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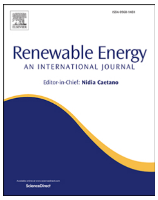

Development of offshore wind farms from an environmental perspective

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ABSTRACT

This study presents an integrated, multi-criteria spatial assessment for the sustainable siting of OWFs around the island of Crete, combining expert-derived weights, a GIS-based weighted overlay analysis, and an updated socio-environmental exclusion framework. Sixteen evaluation criteria were incorporated, reflecting environmental, technical, economic, and socio-political dimensions, each adapted to the unique geographic and ecological conditions of the Mediterranean island environment.

Results confirm the robustness of the original multi-criteria model while refining local suitability by incorporating real environmental evidence. In particular, areas characterised by circalittoral rocky substrates and low biodiversity (e.g., Agios Nikolaos, Chersonissos) align with previously identified high-suitability zones. In contrast, sites under archaeological or ecological protection (e.g., Zakros, Elounda–Spinalonga) were validated as unsuitable.

Several areas along the northern and eastern coasts emerged as comparatively favourable due to the combination of strong wind potential and relatively short distances to existing transmission infrastructure and coastal access points. Approximately 493 km^2 of marine areas were classified as moderately to highly suitable. Detailed engineering, geotechnical, financial, and grid-integration analyses would be required to assess practical feasibility and project-scale implementation. Nevertheless, the analysis also underscores the importance of integrating ecological sensitivity into planning processes, particularly for migratory birds and species that rely on soaring–gliding flight.

Overall, the findings indicate that Crete has significant spatial potential for offshore wind development within a strategic planning framework, particularly given advances in floating wind technologies and ongoing grid interconnection projects.

Abbreviations list

AHP	Analytical Hierarchy Process
EMODnet	European Marine Observation and Data Network
GIS	Geographic Information Systems
HEREMA	Hellenic hydrocarbons and Energy Resources Management Company
MCDA	Multi-Criteria Decision Analysis
OWF(s)	Offshore Wind Farm(s)
ROV	Remote Operated Vehicles
TRI	Terrain Ruggedness Index

1. Introduction

The increasing global demand for renewable energy has accelerated the development of offshore wind power, which is viewed as a crucial component of the clean energy transition [1]. Compared with onshore wind farms, Offshore Wind Farms (OWFs) offer several benefits, including stronger wind resources, a steadier wind pattern, fewer conflicts with land uses, and the ability to generate energy at scale. In the Mediterranean region, the island of Crete is a strong candidate for offshore wind energy development due to its high energy demand,

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strategic position, and substantial wind energy potential [2]. However, identifying ideal sites for OWFs requires a multi-criteria assessment that considers environmental, technical, and socio-economic factors [3].

This study conducts a preliminary site selection analysis for OWFs around Crete, using a structured methodology that includes spatial exclusion criteria, evaluation metrics, stakeholder input, and field surveys [4]. The assessment follows a step-by-step process: (i) exclusion of unsuitable marine areas based on environmental, regulatory, and navigational constraints; (ii) evaluation of potential sites using multi-criteria decision analysis, incorporating stakeholder input through the Analytical Hierarchy Process (AHP) [5]; (iii) on-site inspections to verify land-sea interactions, infrastructure accessibility, and potential socio-environmental impacts; and (iv) initial seabed research to assess geological stability for wind turbine foundations. Building on our previous study [2]. This research will test the methodology again with newly added criteria, as well as new aspects related to the surrounding areas and the seabed.

Building on the methodological framework previously developed for offshore wind siting in Crete [2]. This study advances the analysis by incorporating empirical data from field surveys, seabed research, and avifauna monitoring. The proposed approach integrates spatial multi-criteria decision analysis (AHP-GIS) with real-world environmental verification, yielding a more comprehensive and evidence-based framework for sustainable OWF planning in insular regions. The study's hypothesis is that integrating expert-based weighting with field-informed environmental screening can significantly improve the robustness and transparency of early-stage offshore wind siting in environmentally sensitive island regions.

The results of this research include the relative weights of stakeholder preferences derived from AHP analysis, geospatial mapping of exclusion zones and high-potential areas, an energy potential assessment of the most suitable sites, and findings from on-site inspections of selected areas, including seabed conditions. By integrating multiple data sources and evaluation techniques, this study provides a foundational framework for offshore wind site selection, supporting sustainable energy planning and investment in the region. The original contribution of this work lies in:

- The integration of desk-based GIS suitability mapping with structured stakeholder weighting (AHP),
- The incorporation of a high number of regulatory and spatial exclusion criteria,
- The validation of spatial outputs through targeted field observations and ROV surveys,
- The application and validation of a previously developed methodological framework in a real island case study (Crete).

Unlike prior broad-scale national assessments, this study demonstrates that preliminary field autopsies can significantly alter large-scale GIS suitability outputs [5] [6] [7]. This research contributes to the broader discussion on offshore wind energy development in the Mediterranean, aligning with national and EU energy transition objectives [8]. The findings are expected to assist policymakers, investors, and energy planners in making well-informed decisions regarding the deployment of offshore wind infrastructure in Crete and similar coastal regions.

The present study addresses the following research question: How does offshore wind spatial suitability change when a generalized national-scale GIS–AHP framework is re-applied at the island scale with stricter exclusion logic, floating wind integration, and field-informed validation? The working hypothesis is that incorporating of conservative regulatory filtering, extended depth thresholds, logistical constraints, and visual-ecological refinement significantly modifies both the extent and spatial configuration of suitable marine areas. By testing this hypothesis in the context of Crete, the study advances from large-scale screening towards a high-resolution, island-specific spatial planning framework.

2. State-of-the-Art

Offshore wind energy has attracted considerable attention in recent years as a vital component of the global renewable energy transition. Improvements in site selection methods, wind resource assessments, and multi-criteria decision-making frameworks have improved the practicality and effectiveness of OWF development. This section offers an overview of the current research on offshore wind site selection, focusing on exclusion and assessment criteria, stakeholder involvement through multi-criteria decision analysis (MCDA), and geophysical surveys for seabed evaluation.

2.1. *OWF site selection approaches*

Identifying optimal OWF locations requires a systematic evaluation of multiple environmental, technical, and socio-economic factors. Geographic Information Systems (GIS) combined with MCDA techniques are widely used for spatial analysis and decision-making in offshore wind energy projects [9]. Exclusion criteria typically include environmental constraints (e.g., protected marine areas, bird migration routes), technical limitations (e.g., seabed depth, distance to shore), and socio-economic considerations (e.g., fishing zones, shipping routes) [10]. Studies have demonstrated that integrating exclusion and evaluation criteria through GIS-based frameworks enhances decision-making efficiency and minimises environmental conflicts [5].

2.2. *MCDA in offshore wind site selection*

MCDA methods, such as the AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), have been widely applied to OWF site selection to prioritise suitable areas based on stakeholder preferences [11] [12]. AHP, in particular, facilitates the structured assessment of conflicting criteria by assigning relative weights derived from expert opinions and stakeholder input. Recent studies have emphasised the importance of involving stakeholders in site selection to ensure social acceptance and regulatory compliance [13].

2.3. *Field-based assessments: autopsies and seabed research*

Recent advances in offshore wind siting research have highlighted the importance of in-situ seabed and benthic assessments as complements to GIS-based spatial analyses. For instance, this research [14] created a geological seabed stability model for Ireland by collecting new seabed samples and integrating them into a probabilistic geospatial framework, thereby enhancing the reliability of site selection and foundation design. The United States Bureau of Ocean Energy Management (BOEM) [15] also stresses that “site investigations that identify shallow hazards, geologic hazards, biological conditions, geotechnical properties, and archaeological resources” are vital for the feasible development of offshore wind projects. Likewise, the Estuaries & Coasts case study at the Block Island Wind Farm employed a multi-modal survey approach—combining multibeam bathymetry, still imagery, and video—to map benthic habitats around foundations and document impacts on moraine substrates [16]. These studies collectively emphasise the importance of integrating remote and spatial modelling with detailed field-verified seabed and ecological data. Following this trend, the current work implements a structured programme of coastal inspections, seabed terrain and substrate characterisation, and benthic habitat mapping across multiple zones around Crete, advancing the shift from desk-based suitability modelling to field-validated site assessment within a Mediterranean island context.

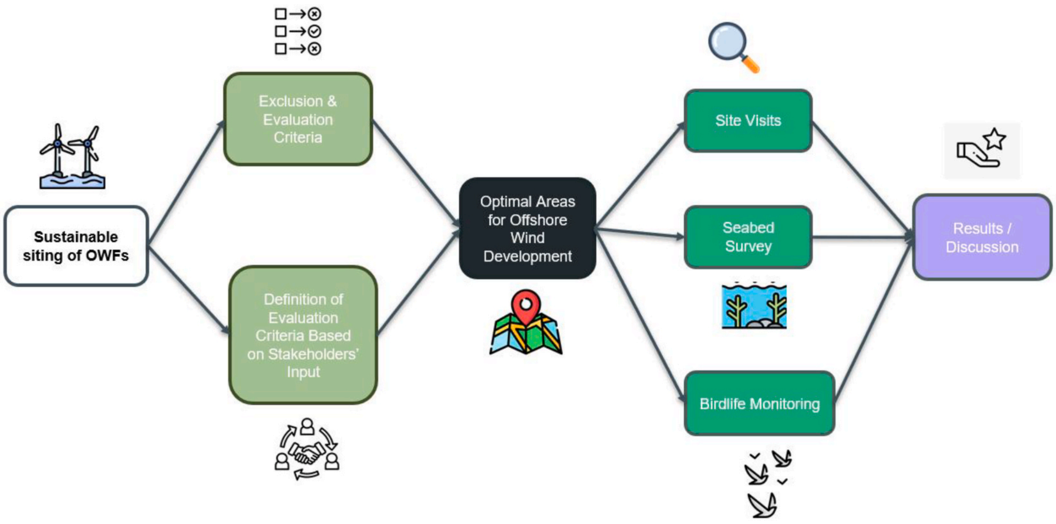

Fig. 1. Methodological workflow of the Step-AP framework for offshore wind siting in Crete.

2.4. *Recent developments in offshore wind in the Mediterranean region*

The Mediterranean region has lagged behind Northern Europe in offshore wind development, mainly because of deeper waters and regulatory hurdles. However, advances in floating wind technology have improved the viability of offshore wind projects in Mediterranean waters, where fixed-bottom turbines are less practical. Crete, in particular, has been recognised as a strategic site for offshore wind energy due to its high wind potential and energy demand [7].

This study advances OWF site selection by incorporating a comprehensive set of exclusion and evaluation criteria, significantly improving the decision-making process. A total of 37 exclusion criteria (21 primary and 16 sub-criteria) and 16 evaluation criteria are employed, providing a thorough and multidimensional assessment framework. Additionally, the study incorporates expert insights through 24 structured questionnaires, ensuring diverse stakeholder representation across eight categories, with at least three experts in each. A key innovation is the introduction of new exclusion criteria, such as Geoparks, underwater antiquities, aquaculture zones, and diving parks, aligning with Greek government policies and addressing previously neglected constraints. The research also advances previous studies by conducting on-site inspections of identified areas, assessing environmental, cultural, and social factors that could impact project feasibility and public acceptance. Furthermore, a preliminary seabed analysis is conducted using existing geological data to provide an initial assessment of seabed conditions in potential development zones. This integrated approach enhances the accuracy and practicality of offshore wind site selection, bridging gaps in prior methodologies.

Despite the growing body of research on offshore wind siting, several limitations remain evident in the Mediterranean context. Existing studies often focus either on large-scale GIS-based screening without field validation, or on site-specific technical investigations lacking an integrated spatial-planning framework. Furthermore, limited research has combined structured stakeholder-derived weighting, extensive exclusion mapping aligned with national regulatory frameworks, and ecological refinement layers within an island-scale planning approach.

In the case of Crete, although its wind potential has been recognised, a comprehensive, multi-layered spatial suitability assessment that integrates environmental constraints, stakeholder priorities, and site-level validation has not been systematically developed.

This study addresses this gap by proposing an integrated planning framework that sequentially combines exclusion mapping, stakeholder-guided AHP weighting, GIS-based spatial modelling, targeted field validation, visual impact assessment, and ecological sensitivity overlays within a unified methodological structure.

3. Materials and methods

The methodological framework follows a sequential and interlinked structure. Stakeholder input informed the weighting of evaluation criteria via the AHP process, which was then applied within the GIS-based weighted overlay analysis to generate preliminary suitability zones. These spatial outputs guided targeted site visits and seabed observations, focusing on areas identified as comparatively favourable. In addition, visual exposure was assessed within the high-suitability zones through distance-from-shore criteria and the development of photo-realistic simulations from selected coastal viewpoints. This allowed the evaluation of potential landscape intrusion and tourism-related sensitivity in an insular environment such as Crete. Finally, ecological monitoring data were overlaid as a refinement layer to assess biodiversity sensitivity within the candidate zones. This stepwise integration ensured that spatial modelling, field validation, visual assessment, and ecological analysis functioned as components of a unified planning framework rather than independent analytical exercises.

3.1. *Sustainable siting*

The present study builds on the methodological framework established in earlier research on OWF siting around Crete [2], refining and expanding it with updated data layers and field-based environmental assessments. The previous approach combined AHP with GIS, using expert-driven pairwise comparisons across 16 evaluation criteria to assess spatial suitability for offshore wind development. Eight stakeholder groups—including policymakers, academia, port authorities, NGOs, and the energy sector—were involved to ensure a comprehensive representation of political, social, community, and market acceptance, which are crucial dimensions of public acceptability in renewable energy planning. The analytical methodology is illustrated in Fig. 1.

Currently, this foundation is being expanded by integrating updated exclusion and evaluation layers, alongside in-situ investigations such as field surveys, seabed characterisation (ROV operations), and avifauna mapping to validate and refine the previous spatial model. The improved methodology thus combines expert-based multi-criteria decision-making with empirical environmental data, enhancing the robustness and applicability of the site selection framework for future offshore wind development in deep-water Mediterranean environments.

More specifically, unlike our previous study [2], which introduced a generalized GIS–AHP methodological framework focused primarily on

Table 1
Responses per category and organisation.

	1	2	3
Regional Policymakers	Regional Unit of Chania	Regional Unit of Lassithi	Decentralized Administration of Crete
Academia	Hellenic Mediterranean University	Technical University of Crete	University of the Aegean
Municipalities	Municipality of Hersonissos	Municipality of Kissamos	Municipality of Platanias
Transmission and Distribution of energy	Independent Power Transmission Operator (IPTO)	Hellenic Electricity Distribution Network Operator (HEDNO)	DAPEEP S.A. Operator of Renewable Energy Sources & Guarantees of Origin
Port Authorities	Municipal port fund of Chania	Heraklion Port Authority S.A.	Chania Coast Guard
Non-Governmental Organizations	Greenpeace Greece	Hellenic Marine Environment Protection Association (HELMEPA)	Heinrich Bell
Energy Production-Energy producers' associations	Hellenic Wind Energy Association (HWEA/ELETAEN)	HAIPP (Hellenic Association of Independent Power Producers)	Metlen Energy & Metals
Tourism -Tourist Associations	Rethymno Hoteliers Association	Chania Botanical Park	Chamber of Commerce of Chania
Sum			24

fixed-bottom offshore wind installations (≤100 m water depth) at a broader planning scale, the present study substantially extends and refines that framework.

- Extension of the water depth range to 1000 m, enabling the integration of floating offshore wind systems. This modification significantly alters the spatial planning logic by expanding the potential offshore area, allowing siting further from the coastline, thereby reducing visual and social disturbance constraints, while reflecting current technological developments in floating foundations.
- Implementation of upfront exclusion filtering, rather than deferred evaluation. In contrast to the referenced national-scale study [7], where several constraints were examined in later planning phases, the present study excludes from the outset: Special Protection Areas (SPA) for avifauna, Natura 2000/Sites of Community Importance (SCI), Hydrocarbon concession blocks, Major navigation routes, Aquaculture zones, Fishing activity areas, and Maximum distance constraints from onshore access roads.
- Criteria that are typically examined in later development stages of national-scale assessments are integrated here as evaluation criteria. These include distance from the electrical grid, distance from ports, distance from onshore road infrastructure, fishing activity areas, and major navigation routes. By incorporating these logistical, environmental, and socio-spatial constraints into the evaluation stage, the analysis moves beyond theoretical suitability toward spatially realistic early-stage planning.
- Adoption and strict refinement of HEREMA criteria [7], with more conservative exclusion thresholds. For example, archaeological buffer zones were expanded from 1652 m to >3000 m, shipping lane buffers were increased from 500 m to 926 m, a minimum 1500 m exclusion distance was imposed from cities, settlements, and outdoor recreational activities. exclusion buffers in the present work, introducing a more precautionary spatial filtering approach.
- Furthermore, while visual impact is often postponed to later project phases [7], this study includes a preliminary appraisal of visual disturbance using photorealistic simulations in Google Earth Pro. Multiple representative viewpoints were selected for each candidate area, providing an initial estimation of landscape exposure and visual interaction for the most suitable zones.

This results in a more conservative and environmentally restrictive early-stage suitability map. The shift from national-scale screening to island-specific high-resolution application and validation, including: Field-informed verification, site-level constraint identification not captured in large-scale GIS datasets. Therefore, the present study does not merely replicate the methodological framework of [2], but substantially advances it by: Incorporating floating offshore wind considerations, applying stricter regulatory exclusion logic, integrating conservative environmental filtering from the outset, demonstrating how large-scale planning outputs change when applied to a complex island context.

The organizations or departments involved in the research are listed in Table 1.

3.2. Exclusion criteria & evaluation criteria

The analysis followed a two-step logic: (i) Hard constraints (exclusion phase): Legally restricted and environmentally protected areas (e.g., Natura 2000 sites, SPA zones, hydrocarbon blocks, aquaculture areas, major navigation routes, etc.) were removed entirely from the analysis at the initial stage; (ii) Soft constraints (evaluation phase): After exclusions were applied, a prioritisation process was conducted among the remaining areas using weighted evaluation criteria.

In this context, certain spatial parameters (e.g., distance from shore, shipping routes, settlements, or military zones) serve as both exclusion and evaluation criteria, but under different logical roles. A minimum legally or operationally required buffer was first applied as a hard exclusion threshold. Beyond that threshold, increasing distance was treated as a graded suitability factor in order to minimise potential disturbance, visual exposure, and operational conflicts. This dual use reflects a precautionary planning approach rather than methodological inconsistency.

To avoid conflicts with other uses of the marine areas near Crete, the initial step was to exclude certain areas based on the criteria set out in Greek legislation 2464/B/2008: Special Framework for Spatial Planning and Sustainable Development for RES sources (SFSPSD) [17] and N. 3851/2010 [18]. It is also worth noting that this study took into account the research conducted by HEREMA (Hellenic Hydrocarbons and Energy Resources Management Company) [7].

In the present study, the exclusion and evaluation framework originally developed for Crete was further refined to reflect a more rigorous socio-environmental context and to align with updated regulatory and ecological considerations. The methodological process remained adaptable to the distinct geographical, ecological, and socio-economic characteristics of the island, ensuring that local sensitivities were incorporated at every stage of spatial analysis.

The exclusion criteria were systematically grouped into four main categories: environmental, regulatory, safety, and technical constraints. Additionally, the evaluation criteria were chosen following an extensive review of international literature, adapted to the Mediterranean context, and customised to parameters relevant to Crete's environmental, techno-economic, and socio-political conditions. Each criterion was normalised and rated on a five-level suitability scale (1 = very low suitability, 5 = very high suitability), enabling a transparent and comparable assessment framework. Regarding threshold definition and class intervals, the limits applied in the analysis were based on relevant literature, national planning guidelines, and regulatory constraints where available. For the purposes of the five-class suitability classification, continuous distance variables were divided into five equal intervals within the established regulatory or literature-supported bounds. For example, the upper limit of 11,112 m (6 nautical miles) was adopted as the maximum allowable distance from shore for installation, reflecting the territorial waters

Table 2
Exclusion and evaluation criteria for sustainable OWF siting.

Category	Exclusion Criteria (and Sub-criteria)	Evaluation Criteria
Environmental	• Natura 2000 sites • *Posidonia oceanica* meadows • Important Bird Areas • Migratory bird corridors • Greek Geoparks	• Distance from areas of environmental interest • Distance from Fishing areas
Legal/ Administrative	• Maximum distance from the road network • Underwater antiquities, shipwrecks, and their protection zones • Enclosed bays with a width of less than 1500 m • Fishing areas • Distance from cultural heritage monuments • Distance from Shore • Zone A of absolute protection of archaeological sites • Declared cultural monuments and historical sites • Cities and settlements >2000 and < 2000 inhabitants • Monasteries • Traditional settlements • Minimum distance from the coast, considering the polygon of the OWF • Quarrying zones • Mining and extraction zones • POPA (Organized Development Areas for Productive Activities) and other areas of organized development of productive activities in the tertiary sector • Distances from SEVESO industries • High-voltage lines • Swimming beaches included in the water quality monitoring program • Other settlements • Organized development of primary or secondary residences (PERPO, cooperatives, etc.) • Isolated residences • Main road axes, road network under the jurisdiction of local authorities (OTAs), and railway lines	
Safety	• Military exercise areas • Areas licensed for hydrocarbon exploration and exploitation • Distance from shipping routes • Distance from airports • Telecommunication infrastructure • Aquaculture and fish farming • Diving parks	• Distance from shipping routes • Distance from airports • Distance from underwater cables • Distance from military exercise areas • Distance from residential activities • Distance from mining areas and activities
Techno-economical	• Water Depth • Wind speed • Distance from underwater cables	• Wind Speed • Water Depth • Distance from Ports • Distance from the electrical grid • Seabed Type • Distance from Shore • Distance from the road network
Cultural	—	• Distance from cultural heritage monuments

constraint applicable in the study area. Within this legally defined range, equal interval classification was applied to enable transparent and comparable suitability grading.

In total, sixteen evaluation criteria were included—grouped into five thematic categories—to reflect the multidimensional aspects of offshore wind siting, balancing technical feasibility with environmental protection and social acceptance. The selected exclusion and evaluation criteria are systematically detailed in Table 2 for each category.

3.3. *Site-level validation and visual assessment*

Following the GIS-based identification of high-suitability marine zones, five adjacent coastal areas (Agios Nikolaos, Kato Zakros, Ierapetra, Messara, and Hersonissos) were selected for site-level validation. The selection was based either on proximity to areas announced by HEREMA or on the spatial extent of suitability polygons indicating higher development potential [7].

Field visits were conducted to assess (i) landscape characteristics and coastal morphology, (ii) visual exposure from nearby settlements, (iii) demographic and socio-economic context, and (iv) archaeological and environmental sensitivities not fully captured in spatial datasets. Visual impact was examined through photographic documentation and photorealistic simulations from representative viewpoints in neighbouring settlements. This enabled a preliminary evaluation of potential landscape intrusion within an island tourism-driven setting [19].

The findings from these site-level observations were not treated as independent assessments but as refinement inputs to contextualise and critically interpret the GIS-derived suitability outputs.

3.4. *Offshore wind turbines and impacts on migratory birds*

With regard to OWFs, their siting at sea is increasingly recognised as a key technology in the transition toward renewable energy. Although offshore wind exploitation provides substantial environmental benefits—such as reducing dependence on fossil fuels and decreasing greenhouse gas emissions—the construction and operation of OWFs raise concerns about their potential effects on wildlife, especially migratory [20]. The main reasons are: (a) Collision risk, (b) Displacement and habitat loss, (c) Barrier effects, (d) Disturbance, (e) indirect ecological effects and (f) Cumulative and synergistic impacts.

3.4.1. *Effects on migratory bird routes*

Migratory birds rely on clearly defined routes to travel between breeding and wintering grounds, often following narrow corridors ("bottlenecks") along coasts and across open seas. The presence of OWFs can interfere with these routes, causing both direct and indirect effects on bird populations.

3.4.2. *Collision risk*

The most immediate threat posed by offshore turbines is collision risk, in which individuals may strike rotating turbine blades, especially under poor visibility (e.g. fog, rain, night). Susceptible species include seabirds as well as migratory raptors that exhibit low manoeuvrability and often fly at rotor-swept altitudes (20–150 m); Birds—especially nocturnal migrants or those flying in low-visibility conditions—may fail to detect turbines in time. Numerous studies have documented bird fatalities at onshore wind farms, and similar risks are expected offshore, particularly for sensitive species [21]. The large spatial footprint of OWFs increases the likelihood of birds encountering obstacles, especially in areas functioning as important stopover sites during migration. Many species migrate in large flocks, increasing the probability of mass collision events [22].

3.4.3. *Displacement & disruption of migratory routes*

OWFs may alter bird flight paths in several ways. Many birds lose access to foraging or resting habitat or experience reduced feeding efficiency because they avoid wind-farm areas. In addition, migratory species often rely on geomorphological features—such as coastlines, peninsulas, capes, and mountain ridges—for navigation. The introduction of large offshore structures may force them to deviate from their optimal trajectories, increasing energy expenditure or exposing them to new risks [23]. For instance, individuals may be pushed farther offshore or compelled to take longer detours to avoid turbine arrays, thereby reducing migration success [24]. Offshore turbines may also influence the distribution of foraging hotspots, which serve as essential stopover sites for refuelling during long-distance flights. Alterations in local ecosystems associated with turbine installation may reduce prey availability, limiting birds' ability to replenish energy during migration [25].

3.4.4. *Behavioural/ethological changes*

OWFs may alter bird flight paths in several ways. Many birds lose access to foraging or resting habitat or experience reduced feeding efficiency because they avoid wind-farm areas. In addition, migratory species often rely on geomorphological features—such as coastlines, peninsulas, capes, and mountain ridges—for navigation. The introduction of large offshore structures may force them to deviate from their optimal trajectories, increasing energy expenditure or exposing them to new risks [26]. For instance, individuals may be pushed farther offshore or compelled to take longer detours to avoid turbine arrays, thereby reducing migration success [27]. Offshore turbines may also influence the distribution of foraging hotspots, which serve as essential stopover sites for refuelling during long-distance flights. Alterations in local ecosystems associated with turbine installation may reduce prey availability, limiting birds' ability to replenish energy during migration [27].

3.4.5. *Noise and light pollution*

The construction and operation of OWFs generate noise and light that may disturb bird species, particularly during migration [28]. Migrants are highly sensitive to environmental change, and construction noise may displace birds from foraging areas. Operational noise can also displace birds and reduce foraging efficiency, potentially lowering survival rates during migration [22]. Aviation safety lights on turbines may disrupt navigation in nocturnal migrants, causing disorientation or collisions with structures [29].

3.4.6. *Sensitive species and critical areas in crete*

Based on the literature review above, the species requiring priority consideration for offshore wind development in Crete are those that depend on thermal updrafts for soaring–gliding flight and occur locally during migration. These include primarily medium- and large-sized raptors such as the Egyptian Vulture (*Neophron percnopterus*), Eastern Imperial Eagle (*Aquila heliaca*), Osprey (*Pandion haliaetus*), European Honey Buzzard (*Pernis apivorus*), kites (*Milvus* spp.), and harriers (*Circus* spp.). In addition, Eleonora's Falcon (*Falco eleonorae*)—a summer visitor that breeds on satellite islets around Crete and forages over the open sea at "critical heights"—is also considered vulnerable. Other migrant species passing through Crete that may be susceptible to collision or displacement include the White Stork (*Ciconia ciconia*), pelicans (*Pelecanus* spp.), and herons (*Ardea* spp.).

Additionally, certain seabirds—such as the Scopoli's shearwater (*Calonectris diomedea*) and the Mediterranean shag (*Gulosus aristotelis*), —which breed on islets around Crete and forage offshore, are vulnerable to turbine collisions, displacement, and visual disturbance. Moreover, the former species is predominantly nocturnal, making it highly susceptible to blade strikes and light-induced disorientation. Future research on the migration ecology of these species in Crete should prioritise:

(1) the elongated mountain ranges running along a north–south axis,
(2) the peninsulas and capes of northern Crete,
(3) the terrestrial corridors formed between major mountain masses, and
(4) the coastal zones situated between ecological barriers, such as mountain ranges and adjacent marine areas.

Regarding coastal areas, existing telemetry data cover only three species: *Falco eleonorae, Gulosus aristotelis*, and *Calonectris diomedea*. For Eleonora's falcon, a 17-km radius around major colonies defines the minimum core foraging zone during the breeding period. For the European shag, the 150-m depth contour encompasses nearly the entire breeding and foraging area [30]. Finally, for Scopoli's shearwater (*Calonectris diomedea*), telemetry data were collected during 2024 from a limited sample of radio-tracked individuals (n = 5) originating from three breeding sites around Crete. In total, 3500 radio locations recorded at a 15-min sampling interval were analysed using kernel density estimators [31]. These preliminary analyses suggest that the KDE-50% utilization distribution, representing the core foraging area during the chick-rearing period, is predominantly located at distances of approximately 30–35 km from the breeding colonies.

However, these findings should be considered indicative given the small sample size. A substantially larger number of tagged individuals is required to robustly characterize space-use patterns, while a detailed flight-height analysis is necessary to support the development of reliable collision-risk models.

3.5. *Seabed research in the selected areas*

3.5.1. *Preliminary seabed research in the selected areas - data sources and geospatial processing framework*

To support the marine spatial analysis, a thorough review and processing of publicly available marine geospatial datasets were carried out. Bathymetric, geological, and benthic habitat information was mainly sourced from the European Marine Observation and Data Network (EMODnet), a key marine data infrastructure funded by the European Commission (DG MARE) that offers harmonised, FAIR-compliant datasets across European Seas.

Specifically, EMODnet Bathymetry (DTM tiles, 2022) [32] was utilised to determine the average, minimum, and maximum depths per analysis polygon, along with seabed slope and the Terrain Ruggedness Index (TRI), which indicates local seabed variability. Data were processed in QGIS, employing SAGA GIS and GDAL libraries for raster analysis and terrain modelling.

Substrate composition was derived from EMODnet Geology (multiscale – Folk 16) [33], which classifies seabed sediments into five main categories (mud, sand, coarse sediment, mixed sediment, and rocky substrates) based on the modified Folk triangle. These data were complemented by EUSeaMap 2023, a predictive broad-scale seabed habitat model developed by EMODnet Seabed Habitats, providing benthic habitat types (e.g., circalittoral mud, infralittoral sand, hard substrata) at a 100 m resolution [34].

Additionally, environmental and oceanographic parameters were examined from the Copernicus Marine Service, which provides global and regional biophysical datasets (e.g., nutrients, oxygen, temperature). However, due to the coarse resolution (≈1 km), these were not incorporated into the local-scale spatial analysis.

The harmonised multi-source data facilitated the calculation of key morphometric indicators (depth, slope, roughness) and substrate composition across the candidate areas. These parameters provided the geophysical foundation for assessing seabed suitability for offshore wind infrastructure and were subsequently combined with ecological and environmental criteria in subsequent analytical steps.

3.5.2. Seabed research in the selected areas

The objective of the study is to provide a strategic, early-stage spatial suitability assessment rather than a detailed engineering or geotechnical feasibility study. The EMODnet datasets were used for macro-scale bathymetric and seabed characterization appropriate to preliminary spatial screening. Field surveys and ROV observations were not intended as exhaustive ecological or geotechnical investigations. Instead, they served as validation tools to identify site-level constraints and contextual factors not captured by desk-based GIS datasets.

It should be clarified that this study does not claim to provide detailed sediment strength analysis, anchoring feasibility assessment, slope stability modelling, or foundation-specific geotechnical design. The term “suitability” is therefore used strictly in a spatial-planning sense, referring to environmental, regulatory, bathymetric, and logistical compatibility, rather than engineering readiness.

It should be clearly stated that the term “suitability” in this study refers strictly to spatial planning compatibility and does not imply engineering feasibility or development readiness for floating offshore wind installations. The analysis does not include detailed geotechnical investigations such as sediment strength characterization, anchoring feasibility assessment, or slope stability modelling. Consequently, no conclusions are drawn regarding foundation design adequacy or construction viability. Such investigations constitute a necessary subsequent step prior to any project-level decision or development process.

In the areas selected based on the previous analysis, depths exceed >50 m. In these areas, an ROV will be used to record seabed type, elements of megabenthic biodiversity, and other morphological characteristics.

The FIFISH V6 Expert system was used, as well as the BlueROV2, due to a hardware failure of the former, which left in operate. Additionally, at the 2 northern sites, technical dives were carried out using TRIMIX gases in the 50-60m bathymetric zone to gain time until the replacement machine was received.

At each site, a seascape survey was conducted to record 15-min videos from which 50 photographs were extracted. These images capture the seabed, biodiversity, and specific morphological features of each site. Additionally, during the analysis, the seabed typology is recorded for each site according to EUNIS Level A [35].

At all locations, data collection was carried out at depths between 50 and 100m, which are the operational depths of the available ROVs. These depths are also where scientific diving using TRIMIX gases (helium-nitrogen-oxygen) is possible, either in Open Circuit Systems or in Closed Circuit Systems/Rebreather Machines.

4. Results and discussion

A direct comparison with the previous framework [2] highlights an important methodological refinement emerging from the present study. While the national-wide generalized GIS–AHP approach identified several offshore zones as highly suitable based on wind potential, bathymetry, and regulatory screening, the island-scale application combined with stricter exclusion thresholds and field-informed verification significantly altered the spatial configuration of the final candidate areas.

In particular, the extension to floating offshore wind systems (up to 1000 m water depth) shifted part of the suitability envelope further offshore. However, the incorporation of stricter buffers (e.g., >3000 m from archaeological sites, 1500 m from settlements and outdoor activities, 926 m from shipping lanes) and the early inclusion of infrastructure-related criteria reduced and reshaped the initially suitable zones [7].

Most critically, the preliminary field autopsies and visual simulations demonstrated that even areas classified as fully suitable under conservative desktop screening may reveal site-level constraints when assessed in situ. A characteristic example is the Elounda case study, where photorealistic simulations using Google Earth together with on-site observation, revealed substantial landscape exposure from multiple coastal viewpoints. Although the area satisfied all environmental, bathymetric,

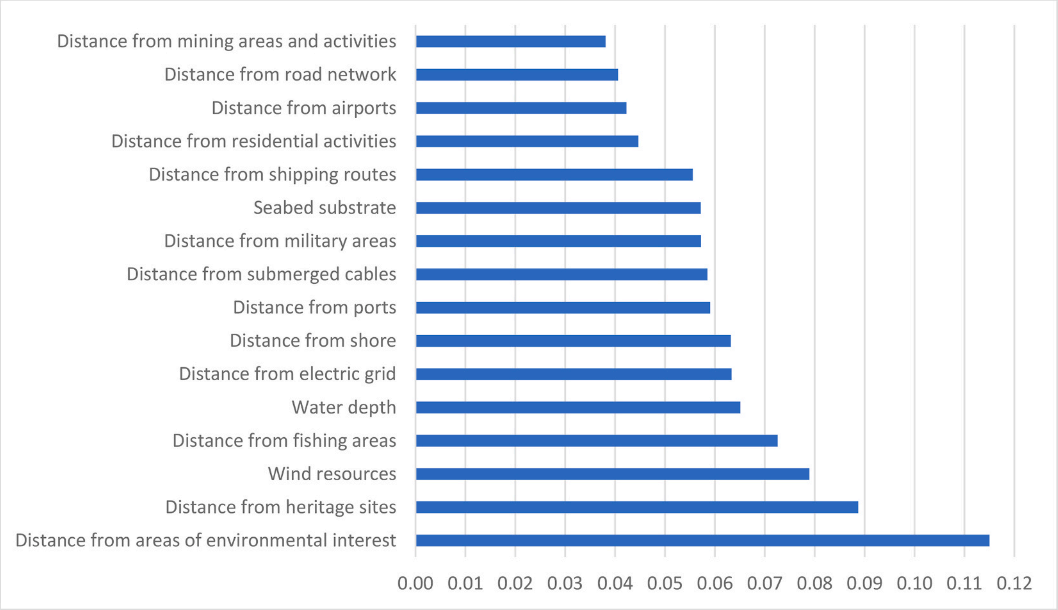

Fig. 2. Relative importance (%) per evaluation criterion.

Fig. 3. Ranking of available areas for OWFs siting.

and regulatory criteria within the GIS-based framework, the entire eastern and southern visual envelope exhibited strong visual interaction with inhabited and touristic zones. As a result, that portion of the initially suitable area would need to be excluded in practical planning terms.

This example illustrates that large-scale GIS-based suitability assessments, even when methodologically rigorous and conservatively filtered, may overestimate spatial feasibility without early-stage visual and field-based validation. The integration of autopsies and photo-realistic simulations does not replace detailed environmental or engineering assessments but functions as a critical intermediate filter between macro-scale screening and project-level design.

Therefore, compared with the previous generalized framework, the present study demonstrates that conservative exclusion thresholds combined with site-specific validation substantially enhance spatial realism in offshore wind planning, particularly in complex island environments.

4.1. Results from the sustainable siting

4.1.1. Stakeholder evaluation results

In this section, the updated results of the stakeholder evaluation process are presented, reflecting the continued implementation of the multi-criteria decision framework developed in our previous study [2]. Twenty-four experts and stakeholders participated voluntarily, representing eight key sectors: regional policymakers, academia, municipalities, port authorities, transmission and distribution operators, energy producers' associations, environmental NGOs, and tourism representatives. It is important to clarify that the stakeholder sample was not designed to be statistically representative. The approach follows an explanatory and exploratory logic, based on structured personal interviews with at least three representatives from each stakeholder and expert group. The objective was not to produce population-level inference but to capture a structured representation of stakeholder attitudes in the context of preliminary spatial planning for Crete. In this sense, the sample provides an informed reflection of local perspectives rather than a statistically generalizable dataset [36].

Their inputs were used to conduct pairwise comparisons among the sixteen evaluation criteria following the AHP. For each comparison matrix, the consistency ratio (CR) was calculated to ensure methodological reliability. When the initial CR exceeded the acceptable threshold ($CR > 0.1$), the corresponding judgments were re-examined in consultation with the respondents and adjusted accordingly until consistency was achieved. All final matrices satisfied the recommended consistency requirement ($CR < 0.1$). To enhance transparency, the paper explicitly reports the calculated consistency ratios for all stakeholder groups and provides a clearer description of the verification and adjustment procedure applied during the weighting process.

The combined weights from all stakeholder groups are shown in Fig. 2, where the relative importance (%) of each evaluation criterion is depicted. The criterion "Distance from Areas of Environmental Interest" again emerged as the most influential factor (12%), followed by "Distance from Heritage Sites" (9%) and "Wind Resources" (8%). These results reaffirm the strong environmental awareness among stakeholders,

Table 3

List of available siting areas for OWFs, adapting six scenarios of different commercial models of offshore wind turbines with the number and MW supported, respectively.

a/a	Geographical region	Suitability (range)	Total area (km^2)	Wind turbines (Number) Scenario 1	Installed capacity (MW) Scenario 1	Wind turbines (Number) Scenario) 2	Installed capacity (MW) Scenario 2	Wind turbines (Number) Scenario 3	Installed capacity (MW) Scenario 3	Wind turbines (Number) Scenario 4	Installed capacity (MW) Scenario 4	Wind turbines (Number) Scenario 5	Installed capacity (MW) Scenario 5	Wind turbines (Number) Scenario 6	Installed capacity (MW) Scenario 6
1	Agios Nikolaos North 6	3 and 4	121.9	66	660	44	660	172	1032	110	495	104	624	92	773
2	Agios Nikolaos South 2	3 and 4	118.9	65	650	43	645	168	1008	107	482	102	612	90	756
3	Heraklion South 2	3 and 4	60.9	33	330	22	330	86	516	55	248	52	312	46	386
4	Agios Nikolaos South 3	3 and 4	34.3	18	180	12	180	48	288	31	140	29	174	26	218
5	Agios Nikolaos East 2	3and 4	23.9	13	130	8	120	33	198	21	95	20	120	18	151
6	Heraklion North 1	3 and 4	20.0	10	100	7	105	28	168	18	81	17	102	15	126
7	Agios Nikolaos East 1	3and 4	18.4	10	100	6	90	26	156	16	72	15	90	13	109
8	Mesara 1	3 and 4	15.8	8	80	5	75	22	132	14	63	13	78	11	92
9	Chania North 1	3 and 4	12.6	6	60	4	60	17	102	11	50	10	60	9	76
10	Agios Nikolaos South 1	3	10.4	5	50	3	45	14	84	9	41	8	48	7	59
11	Agios Nikolaos North 2	3 and 4	8.4	4	40	3	45	11	66	7	32	7	42	6	50
12	Agios Nikolaos North 3	3 and 4	8.0	4	40	2	30	11	66	7	32	6	36	6	50
13	Agios Nikolaos East 3	3 and 4	7.3	3	30	2	30	10	60	6	27	6	36	5	42
14	Heraklion North 4	3 and 4	5.8	3	30	2	30	8	48	5	23	4	24	4	34
15	Heraklion South 1	3	5.6	3	30	2	30	7	42	5	23	4	24	4	34
16	Agios Nikolaos North 1	3	4.4	2	20	1	15	6	36	3	14	3	18	3	25
17	Agios Nikolaos North 4	4	3.1	1	10	1	15	4	24	2	9	2	12	2	17
18	Heraklion North 6	3	2.8	1	10	1	15	4	24	2	9	2	12	2	17
19	Heraklion North 3	3	2.7	1	10	0	0	3	18	2	9	2	12	2	17
20	Heraklion North 2	3	2.4	1	10	0	0	3	18	2	9	2	12	1	8
21	Chania North 2	3	1.9	1	10	0	0	2	12	1	5	1	6	1	8
22	Agios Nikolaos North 5	3	1.5	0	0	0	0	2	12	1	5	1	6	1	8
23	Agios Nikolaos East 4	3	1.3	0	0	0	0	1	6	1	5	1	6	1	8
24	Heraklion North 5	3	0.7	0	0	0	0	0	0	0	0	0	0	0	0
	Sum		**493**	**258**	**2580**	**168**	**2520**	**686**	**4116**	**436**	**1962**	**411**	**2466**	**365**	**3066**

Note: Installed capacity values represent theoretical maximum layouts assuming uniform turbine spacing and do not reflect detailed micro-siting or engineering constraints.

Table 4
Supplement of Table 3 with the relevant definitions.

Scenario	Wind turbine model. MW and rotor diameter	References
1	Siemens Gamesa: SG 10.0-193 DD, 193m	[37] [39]
2	Siemens Gamesa: SWT-6.0-120, 120m	[37] [39]
3	Vestas: V236-15.0 MW, 236m	[37] [40]
4	Vestas: V150-4.5 MW, 150m	[37] [40]
5	Hywind project: 6 MW, 154m	[41]
6	Windfloat-atlantic project: 8.4 MW, 164m	[42]

emphasising the increasing recognition that cultural and ecological preservation should be incorporated into the early planning stages of offshore wind development. As expected, environmental NGOs and academic representatives assign the highest priority on environmental and heritage protection, while energy producers and grid operators focus on resource availability and technical feasibility. Municipalities and tourism stakeholders demonstrate intermediate priorities, reflecting a balance between environmental stewardship and socio-economic opportunities.

Overall, the results suggest a convergence of perspectives across sectors, pointing to a shift toward more environmentally conscious and socially integrated offshore wind planning. Compared with the previous study, the weighting pattern remains broadly consistent. Still, it shows a slightly greater dispersion among socio-economic criteria—indicating that stakeholder awareness is becoming more nuanced and sector-specific as the offshore wind discussion matures.

4.1.2. Spatial suitability mapping results

Fig. 3 presents the spatial distribution of available marine areas around Crete (Annex Fig. 1), categorized into five classes of suitability for OWF development, with 5 representing the highest suitability. These results were produced through a weighted sum overlay analysis in GIS, integrating the relative weights of the sixteen evaluation criteria derived from the stakeholder survey. The darker green zones correspond to areas of very high suitability (class 5), while the yellow to orange zones indicate moderate to low suitability (classes 3–2).

The analysis identified a total of 493 km^2 of marine space with suitability scores of 3 to 5, which are considered potentially exploitable for OWF deployment (see Table 3 and Table 4). This spatial outcome reflects the balanced integration of technical, environmental, and socio-political criteria, as defined through the participatory AHP framework.

It is essential to emphasise that, while the methodological framework and evaluation criteria are universally applicable, their implementation in this study was tailored to the specific characteristics of an insular Mediterranean environment. The island of Crete serves as an ideal testing ground for this adaptation, combining high and stable wind potential, proximity to the existing high-voltage transmission grid, and relatively short distances from shore, which collectively improve the technical and economic viability of offshore wind development. This regional application demonstrates how a standardised, multi-criteria decision framework can be effectively customised to local marine, geomorphological, and socio-environmental conditions without compromising methodological consistency.

Compared with previous studies conducted in the broader Hellenic Sea region, the current results further validate Crete as a key strategic location for offshore wind development. Differences between the identified high-suitability areas in this and earlier research primarily stem from the different bathymetric constraints considered. Previous studies extended into deeper waters suitable for floating turbines, whereas the present analysis focused on depths consistent with the AHP-defined exclusion parameters.

4.1.3. Energy assessment of highly suitable areas

Finally, Table 3 presents the available marine areas (km^2) suitable for OWF installation around the island of Crete; however, only those with a suitability score of 3–5 were selected for the stricter scenario. In addition, the subsequent columns show the number of wind turbines and total installed capacity (MW) each available area could accommodate.

Further analysis was conducted on the largest available marine areas based on the characteristics of six different commercial wind turbine models — four fixed-bottom and two floating. The selected models are: Siemens Gamesa SG 10.0-193 DD, Siemens SWT-6.0-120, Vestas V236-15.0 MW, Vestas V150-4.5 MW, Hywind 6 MW–154, and WindFloat Atlantic 8.4 MW–164.

Models from Vestas and Siemens Gamesa Renewable Energy (SGRE) were chosen, as these two companies are the most experienced in the offshore wind sector and represent the two leading manufacturers, together holding approximately 90% of the European market share [37]. The Supplementary Table 4 provides clarification for the numerical codes (1–6) used in Table 3, describing the corresponding turbine models, rated power (MW), and rotor diameters selected for each scenario.

Furthermore, following a consultation with local experts. Eastern Crete is regarded as a privileged area, that meets many of the selected criteria. It is worth mentioning that according to RAE [38]. There are already several onshore wind parks in this region.

Table 3 presents the available marine areas around Crete with a suitability score of 3–5 for OWF installation, as well as the estimated capacity in terms of the number of wind turbines and total MW for six different commercial models-Scenarios. Overall, the available marine area amounts to approximately 493 km^2, with a total estimated installed capacity ranging from 1962 MW to 4116 MW, depending on the scenario and turbine type.

The Agios Nikolaos region demonstrates the highest potential, accounting for over 60% of the total capacity. Key subareas include Agios Nikolaos North 6 (121.93 km^2 – up to 1032 MW) and Agios Nikolaos South 2 (118.94 km^2 – up to 1008 MW). These locations feature extensive marine areas, favourable bathymetric and slope conditions, and high suitability scores (3–4), making them ideal candidates for offshore development.

Next in potential are the Heraklion regions, contributing a substantial portion of the total estimated capacity (approximately 15–20%). Smaller yet promising areas are also found in Messara and Chania, which, despite their limited spatial extent, could host smaller-scale floating offshore wind configurations suitable for demonstration or hybrid projects.

4.2. Results from on-site autopsies of the selected areas

Fig. 4 a) presents the 5 areas for extra investigation that have emerged after the aforementioned methodology, whereas Fig. 4 b) presents the 4 areas that have been announced by HEREMA [7], for the development of OWFs in the region of Crete, Greece. It has been noted that the areas a) and b) are very close to the national study for the same purpose.

«Agios Nikolaos» (ID: 16) was selected as one of the 5 study areas based on the research carried out in the present research, as well as previous research carried out for the island of Crete regarding the sustainable siting of OWFs [2] [44]. The area is about 23.9 km^2, according to the Global Wind Atlas. It can be seen in Fig. 6 that the average wind speed in the area is approximately 10.06 m/s at 100 m height [45].

Although the suitability analysis initially identified the specific polygon in Agios Nikolaos as highly favourable for offshore wind siting, subsequent investigation excluded the easternmost section of the “Aforesmenos Cape” from further consideration. This adjustment was driven by the need to protect the wider Elounda area, which includes ecologically and culturally sensitive zones, as well as by strong concerns expressed by local communities about potential visual, ecological, and socio-economic impacts. The findings from the field visit reinforced these concerns, revealing site-specific characteristics that could not be fully captured through remote spatial analysis alone. This highlights a

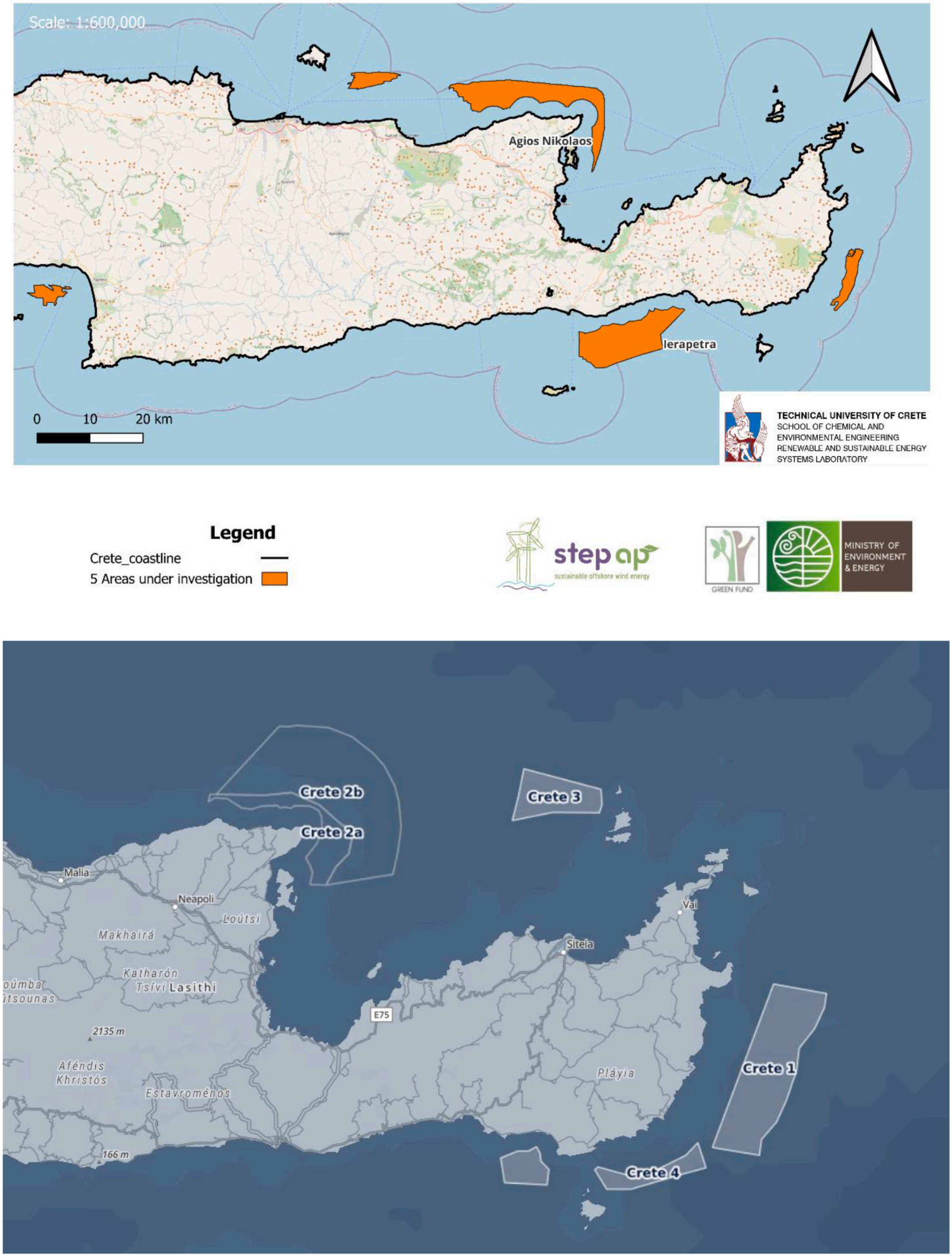

Fig. 4. a) The 5 areas to be investigated in the island of Crete, b) The 4 announced areas from HEREMA, Greece [7] [43].

critical point for offshore wind planning: GIS-based suitability assessments must always be complemented by on-site inspections, particularly in regions with complex coastal morphology and high environmental or social sensitivity.

To determine which villages would exhibit the most significant visual impacts, various scenarios were run using the Google Earth Pro projection tool. The selected areas are shown on the map below, Fig. 5. In this study, the initial number of observer points selected was 5, but, with the exception of Elounta, it was finally reduced to 4.

Regarding the micro-siting of the area. The layout was chosen to be 7Dx7D, where D is the rotor diameter of the wind turbine, and this layout has been shown to be very close to the average spacing of OWFs

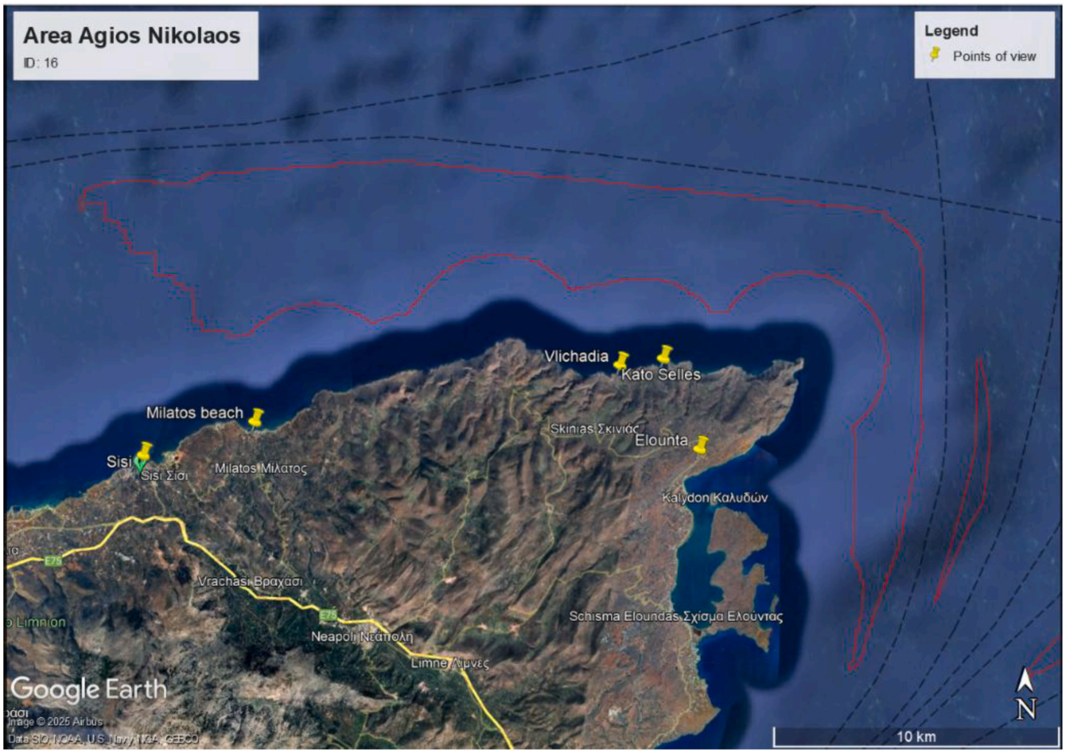

Fig. 5. Observer points Agios Nikolaos.

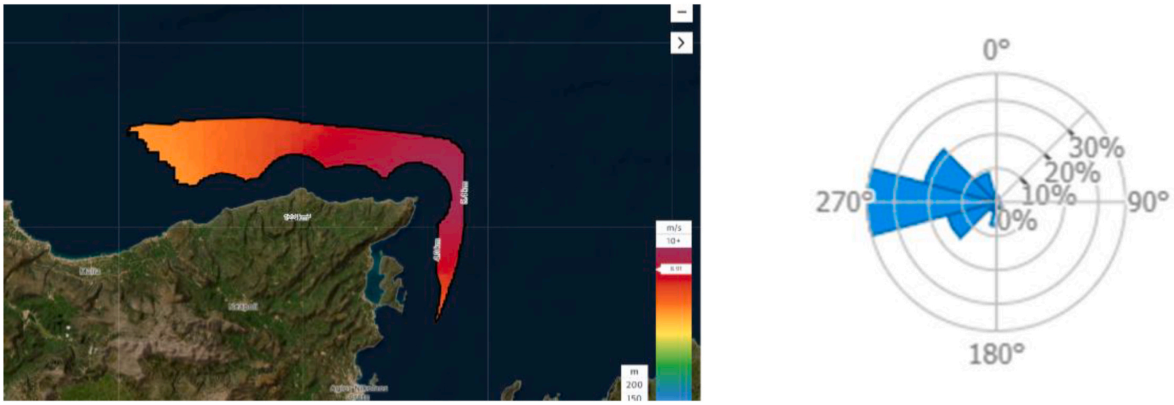

Fig. 6. a) Average wind speed and b) main direction wind for the area of Agios Nikolaos.

in Europe (downwind 7.5D and crosswind 5.9D) [46].

The wind turbine model chosen for this analysis is Siemens Gamesa: SG 10.0-193 DD, with 193m rotor diameter. 100m height and 10 MW rated power [39]. Micro-siting of wind turbines is always done according to the prevailing wind direction in the respective area. Therefore, the wind turbines should be placed northwest in the area (330°), which is the wind's dominant direction based on the Global Wind Atlas [45] (Fig. 6).

Finally, the indicative location of the area is shown in detail in Fig. 7 below. with the help of AutoCAD and QGIS software. A total of 14 A/Cs were sited. 10 MW each. with a total installed capacity of 140 MW.

The visual nuisance assessment focused on four key observation points along the coastal zone of Agios Nikolaos. These points correspond to small settlements and coastal villages with very low population density, according to the 2021 census.

Specifically, the village of Sisi has a population of 1,001, while Milatos Beach is a much smaller coastal settlement with around 130 residents. The nearby Vlichadia hosts only 44 inhabitants, and Kato Selles is almost uninhabited, with a recorded population of just four people.

Overall, the study area's demographic profile indicates very low population density along the coastline, suggesting minimal visual disturbance from potential OWF installations in the surrounding marine zones. The areas and their corresponding populations, which will be examined for visual nuisance, are four and are presented in Fig. 5 (Annex Fig. 5). The following images in Fig. 8 are the simulation images of the potential OWF in the area, created with the help of Google Earth Pro and the special plugin Virtual Animated Turbine [47].

4.2.1. *Critical observations-findings (E.g. if there is posidonia, algae species, etc.)*

During the on-site inspections of the four coastal areas examined, it is worth noting that no seagrass or macroalgae were observed along the shorelines. Milatos beach consisted mainly of pebbles, while the remaining locations were characterised by rocky shores. This observation suggests that *Posidonia oceanica* meadows are likely absent from the

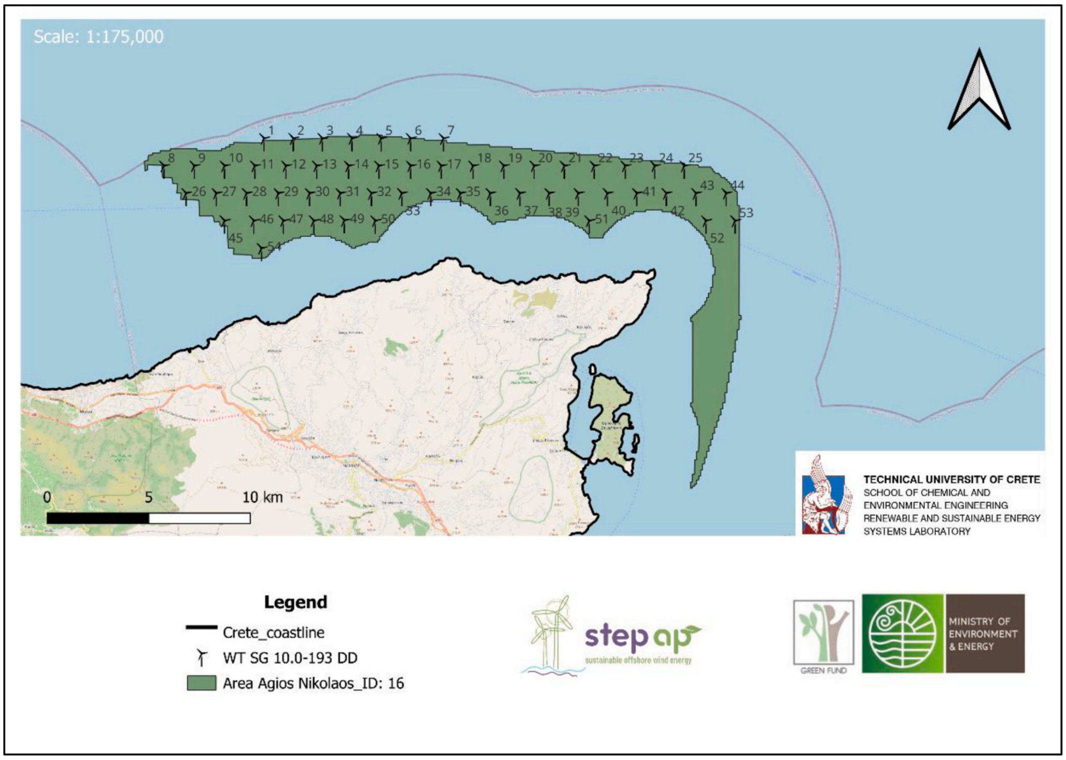

Fig. 7. Micro-siting of WT area of Agios Nikolaos. SG 10.0-193 DD. 7x7 RD.

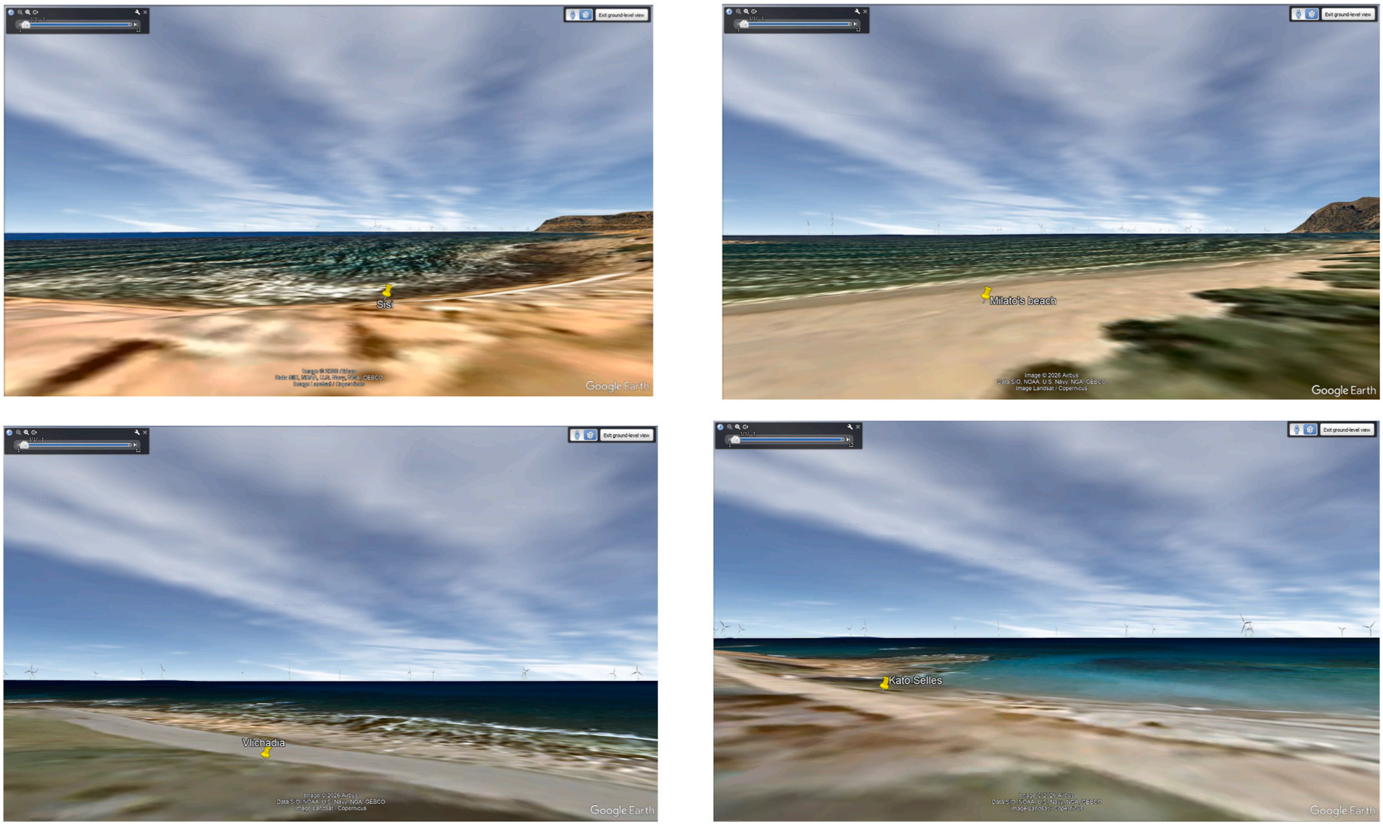

Fig. 8. Observer points Agios Nikolaos with animated wind turbines - a) Sisi, b) Milato's beach, c) Vlichadia, d) Kato Selles.

examined coastal zone. However, this assumption will be verified with greater certainty during the subsequent stage of seabed surveys in the same areas.

Furthermore, the coastal stretch under investigation—apart from the

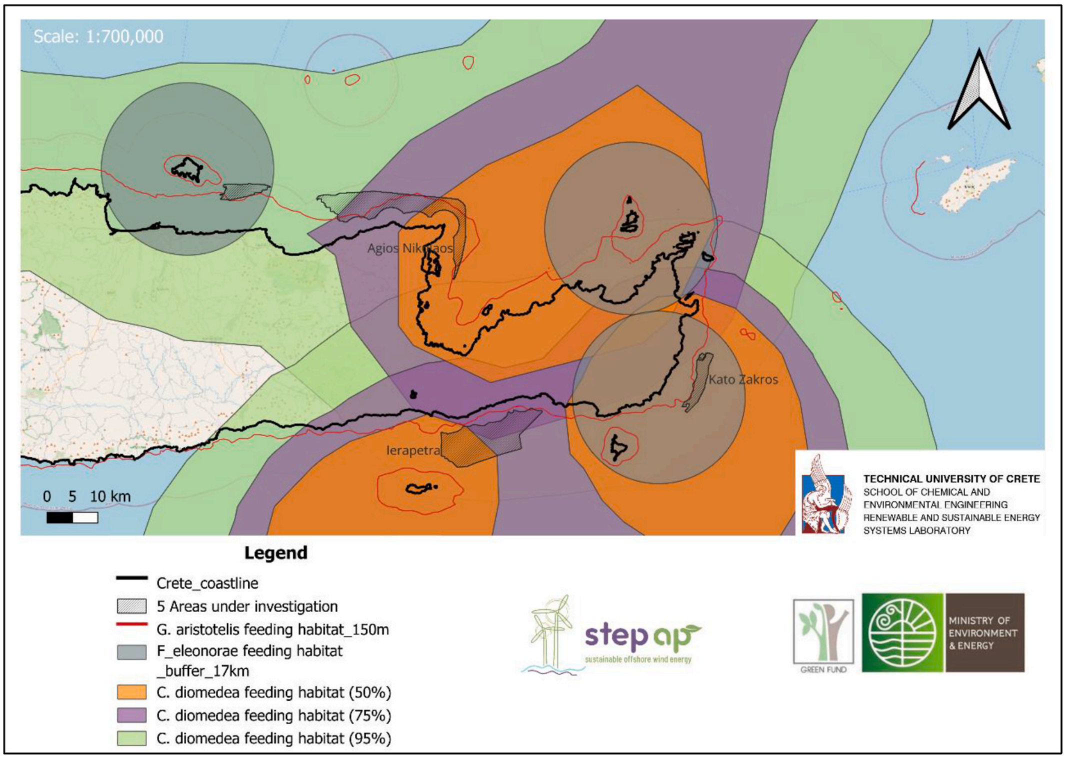

Fig. 9. The 5 study areas in relation to the critical coastal zones of Crete that are important for the migration and foraging of seabird species; were analysed to assess their environmental compatibility for OWF siting.

Table 5
Summary table of environmental compatibility.

Area	*C. diomedea*	*F. eleonorae*	G. aristotelis	Overall Environmental Compatibility Assessment
Agios Nikolaos	Partial overlap at 50%–75%–95% zones	Outside	Partial overlap	Moderate compatibility
Kato Zakros	Within 50% zone	Within	Outside	Low compatibility
Ierapetra	Partial overlap at 50%–75% zones	Outside	Outside	Moderate to low compatibility
Messara	Outside	Outside	Partial overlap	Relatively high compatibility
Hersonissos	95% overlap	Within	Outside	Moderate to high impact

small settlements of Sissi and Milatos Beach—is almost uninhabited. With only a few scattered houses (many of which appear abandoned) and minimal human activity or commercial presence. Consequently, potential visual disturbance caused by offshore wind development is expected to be very limited. Another factor confirming the suitability of the wider area is the presence of an existing onshore wind farm nearby. indicating a degree of social acceptance of wind energy infrastructure.

4.3. Results of the bird fauna in the area

The analysis examined potential overlaps between the candidate sites and the vital or feeding areas of three protected seabird species — Calonectris Diomedea, *Falco eleonorae* and Gulosus aristotelis — revealing notable differences in environmental impact and potential conflict levels. The evaluated areas are: Agios Nikolaos. Kato Zakros. Ierapetra. Messara. and Hersonissos Fig. 9.

According to Table 5, in Agios Nikolaos, it is shown that partial overlap with the 50%. 75% and 95% zones of *C. diomedea* mainly along its eastern edge. No significant overlap was observed with *F. eleonorae*, while limited interaction with G. aristotelis occurs in localized sections. Overall, the area is considered to have a moderate environmental impact. with a heterogeneous ecological footprint. Localized assessment and targeted monitoring are recommended to ensure reliable documentation.

4.4. Results from the preliminary research on seabed of the selected areas

From the analysis of the bathymetric products, such as those provided by EMODnet Bathymetry. it appears that the areas are at depths exceeding 40m reaching 1300m (Fig. 10). The data have a spatial resolution of 106 m (pixel size). It is estimated that the accuracy of the bathymetric data is not very high, especially in terms of depth values in shallow waters. A Box-Plot for mean, maximum and minimum depth values is illustrated in Fig. 11 (Annex Table 1).

Fig. 10 show the results from the analyses regarding the slopes and the roughness of the areas. Regarding the slope, it seems that the sites in the south/east of Crete present moderate slopes (>15°). In contrast to the sites in the northern part of Crete that have smaller ones (Table 6, Fig. 12).

In terms of roughness the image is similar to the gradient image with a strong differentiation of North-South/East positions. In the southern locations. The polygons resulting from the analyses appear to be in steep slopes and rugged underwater landscape as they enter the slope of the Cretan continental shelf.

Finally, the following maps show the depth, slope, roughness and type of bottom focused for the selected area Agios Nikolaos Fig. 12.

Bathymetry: The area shows a steep depth gradient reaching approximately −346 m at a relatively short distance from the coastline, making it suitable exclusively for floating wind turbine installations.

Seabed slope: It generally ranges at moderate levels with local increases up to 22° mainly in the central part of the site. Zones with lower slope values near the edges are considered more suitable for potential

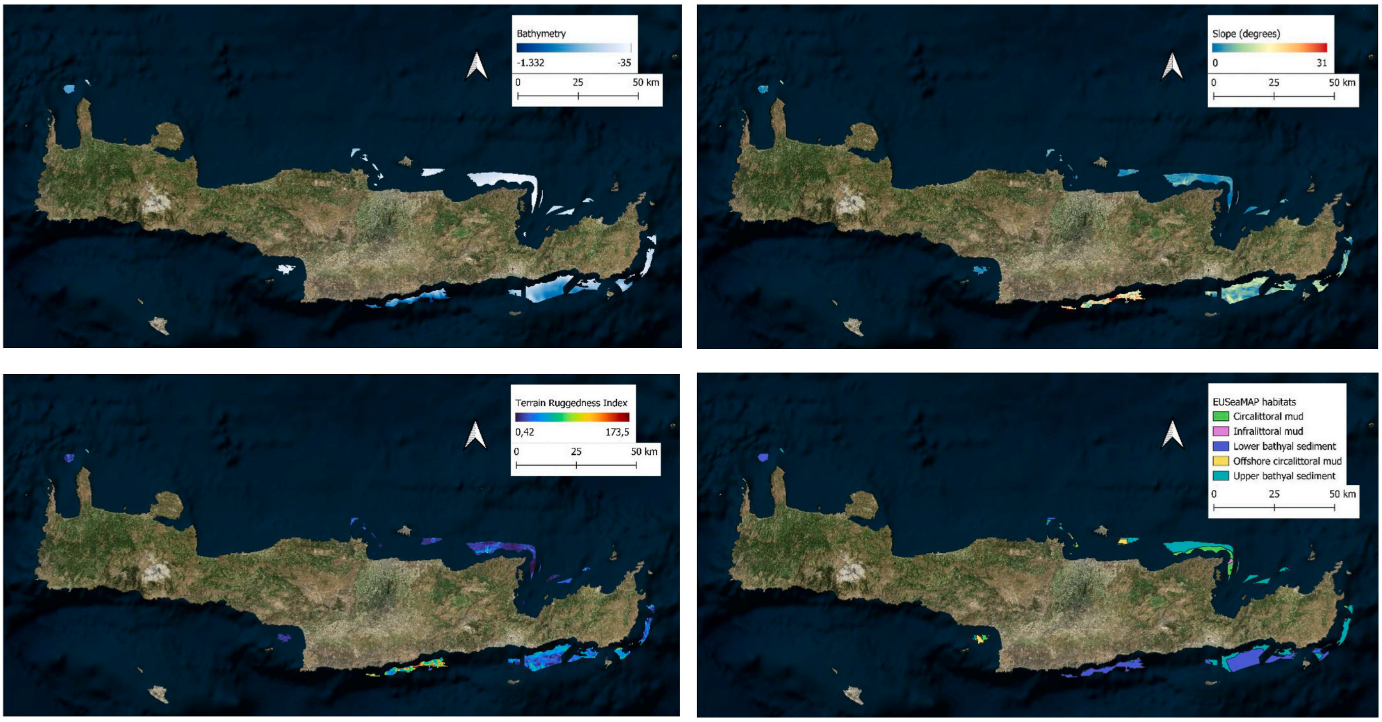

Fig. 10. The bathymetry. slope. TRI index and seabed type of the selected polygons.

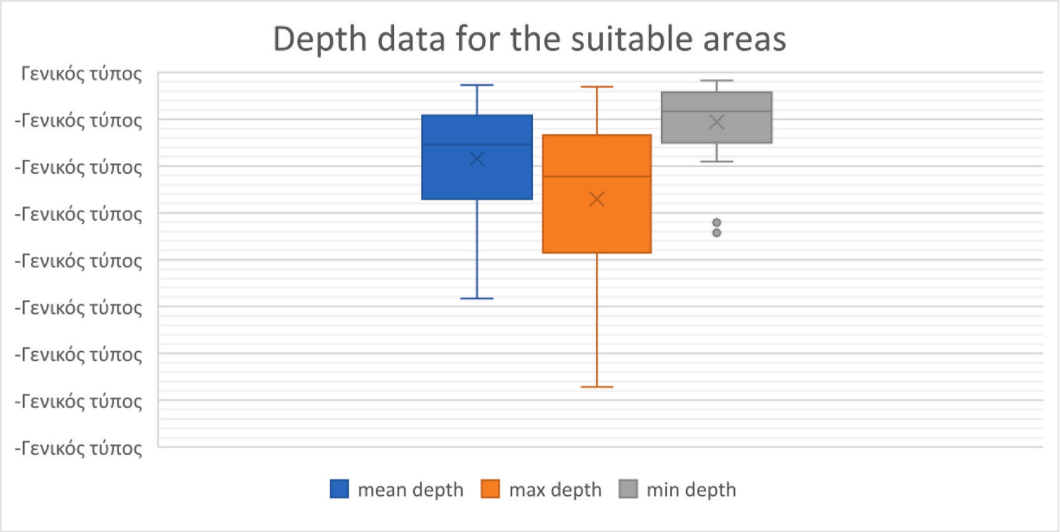

Fig. 11. Box-Plot for mean, maximum and minimum depth values.

development.

Seabed roughness (TRI): The seabed exhibits significant heterogeneity with high roughness values in the central–southwestern section (>130) indicating a steep relief and the need for technically adapted foundation systems. The eastern and northern parts display smoother terrain, which is more favourable for uniform infrastructure placement.

Substrate type/EUSeaMap Habitats: The substrate consists predominantly of soft sediments (Upper bathyal sediment circalittoral mud) with limited presence of infralittoral and offshore circalittoral mud. This composition supports the deployment of floating foundations. although a detailed geotechnical assessment is required to ensure proper anchoring on muddy substrates (Annex Figs. 2, 3 & 4).

Based on the ROV dive footage presented in Fig. 13, the surveyed seabed is classified as A4 – Circalittoral rock and other hard substrata, characterised predominantly by rocky outcrops, sponges, coralline algae, and patches of macroalgae. The ROV also recorded a dusky grouper (*Epinephelus marginatus*), a species typically found in deep reef environments. No elements of high ecological sensitivity—such as habitats or species listed under national or EU protection frameworks—were detected during the ROV inspections.

4.5. *Sensitivity analysis*

To evaluate the influence of stakeholder-derived weights, a sensitivity scenario was developed using equal weights across all evaluation criteria Fig. 14. Under equal weighting, a substantially larger number of areas are classified in the highest suitability class (5), whereas in the stakeholder-weighted scenario, the distribution is more conservative,

Table 6
The statistics from the spatial analysis of the bottom slope. Shown per polygon (id) is the mean maximum and minimum slope in degrees.

id	_slope mean	_slope min	_slope max
1	3.3	0.1	9.1
2	35.4	15.0	67.0
4	27.7	0.9	78.3
5	10.3	0.1	27.6
6	11.3	0.1	46.8
7	12.1	0.6	33.6
8	16.6	1.7	73.0
9	9.2	0.2	29.9
10	8.4	0.4	38.6
11	8.6	2.6	16.4
12	7.4	2.3	10.9
13	2.1	0.1	5.7
14	8.0	3.7	14.4
15	1.7	0.5	3.1
16	4.5	0.0	41.4
17	4.1	0.3	17.6
18	4.2	0.3	9.0
19	2.3	0.7	5.7
20	7.7	2.8	13.7
21	1.9	1.2	2.5
22	4.0	0.1	19.6
23	19.8	12.9	31.1
24	6.7	2.8	9.3
25	24.6	8.0	38.0

with very few or no areas reaching the maximum class.

However, the spatial pattern of suitability remains consistent. The eastern and southeastern coastal sectors, including the broader Agios Nikolaos region, remain the most favourable areas under both weighting schemes. This indicates that the exclusion filtering defines the primary spatial envelope of suitability, while stakeholder weighting refines the internal prioritisation and introduces a more restrictive ranking structure. The weighting scheme, therefore, affects the intensity of suitability classification rather than the geographic location of candidate zones.

These findings strengthen the study's methodological transparency by demonstrating how weighting assumptions influence classification outcomes. This comparison suggests that the exclusion framework primarily determines the spatial extent of potentially developable areas, while stakeholder weighting influences the relative prioritisation and restrictiveness of final classifications.

4.6. Limitations, challenges, and future research

Despite the comprehensive methodology applied in this study, several limitations and challenges remain. First, the assessment relies on static datasets and expert-elicited weights, which, although robust, cannot fully capture the temporal variability of marine ecosystems, migratory bird behaviour, or socio-economic dynamics. Additionally, the GIS-based analysis is constrained by the resolution, accuracy and availability of spatial data, particularly regarding marine biodiversity, underwater noise propagation, and detailed seabed substrate information.

A key challenge arises from the limited in situ verification. Although site-specific constraints (environmental, social, and technical) were integrated into the analysis, the absence of field-scale offshore wind demonstration projects in Greece—and more broadly in the Eastern Mediterranean —creates uncertainty regarding the real-world performance of floating wind technologies under local metocean conditions. The Eastern Mediterranean is characterised by steep bathymetry, high seasonal variability of winds, strong stratification, and increased environmental sensitivity, all of which require dedicated testing before large-scale deployment.

For this reason, future research should prioritise the development of offshore wind demonstration projects in carefully selected areas of Crete. Such pilot installations are essential to:

- empirically evaluate environmental impacts (particularly on migratory birds and sensitive marine megafauna),
- validate modelling assumptions related to noise, visibility, anchoring systems and wake effects,
- determine which turbine and platform configurations are best suited for the Mediterranean (e.g., medium-depth floating platforms,

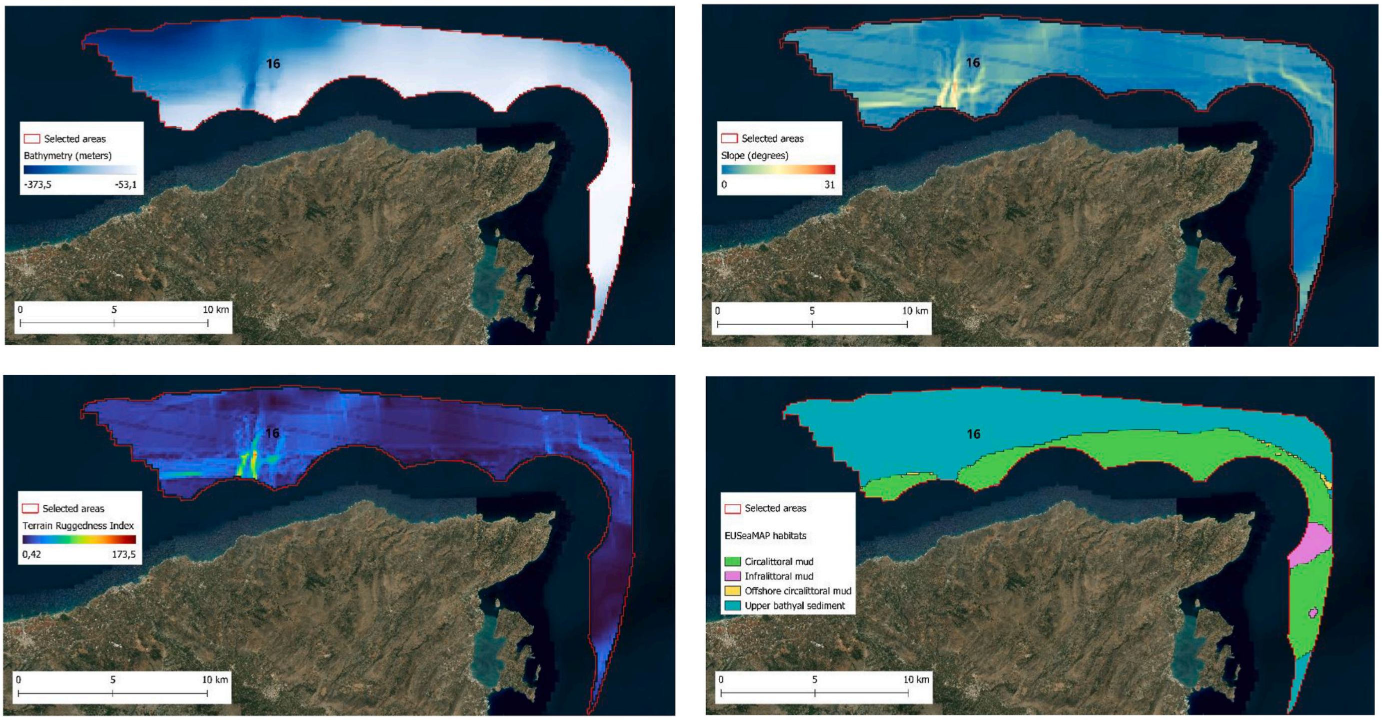

Fig. 12. Bathymetry, Slope, Seabed roughness (TRI) and Seabed type Area "Agios Nikolaos" (ID: 16).

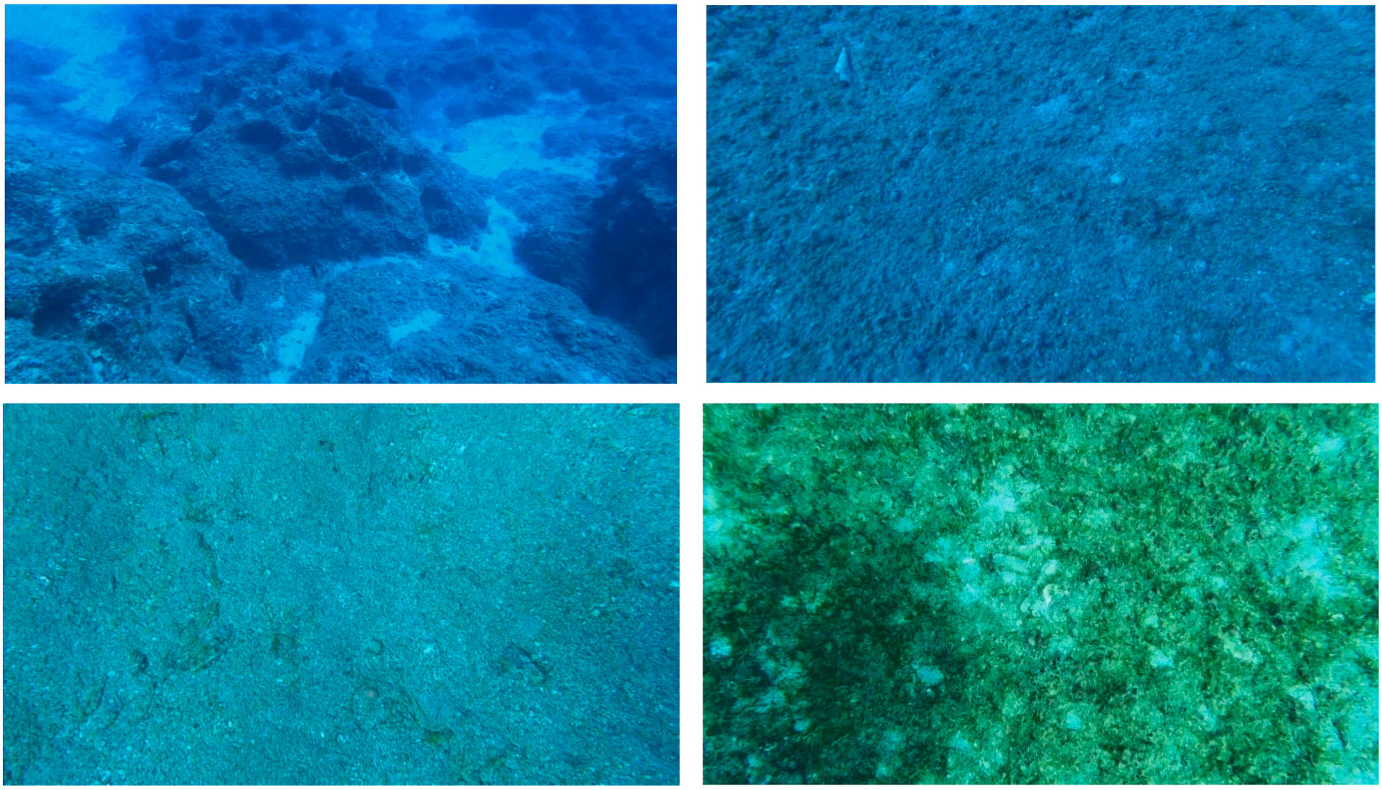

Fig. 13. Typical formations recorded at the "Agios Nikolaos" site (ID: 16).

reduced lighting systems to minimise bird attraction, adaptive shutdown protocols, and low-noise installation techniques),

- assess the socio-economic acceptance of offshore wind infrastructure through real operational experience.

Furthermore, future studies should expand high-resolution ROV surveys, long-term bird telemetry campaigns, and hydrodynamic–ecological modelling, in order to refine exclusion zones and site-selection criteria. A dynamic, adaptive spatial planning framework—incorporating real-time monitoring, cumulative impact assessments, and stakeholder co-design—will be crucial for ensuring that offshore wind development in Crete and generally in across the Mediterranean region remains both technically feasible and environmentally responsible.

Although the study includes preliminary references to turbine spacing and potential layout density to estimate theoretical capacity, it does not undertake detailed micro-siting optimisation. Instead, it demonstrates that large-scale GIS-based suitability assessments, particularly at national or continental scales, may overlook site-specific environmental and socio-cultural constraints that become evident during preliminary field-based validation.

The integration of targeted autopsies, visual simulations, and ecological overlays within this framework highlights the importance of bridging macro-scale spatial modelling with meso-scale contextual evaluation, without transitioning into project-level engineering design.

5. Conclusions

This study presented an integrated, multi-criteria spatial assessment for the sustainable siting of OWFs around the island of Crete, combining expert-derived weights, a GIS-based weighted overlay analysis, and an updated socio-environmental exclusion framework. Sixteen evaluation criteria were incorporated, reflecting environmental, technical, economic, and socio-political dimensions, each adapted to the unique geographic and ecological conditions of the Mediterranean island environment.

The final suitability map indicates that approximately 493 km^2 of marine areas were classified as moderately to highly suitable (scores 3–5). It is important to emphasise that this Fig. 3 represents spatial compatibility under the applied regulatory, environmental, and infrastructural criteria and should not be interpreted as directly developable capacity. Detailed engineering, geotechnical, financial, and grid-integration analyses would be required to determine practical feasibility and project-scale implementation.

The spatial distribution of higher suitability zones aligns with broader findings in the Hellenic Seas while refining results for Crete's specific physiographic and insular conditions. Several areas along the northern and eastern coasts emerged as comparatively favourable due to the coexistence of strong wind potential and relatively shorter distances to existing transmission infrastructure and coastal access points. However, no quantitative economic modelling (e.g., LCOE estimation, grid reinforcement cost analysis, or comparative investment scenarios) was conducted within the scope of this study. Therefore, references to potential cost advantages are limited to spatial-logistical proximity considerations rather than financial performance assessments.

Nevertheless, the analysis also demonstrates the importance of integrating ecological sensitivity into planning processes, particularly concerning migratory birds and species that rely on soaring–gliding flight. Overlaying suitability results with known migratory corridors, raptor flyways, seabird foraging radii, and critical coastal bottlenecks highlights specific zones where OWF development might pose collision or displacement risks. These findings emphasise the need to incorporate high-resolution ecological datasets into early-stage planning to prevent siting conflicts and ensure adherence to biodiversity protection goals.

Overall, the findings suggest that Crete has significant spatial potential for offshore wind development within a strategic planning framework, particularly given advancing floating wind technologies and ongoing grid interconnection projects. Nevertheless, the results should

Fig. 14. Ranking of available areas for OWFs siting - Equal weights.

be interpreted as a macro-to-meso scale planning tool rather than a direct development blueprint. The methodological framework developed in this paper provides a reproducible, evidence-based tool that can support national marine spatial planning, enhance transparency in stakeholder conversations, and help decision-makers promote environmentally sustainable and socially acceptable offshore wind deployment.

CRediT authorship contribution statement

P. Gkeka-Serpetsidaki: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **I.C. Dimitriou:** Software. **D. Poursanidis:** Software, Resources, Investigation, Formal analysis, Data curation. **S. Xirouchakis:** Software, Resources, Formal analysis, Data curation. **G. Skiniti:** Project administration, Data curation. **S. Tournaki:** Project administration. **T. Tsoutsos:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) for language editing and clarity improvement. After using this tool, the author(s) carefully reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

NONE.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2026.125649.

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