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Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece

Dimitra G. Vagiona * and **Manos Kamilakis**

Department of Spatial Planning and Development, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece; kamilakismanos@hotmail.com

* Correspondence: dimvag@plandevel.auth.gr; Tel.: +30-231-099-5954

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Abstract: The present research study develops and implements an integrated methodology for the evaluation and prioritization of appropriate sites for sustainable offshore wind-farm development at a regional level. The methodological framework includes the application of several siting criteria (technical, spatial, economic, social and environmental) proposed either by the national legislative framework (Specific Plan for Spatial Planning and Sustainable Development for Renewable Energy) or the international literature with the combined use of geographic information systems (GIS) and multi-criteria decision methods, namely the analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS). The whole methodology provides a decision-making process for offshore wind-farm planning at regional level. The proposed methodology and the outputs of this work can be used to ensure the sustainable spatial development and policy of renewable energy resources.

Keywords: offshore wind farm siting; renewable energy; geographical information systems (GIS); multicriteria decision analysis; spatial analysis

1. Introduction

Conventional energy stocks, due to their nature and origin, incline towards depletion, giving a rightful place to renewable energy sources (RES) in order to fulfil global energy needs. Wind power constitutes the most well-known form of RES, as it possesses both financial viability and advanced technology. More specifically, by the end of 2016 in Europe wind farms of total capacity of 160.00 MW had been installed [1]. It is worth mentioning that during the past decade, a new practice of wind-power exploitation has been established, leading to the installment of wind turbines within the marine space with total capacity of 11,830 MW (2006–2016) [2]. The main reason for the appearance of such a practice is attributed to the existence of powerful wind capacity within marine areas in comparison to land areas, which leads to greater energy efficiency. Furthermore, this practice enables countries with limited land areas but extended marine areas to proceed with the production of environmentally-friendly energy.

Nevertheless, there are significant differences between offshore and onshore wind conditions, and that is of great importance when considering the siting, development and installation of wind farms. For example, offshore winds are greater in strength and more stable (spatially and temporally) than onshore winds; subsequently, the former can utilize more frequent and powerful winds that are available in offshore locations and produce considerably more energy over time. Furthermore, there are offshore areas available with continuous ample space suitable for major projects, in contrast to cramped onshore sites. In addition, offshore developments reduce significantly noise and aesthetic impacts and avoid land-use disputes. On the other hand, however, offshore wind farms have a higher overall cost of implementation than onshore projects, and also involve greater risks and uncertainties, given the immature technology and lack of knowledge and expertise regarding the impact of offshore wind farms on the socio-economic and environmental characteristics of a potential location [3–6]. According to Wind Europe, in the year 2016 alone land wind farms of total capacity of 10,923 MW and total value of 9.3 billion euros, and marine wind farms of total capacity of 1567 MW and total value of 18.2 billion euros, were installed [1]. Comparatively, marine wind installments are 13.64 times financially more valuable than the land ones. In addition, one of the most notable and fundamental problems in planning and developing a marine wind farm is the preliminary identification of suitable areas that fulfill specific criteria.

Choosing an appropriate site is, therefore, a complicated process that is based on various technical/mechanical, environmental, socio-economic parameters, as well as the relevant national legislation concerning marine spatial planning [7]. Wind capacity is the most crucial parameter of such projects, as it provokes the development of such installments, which is attributed to its close relationship with its financial efficiency. Another crucial parameter is the seabed depth as this affects the installment and function of the project and entails the avoidance of high costs due to docking, anchorage and wiring. Moreover, other parameters are the demarcation of safety distance limits in order to preserve vulnerable areas, such as the Natura network and the migration routes of birdlife, and to distance the project from maritime links that may exist within the marine area, especially in areas with great commercial and tourist maritime presence. Finally, another parameter used, in order to evaluate the necessity of an offshore wind farm, is its distance from residential areas which is measured in parallel to define the amount of population and the energy demand of the area.

GIS has become a major tool used to select the most suitable sites for onshore and offshore wind farm installations [8]. GIS methods for offshore wind projects have been applied in several countries around the world, such as Taiwan [9], China [10], Denmark [11], Greece [12,13], Ohio [14], South Korea [15] and the Baltic States [16]. For instance, ref. [9] evaluate wind energy resources with the aid of a GIS according to actual local conditions. Several local restrictions, such as wind speed, water depth, land use and ecological environments, are considered in this analysis. With the aid of GIS, offshore wind potential in China is evaluated by [10], as a combination of wind resources, technical projections of wind turbines, economic costs and spatial constraints of offshore wind farms. A model is presented by ref. [11] called the spatially continuous resource economic assessment model for offshore wind energy (SCREAM-offshore wind) based on GIS and supply-cost curve analysis. Technical and environmental constraints through GIS are applied by [12] to all coastal areas in Greece to identify potential areas for offshore wind farm development. GIS is used by [13] to identify the sustainable siting of an offshore wind farm based on legal limitations, with respect to ecological and economic resources, using the island of Crete as an example. The design and implementation of a web-based Participatory Geographic Information System (PGIS) framework is presented by [14] to evaluate the importance of three decision alternatives using different evaluation criteria for offshore wind farm suitability within Lake Erie, Ohio. Classified data and GIS are used by [15] to apply four different marine spatial planning scenarios to Jeju Island, where offshore wind power plans have been designed and are being implemented. A preselection phase is introduced by [16] which is based on a predefined set of GIS layers to identify a limited set of candidate sites for offshore wind farm development in the Baltic States.

Moreover, multi-criteria decision analysis plays a crucial role in offshore wind-farm siting. Several researchers have applied multi-criteria techniques to rank offshore wind-farm siting alternatives. An analytical hierarchy process (AHP) is applied by [12] which divides the decision-making process into three parts in hierarchical terms, namely the goal (effective offshore wind farm selection in Greece), the evaluation criteria, and the alternatives (all areas not excluded in the exclusion phase). Multi-attribute decision analysis (MADA) is applied by [14] to rank three spatial alternatives associated with different site locations within Lake Erie (Ohio) in relation to eight different evaluation criteria. An evaluation system of 74 offshore sites along the Spanish coast, as regards their potential for RES development, is used by [6] along with multiple criteria decision analysis through the GIS system.

In the present paper, a methodological framework for identifying the most appropriate marine areas in the South Aegean, Greece, to deploy offshore wind farms is developed and presented. The methodology followed includes three phases: data collection, exclusion and evaluation. Three tools, namely GIS, AHP and TOPSIS are integrated in order to propose a methodological framework for offshore wind-farm site selection. GIS serves as a data-generation tool for different thematic layers and, in addition, contributes to the evaluation phase. Initially, marine areas unsuitable for the siting of offshore wind farms are identified considering a set of environmental, economic, technical and social constraints. This process includes the creation of various thematic maps and their overlapping results in eligible marine areas that are further evaluated and prioritized using TOPSIS based on a set of evaluation criteria related to financial, environmental and operational parameters. The evaluation criteria are previously evaluated through pairwise comparisons used in the AHP method. The final result of the whole methodology is the determination of the most appropriate and efficient sites for offshore wind-farm siting in the South Aegean marine environment. It should be noted that it is the first time that an integration of AHP and TOPSIS (multicriteria decision making methods (MCDM)) is performed to address renewable-energy (RE) siting issues.

In addition, the present paper contributes to the field of renewable-energy resources in the spatial level of application. The most relevant studies for offshore wind farms have been applied either for whole countries (e.g., [11,12,17]) or for islands (e.g., [13,15,18]). By contrast, the whole application of the present study is performed in the South Aegean region, Greece, that is divided into 13 regional units and formed around major islands. The spatial level of application is an extremely important issue. The present study focuses on a regional application that presents significant advantages in terms of energy self-efficiency. It should be noted that 100% RE supply within the electricity sector is usually only feasible on the regional level [19] and that islands present sustainable-energy growth challenges for numerous reasons such as remoteness, limited energy resources, vulnerability to external events and strong dependence on international trade agreements [20]. However, islands are often not or only partially connected to continental electrical networks and have to manage their energy supplies in reaching the production/demand balance while ensuring the quality of the electricity delivered [21]. In addition, islands should address the demand peaks as energy demand is formulated mainly by tourists during summertime.

The rest of this paper is organized as follows: Section 2 describes the methodological framework developed, as well as the exclusion and evaluation criteria used in the analysis; in Section 3, the results of the applied methodology are presented and discussed through the formulation of various thematic maps and discussed; and Section 4 provides the main conclusions of the present study.

2. Materials and Methods

The process of identifying the optimum sites for wind farms in a geographical region includes various stages, which are determined by the individual researcher. In the present paper, a combination of applied methodologies is used and integrated with the criteria found in the legislative framework of the Special Framework for Spatial Planning and Sustainable Development for renewable energy sources (SFSPSD-RES) [22] and in the international literature. More specifically, the proposed methodology is divided into three stages. The first stage is the data collection phase, which includes the creation of a GIS database as well as the depiction of information in different thematic layers. The second stage, which is the exclusion stage, consists of three distinct phases which involve the exclusion of incompatible areas according to selected exclusion criteria and the application of surface restrictions. Next, there is a transition to the evaluation stage, where areas deemed to be suitable in the previous stage are further evaluated according to a set of criteria (evaluation criteria). It is important to note that some of the exclusion criteria are also used as evaluation criteria, mainly due to their nature, and their selection is explained in detail below. The proposed methodology is depicted in Figure 1.

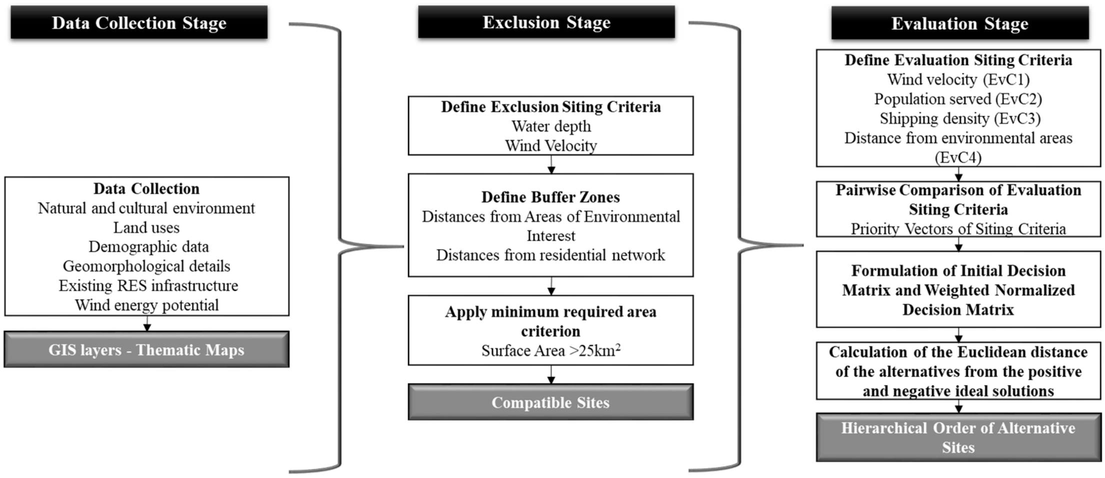


Figure 1. Methodological process.

2.1. Data-Collection Stage

A first step regarding the siting of any project is to analyse the characteristics of the study area. The main reason for this is to examine the profile of the area. The basic features of an area include its natural and cultural environment, demographic data, land uses, geomorphological details, existing RES infrastructure, as well as the area's wind-energy potential. The above features are required in order to exclude areas with incompatible uses.

2.2. Exclusion Stage

2.2.1. Definition of Exlusion Siting Criteria

The first stage for initiating the process of locating suitable areas for the siting of wind farms is to exclude the areas which are deemed incompatible for the siting of offshore wind farms. Two criteria are used for this purpose: (a) the depth of the sea basin, so as to exclude sites where the installation of a marine wind farm cannot be carried out with the existing technology; and (b) the available wind-energy potential. The restrictions of the above criteria are formulated according to the dominant values found in the literature.

Water Depth

The water depth is of primary importance since the greater the depth the higher the cost (due to the mooring, anchorage and cabling). Moreover, the installation formula also changes depending on the water depth. More specifically, current technologies provide the possibility to develop marine wind farms at a maximum depth of 60 m with a stable offshore structure [16,22–24]. Thus, in order to avoid high installation costs, a depth of over 60 m is excluded in the present paper.

Wind Velocity

Wind velocity is directly linked to the economic efficiency of the project and is therefore a major variable in choosing the right site. It is therefore a very important criterion, which is used at this stage so as to exclude all areas with a weak wind-energy potential. The available offshore wind potential can be quantitatively expressed through the mean wind velocity 10 m above the mean water level. Marine areas with mean wind velocity smaller than 6 m/s are considered unsuitable for offshore energy projects according to several studies found in the literature (e.g., [12,23,25–27]).

2.2.2. Definition of Buffer Zones

To complete the second stage, it is necessary to determine the minimum distances that need to be maintained, in order to identify the most suitable areas for the installation of a marine wind farm. For further minimum distance exclusion, criteria are used which aim to prevent conflicts between existing land uses and marine wind farms, protect environmentally sensitive areas, and maintain the area's profile intact.

Distance from Areas of Environmental Interest

The categories of environmental interest areas that need to be examined during the first exclusion stage are the Special Protection Areas (SPAs) of Natura 2000, wildlife refuges, migration corridors, as well as swimming beaches awarded the Blue Flag. Of these areas, wildlife refuges and migration corridors are not included in the areas for which minimum distances are recommended in the SFSDSP-RES [22]. Nevertheless, wildlife refuges are granted the same minimum distances as the Natura network, due to their high ecological value. As regards migration corridors, a buffer distance of 3 km is recommended, according to [10]. Thus, the minimum distance recommended for protection areas under these two categories is 1000 m, and 1500 m for Blue Flag beaches.

Distance from Residential Network

The residential network is selected as a criterion in order to eliminate to the greatest extent the parameter of visual disturbance, caused by the development of a marine wind farm. The SFSDSP-RES [22] defines the minimum distances from residential activities according to the following categories: (a) for all settlements (not traditional ones), the recommended distance is 1000 m; and (b) for traditional settlements, the recommended distance is 1500 m. It is worth noting that there are also other restrictions in the special framework regarding settlements of a smaller scale, but these are not taken into account since they fall under the first restriction.

2.3. Evaluation Stage

2.3.1. Tools

The second stage of the methodology involves an evaluation of the candidate sites that emerged from Stage 1, in order to identify the optimum installation area for a wind farm in the study area. The areas that have been identified up to this stage are mainly suitable according to spatial criteria regarding the installation of wind farms. At the second stage, an attempt is performed to carry out a comparison of the available areas in order to arrive at the best siting position from an economic, social and efficiency perspective. In order to achieve this, two widely applied multi-criteria analysis tools are integrated. Pairwise comparisons of the evaluation criteria by using the AHP are initially applied and each criterion is given a weight depending on the importance assigned to it by the researcher.

The AHP is a pairwise comparison method, developed by Saaty [28], whereby each element is scored against the rest, in order to evaluate its relative importance. The method in question functions by decomposing a complex problem into parts, according to a specific hierarchy [29]. More specifically, according to this model, the main objective is at the top of the hierarchy, the criteria and sub-criteria are on the other levels and sub-levels of the hierarchy, and alternative decisions are at the base [30]. This process uses pairwise comparison to develop a priority scale between activities, based on the decision-makers' inputs. The pairwise comparison takes values from Saaty's fundamental scale (1–9), where 1 corresponds to 'equally important', 3 to 'slightly more important', 5 to 'much more important', 7 to 'far more important' and 9 to 'extremely more important' (Table 1). If the relation of importance is reverse, then the index rating is also reversed, i.e., 1/3, 1/5, 1/7, 1/9. The values 2, 4, 6 and 8 have been defined as intermediate values and can also be used in pairwise comparison. The latter are used to determine the weighting of the criteria.

Table 1. Pairwise comparison ratings.

Rating	Index of Importance
1	Equally important
3	Slightly more important
5	Much more important
7	Far more important
9	Extremely important

In this way, a matrix is created where the number of columns and rows corresponds to the number of criteria, and the successive steps to be taken are as follows: (i) the matrix elements are completed based on the pairwise comparisons made; (ii) the sum of elements in each column is calculated; (iii) each element of the matrix is divided with the sum of its column and a new matrix with an equal number of rows and columns to the original is created, as a result of the new calculations; (iv) the mean of each row of the new matrix is calculated and recorded in a new column, which comprises the priority vector of the criteria.

The AHP also provides mathematical measures to test the consistency of the comparisons, i.e., to test their objectivity. The consistency index for each formulated comparison matrix is calculated as follows:

- by multiplying the sum of the elements in the matrix with the relative weight of the respective criterion;
- by adding all these products for all columns and defining the result as A.

Thus, the consistency index (CI) is defined through Equation (1) given by [31]:

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

where n is the number of criteria.

To get a broader perspective, the CI is compared with the index obtained from an arbitrary comparison matrix, whose entry data are randomly selected. Through a simulation, Saaty obtained the results in Table 2, where n is the dimension of a specific comparison matrix and RI is the random index calculated using the CI mean on a large sample of random comparison matrices. The level of consistency (CR) is defined by the consistency ratio (CR) through Equation (2) that should have a value of less than 0.1 [31]:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

Table 2. Random index (RI) values.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

The priority vector of each evaluation criterion is used in the second multi-criteria method (TOPSIS), which is applied for the final assessment and hierarchical ranking of the alternative siting locations.

The TOPSIS method is a multi-criteria decision analysis method, which was originally developed by Hwang and Yoon in 1981 [32] with further developments by [33,34] in 1993.

TOPSIS simultaneously considers the distances to both positive ideal solution (PIS) and negative ideal solution (NIS), and a preference order is ranked according to their relative closeness, and a combination of these two distance measures [34].

A prerequisite for the application of this method constitutes the generation of an $m * n$ initial decision matrix (m = number of alternatives, n = number of evaluation criteria) that includes specific values (qualitative scale 1–7) of each offshore siting location in respect to the evaluation criteria. Additionally, the following steps of TOPSIS process are executed [32].

Step 1: Normalization of the Initial Decision Matrix

Each field of the initial decision matrix (r_{ij}) is normalized using the equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$$

x_{ij} is the intersection of each alternative (i) and criteria (j), $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots m$.

Step 2: Construction of the Weighted Normalized Decision Matrix

The weights of each evaluation criteria (pairwise comparisons are multiplied with the normalized values of the alternative siting locations in order to produce the weighted normalized decision matrix.

Step 3: Determination of the Positive Ideal Solution (S^+) and the Negative Ideal Solution (S^-)

Precondition for the determination of the positive and negative ideal solution is the identification of the function type (cost or benefit) that each evaluation criteria indicates. If for example, the criterion represents a cost function, the positive ideal solution receives the minimum value between the values of the siting alternatives and the negative ideal solution the maximum value. Reverse is the case when the criterion represents a benefit function.

Step 4: Calculation of the Euclidean Distance of the Alternatives from the S^+ and S^- Solutions

The following equations are used to calculate the Euclidean distances:

$$\mathrm{Si}^+ = \sqrt{\sum_{i=1}^{m} \left(v_{ij} - v_i^+\right)^2},\ i = 1,\ 2,\ \ldots\ m$$

$$\mathrm{Si}^- = \sqrt{\sum_{i=1}^{m} \left(v_{ij} - v_i^-\right)^2},\ i = 1,\ 2,\ \ldots\ m$$

Step 5: Calculation of the Relative Closeness (Ci^+) to the Positive Ideal Solution

The relative closeness of each alternative in respect to the positive ideal solution is calculated using the equation:

$$\mathrm{Ci}^+ = \frac{\mathrm{Si}^-}{(\mathrm{Si}^+ + \mathrm{Si}^-)},\ i = 1,\ 2,\ \ldots\ m$$

Step 6: Results and Determination of the Ranking Order of the Alternatives Based on the Relative Closeness (Ci^+) Measure

In final stage, the results of the TOPSIS method process are concentrated in an overall matrix and the ranking order of siting alternatives is determined. The best/preferred alternatives are the ones with the highest score.

2.3.2. Evaluation Criteria

The evaluation criteria aim to preserve the existing environment of the study area unchanged and also to prevent the occurrence of any new conflict over land use. It is therefore necessary for the evaluation criteria primarily to involve the economic efficiency of the project and the minimization of land-use conflicts, while catering for as many needs as possible. Nevertheless, the parameter of environmental protection is also taken into account at this stage, since some of the exclusion criteria are also chosen as evaluation criteria, in order to select the optimum siting position. Thus, the selected criteria include wind velocity (EvC1), population served (EvC2), shipping density (EvC3) and distance from environmentally protected areas (EvC4). The evaluation criteria are presented in Table 3 and described in detail below.

Table 3. Evaluation criteria.

A/A	Criterion	Type	Brief Description
EvC1	Wind velocity (m/s)	Financial	The greater the wind speed in an area, the more efficient it is considered to be as regards the generation of electricity.
EvC2	Population served (residents)	Operational	The larger the population served in each area, the greater the need for siting a marine wind farm in that area.
EvC3	Shipping density (units)	Financial and Operational	The more shipping networks there are in an area, the harder it is to site such a project in that area.
EvC4	Distance from environmentally protected areas (km)	Environmental	The greater the distance from environmental areas, the more possible it is to ensure the protection of the environment in that area.

Wind Velocity (EvC1)

An exceptionally important criterion is the wind-energy potential of an area, since it determines its energy-producing capacity. Therefore, this criterion is considered essential in order to calculate the suitability of an area as regards the siting of marine wind installations. Priority is naturally given to areas which develop a higher concentration of wind-energy potential on average, and therefore produce more energy. This criterion is also used in the first stage of the methodology, but in the present stage it is diversified, since it contributes towards identifying the siting area with the best performance.

Population Served (EvC2)

The population served percentage is used as a defining criterion in the evaluation stage, since it is used to evaluate the degree of coverage of the population's energy requirements in each recommended location. More specifically, the total population was calculated for each candidate site, identified during the first stage, which is located at a distance of 100 km (from the centre of each area). The area with the most residents receives the highest score, since the project will then cumulatively cover the needs of a larger part of the population [14,23].

Shipping Density (EvC3)

This criterion mainly involves areas with intense maritime freight and passenger traffic, such as the South Aegean region. At the planning stage, all shipping routes must be taken into account when the siting area is determined. Areas with a large number of shipping networks render the siting of a marine wind farm harder to achieve. Furthermore, the development of wind farms in areas traversed by passenger or freight vessels can lead to land-use conflicts with the relevant sectors. For this reason, the fewer the existing shipping connections, the higher the ranking given to that area, in order to effectively eliminate any land-use conflicts.

Distance from Environmentally Protected Areas (EvC4)

This criterion is used in the previous stage, but it is also used in the evaluation stage in order to give priority to areas that are situated at the greatest possible distance from environmentally sensitive areas. This means that the said regions will theoretically not suffer any environmental impact throughout the lifecycle of the project.

3. Results and Discussion

3.1. Analysis of the Study Area and Data Collection

The South Aegean region covers a huge marine zone, which spreads from the coast of Attica (Makronisos) to the southern coast of Turkey (Kastelorizo). It consists of 79 islands, 55 of which are inhabited, and 178 rocky islets. The total area of the region is 5286 sq·km (4% of the area of Greece) [35]. Its land area is distributed as follows: 28% mountainous, 43% semi-mountainous and 29% plains. The South Aegean is a Greek region with a double role, as an external border of Greece and of the European Union. The region also includes the easternmost point of the European Union, namely Strongyli Island [36]. It consists of the prefectures of Cyclades and the Dodecanese and is administratively divided into 13 regional units and 34 municipalities. It should be noted that the region includes 5 urban centres, namely Rhodes, Kos, Ialysos, Kalymnos and Ermoupoli. The most densely populated municipality in the region is the municipality of Rhodes, which accounts for 37.4% of the population, with 115,490 permanent residents; nevertheless, the region's capital is Ermoupoli in Syros with 21,507 residents.

The South Aegean region hosts the largest number of areas of the Natura network in Greece (62 areas). As regards areas of natural beauty in general, they cover a large part of the region, and in some cases correspond to whole islands. It also includes monuments of international acclaim in Thera, Delos, Lindos, Rhodes, Patmos and Kos, three of which are World Heritage monuments (UNESCO): the Medieval City of Rhodes, Delos, and the Historic Centre with the Monastery of Saint John the Theologian and the Cave of the Apocalypse on the island of Patmos.

The primary characteristics of the energy system in the region is its great dependence on imported energy sources, and in particular oil, the problems with covering the energy requirements of the island areas, the great increase in the demand for energy, the high energy intensity, the lack of strong connections to European natural gas and electricity networks, and the predominance of the public sector in the electricity and natural gas markets [35].

The energy produced by the existing infrastructure of autonomous energy-generating plants amounts to 1.7 (TWh) and fairly adequately covers the needs of the region, apart from the summer months when there is increased demand.

Wind energy is exploited to a limited degree in the region, despite the existence of a satisfactory wind velocity in most areas. The South Aegean currently has an installed capacity of 20.1 MW in wind farms or 3.2% of the total installed capacity of the country.

The primary data are retrieved from the sources listed below:

1. Wind velocity [7]
2. Water depth [37]
3. Environmental protected areas [35,36]
4. Land uses [35]
5. Population [38]
6. Blue Flag Awards [39]
7. Settlements [40]
8. Traditional settlements [35,36]
9. Wind-farm infrastructures [41]

The wind farm infrastructures in the South Aegean region are presented in Figure 2 and are categorized according to their authorization process. According to the Greek Regulatory Authority for Energy [41], regarding the offshore wind farms there is no wind farm either under production or operational license. Eight wind farms are under evaluation (one near Andros, one near Makronisos, two near Karpathos and four near Kasos), while one (near Andros) have already been rejected. It should be noted that these areas are not excluded from the analysis as no decision has been undertaken yet.

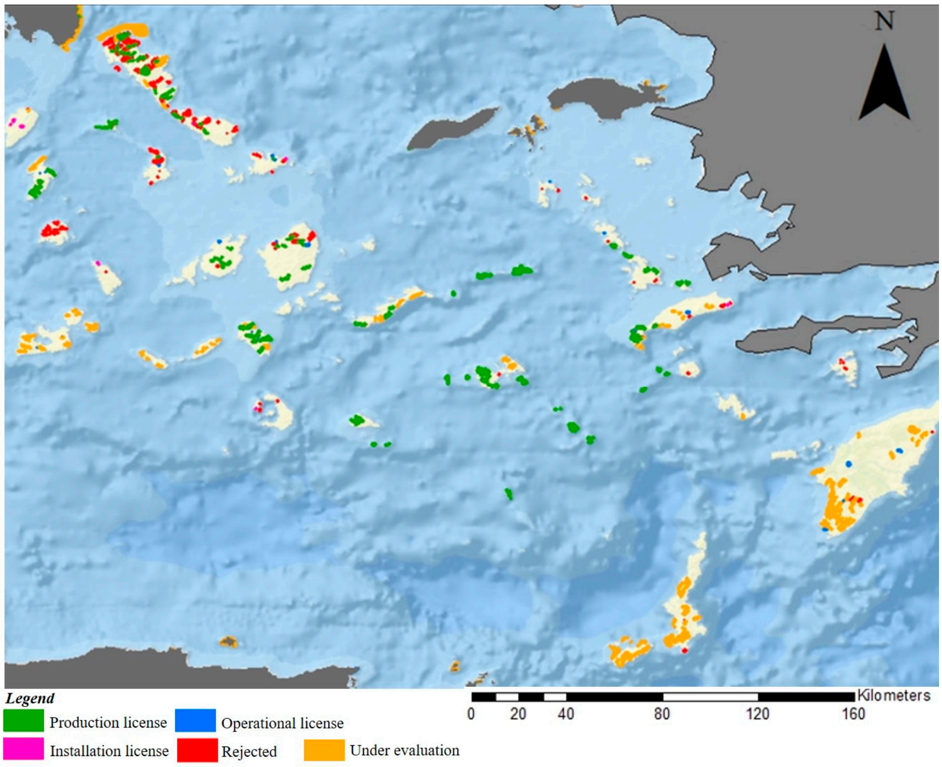


Figure 2. Mapping of status of wind installations in the South Aegean region.

3.2. Exclusion Stage

3.2.1. Exclusion of Incompatible Areas

Water Depth

The sea covering the South Aegean, namely the Northern Sea of Crete and the Aegean Sea, mostly feature deep waters. Nevertheless, there are also shallow waters between the formed island complexes, mainly in the north-east and north-west parts of the region. Figure 3 shows the depth of the sea basin divided into 5 categories. The areas which are technologically eligible for the development of a marine wind farm are those with a water depth of less than 60 m.

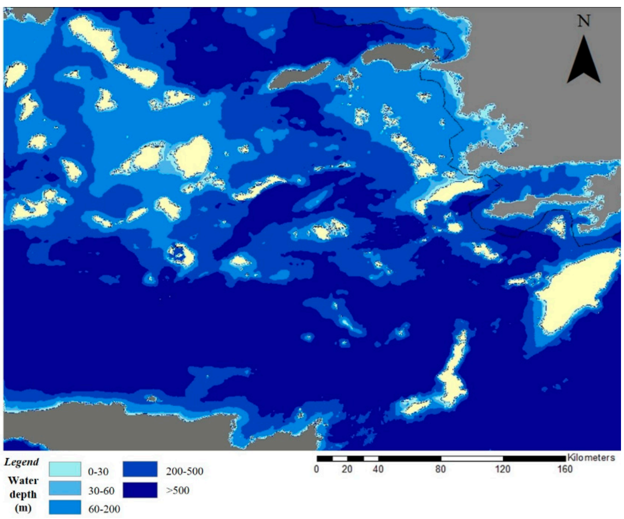


Figure 3. Bathymetric map of the study area.

Wind Velocity

Figure 4 shows the wind velocity divided into 6 speed classes. It is worth observing the data concerning the average annual wind velocity at 10 m from the surface of the sea during the period 1995–2009 [7], as the South Aegean area has a powerful wind velocity due to the 'meltemi' winds, which blow all across it. The areas excluded are those with a low wind velocity under 6 m/s.

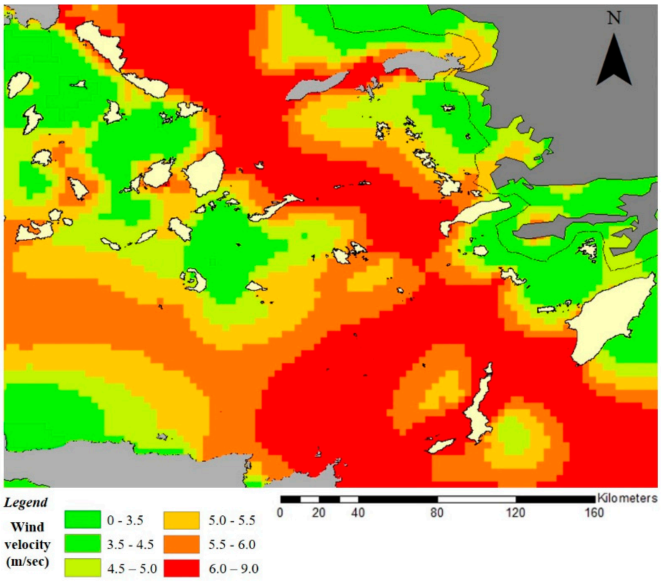


Figure 4. Wind velocity map.

3.2.2. Exclusion of Incompatible Zones

In the second phase of the first stage of planning, the exclusion of the minimum distances for each individual criterion is carried out. The exclusion of the areas is based on the application either of the restrictions proposed in the Greek institutional framework, namely Article 6 of the SFSPSD-RES [22], or of the prevalent value from the literature review of the exclusion criteria.

More specifically, Figure 5a shows the exclusion areas which are formed at a buffer distance of 1500 m in order to avoid visual disturbance and the distortion of the landscape, which could be caused by the potential installation of a marine wind farm. Figure 5b shows the exclusion areas based on environmentally sensitive areas. For the areas of the Natura network and wildlife refuges, an exclusion buffer distance of 1 km is applied. Furthermore, an exclusion buffer distance of 3 km is applied for the protection of the avifauna from potentially crashing into wind turbines during the migration period. In order to avoid problems such as noise and visual disturbance, a safety buffer distance of 1 km (Figure 5c) is applied for all settlements; as regards traditional settlements, a safety buffer distance of 1.5 km (Figure 5d) is applied in order to preserve their image and local character unchanged.

The application of the exclusion criteria results in a total number of 17 proposed sites that fulfill the criteria (Figure 6). Most of the proposed areas cover a small area (Table 4). Thus, prior to the completion of the exclusion phase, yet another exclusion criterion is applied to the proposed sites, in order to exclude all areas where the development of a marine wind farm is unfeasible due to their small size. According to [42], the minimum required area is 25 km^2. After the application of the minimum required area for the development of a marine wind farm, out of the 17 proposed sites, the final proposed sites are area 17 (site A) which is situated between the islands of Kos and Kalymnos, and area 16 further south (site B), between the islands of Kasos and Karpathos (Figure 6).

Table 4. Area of proposed sites.

Area	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Surface (km^2)	3	7.1	10.8	0.5	0.9	10.5	1.8	6.2	4.2	8.9	0.6	1.9	1.7	14.7	5.4	48.8	59.1

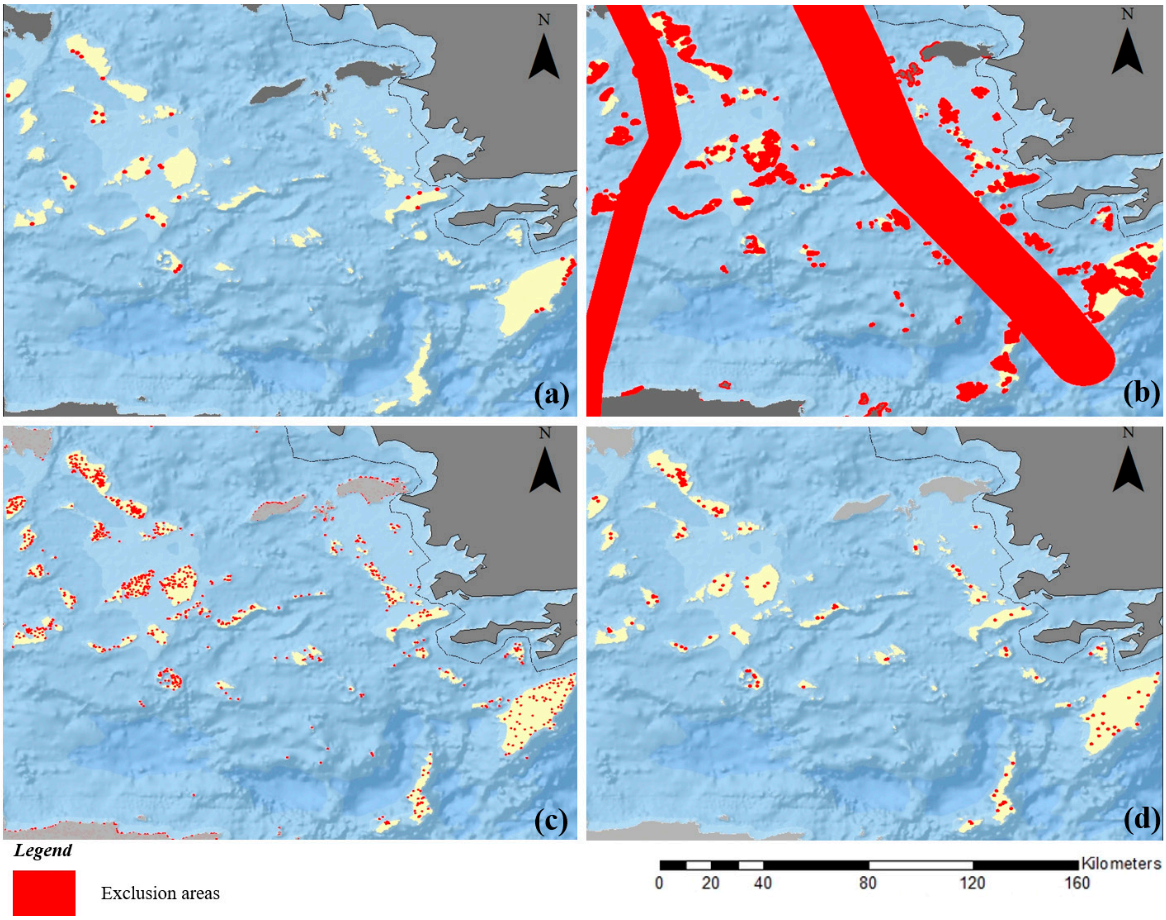


Figure 5. (**a**) Areas excluded from siting by the 'Blue Flag beaches' criterion; (**b**) areas excluded from siting by the 'environmentally sensitive areas' criterion; (**c**) areas excluded from siting by the 'settlements' criterion; (**d**) areas excluded from siting by the 'traditional settlements' criterion.

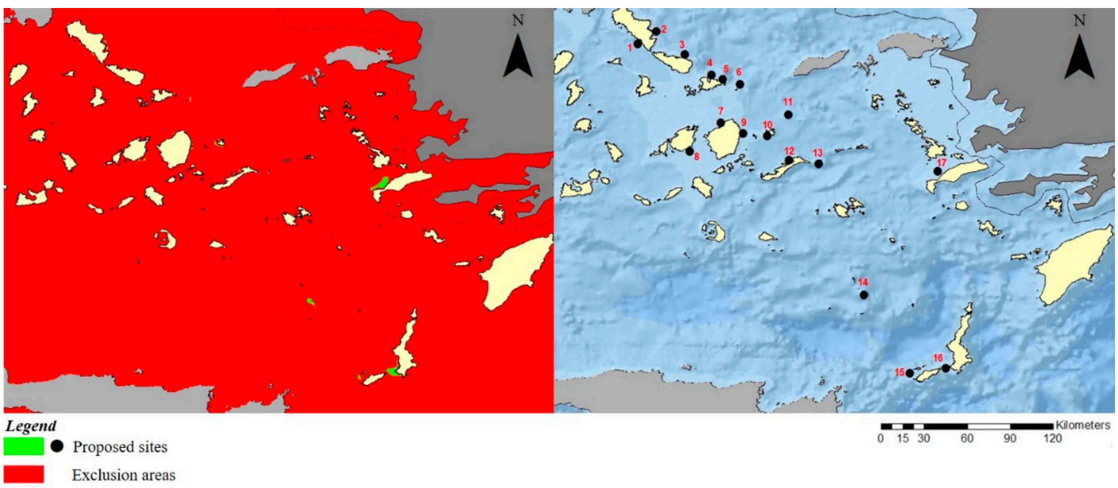


Figure 6. Composition of exclusion criteria.

3.3. Evaluation of Decision Alternatives

In the second stage of identifying the optimum site for the installation of a wind farm, an evaluation is carried out of the two decision alternatives (A and B) which emerged from the previous stage as suitable for siting, based on the four evaluation criteria (EvCi, i = 1–4).

The combined AHP and TOPSIS method is used for this purpose, according to which the problem is broken down into the evaluation criteria and the siting areas, and their hierarchical classification into levels.

At the first classification level, there is a pairwise comparison of the evaluation criteria which produces the weight of each criterion (Table 5).

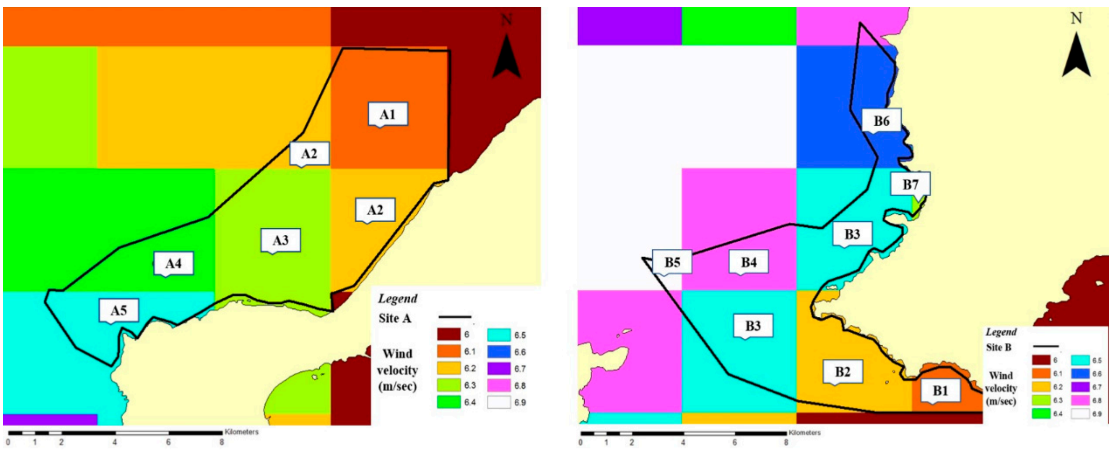
Table 5. Pairwise comparison matrix and relevant weights of evaluation criteria EvCi, i = 1–4 with respect to the goal.

	EvC1	EvC2	EvC3	EvC4	Relevant Weight
EvC1	1	3	5	3	0.52
EvC2	1/3	1	3	1	0.20
EvC3	1/5	1/3	1	1/3	0.08
EvC4	1/3	1	3	1	0.20

Next, each siting area is evaluated according to each evaluation criterion.

WV: Wind Velocity (EvC1)

The average centroid wind velocity is calculated for areas A and B, according to the wind velocity that develops in each sub-area ($A_{1–5}$, $B_{1–6}$) and the area it covers (Figure 7a,b, respectively). The average centroid wind velocity for areas A and B is calculated as being 6.27 m/s and 6.46 m/s, respectively.



(**a**) (**b**)

Figure 7. (**a**) Average centroid wind velocity site A; (**b**) average centroid wind velocity site B.

PS: Population Served (EvC2)

This criterion refers to the number of people that will be served by the project if it is realized in that specific area. The larger the population recorded, the higher the ranking that will be given to that area during its evaluation [14]. After taking into account the fact that the study area consists of islands, the fact that its area is greatly fragmented and the scale of the study, the maximum distance covered was set at 100 km.

According to Figure 8, site A covers the islands of Kos, Kalymnos, Pserimos, Leros and Nisyros, with a total population of 58,492 people, while site B covers the islands of Karpathos and Kasos, with a total population of 8394 people.

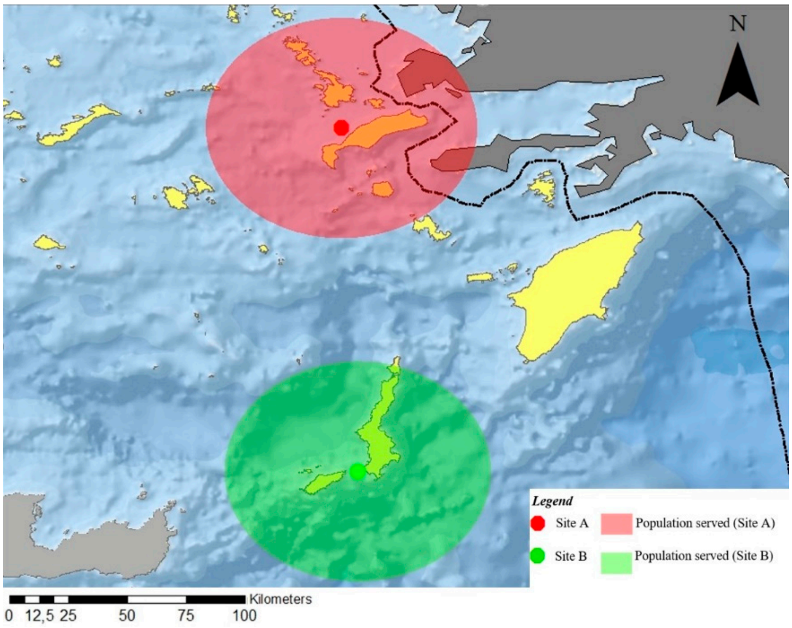


Figure 8. Population served.

SD: Shipping Density (EvC3)

The South Aegean region has a large number of shipping connections, which is to be expected due to the fact that it consists of many islands and is a popular tourist destination. In order to ensure the safety of shipping routes, a buffer distance of 3 miles was applied in accordance with [14]. The fewer the shipping routes in an area, the higher the ranking it will receive during the AHP process. As observed in Figure 9, one route crosses through site A, and two through site B.

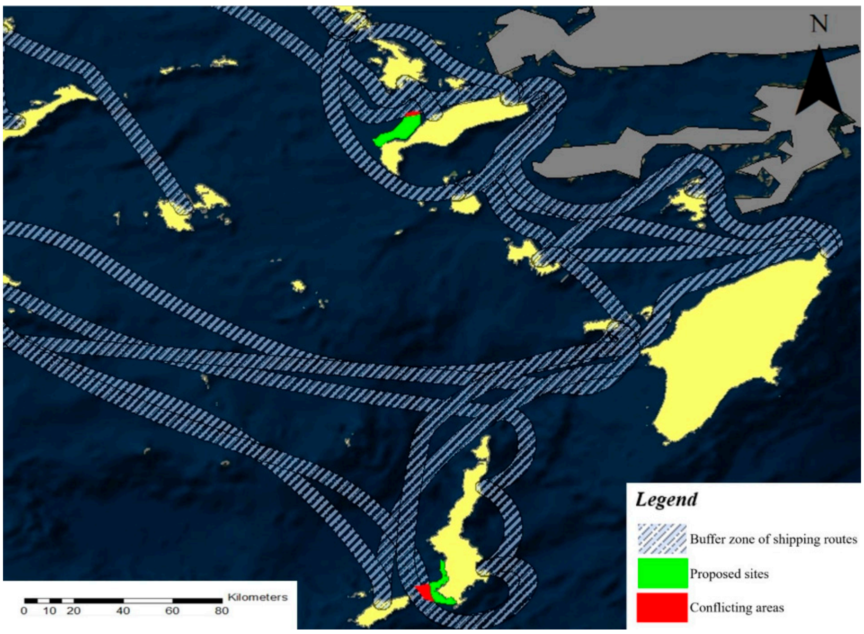


Figure 9. Buffer zones of shipping connections.

DEPA: Distance from Environmentally Protected Areas (EvC4)

In order to evaluate the sites according to this criterion, the minimum distance of each site from the Natura areas is recorded (Figure 10). Subsequently, the calculated distances are 7.7 km and 1.5 km for sites A and B respectively.

The matrices of the TOPSIS method application are then generated in order to prioritize the two siting alternatives (sites A and B). Table 6 illustrates the generation of the initial decision matrix including the performances of the siting alternatives in respect to the evaluation criteria as well as the calculation of the Euclidean distances (Si^+, Si^-) and the final results of siting alternatives prioritization, based on the relative closeness measure (Ci^+).

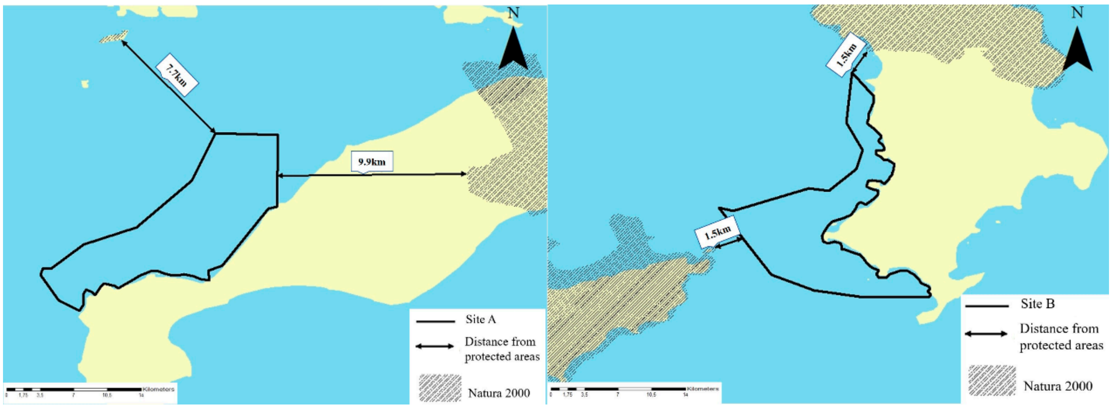


Figure 10. Proximity to Environmentally Protected Areas.

Table 6. Initial decision matrix: calculation of Euclidean distances and relative closeness measures (final prioritization).

	EvC1	EvC2	EvC3	EvC4	Si^+	Si^-	$Si^+ + Si^-$	Ci^+
Site A	3	6	6	6	0.104	0.18	0.284	0.63
Site B	4	2	5	2	0.18	0.104	0.284	0.37

Site A has a better ranking for three of the four evaluation criteria, whereas site B prevails as regards the most important criterion of all, wind energy potential. Site A is therefore considered to be more suitable for the development of a marine wind farm than site B.

The results obtained after the application of the methodology are of particular interest, since both of the proposed sites are located at a minimum distance from installed onshore wind farms or wind farms that are currently at the licensing stage. More specifically, site A is close to two wind farms which are already in operation and six which are at the production phase, while site B includes and contains two marine wind farms at the evaluation stage; it is also close to 14 onshore wind farms that are currently at the evaluation stage and two at the licensing stage.

4. Conclusions

The methodology used in the present paper is an integrated proposal for the siting of an offshore wind farm, whose planning stages and criteria can be adopted and used in various applications and scales of planning. The proposed methodology is applied on a regional level in the South Aegean, in order to pinpoint suitable areas for the development of marine wind farms. The main reason that this study area is selected is the high wind-energy potential of the region, which is caused by the creation of extensive high-pressure systems in the Balkans, to the north of Greece, in combination with the extensive low-pressure system of Asia Minor and the eastern Mediterranean. The paper is based on the use of geographic information systems (GIS) through the ArcMap (GIS) programme in order to create spatial databases and exclude incompatible areas. Furthermore, a combination of AHP and TOPSIS is used as a multi-criteria analysis method in order to evaluate and hierarchically rank the suitability of the areas.

On a broader framework, as regards the present paper, it is found that the siting of RES projects is a complex and multi-dimensional issue that includes various technological, special, socio-economic and environmental parameters. As has been mentioned, Greece, as a member-state of the European Union, must significantly increase its rate of RES installations, so that RES account for 20% of its total energy consumption by 2020. Consequently, a national strategy has been developed for the gradual development of RES in order to increase their share in the energy consumption map of the country; thus, the need for successful and effective siting of RES is a fundamental issue. On the other hand, the installation of new RES will make a decisive contribution to the country's sustainable development through the production of energy from these sources.

To be specific, wind power is developing at a very rapid pace on a global level, involving both onshore and offshore installations. Marine sites have proven to be more efficient, primarily due to the stronger wind velocity which develops at sea. By combining a review of the relevant literature and the Greek institutional framework, the exclusion and evaluation criteria are selected for use. The basic parameters reviewed in order to select the criteria, along with the reduction or avoidance of any likely impact caused by the siting of a marine wind farm, are also the geographical profile (island structure) and scale of the study area. The applied methodology is divided into three stages. The first stage includes data collection, spatial depiction and development of thematic layers. In the second stage, exclusion of the incompatible areas for siting is carried out, where the criteria of installation potential, social benefit and environmental protection are taken into consideration. In the evaluation stage, the criteria used cover aspects of economic efficiency, operational integrity and environmental sensitivity.

After the completion of the exclusion stage, 15 areas are initially identified as suitable for the siting of offshore wind farms. These areas are reduced further after the exclusion of areas of a small and inadequate size for an offshore wind farm, since such a project is economically unviable. For this reason, and although only two sites are finally put forward due to the strictness of the criteria, they are eligible for the extensive siting of wind farms, in order to fulfil the national goal of increasing the RES share, and the regional goal of covering the energy requirements of as many residents as possible. In the evaluation stage, the eligible areas are placed in hierarchical order with the use of the combined analytic hierarchy and TOPSIS process. The results of the application of this methodology are of particular interest, since the two proposed areas are located at a minimum distance from existing onshore wind farms or wind farms which are currently at the licensing stage.

Numerous extensions of the present paper could be performed including stakeholder involvement and public participation in the evaluation stage. In addition, the proposed methodology could be applied at any spatial scale from local to national, enhancing the decision-making process of spatial multi-criteria problems and contributing to the sustainable exploitation of wind-energy resources.

Author Contributions: Dimitra Vagiona is the supervisor of this research and proposed the idea of the methodological framework. She wrote the introduction, literature review, results—discussion, conclusions and performed multicriteria analysis. Manos Kamilakis performed the literature review, collected all the necessary data, produced all the maps, provided input to the multicriteria analysis and contributed to the whole writing of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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