



Spatial energy planning of offshore wind farms in Greece using GIS and a hybrid MCDM methodological approach

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Abstract

The present paper focuses on the efficient development of offshore wind farms in shallow waters in Greece. An integrated spatial energy planning approach is introduced. The proposed methodology is implemented using geographic information system and Statistical Design Institute software and applied at the national spatial planning scale. It consists of four distinct stages: (1) identifying appropriate areas to site offshore wind farms (the macro-siting configuration), (2) determining the principal technical specifications of the offshore wind turbines as well as the micro-siting configurations of offshore wind projects, (3) estimating the total investment cost of each potential offshore wind project, and (4) prioritizing the most suitable potential sites for offshore wind farms based on specific assessment criteria. The final outcomes of the proposed methodology are the development of a marine site suitability index and an assessment of the effects of different policy orientations for offshore wind farm siting on that index. Four ‘what-if’ critical scenarios are applied to test the robustness of the overall suitability index to the subjectivity of expert judgments of potential sites and thus assess the reliability of the proposed methodology. The implementation of the proposed methodology could facilitate the fulfillment of national targets for the energy sector and encourage energy interdependence among many geographic areas in Greece, since the total estimated production capacity of all the proposed offshore wind projects is expected to reach 1,185 MW.

Keywords Spatial energy planning · Site selection process · Offshore wind farms · Geographic information systems · Multicriteria decision-making · Sensitivity analysis

Introduction

Offshore wind energy has recently become prominent in the growing wind energy market for reasons such as the existence of stronger winds of longer duration offshore and restrictions on land availability for onshore siting. Indeed, the total installed capacity of offshore wind energy in Europe reached a record figure of 3148 megawatts (MW) in 2017 (Wind Europe Business Intelligence et al. 2018). In 2018, 409 new offshore wind turbines in 18 offshore wind projects were connected to the electricity grid in Europe (Wind

Europe Business Intelligence et al. 2019). This brought 2649 MW of net additional capacity online, meaning that the cumulative offshore wind capacity in Europe reached 18,499 MW at the end of 2018 (Wind Europe Business Intelligence et al. 2019). Thus, including sites with a partial grid connection, there are now 105 offshore wind farms (OWFs) in 11 European countries, corresponding to 4543 grid-connected wind turbines (Wind Europe Business Intelligence et al. 2019). Moreover, the UK currently has the largest offshore wind capacity in Europe (8183 MW), followed by Germany, with 6,380 MW (Wind Europe Business Intelligence et al. 2019), while OWFs are yet to be developed in Greece.

State of the art and innovation

The extensive spatial diffusion of OWF sites is accompanied by many important environmental, social, economic, political, legal, and technical issues. Geographic information systems (GISs) have been used in combination with multicriteria decision-making methods (MCDMs) to address

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the issue of OWF siting in a large number of case studies (Beacham et al. 2009; Kim et al. 2010, 2016, 2018; Lee et al. 2010; Hong and Möller 2011; Möller 2011; Christidis and Law 2012; Vagiona and Karanikolas 2012; Mani Murali et al. 2014; Argin and Yerci 2015; Fetanat and Khorasaninejad 2015; Mekonnen and Gorsevski 2015; Waewsak et al. 2015; Saleous et al. 2016; Stefanakou and Nikitakos 2016; Chaouachi et al. 2017; Christoforaki and Tsoutsos 2017; Mahdy and Bahaj 2018; Schallenberg-Rodríguez and Montesdeoca 2018; Vagiona and Kamilakis 2018; Wu et al. 2018; Argin et al. 2019). However, studies of integrated OWF siting (i.e., studies that consider both the macro- and micro-siting configurations of OWFs) are rare. Only three of the studies cited above (Christoforaki and Tsoutsos 2017; Schallenberg-Rodríguez and Montesdeoca 2018; Argin et al. 2019) consider both the macro- and micro-siting of OWFs, despite the fact that optimum micro-siting is essential to minimize array losses in wind energy projects sited in areas earmarked as suitable based on the macro-siting configuration. In particular, Christoforaki and Tsoutsos (2017) developed a GIS-based methodology consisting of the following three phases: (1) excluding unsuitable areas based on geological restrictions, visual and acoustic disturbances, and safety and environmental conditions; (2) evaluating environmental impacts on birdlife, Special Protection Areas, and Sites of Community Importance; and (3) assessing suitable sites based on two factors: wind potential and power capacity, estimated based on the micro-siting configuration and available surface area. This methodology was applied to the Regional Unit of Chania in Greece. The offshore wind potential of the Canary Islands was determined at the regional spatial planning scale by Schallenberg-Rodríguez and Montesdeoca (2018), considering technical, economic, and spatial constraints. The aforementioned study utilized a GIS to (1) investigate suitable areas for OWF development and (2) determine the optimal OWF configuration. The cost of wind energy generation was also estimated by calculating the levelized cost of energy for each wind turbine, the cost–resource curve, and the marginal offshore wind energy potential. Finally, Argin et al. (2019) explored suitable OWF sites in the national territorial waters of Turkey by performing a wind energy potential assessment of 55 coastal regions. In that study, determining the micro-siting configuration of the wind turbines was crucial to estimating the offshore wind energy potential of Turkey.

In the study reported in the present paper, the proposed methodology is implemented using GIS and Statistical Design Institute software and includes the following four distinct stages: (1) identifying appropriate areas to site OWFs based on specific exclusion criteria and incompatibility zones (the macro-siting configuration); (2) determining the principal technical specifications of the offshore wind turbines as well as the micro-siting configurations of suitable

offshore wind projects; (3) estimating the total investment cost of each offshore wind project by calculating the capital expenditure (CAPEX), the operating expenses (OPEX), and the decommissioning expenses (DECEX); and, finally, (4) prioritizing the most suitable areas to site OWFs based on specific assessment criteria (AC) and a sensitivity analysis.

Regarding the tools and the techniques applied in the present methodology, GIS is used in two ways in three of the above stages (1, 2, and 4): (1) to pinpoint suitable areas for OWFs in shallow waters in Greece and (2) to configure the micro-siting of wind turbines in each proposed offshore wind project, which allows its energy capacity to be determined. Moreover, in the present study, Statistical Design Institute software was used at stage 4 to: (1) determine the relative importance of each AC using the analytic hierarchy process (AHP) and prioritize the most suitable sites for OWFs via the technique for order of preference by similarity to ideal solution (TOPSIS) and (2) perform a sensitivity analysis (four critical ‘what-if’ scenarios).

There are some important advantages of the proposed methodological framework: (1) it introduces a holistic OWF siting approach, i.e., it considers both the macro- and the micro-siting configurations; (2) it adopts a long-term planning approach (it covers a period of 25 years after the plan’s implementation), (3) it utilizes a multidisciplinary approach, as it considers technical, economic, environmental, legal, societal, and political issues, and (4) it considers most of the relevant crucial issues that an OWF developer or/and renewable energy planner should analyze and resolve, i.e., technical, economic, and decision-making issues. The final outcome is that all of the potential offshore wind projects are assessed and ranked based on specific AC (including total investment cost and project capacity). A thorough sensitivity analysis of the overall site suitability index (i.e., of the proposed solutions of the decision-making problem) was also performed in the present study. The proposed methodological approach was applied at the national spatial planning scale to the shallow waters of the EEZ of Greece.

European and national energy policies

The European Union (EU) is committed to reducing greenhouse gas emissions to 80–95% below 1990 levels as a target for 2050 in the context of appropriate reductions by developed countries (European Commission 2012). In the proposed decarbonization scenarios, the EU included strong support measures to ensure that renewable energy sources (RESs) comprise a very high share of the gross final energy consumption (75%) in 2050 and the share of the total electricity consumed generated by RESs reaches 97% in 2050 (European Commission 2012). Wind energy is one of the most promising RESs. It is gaining global acceptance due to the multiple benefits that it provides, such as

easy accessibility to efficient multimegawatt wind turbines (Baseer et al. 2017). Specifically, by 2050, wind energy sources will provide more electricity than any other type of energy source in the high-renewables decarbonization scenario of the EU (European Commission 2012).

In Greece, the national effort to reduce greenhouse gas emissions is also focused on the energy sector. The policy plan for Greece, “National Energy Plan: Roadmap to 2050,” was posted by the Ministry of Environment and Energy in 2012 (Georgopoulou et al. 2014). The national roadmap contains a complete description of the policies and measures that will be implemented to reduce CO₂ emissions from the energy sector by 60–70% by 2050 (as compared to emission levels in 2005), with 85–100% of the electricity coming from RESs in 2050 (Georgopoulou et al. 2014). The Greek energy roadmap for 2050 is the basic long-term energy plan for Greece (Georgopoulou et al. 2014). It fully incorporates the National Renewable Energy Action Plan for 2020 and the National Energy Efficiency Action Plan for 2020; however, the Ministry of Environment and Energy is yet to officially adopt it (Moirasgentis et al. 2017). Furthermore, it should be noted that the Specific Spatial Framework for RESs of Greece, which was officially adopted in 2008, is currently being revised by the Ministry of Environment and Energy (2019). The above considerations highlight the importance and added value of the proposed spatial energy planning methodological framework for the country, and the efficient deployment of offshore wind farms in Greece, as presented in this study, could help to achieve the energy goals set by the EU and national energy policies.

The remainder of the article is structured as follows. The next section briefly presents the proposed methodological approach. After that, the exclusion criteria and the relevant

incompatibility zones are defined, and the method used to process the required spatial data is presented along with the data sources. The principal technical specifications of offshore wind turbines and the micro-siting configurations of suitable offshore wind projects are then provided. Next, the method applied to estimate the CAPEX, OPEX, and DECEX during the project life cycle—and thus the total investment cost of each offshore wind project—is presented. Then, the AC used to prioritize the most suitable areas to site the OWFs are explained, along with the sensitivity analysis. The penultimate section presents and discusses the results from all of the above stages of the proposed methodology in detail. The final section provides concluding remarks.

Methodological approach

In the study presented here, a combination of scientific tools were developed and applied to create an integrated methodology that can be used in the spatial energy planning of OWFs in Greece. The proposed methodological approach is presented in Fig. 1 and consists of four distinct stages, as described below.

Stage 1—Excluding unsuitable areas. At this stage, all prohibited and unsuitable areas are excluded from further OWF siting analysis by implementing various exclusion criteria. The exclusion criteria and their incompatibility zones are defined based on the characteristics of the study area as well as the relevant provisions of the Greek Specific Framework for the Spatial Planning and Sustainable Development for the Renewable Energy Sources (SFSPSD-RES) (Ministry of Environment and Energy 2008). The exclusion procedure

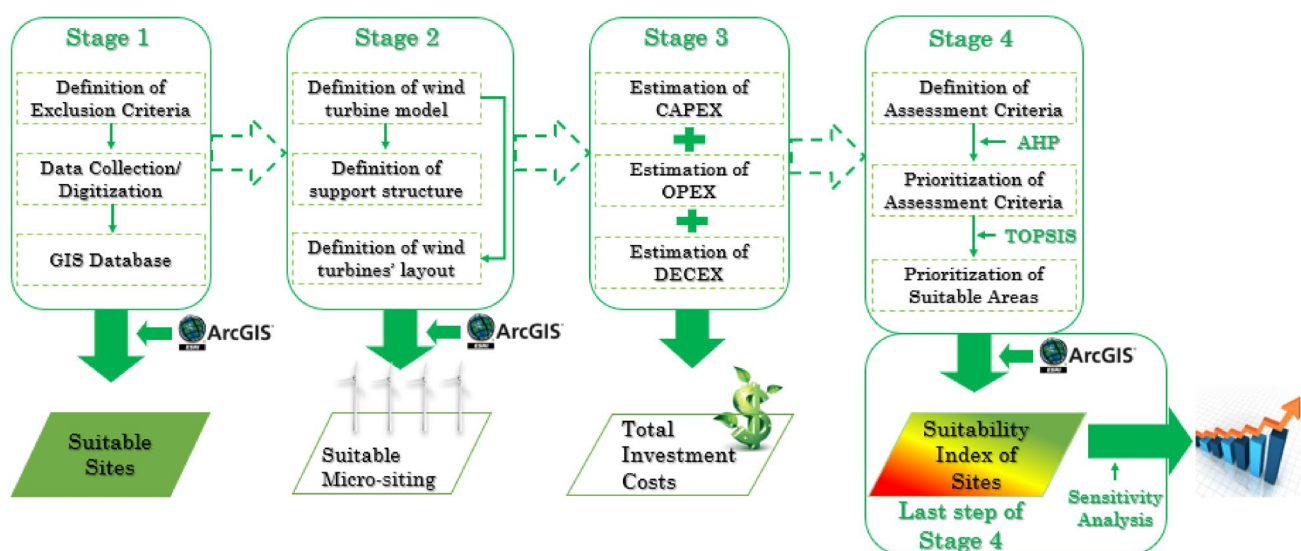


Fig. 1 Schematic of the proposed methodological approach

is implemented in ArcGIS software using the built-in geoprocessing tools. Subtracting all unsuitable areas reveals suitable areas to site OWFs at the national scale.

Stage 2—Determining technical specifications and micro-siting configurations. The principal technical specifications of offshore wind turbines (such as the most suitable type of support structure) as well as the available and suitable micro-siting configurations of the wind turbines in an OWF are determined at this stage. The technical specifications are determined as follows: (1) by analyzing the specific characteristics of the suitable sites (wind velocity, wind direction, water depth, and the available surface area/shape of the proposed site) and (2) by studying similar projects that have been completed and are in full commission to this day (4C Offshore 2019). Additionally, micro-siting configurations are implemented in ArcGIS software using the built-in advanced editing tools.

Stage 3—Estimating the total investment cost of each OWF. At this stage, the CAPEX, OPEX, and DECEX of each proposed offshore wind project are estimated, taking into account relevant data available for similar completed projects that are still in commission (4C Offshore 2019).

Stage 4—Assessing/prioritizing suitable areas and performing a sensitivity analysis. The objective of this stage is to assess the suitable areas based on specific AC (including the total investment cost and project capacity) in order to prioritize the most suitable proposed offshore wind projects. In the final step of this stage, a ‘what-if’ sensitivity analysis is applied to check the stability of the results against the subjectivity of expert judgments. The assessment and prioritization of suitable areas as well as the sensitivity analysis are performed using Statistical Design Institute software with the aid of the Triptych (i.e., implementations of the AHP and TOPSIS) and Apogee tools, respectively. Finally, a marine site suitability index is developed to show the distribution of the suitability of potential sites and to visualize their spatial allocation on the final suitability map. This is achieved by integrating the results from this stage using ArcGIS software.

Exclusion criteria and data collection/digitization

Exclusion criteria

The study area was defined as the Exclusive Economic Zone (EEZ) of Greece; any area outside of this is legally excluded from consideration (United Nations 1982). The EEZ of Greece has a total surface area of 493,708 km² (Sea Around

Us 1982). The remaining exclusion criteria considered in the present work are discussed below.

Wind velocity. Offshore wind projects must be installed in areas with high wind velocity potential for the projects to be technically and economically viable. Therefore, an accurate and detailed analysis of wind data is important as it allows potential wind energy assessments to be carried out for proposed suitable areas. In the present study, wind velocity data based on 10 years (2009–2018) of hourly measurements made at a height of 80 m were utilized. In this OWF siting analysis, marine areas in which the annual average wind velocity is lower than 6 m/s at a height of 80 m above the mean water level were considered unsuitable areas to site OWFs (Schallenberg-Rodríguez and Montesdeoca 2018).

Water depth. The water depth at the site significantly affects the investment cost of the installation; more specifically, it affects the selection of the wind turbine support structure as well as the CAPEX and OPEX of the OWF project, both of which increase significantly for OWFs installed in deeper waters. In this work, the limit on the water depth was set at 50 m, based on the economic viability of the OWFs and market maturity, given that most wind turbines have been installed at sites with water depths of less than 50 m (Zountouridou et al. 2015; 4C Offshore 2019).

Seismic hazard zones. Seismic hazards should be considered in the site selection process, as the presence of such hazards impacts on construction costs. Greece is one of the most seismically active countries worldwide. Therefore, all infrastructure, including wind turbine support structures, should be adequately designed to withstand earthquakes, which may lead to increased construction costs. Thus, areas in seismic hazard zone III (the zone with the strongest seismic activity; PGA: 0.36 g) in Greece were excluded.

Military zones. There are marine areas that are officially used by the Hellenic Navy, the Hellenic Air Force, the Hellenic Army, and the Hellenic National Defense General Staff for training purposes or as firing fields. These areas obviously could not be considered during OWF site selection process.

Underwater cables. There are underwater cables on the seafloor in the EEZ of Greece used for electricity transmission or telecommunication purposes. These cables should not be exposed to any damage caused during the installation of OWFs.

Distance from a port. The distance of an offshore wind project from a port is an important economic factor as it has a direct impact on the installation costs, operational and maintenance costs, and decommissioning costs of OWFs (Myhr et al. 2014). In particular, the total investment cost of a project increases with the distance of the OWF from a port. In the present work, the limit on the distance of an OWF from a domestic port was defined as 80 km, so marine areas that were more than 80 km from a port were excluded.

Distance from the high-voltage electricity 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. A connection to the high-voltage grid is necessary because a connection to a medium- or low-voltage grid could lead to a serious risk of cable destruction from electricity grid overloading (Lynch et al. 2012; Waewsak et al. 2015; Chaouachi et al. 2017). In this study, suitable sites had to be no more than 80 km from an existing or potential officially approved part of the high-voltage electricity grid.

Landscape protection/visual and acoustic disturbances. This criterion refers to the distance of an OWF from the coast, and is used to ensure landscape protection, avoid visual and acoustic disturbances, and aid the social acceptance of the OWF. Specifically, the visual and acoustic impact of an OWF can be minimized by locating the wind turbines further from the coastline. In this study, suitable sites had to be at least 5 km from the coast, as 5 km corresponds to approximately 35 times the total height of the defined offshore wind turbine.

Distance from shipping routes. In order to ensure that shipping routes connecting the plethora of Greek islands to the mainland for the purposes of trade or tourism are protected, a safe distance of at least 3 miles from these routes to OWFs was defined in this work (Mekonnen and Gorsevski 2015; Vagiona and Kamilakis 2018).

Distance from marine protected areas. In this study, marine protected areas comprised Sites of Community Importance (SCI) of Natura 2000, national marine environmental parks, coastal bathing waters that are monitored and assessed in the framework of the Monitoring Programme of Bathing Water Quality according to the provisions of Directive 2006/7/EC, and swimming beaches

awarded a Blue Flag. The minimum distance from any of the aforementioned areas was defined in this work as 2 km, given that Möller (2011), Christoforaki and Tsoutsos (2017), and Vagiona and Kamilakis (2018) define the safe distance as 1–2 km.

Distance from wildlife refuges and migration corridors. Siting an OWF too close to a migration corridor or wetland of international importance (as defined according to the Ramsar Convention) would lead to a significant risk of birds colliding with the wind turbines (mainly during their migratory period). Thus, OWF sites within or closer than 3 km from the boundaries of the aforementioned areas were defined as unsuitable in the present study (Hong and Möller 2011; Vagiona and Kamilakis 2018).

Distance from a residential area. According to the national legislative framework (SFSDSP-RES) (Ministry of Environment and Energy 2008), OWFs cannot be sited less than 1 km from residential settlements or less than 1.5 km from traditional settlements.

Thus, 13 exclusion criteria (Table 1) were applied in the present study to identify suitable areas for OWF development in shallow waters in Greece.

Data collection/digitization

In stage 1, all necessary geographic information data regarding the predefined exclusion criteria were collected from national institutes, research centers, services, and official international and national websites that provide officially approved cartographic data. The data were digitized if necessary. Table 2 summarizes the geographic information datasets (GID) considered in the present study as well as the relevant data sources and processing.

Table 1 Exclusion criteria and incompatibility zones

No.	Exclusion criterion	Factor	Unsuitable area or distance
EC.1	Exclusive economic zone	Legal	Outside the boundaries
EC.2	Wind velocity	Economic	< 6 m/s
EC.3	Water depth	Economic/technical	> 50 m
EC.4	Seismic hazard zones	Protective/restrictive	Zone III (0.36 g)
EC.5	Military zones	Political /restrictive	All
EC.6	Underwater cables	Protective/technical/restrictive	All
EC.7	Distance from a port	Economic/technical	> 80 km
EC.8	Distance from the high-voltage electricity grid	Economic/technical	> 80 km
EC.9	Landscape protection/visual and acoustic disturbances	Societal/political/protective	≤ 5 km
EC.10	Distance from shipping routes	Societal/political/protective	≤ 3 miles
EC.11	Distance from marine protected areas	Environmental/protective	≤ 2 km
EC.12	Distance from wildlife refuges and migration corridors	Environmental/protective	≤ 3 km
EC.13	Distance from a residential area	Legal/societal/protective	≤ 1 km (non traditional settlements) ≤ 1.5 km (traditional settlements)

Table 2 Geographic information datasets, data sources, and data processing employed in the present study

No	Geographic information dataset	Collection/digitization	Data source/data processing
GID.1	Water depth	Collection	Hellenic Navy Hydrographic Service
GID.2	Wind velocity	Collection	Hellenic Centre for Marine Research
GID.3	EEZ of Greece, Mediterranean Sea, Greece	Collection	European Statistical Service
GID.4	SCI, National Marine Environmental Parks, coastal bathing waters, swimming beaches, wetlands	Collection	GEODATA (official national website)
GID.5	Underwater telecommunication cables	Collection	EMODnet (European website)
GID.6	Verified shipping routes	Digitization	The most recent basemaps of ArcGIS, using the same projected coordinate system
GID.7	Military zones	Digitization	Maps (in analog format) from the Hellenic Navy Hydrographic Service
GID.8	Migration corridors	Digitization	Maps (in image format) from the Hellenic Ornithological Society
GID.9	Domestic ports	Digitization	MarineTraffic website
GID.10	Seismic hazard zones	Digitization	Maps (in image format) from the Technical Chamber of Greece
GID.11	Underwater cables of the electricity grid, 400 kilovolt (kV) high-voltage centers, 150 kV high-voltage substations	Digitization	Maps (in pdf format) from the Independent Power Transmission Operator S.A.

Technical specifications and micro-siting configurations of OWFs

Defining the wind turbine model

The Generic 5 MW wind turbine model developed by the National Renewable Energy Laboratory (NREL) (Jonkman et al. 2009) was selected for this study, taking into account: (1) the specific characteristics of the suitable areas (wind velocity and available surface area) and (2) the availability of the relevant information for estimating the total investment cost of each proposed offshore wind project. The aforementioned wind turbine model has also been used in several previous studies by Fischer et al. (2010), Bjerckseter and Agotnes (2013), Myhr et al. (2014), and Myhr (2016), while a large number of existing and fully or partially commissioned OWFs worldwide (ten in Europe and six in Asia) have deployed offshore wind turbines with the same nominal power (4C Offshore 2019).

Selecting the wind turbine support structure

The most suitable wind turbine support structure was selected based on the water depth in suitable areas (the water depth data were obtained during stage 1 of the proposed methodological approach). Suitable areas were located at water depth of no more than 50 m, so bottom-fixed platforms were preferred as support structures (Schwartz et al. 2010; Bjerckseter and Agotnes 2013; Myhr et al. 2014; Schallenberg-Rodríguez and Montesdeoca 2018). In our study, monopile and jacket support structures were selected

for water depths of 0–30 m and 30–50 m, respectively. The most suitable support structure for shallow waters (up to 30 m) in terms of economic viability and maturity of technology is the monopile design (Myhr et al. 2014). However, typically at a depth of around 30 m, the monopile design reaches its engineering limits in terms of pliable diameter and wall thickness (Bjerckseter and Agotnes 2013; Myhr et al. 2014). Therefore, for intermediate water depths (30–50 m), beyond the reach of monopiles, the more expensive jacket support structure is suited, which is also more competitive under harsher weather conditions than the monopile design (Bjerckseter and Agotnes 2013; Myhr et al. 2014).

Configuring the micro-siting of each OWF

It is important to apply an appropriate micro-siting configuration of wind turbines in an OWF due to the wake effect. This effect results from the turbines' wind power extraction and leads to reduced wind speeds and increased turbulence (Deutsche WindGuard GmbH 2018). Determining the appropriate micro-siting of wind turbines corresponds to an optimization problem. When defining the layout of an OWF, the distance between two successive turbines along lines parallel and perpendicular to the prevailing wind direction are denoted dx and dy respectively, while D_{rotor} denotes the rotor diameter. For existing fully commissioned European OWFs (e.g., the Nysted OWF in Denmark, the Eneco Luchterduinen OWF in the Netherlands, and the Kentish Flats OWF in the United Kingdom), values of dx range approximately between 4.6 and $12.1D_{rotor}$, while the corresponding range for dy is $3.2 \sim 8D_{rotor}$ (Deutsche WindGuard GmbH 2018). Additionally, NREL recommends

values of dy that correspond to $5 \sim 10D_{\text{rotor}}$ (Lynch and Murphy 2012). In the present study, to minimize array losses in the proposed OWF projects, the wind turbines' micro-siting was determined using advanced editing tools in ArcGIS and based on: (1) the main wind direction at the site, (2) the D_{rotor} of the selected wind turbine model, (3) the shape of the OWF site, and (4) European standards. Considering all of the above, the dx and dy values for the wind turbines' layout in the proposed OWFs were defined as $8D_{\text{rotor}}$ and $8D_{\text{rotor}}$, respectively.

Total investment cost of each OWF

Estimating the CAPEX

The components of the CAPEX considered in this study were: (1) development and consents, (2) construction phase insurance, (3) rotor-nacelle-assembly costs, (4) production costs (including those for the tower and support structure), (5) grid costs (including installation), and (6) installation of the whole wind turbine system. In Gonzalez-Rodriguez (2017), Stehly et al. (2017), Ioannou et al. (2018), and Schallenberg-Rodríguez and Montesdeoca (2018), the CAPEX was estimated based on the water depth and the distance from the shore. In this study, in order to more accurately estimate the CAPEX, the distance from a port and the distance from the electricity grid were employed instead of the distance from the shore. In addition to these factors, the CAPEX of each OWF was estimated based on: (1) the wind turbine support structure deployed (Bjerkseter and Agotnes 2013; Myhr et al. 2014; Myhr 2016; Schallenberg-Rodríguez and Montesdeoca 2018) and (2) the nominal power of the wind turbine.

Estimating the OPEX

The OPEX of a large-scale OWF project is a significant part of the total investment cost and is directly linked to and affected by the distance of the OWF from a port and the water depth. In this study, the OPEX was considered to be 3.27% of the CAPEX (€/MW) for wind turbines with a monopile support structure and 3.06% of the CAPEX (€/MW) for wind turbines with a jacket support structure, based on Bjerkseter and Agotnes (2013) and Myhr et al. (2014). In order to calculate the OPEX for the full life cycle of the offshore wind project (25 years), the following formula for the present value of annually allocated expenses (PVAAE) was applied (Brigham and Houston 2015):

$$\text{PVAAE} = \frac{(1+i)^n - 1}{i(1+i)^n}, \quad (1)$$

where n is the years of operation (25) and i is the interest rate (2.5%).

Estimating the DECEX

The DECEX of an OWF project can correspond to 0–4% of the total investment cost (Bjerkseter and Agotnes 2013; BVG Associates 2016; Ioannou et al. 2018; Schallenberg-Rodríguez and Montesdeoca 2018). In our study, the DECEX was defined as 2% of the corresponding total investment cost.

Assessment of suitable areas and sensitivity analysis

Defining the AC

Stage 4 includes an assessment of site suitability and a sensitivity analysis of the proposed OWFs based on the following seven AC: (1) wind velocity (80 m) (AC.1), (2) water depth (AC.2), (3) project capacity (AC.3) (results from stage 2), (4) distance from a port where the water depth is > 10 m (AC.4), (5) proximity to the national electricity grid (high voltage) (AC.5), (6) distance from marine protected areas (AC.6), and (7) the total investment cost (CAPEX + OPEX + DECEX) (AC.7) (results from stage 3).

Weighting the AC

The above AC were used to establish a 7×7 judgment matrix. The AHP was then implemented by performing pairwise comparisons based on the matrix. It was performed using Statistical Design Institute software with Triptych tools and based on the authors' judgments arising from their expertise in spatial and renewable energy planning. The consistency ratio calculated by Statistical Design Institute software reached 99.981% (Fig. 2).

Prioritizing the most suitable areas

After subtracting all unsuitable areas from those considered at stage 1, two MCDM methods—the AHP and TOPSIS—were used to rank the proposed offshore wind projects in order of site suitability. This ranking of suitable areas was

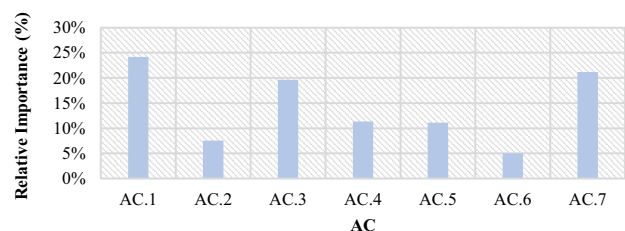


Fig. 2 Relative importance (%) of the AC

performed by automatically integrating the results from the AHP into the decision-making process (i.e., into the TOPSIS) using Statistical Design Institute software with Triptych tools. Finally, by integrating all of the above results in the ArcGIS software, a marine site suitability index was developed to show the suitability distribution of potential sites and to visualize their spatial allocation on the final suitability map.

Sensitivity analysis

Uncertainty is often inherent to MCDM problems for a variety of reasons, such as the presence of limited or imprecise information about the decision-making problem and inconsistency between the decision makers' preferences (Malczewski 1999). Therefore, it is recommended that a 'what-if' sensitivity analysis should be performed to check the robustness of the results to the subjectivity of the expert judgments and assess the reliability of the proposed methodology at identifying the most suitable solutions. In the present study, a sensitivity analysis of the overall site suitability index (i.e., of the proposed solutions of the decision-making problem) was performed by changing the decision weights of the AC. Thus, four 'what-if' scenarios were considered using the Apogee tools for Statistical Design Institute software.

Scenario 0 (S.0): Baseline scenario (AC.1 = 24.18%, AC.2 = 7.56%, AC.3 = 19.65%, AC.4 = 11.34%, AC.5 = 11.08%, AC.6 = 5.03%, AC.7 = 21.16%).

Scenario 1 (S.1): All AC have equal weights (AC.1 = AC.2 = AC.3 = AC.4 = AC.5 = AC.6 = AC.7 = 14.29%).

Scenario 2 (S.2): Policy scenario focusing on environmental criteria (AC.1 = AC.2 = AC.3 = AC.4 = AC.5 = AC.7 = 11.11%, AC.6 = 33.33%).

Scenario 3 (S.3): Policy scenario focusing on economic criteria (AC.1 = AC.2 = AC.3 = AC.4 = AC.5 = AC.7 = 16.13%, AC.6 = 3.22%).

Scenario 4 (S.4): Policy scenario focusing on energy-related criteria (AC.1 = AC.3 = 27.27%, AC.2 = AC.4 = AC.5 = AC.6 = AC.7 = 9.09%).

Results and discussion

Identification of suitable sites

Thirteen exclusion criteria (Table 1) were defined and applied to identify suitable areas for offshore wind projects in shallow waters in Greece. This led to the creation

of several thematic maps of the resulting GIDs, including those for wind velocity (EC.2; Fig. 3a), water depth (EC.3; Fig. 3b), marine protected areas (EC.11; Fig. 4a), underwater cables (EC.6; Fig. 4a), and landscape protection/visual and acoustic disturbances (EC.9; Fig. 4b). By creating, editing, and managing three different linear models using geoprocessing tools provided by ModelBuilder in ArcGIS software, suitable sites for offshore wind projects in shallow waters in Greece were identified. All prohibited and unsuitable areas were excluded from the study area based on the limitations defined in stage 1.

The five marine sites that were found to be suitable (see the section "[Prioritizing the most suitable OWFs and performing the sensitivity analysis](#)") had a total surface area of 237 km² and represented only 0.048% of the total surface area of the EEZ of Greece. Suitable sites that were less than 2 km² in size were excluded from the analysis because the installation of wind turbines in such a small area is considered economically unviable.

Micro-siting configurations of the OWFs

The appropriate micro-siting configurations of the proposed offshore wind projects were identified using the advanced editing tools in the ArcGIS software. The project capacity (AC.3) was calculated for each offshore wind project, and all the results obtained during stage 2 are presented in Table 3. The micro-siting configuration selected for one OWF (OWF2) is presented in Fig. 5.

Total investment cost of each OWF

The CAPEX of 5 MW offshore wind turbines with monopile and jacket support structures that are located 200 km from a port, 200 km from the electricity grid, and at a water depth of 30 m were estimated to be 3.521×10^6 €/MW and 3.759×10^6 €/MW, respectively, based on Myhr et al. (2014). Additionally, it was shown by Ng and Ran (2016) that increasing the water depth or the distance from the shore by 10% will increase specific investment costs (installation and grid connection costs) as well as support structure costs (including installation) by 1%. The CAPEX of all the proposed OWFs were then estimated using this rule of thumb as well as the estimated values of the components of the CAPEX and the estimated values of relevant characteristics of the proposed offshore wind projects (i.e., water depth as well as the distances from a port and the electricity grid, both of which are related to the distance from the shore). The methods used to estimate the OPEX and DECEX are described in the "[Estimating the OPEX](#)" and "[Estimating the DECEX](#)" sections, respectively. The total investment cost (i.e., CAPEX + OPEX + DECEX) of each proposed offshore wind project

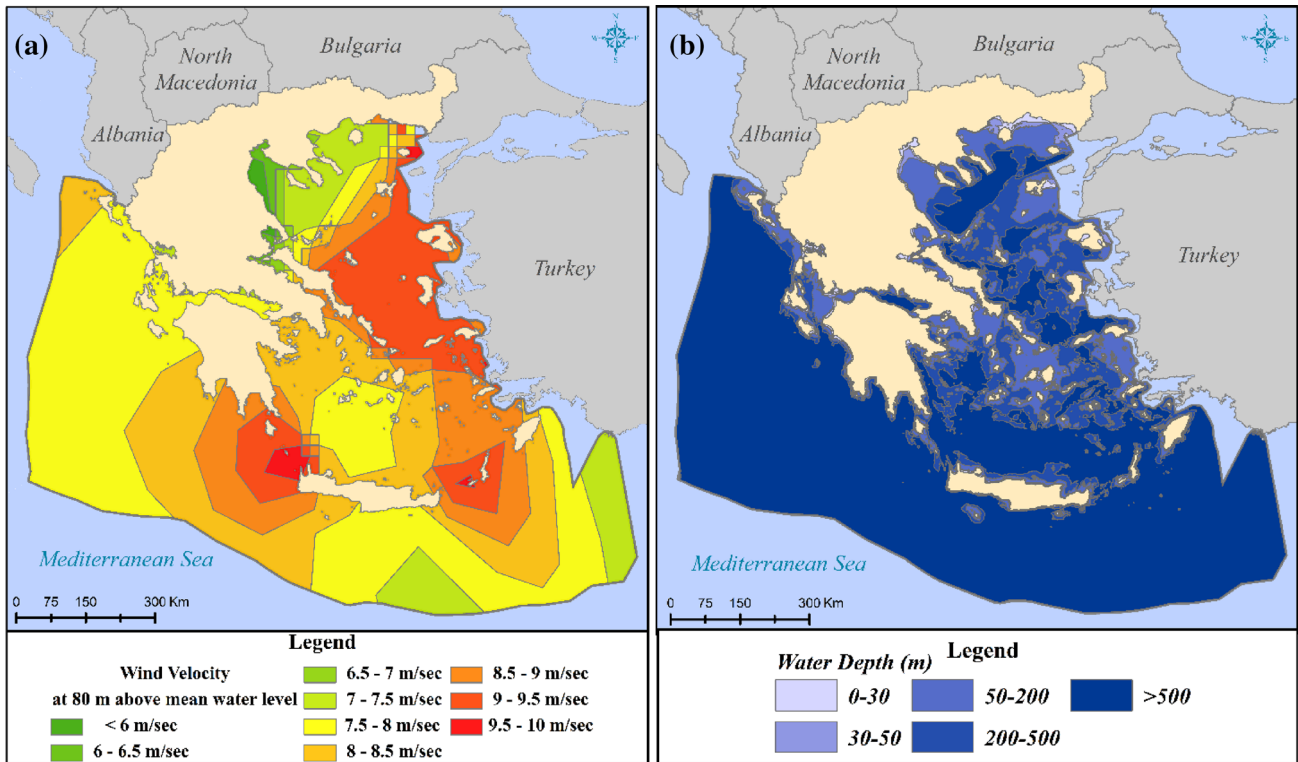


Fig. 3 Thematic maps of a wind velocity (EC.2) and b water depth (EC.3)

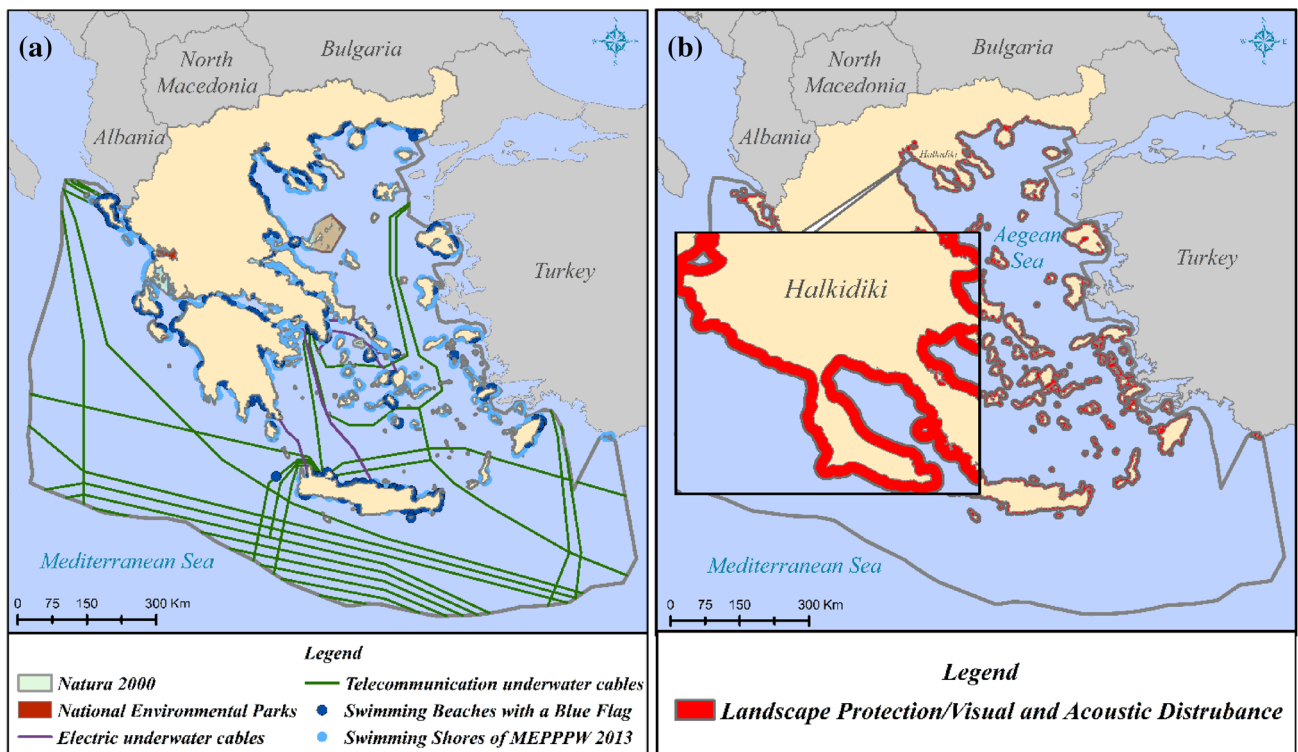


Fig. 4 Thematic maps of a marine protected areas (EC.11) and underwater cables (EC.6) and b landscape protection/visual and acoustic disturbances (EC.9)

is presented in Table 4. The proposed OWFs could be financed by the European Investment Bank (EIB), given that the EIB Board approved nearly 7 billion euros of support for strategic infrastructure investment in new OWFs in the UK and Belgian coasts in 2015 (Russell 2015). Additionally, the aforementioned offshore wind projects could be financially supported by both private funds (e.g., from Greek private banks) and public funds (e.g., from the Greek public bank).

Prioritizing the most suitable OWFs and performing the sensitivity analysis

A marine site suitability index was developed to show the suitability of the potential sites as well as to visualize their spatial allocation on the final suitability map (Fig. 6). Since the examined characteristics of the proposed OWFs (i.e., the AC) had different values and ranges (see Table 4), it was necessary to convert each assessment criterion to a common

Table 3 Results from stage 2

OWF no.	Name of OWF	Area (km ²)	Wind turbine support structure	No. of OWTs	OWF layout (dx × dy)	Project capacity (MW)
OWF1	Aristotle	149.16	Monopile	154	$8D_{rotor} \times 8D_{rotor}$	770
OWF2	Plato	55	Jacket	50	$8D_{rotor} \times 8D_{rotor}$	250
OWF3	Democritus	25.7	Jacket	25	$8D_{rotor} \times 8D_{rotor}$	125
OWF4	Socrates	4.3	Jacket	4	$8D_{rotor} \times 8D_{rotor}$	20
OWF5	Protagoras	2.8	Jacket	4	$8D_{rotor} \times 8D_{rotor}$	20
<i>Total</i>	<i>Shallow OWFs</i>	<i>236.96</i>	<i>Monopile and jacket</i>	<i>237</i>		<i>1,185</i>

Fig. 5 Micro-siting configuration of OWF2

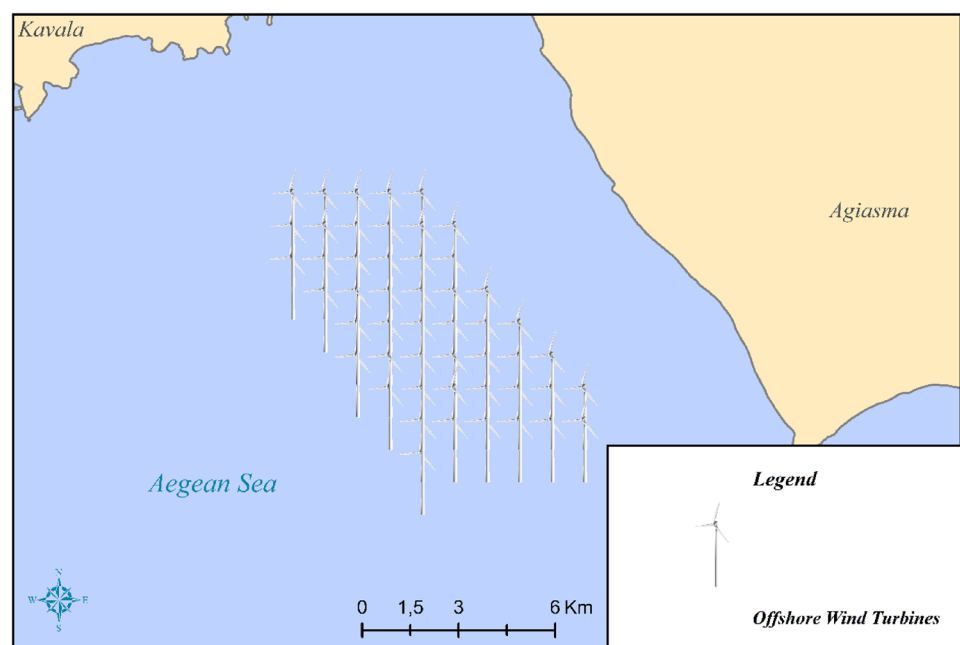


Table 4 The examined characteristics of the proposed OWFs and their site suitability index values

OWF no.	AC.1 (m/s)	AC.2 (m)	AC.3 (MW)	AC.4 (km)	AC.5 (km)	AC.6 (km)	AC.7 (€)	Site suitability index value
OWF1	8.5–9	0–30	770	72	28.5	5.5	4.322×10^9	4.6 (Low)
OWF2	7–7.5	30–50	250	10.5	12.5	7	1.455×10^9	5.4 (Moderate)
OWF3	8.5–9	30–50	125	43	12	7.5	732.302×10^6	5.2 (Moderate)
OWF4	7.5–8	30–50	20	23	16.5	5.5	116.704×10^6	5.3 (Moderate)
OWF5	8–8.5	30–50	20	23.5	11	7	116.716×10^6	5.3 (Moderate)

reference scale. Therefore, each criterion was processed and multiplied by its weight according to the TOPSIS. The final suitability of each proposed site on a scale from 0.01 (0.00 corresponds to an unsuitable area) to 10.00 (the most suitable area) was then obtained. In this study, suitability index (SI) values were categorized into either low suitability (0.01–4.99), moderate suitability (5.00–6.99), or high suitability (7.00–10.00). The majority (62.95%) of the area found to be suitable for siting OWFs was categorized as being of low suitability, while 37.05% was categorized as being of moderate suitability, and none of the suitable sites were categorized as having high suitability.

Afterwards, four ‘what-if’ scenarios were considered in order to examine the effects of modify the policy orientation for siting on the SI. The results of the sensitivity analysis of the site suitability index for the potentially suitable areas are shown in detail in Fig. 7. It is noticeable that, except for S.4, the main results are the same for all scenarios (i.e., 62.95% and 37.05% of the potentially suitable area can be considered of low and moderate suitability, respectively) and the differences in the values of the overall suitability index between the scenarios are negligible. However, S.4 did yield notable differences in suitability from the other scenarios for all of the proposed sites (Fig. 7). In particular, in S.4, the SI value of OWF1 was high rather than low due to highly significant values of both AC.1 and AC.3, whereas the SI values of the four remaining suitable sites were low rather



Fig. 6 Site suitability analysis of the proposed OWFs

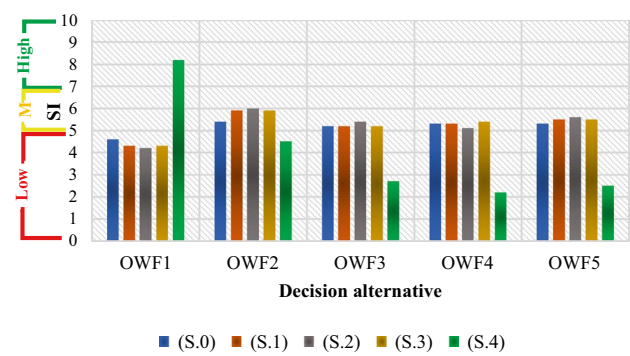


Fig. 7 Sensitivity analysis (‘what-if’ scenarios)

than moderate due to very low or moderate values of AC.3 and moderate values of AC.1. These significant variations reflect the importance of considering all relevant economic criteria (i.e., S.3) before deciding on the site for a large-scale project, as the sensitivity analysis shows that focusing only on AC that relate directly to the profit can promote secondary options and demote the primary ones. Thus, ignoring important economic AC such as AC.7 can negatively influence the decision-making process. These results also highlight the importance of stage 3 (the estimation of the total investment cost of each offshore wind project) of the proposed methodological approach.

Conclusions

Combining GIS with MCDM yields a powerful tool for solving decision-making issues relating to energy production. In the work reported in the present paper, an integrated methodological approach was developed that provides both macro- and micro-siting solutions for OWFs and covers economic, societal, environmental, political, technical, and legal issues associated with these large-scale installations. The proposed methodology was applied at the national spatial planning scale (for shallow waters in Greece) and produced sustainable and economically viable solutions for all issues relevant to such installations, specifically: (1) macro- and micro-siting, (2) technical aspects, (3) economic aspects, (4) decision-making, and (5) potential policy orientations applied during the planning process.

Regarding the macro-siting configuration of the OWFs, a total of twenty (exclusion and assessment) criteria were employed to pinpoint the most suitable, sustainable, and economically and technically viable sites for OWFs. This involved the application of two MCDM methods (the AHP and TOPSIS) to rank the proposed offshore wind projects in order of suitability. The ArcGIS software was used to visualize the results and show the geographic locations of suitable sites, as well as to configure the micro-siting of each OWF.

Additionally, the total investment cost of each offshore wind project was calculated by estimating its CAPEX, OPEX, and DECEX. The total investment cost is an important assessment criterion for ranking the OWF sites based on suitability and thus identifying the most suitable and economically viable ones.

A sensitivity analysis of the overall site suitability index was performed to investigate the stability of the results with respect to the subjectivity of expert judgments and to assess the reliability of the proposed methodology. For this purpose, four ‘what-if’ scenarios were applied corresponding to four different policy orientations for offshore wind farm siting. The results of the sensitivity analysis demonstrated the reliability of the methodological approach developed here, since the main results remained the same in each scenario apart from S.4. The SI value of OWF1 in S.4 was indicative of high suitability (rather than the low suitability of OWF1 found in the other scenarios) due to highly significant values of AC.1 and AC.3. Also, the SI values of the other four suitable sites changed from moderate to low suitability in S.4 due to very low or moderate values of AC.3 and moderate values of AC.1. These results demonstrate the importance of considering all relevant economic criteria before deciding on the site of a large-scale project, and highlight the importance of stage 3 of the proposed methodology.

The proposed methodological approach can be applied at the national, regional, and local spatial planning scales by adapting the characteristics considered and the particular requirements for as well as the policies associated with each location that are described and analyzed at each stage of the developed methodological approach. Implementing the proposed methodology could facilitate the fulfillment of national targets in the energy sector and encourage energy interdependence among many geographic areas in Greece. In particular, the total estimated production capacity of all of the proposed offshore wind projects is expected to reach 1185 MW, which (according to the power statistics for 2017 published by the European Network of Transmission System Operators for Electricity 2018) corresponds to approximately 15% of the total amount of electrical energy needed.

The present work could be further extended by including input from stakeholders, experts, and the public in the site suitability analysis of the proposed OWFs in order to reflect different points of view and different policy orientations for OWF siting. Their involvement would improve the selection of suitable marine areas by incorporating extra knowledge and experience into the energy planning process, and would enhance the proposed spatial energy planning approach by incorporating participatory planning tools into the current framework. Finally, determining the AC and quantifying their relative importance based on the requirements and priorities of the various stakeholders involved in the planning process should improve the site suitability analysis from

the perspectives of social acceptance and environmental sustainability.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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