.051	83.2
40–50	1.072	85
50–60	1.089	86.3
60–70	1.106	87.7

For floating applications, Equation (8) helps calculate the project's operating and maintenance costs in USD/MW, depending on the distance of the project from the suitable ports.

$$y = 0.0425x + 39.26, \quad (8)$$

where x is the distance in kilometers.

It should be noted that the different methods presented above do not offer a direct comparison between the two technologies or between criteria, but rather differently changing suitability values in relation to depth or distance from ports.

AC14. Distance from shore

This criterion is divided into the following two categories: acoustic and visual impacts caused. Acoustic disturbance is calculated using Equation (9) [78]:

$$L_p = L_w - 10\log(2\pi r^2) - ar, \quad (9)$$

where:

L_p is the calculated noise level (dB),
L_w is the sound power level of the wind turbine (dB), which is set by the manufacturer at 112.9 dB,
r is the distance from the source to the receiver (m),
a, which is the variable of the atmospheric absorption (dB/m), is defined as 0.005 dB/m.

The threshold for the highest acceptable noise level is set at 45 dB. This limit is exceeded when the distance to the WT (V174-9.5 MW) is reduced below 700 m, based on Vestas' data on the maximum sound power capacity that can be generated. To calculate acoustic impacts based on cumulative noise level of multiple wind turbines, Equation (10) is used [78]:

$$L_{cum} = 10\log\left(\Sigma 10\left(\frac{L_p}{10}\right)\right) \quad (10)$$

For 10 wind turbines (V174-9.5 MW) generating sound at maximum capacity, at a distance of 1500 m, the total resulting sound pressure level is 44 dB. With the elimination of acoustic impacts, from 1.5 km upwards, the remaining percentage is exclusively visual impacts. Using the wind turbine V-174, the distance where the wind turbine will be heard is approximately 1.5 km.

For visual impacts, a simple equation is introduced to quantify the effects it has on people's field of view. It encompasses various studies and other governmental questionnaires that tried to determine the percentage of the population that is against an OWF, based on pictures provided, by making the distance from the observer further [63,79–82]. In most situations, OWFs are barely visible as a casual observer from the shoreline at a distance further than 32 km [63].

$$L_{visual} = 5 - 0.155x \quad (11)$$

where:

L_{visual} is the level of the disturbance caused by the wind turbines,
x is the distance of the observer to the wind turbine in kilometers.

Table 4 presents the levels of visual disturbance caused in relation to Equation (11).

Table 4. Level of disturbance for a casual observer from the seashore, depending on the L_{visual}.

L_{visual}	Level of Disturbance for a Casual Observer from the Seashore
5	Standing in front of the wind turbine
<5–4	Severe (e.g., Formosa 1 Offshore Wind Farm)
<4–3	Major
<3–2	Significant
<2–1	Moderate
<1–0	Minor
0	Trivial/In most cases not visible

AC15. Distance from airports

Considering that OWFs may cause disruptions to the signals of military and commercial use radars and other infrastructures, such as airports, it is recommended to place an OWF at a distance greater than 15 km [83]. The maximum distance affected is considered to be 20 km and, due to the placement of the airport, only the study area for fixed-bottom installations is within this radius. The electromagnetic interference area between radar signals and an OWF can be calculated using the Fresnel zone [66]. A simplified Equation (12) is introduced that aligns with the results of [66,83] and suits the needs of this study. The equation helps determine the approximate value of impacts, which are amplified by the increasing distance. Considering there are six (6) main categories of radius based on overall impact, 0–1.75 km, 1.75–2.5 km, 2.5–5 km, 5–10 km, 10–15 km, and 15–20 km, there is a logarithmic sequence that can give approximate results to a real-life implementation.

The values are calculated using the following equation:

$$L_{airport} = \frac{1}{0.5 + 2x\ln(x^{0.1} + 0.1)} \tag{12}$$

where x is the distance from the OWF to the *airport* in kilometers,

A value bigger than 1.75 km (>1.75 km) is output. The reason for this threshold is that wind farms have never been built closer than this distance to an airport. The equation shows the level of impacts from 1 (maximum probability of interference with electromagnetic signals) to 0 (minimum probability of interference with electromagnetic signals).

2.4. AHP

Based on the assessment criteria, three scenarios have been applied in this study—the environmental, the techno-economic, and the social. Additionally, two more scenarios are developed, the equal weight scenario and the researchers' subjective scenario.

To determine the weights of each criterion, the Analytical Hierarchy Process was used. In the environmental, techno-economical, and social scenarios, the respective criteria receive the highest importance, while the rest receive the least. For example, the relative weights of assessment criteria in the environmental scenario receive the following values: AC1: 0.1428, AC2: 0.1428, AC3: 0.1428, AC4: 0.1428, AC5: 0.03897, AC6: 0.03897, AC7: 0.03897, AC8: 0.03897, AC9: 0.03897, AC10: 0.03897, AC11: 0.03897, AC12: 0.03897, AC13: 0.03897, AC14: 0.03897, AC15: 0.03897. In the equal weight scenario, all the criteria receive the same importance and therefore have the same weights. In the researchers' subjective scenario, the importance of each criterion is determined according to the researchers' point of view. The hierarchy of the criteria was the same for both offshore wind technologies; therefore' the weights stayed the same across both study areas.

The Analytic Hierarchical Process is one of the most recognizable decision-making tools of multi-criteria analyses, initiated by Saaty [84]. It encompasses the breakdown of a situation into a hierarchy, with a target on the top of the hierarchy and criteria at the levels of the hierarchy, offering decision alternatives, at the same time.

The first step in AHP is to formulate a hierarchy that reflects the goal/problem about which a decision is to be made, e.g., in an environmental scenario, the goal is to protect nature at all costs, overlooking all the other criteria, thus setting maximum importance between environmental criteria and minimal between all other.

The second step is the formation of pairwise comparison matrices, or AHP matrices, in which the pairwise comparison of elements at each level of the hierarchy is performed with respect to each criterion on the preceding level.

AHP is recognized for its ability to consider tangible and intangible criteria and it employs a quantitative comparison approach that is based on pairwise comparisons of decision criteria. All individual criteria must be paired against all others and the results must be compiled in a matrix form, in which the number of rows and columns is defined by the number of criteria [85].

One of the main points of the AHP is the nine-point scale measurement utilized for quantifying the advantage of one selection relative to the rest. Table 5 presents the Relative Importance Scale for the pairwise comparison of the criteria in the matrixes.

Table 5. The nine-point scale used in AHP.

Rating	Importance
1	i as important as j
3	i slightly more important than j
5	i more important than j
7	i much more important than j
9	i extremely more important than j
2,4,6,8	Intermediate prices

The next step is the calculation of the priorities of the elements of the AHP table and the pairwise comparison of the criteria. Pairwise comparisons grant accurate, subjective criteria weighting.

The values in the columns of the pairwise comparison matrix are summed up and a normalized comparison matrix is produced, by dividing each number in the matrix by its column sum. The relative weights of the compared criteria, which form the priority vector, w, are derived by computing the average of the elements in each row of the normalized matrix. The priority vector presents the hierarchical ranking of criteria and illustrates the degree of contribution of each criterion to the overall goal.

The accuracy of the pairwise comparisons is examined using the consistency ratio (*CR*) and the Consistency Index (*CI*). The random index is a measure that tests the consistency of the pairwise comparison matrices used in the analytic hierarchical procedure developed by Saaty. The random index of a table is calculated as follows:

$$RI = \frac{\lambda - n}{n - 1,} \tag{13}$$

where λ is the maximum eigenvalue and n is the number of criteria.

The consistency ratio (*CR*) is then obtained by dividing the consistency index (*CI*) of the matrix by the random index (*RI*) of a random matrix, Equation (14). If the *CR* is less than 0.1, then there is acceptable consistency. The *RI* values are given in Table 6.

$$CR = \frac{CI}{RI,} \tag{14}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{15}$$

Table 6. *RI* random index values, where n is the number of criteria [86].

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

AHP is considered one of the most suitable MCDM methods for solving wind farm siting problems. The AHP method does not include complicated mathematic computations. In addition, it can elaborate assessments for various criteria, irrespective of their type (quantitative and qualitative) of subjective assessment. On the other hand, the main disadvantage of the AHP method is that it is a subjective method and the results strongly depend on the expertise, judgements, and opinion of the decision maker. To address this disadvantage in this study, five different scenarios have been performed (environmental scenario, the techno-economic scenario, social scenario, equal weight scenario, and the researchers' subjective scenario) and the most suitable sites are selected based on the comparison of the researchers' subjective with the four other scenarios.

Each criterion weight in every scenario was divided by the respective highest absolute value that it received within each study area, to produce levelized weights. Then, those weights were multiplied by one hundred (100) to compose the aggregated grading scale (Figure 4). Afterwards, the levelized weights were inserted in the ArcGIS Desktop version 10.8.1, and, with the Weighted Sum command, a suitability scale in the form of a raster file was produced.

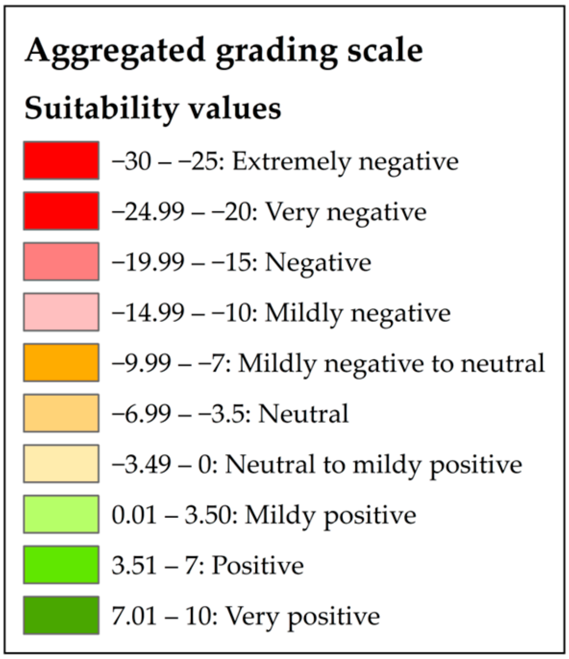

Figure 4. A summarized suitability values scale, fitted for this study. For all other scenarios other than the researchers' subjective, the category "Extremely negative" received values < −25, without specifying the lower limit.

In a hypothetical same weight scenario, where, in a particular cell, all the cost criteria receive the maximum value and the benefit criteria receive a value equal to zero (0), the suitability value would be equal to minus eighty-seven (−87). If the scenario values are inversed, the suitability value would be equal to thirteen (13). The theoretical absolute minimum and the theoretical absolute maximum values are entirely dependent on the scenario, but the values range (in absolute numbers) is always equal to one hundred.

The four scenarios, equal weight, environmental, techno-economic, and social, are presented comparatively with each other, for each technology separately. The conclusions are used to determine if they share similarities with the results of the researchers' subjective scenario. Depending on the last step, two potential areas for each offshore wind technology are drawn and consequently analyzed further between them, leading to a hierarchy of the most to least sustainable/suitable.

Figure 5 represents the criteria weights for the researchers' subjective scenario. The color palette shows each category as follows: yellow—techno-economical, red—social, and green—environmental.

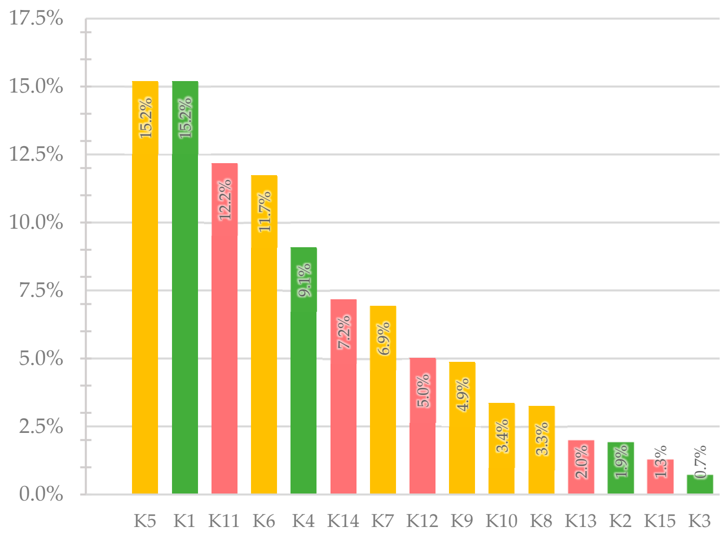

Figure 5. Criteria weights for researchers' subjective scenario.

3. Results

The results were categorized according to suitability value in an aggregated grading scale. The overall level of impact was categorized into three impact classes—negative, neutral, and positive. Not all categories are necessarily present in each map, as the values are not same in all scenarios.

Figure 6 depicts the results after editing in ArcMap for fixed-bottom and floating applications.

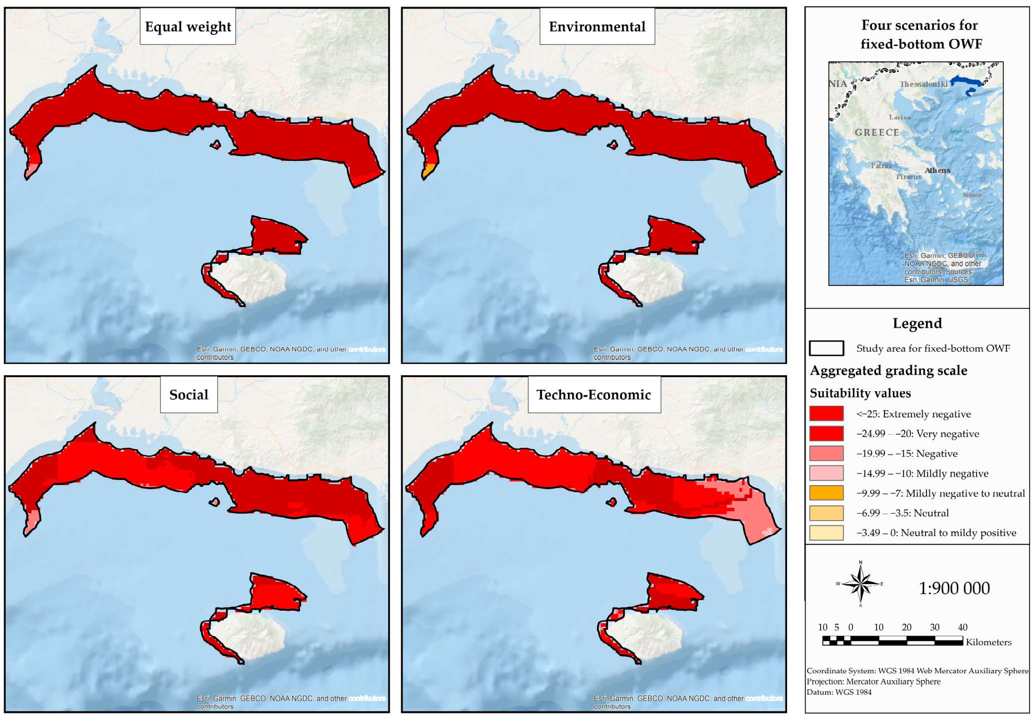

Figure 6. Equal weight, environmental, social, and techno-economic scenarios for fixed-bottom applications. Source for basemap: ESRI, Garmin, GEBCO, NOAA NGDC and other contributors.

For fixed-bottom applications, judging by the four scenarios, four potential areas emerge. The easternmost and westernmost areas of the study area, approximately the middle to western part of the study area, and an area northeast of the island of Samothrace. They all receive suitability values from −3.5 to −24.99. The results show that, environmentally, there is no area that would not have serious impacts on the local environment.

The results from Figure 6 show that the four (4) areas identified are indeed closer to the neutral side of the scale in the researchers' subjective scenario (Figure 7). One more area is emerging from this scenario that could not be identified in the analysis prior—west of Samothrace.

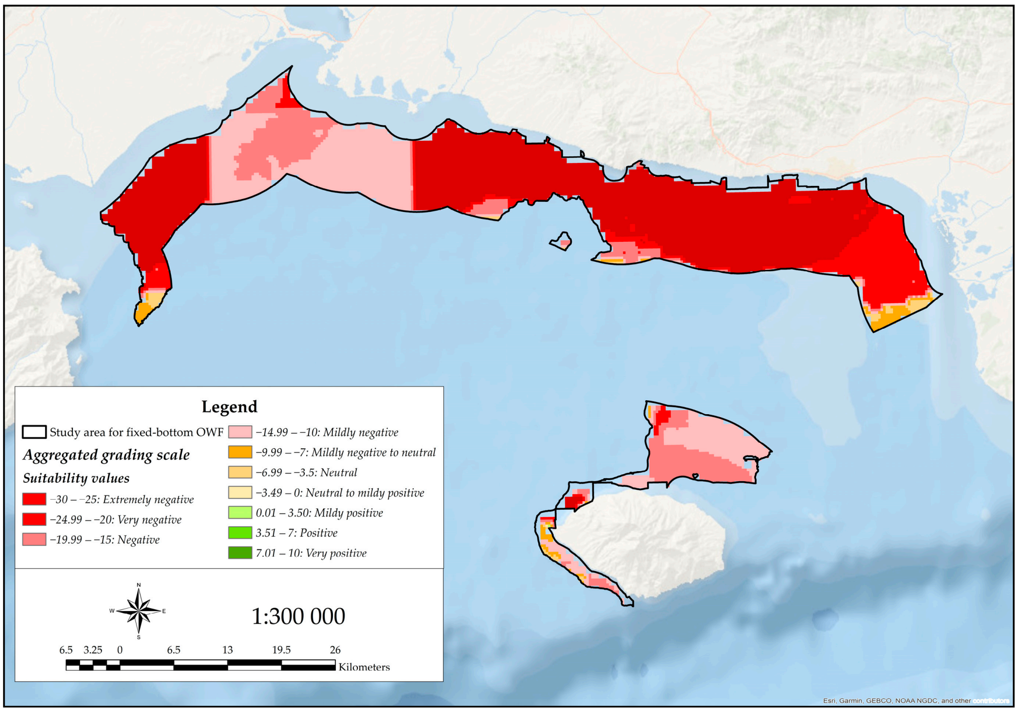

Figure 7. Researchers' subjective scenario for fixed-bottom applications. Source for basemap: ESRI, Garmin, GEBCO, NOAA NGDC and other contributors.

The most suitable potential area is the one on the easternmost point of the study area, followed by the area in the middle of the study area. Two of the areas identified are rejected due to the small plot of sea that they offer, namely the westernmost area and the one west of Samothrace. The area northwest of Samothrace is not considered because of environmental reasons, blocking the migratory birds' route from Samothrace to mainland Greece, and social factors, as it will majorly impact the view from Alexandroupolis to Samothrace and vice versa.

For floating applications, the first area identified is east of the island of Samothrace. In all four scenarios (Figure 8), it receives values lower than −14.99 and is the only area where environmental impacts can be considered neutral. For the second potential area, the selection process is more tedious since no apparent area emerges at first. Deducing from the aggregated grading scale, two potential areas can be identified, south of Samothrace and northwest of the island, as a continuation of the first potential area. A smaller plot of sea with adequate values is also visible on the easternmost side of the study area, but it will not be considered due to its small size.

The results from Figure 9 show that the four areas identified above are indeed on the positive side of the scale. Considering the suitability values, it is straightforward that the most suitable area is the one west of Samothrace, grouped with its expanded territory, followed by the one that is south of the island.

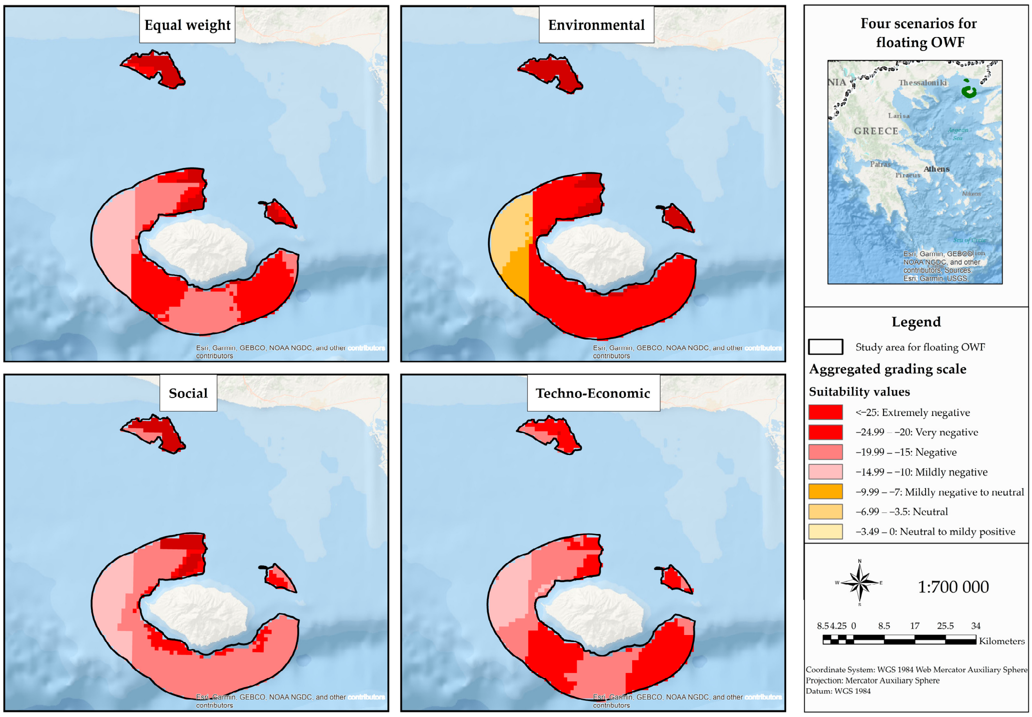

Figure 8. Equal weight, environmental, social, and techno-economic scenarios for floating applications. Source for basemap: ESRI, Garmin, GEBCO, NOAA NGDC and other contributors.

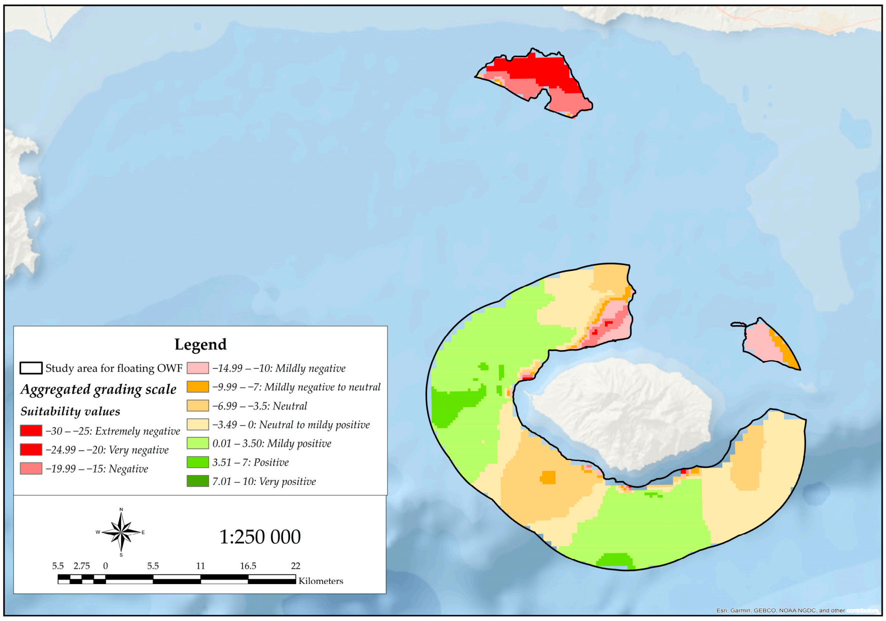

Figure 9. Researchers' subjective scenario for floating applications. Source for basemap: ESRI, Garmin, GEBCO, NOAA NGDC and other contributors.

3.1. Analysis of Most Suitable Sites

Based on the suitability and viability of the sites that emerged from the methodological investigation, the sites with the greatest suitability are selected through a combination of quantitative and qualitative analysis. A comparative analysis between these sites follows. After the analysis, an optimal hierarchy in regard, with suitability being selected according to the personal judgment of the researchers. For the optimal siting, the direction of the wind should be parallel to the nacelle. Using Wind Atlas Analysis and WaSP version 12.8, the appropriate direction was applied with the help of wind roses frequency.

The selection of the final areas discussed above is shown in Figure 10, with the respective amount of wind turbines each area can fit.

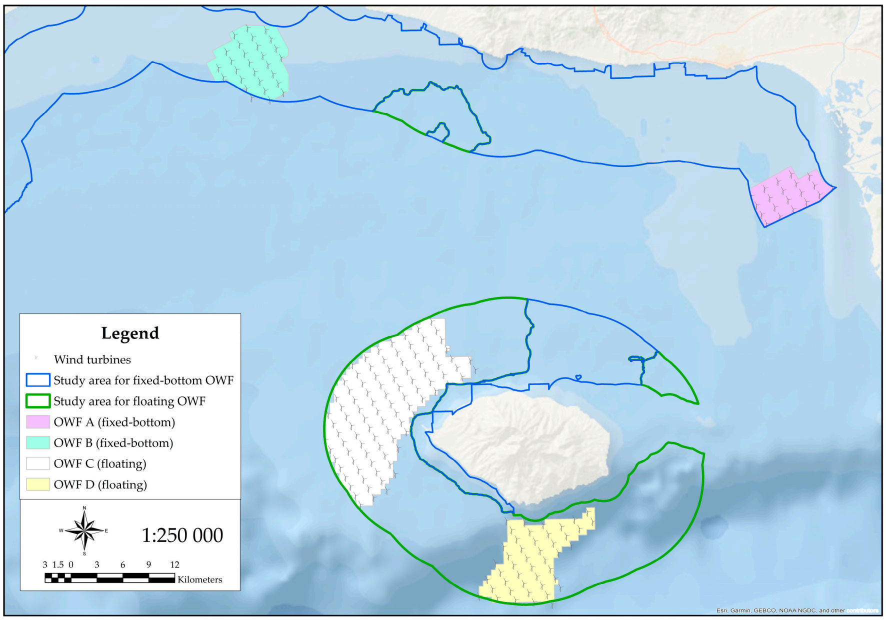

Figure 10. The four sites that were selected. Source for basemap: Source for basemap: ESRI, Garmin, GEBCO, NOAA NGDC and other contributors.

3.1.1. Energy Analysis of Alternative Locations for Wind Turbine Siting

Undoubtedly, the primary role of offshore wind is the efficient production of electricity, with the ultimate goal of decoupling from fossil fuels and strengthening the energy independence of a state. Table 7 presents the average wind speed (m/s) and the average density power (W/m^2) at 150 m for the four selected sites with the highest suitability (OWF A, OWF B, OWF C, and OWF D).

Table 7. The two assessment criteria that determine the potential of electricity generation.

Criterion	OWF A	OWF B	OWF C	OWF D
AC5. Average wind speed at 150 m (m/s)	8.52	6.63	8.84	9.29
AC6. Average density power at 150 m (W/m^2)	735.3	505.8	796.4	1095.8

The most important stage in the design is the micro siting of the site, in order to achieve maximum exploitation of the wind potential. This includes optimal distancing between wind turbines and correct orientation based on the maximum speeds and the frequency of their occurrence.

The two distances between the wind turbines of a wind farm are divided into the downwind spacing, i.e., the rotor from the front row to the next row, and the crosswind spacing, i.e., from one column of turbines to the next.

Based on area limitations and wake effect losses, a downwind spacing of 10D length and a crosswind spacing of 7D length were selected [87]. The aforementioned distances based on the rotor diameter of the V—174 are 1740 m (= 10D) and 1218 m (= 7D). For the correct direction placement of the wind turbines parallel to the prevailing winds, wind roses from WaSP, version 12.8, were drawn.

Based on these constraints and personal modifications, Table 8 presents the maximum number of turbines that can be located within each of the four selected OWFs and the nominal total capacity of each, based on the V174-9.5 MW.

Table 8. Maximum number of wind turbines inside the four selected OWFs and the nominal capacity of each, based on the WT—V174-9.5 MW.

	OWF A	OWF B	OWF C	OWF D
Total WTs	20	28	97	45
Total Capacity (MW)	190	266	921.5	427.5

The total nominal power of all OWFs, consisting of 190 wind turbines type gensets V174-9.5 MW, will be 1.805 GW, enabling Greece to achieve more than half of the target of 2.7 GW set for 2030.

3.1.2. Environmental Analysis

The four assessment criteria that determine the potential effects induced on the natural environment and the suitability category of each OWF in the environmental scenario are shown in Table 9.

Table 9. Assessment criteria and potential environmental impacts in the four selected sites.

Criterion	OWF A	OWF B	OWF C	OWF D
Protected areas (Natura 2000, IBA)	Inside	Bordering	Bordering	Bordering
Migratory bird routes	Inside	Inside	Bordering	Inside
Distribution of *Posidonia oceanica*	Inside	Inside	Outside	Outside
Important marine mammals' area	Inside	Inside	Bordering	Bordering
Suitability value in environmental scenario	−43.1	−39.3	−11.5	−22.1

Based on the environmental criteria, the analysis should be qualitative, as fauna is not restricted by the human boundaries given for protected areas. However, it is worth noting that only one out of the four selected sites overlaps with a protected area (Natura 2000—SPA). Regarding the environmental characteristics of the marine area, a total of five marine protected species are identified under Article 4 of Directive 2009/147/EC and Annex II of Directive 92/43/EEC—1 fish species; 2 species of marine reptiles, for which it is a feeding ground, including the well-known species *Caretta caretta*; and 2 species of marine mammals. The shallow and food-rich waters of the area form an important part of the habitat of the small, endemic, and endangered marine mammal species, the porpoise (*Phocoena phocoena*). The most important feature is the high population density of this species in the area, as it reproduces there [88] and is the only population that has survived in the entire Mediterranean Sea. The wind turbine placement is subject to further modifications according to dominating/prevailing migratory bird routes and other site-specific environmental factors after detailed ornithological and other relevant reports.

Hierarchically, from an ecological standpoint, OWF C is the most responsible choice, since it is situated further away from any protected areas, migratory bird routes, or important mammals' areas; it is in the Aegean Sea and not between Samothrace and mainland Greece; and causes minimal seabed disturbance. Following this is OWF D, which shares a bigger border with a protected area, is inside the migratory bird route passing over Samothrace, and has the same impact in the other two environmental criteria as OWF C. It should be noted that OWF D can be expanded according to the aggregated suitability scale, but a more conservative approach is taken in this study, due to the fact that the cumulative impacts of this many OWFs has not yet been studied extensively.

Considering fixed-bottom applications, OWF B is a slightly better option from an ecological perspective, since it is outside of any protected area and only shares its western boundary with a protected area compared to OWF A, which is closest in vicinity to the National Park of Evros and triggers all four environmental criteria.

3.1.3. Economic Analysis

The most influential criterion is bathymetry, in which costs ascend quicker and sharper. An important element for OWF A is the fact that it is located within a 15 km radius of the electricity grid, which means that the construction of an offshore substation is not necessary, which is not the case for the rest. Regarding the distance to port, OWF A is the most viable, being within the 20 km radius from the port of Alexandroupolis.

Based on Table 10 and the available data, it can be seen that, from an economic point of view, the most viable offshore wind farm with a significant lead is OWF A, followed by OWF B, then OWF C, and finally OWF D, which spans bigger depths.

Table 10. The four assessment criteria that establish the potential effects in relation to economic and technical factors and the suitability category of each OWF in the techno-economic scenario.

Criterion	OWF A	OWF B	OWF C	OWF D
Mean depth (m)	−22	−32	−89	−544
Distance from the grid	Within 15 km	Within 25 km	Within 45 km	Within 65 km
Distance from port	Within 20 km	Within 30 km	Within 60 km	Within 70 km
LNG station, subsea pipeline, and other technical structures	Outside	Outside	Minor undersea transmission lines within the area	Outside
Suitability value in techno-economic scenario (mean)	−16.4	−21.5	−14.9	−18.3

3.1.4. Social Analysis

Considering the social criteria, the answer to which OWF is best is tricky to determine, as it is more perplexing to quantify. According to Table 11, OWF B is the least impactful regarding social aspects, as it receives the lowest/best values in all criteria. For telecommunications and military radars or other types of antennas, OWF A is the most impactful, as it is located within 15 km radius of the Alexandroupoli airport and in direct proximity to the territorial waters of Turkey. OWFs A and C are projected to cause some problems for vessel routes, mostly fishing and passenger routes, based on data provided by the European Marine Observation and Data Network (EMODnet), as parts of the identified area are used for up to 165 and 302 routes per year, respectively. It is worth noting that for OWF C, its core and westernmost parts have half the number of vessel routes than the whole site originally. Out of the four sites, only OWF B does not interfere majorly with the field of vision of a casual observer from a scenic spot or a settlement.

Table 11. The five assessment criteria that determine the potential effects of OWFs in social aspects and the suitability category of each OWF in the social scenario.

Criterion	OWF A	OWF B	OWF C	OWF D
Maximum density of vessel routes within the OWF area	192	50	302	16
Fish farming	Outside	Outside	Outside	Outside
Military training areas	Outside	Outside	Bordering	Outside
Distance from airports	Between 12 and 20 km	Greater than 15 km	Greater than 15 km	Greater than 15 km
Interferes with the field of vision of a settlement or a scenic spot	Settlement and scenic spot	Without major impact	Settlement and scenic spot	Scenic spot
Suitability value in social scenario (mean)	−22.9	−21.9	−15.0	−17.6

3.1.5. Comparative Analysis of Selected Fixed-Bottom and Floating OWF Sites

Based on the previous subsections, two summary tables, Tables 12 and 13, are composed. They offer a combination of quantitative values and qualitative description, with the most important characteristics for each site in each category. They are introduced to give a better overall understanding of each site and balance environmental, technical, economic, and social factors in order to achieve the best site selection. The tables are interconnected but are shown separately for visual purposes.

Table 12. Summary comparison matrix of selected fixed-bottom OWF sites. Suitability value for each OWF's area in the respective scenario's category are presented, as well as individual advantages and disadvantages of each site.

Category	**OWF A**		**OWF B**	
	+	**−**	**+**	**−**
Environmental	−43.1		−39.3	
	No site-specific positive characteristics reported.	1. Fixed-bottom application, affects marine life adversely at the construction and decommissioning stage. 2. Major interference with migratory bird routes. 3. The most environmentally impactful, as the suitability value correctly predicts.	1. Outside of any protected area.	1. Fixed-bottom application, affects marine life adversely at the construction and decommissioning stage. 2. Interference with migratory bird routes.
Techno-economic	−16.4		−21.5	
	1. The most feasible and economically viable project at the current stage, as it offers great wind potential and, at the same time, fixed-bottom technology is more mature. 2. Mean depth of less than 25 m, offering great versatility in terms of foundation technology that can be applied. 3. Less than 20 km from both port infrastructure and electricity grid, greatly reducing costs for the whole life cycle.	No site-specific negative characteristics reported.	1. Can incorporate more wind turbines due to lower environmental impacts compared to OWF A.	1. It is a scale worse at every assessment criterion of this category, except AC 10, which stays the same, compared to OWF A.
Social	−22.9		−21.9	
	No site-specific positive characteristics reported.	1. Will interfere with the field of vision from nearby settlements and scenic spots. 2.The only OWF that is found within 15 km range from an airport. 3. High density of vessel routes within the area compared to OWFs B and D.	1. Based solely on qualitative analysis, it is projected to be the site with the least impact in this category.	No site-specific negative characteristics reported.
Researchers' opinion	−15.2		−12.5	
	The researchers' subjective scenario's most suitable areas are easy to identify and delineate, even without the other scenarios.	In the techno-economic scenario, the suitability values do not offer a direct comparative analysis between technologies. It is the only category that should be analyzed separately for each technology.	-	In the social scenario, the conclusions do not directly corelate with the suitability value received, due to the more qualitative nature of the social analysis.

Table 13. Summary comparison matrix of selected floating OWF sites. Suitability value for each OWF's area in the respective scenario's category are presented, as well as individual advantages and disadvantages of each site.

Category	OWF C		OWF D	
	+	−	+	−
	−11.5		−22.1	
Environmental	1. The least environmentally impactful, also confirmed by the suitability value. 2. Outside of any protected area. 3. Floating application, does not affect marine life as severely.	No site-specific negative characteristics reported.	1. Outside of any protected area. 2. Floating application, does not affect marine life as severely.	1. Interference with migratory bird routes.
	−14.9		−18.3	
Techno-economic	1. At the current stage, the most economically viable out of the two floating OWFs, as it offers great wind potential at a relatively shallow depth of −89 m. 2. It covers a major area, being able to incorporate almost 100 wind turbines, based on calculations in this study.	1. Minor undersea transmission lines within the area.	1. The best wind potential out of all four OWFs and one of the best in the Aegean Sea.	1. A scale further from port infrastructure and transmission lines compared to OWF C. 2. It is deemed as a long-term project due to the deep waters of the site (mean depth of the site −544 m).
	−15.0		−17.6	
Social	No site-specific positive characteristics reported.	1. Very high density of vessel routes since it is in the vicinity of Samothrace port.	1. It will not interfere with any settlement field of view.	1. The south of Samothrace Island offers some scenic spots, which will be affected by the wind turbines' visual interference.
	+2.0		+2.1	
Researchers' opinion	The environmental scenario gave the closest to reality suitability values out of any scenario.	Some data that were used could be improved for overall better results. The most problematic were the migratory bird routes, which for more realistic results will need weighting to be added, so the value throughout the whole territory, which almost wholly covers both study areas, is not constant.	-	-

4. Discussion and Conclusions

The proposed methodology includes the suitability analysis for offshore wind farm deployment in Thrace, Greece, under five different zoning scenarios (equal weight, environmental, social, techno-economic, and researchers' subjective), as well as the micro siting and qualitative assessment of the most suitable sites based on energy, environmental, social, and economic criteria. Seven (7) exclusion criteria and fifteen (15) assessment criteria have been used in the initial analysis. The AHP is used to provide weights on each assessment criterion under five different siting scenarios (equal weight, environmental, social, techno-economic, and researchers' subjective) and the results are inserted into the ArcGIS software, specifically ArcGIS Desktop version 10.8.1, to identify areas with the greatest suitability values for offshore wind farm deployment in the study area. Although AHP is a subjective decision-making method, in this study, the use of four additional scenarios, apart from the researchers' subjective scenario, and the selection of the four potential areas (two for each offshore wind technology) based on the comparative analysis of the performed scenarios lead to more objective results. In addition, these sites are further analyzed regarding energy, environmental, economic, and social issues and are ranked from the most to least sustainable/suitable, ensuring the reliability of results.

Four sites with the highest suitability in the researcher's subjective scenario (OWF A, OWF B, OWF C, and OWF D) have been selected for further analysis. OWF A and OWF B are fixed-bottom applications, while OWF C and OWF D are floating applications. With the help of Geographical Information Systems (GISs) and the software WAsP (Wind resource Assessment, siting and energy yield calculation), specifically WaSP version 12.8, quantitative results are drawn in the energy analysis performed. From an environmental perspective, OWF C emerges as the most ecologically considerate option. Situated in the Aegean Sea, it is distanced from protected areas, migratory bird routes, and the critical mammal habitats between Samothrace and mainland Greece, while also causing minimal disturbance to the seabed. In terms of ecological suitability, the hierarchical order is as follows: OWF C, OWF D, OWF B, and OWF A. From an economic point of view, the most viable offshore wind farm with a significant lead is OWF A, followed by OWF B, then OWF C, and finally OWF D, which spans bigger depths. In terms of total nominal capacity (MW), OWF C presents the highest, followed by OWF D, OWF B, and OWF A. The social analysis considers several qualitative issues and, therefore, it is complicated and difficult to conclude a hierarchical ranking of the selected sites. However, it is evident that OWF B should have the least social impact, as it consistently receives the lowest/best scores across all the criteria being considered. Overall, without technological restrictions, OWF C is considered the most appealing option, particularly its core and westernmost sections, as it has the least environmental and social impacts, while also being economically viable.

The four selected OWFs will make a significant contribution to fulfilling EU objectives and enhancing Greece's energy autonomy. Legislative constraints considered, the maximum nominal capacity allocated for this marine area is confined to six hundred (600) MW of offshore wind power, in accordance with the specifications outlined in Article 174 (No. Sheet 4964, Government Gazette A 103 150/30.7.2022). Therefore, under the current legal framework, a maximum of 63 V174-9.5 MW wind turbines could be installed, representing approximately one-third of the total capacity of the outlined areas.

The present research presents an integrated methodology for offshore wind farm siting in a specific oriented marine area, examining both fixed-bottom and floating offshore wind technologies and including a wide number of criteria (22) in the analysis. What distinguishes the present study from others is the fact that the most suitable sites are selected based on five different scenarios performing both quantitative and qualitative analysis. An additional after-assessment analysis of the selected sites follows that considers energy, environmental, economic, and social aspects. Finally, it should be noted that for certain criteria (depth, distance from grid, distance from port, and distance from shore), a precise methodology including appropriate equations and computations in GISs is introduced in this research.

Some potential future extensions of the present methodology in future studies may include the improvement and reliability of some data used. For example, the migratory bird routes have a constant value throughout the whole territory and a weighting could be added for more realistic results. In addition, the interference with the view, because of an OWF between two land masses, could be quantitatively assessed, not only qualitatively.

The development of offshore wind farms is one of the best prospects for Greece. However, the construction of such a project should be carried out following special studies of ecological assessments and environmental impacts by qualified scientists. The reason why the green transition needs to be accelerated is to protect the natural environment from even more adverse future effects of climate change. Therefore, the design of an OWF must be carried out with the utmost respect to the environment and ensure the integrity of all ecosystems, habitats, and species. Greece is a country with a vast coastline and significant potential for the development of offshore wind energy. With proper planning and a clear methodological framework, such as the one presented in the present paper for the planning stage of these projects, the selection of optimal siting locations, techniques, and mitigation methods will ensure the least possible negative environmental and social impacts, helping Greece become an entirely green and clean energy country.

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