A HYBRID ALTERNATIVES ANALYSIS OF AN OFFSHORE WIND INSTALLATION IN THE MEDITERRANEAN SEA: HOW PIVOTAL ARE THE TECHNOLOGICAL ASPECTS?

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ABSTRACT

The European Commission, through the REPower EU plan, has set a target of 1,236 GW of renewable energy capacity by 2030. The achievement of this target represents an intermediate step towards the zero-emissions scenario by 2050, which requires an extensive deployment of renewable energy capacity that cannot borne exclusively by onshore technologies (e.g., photovoltaic, and onshore wind). Moreover, since the deployment of onshore traditional renewable energy technologies forces a high level of soil consumption, the spatial energy planning of remote and isolated energy systems is crucial, such as the islands of the Mediterranean Sea. The wide presence of protected environmental areas, i.e. Natura 2000 Network, and, cultural-heritage broad zones, reduce the availability of suitable areas to exploit renewable energy increasing the possibility of the birth of the Not in My Back Yard (NIMBY) phenomena. In light of this, despite the current high capital cost, offshore wind facilities play a leading role in the communities' decarbonization pathways as envisaged by the European Commission with the COM (2023) 668 "Delivering on the EU offshore renewable energy ambitions". Even though there will be an increase in the offshore wind's planned capacity in the Mediterranean Sea, a significant mistrust pertains to the small communities causing oppositional movements, mainly enforced by the possible environmental, cultural-heritage and, economic impacts related to the installations of offshore wind farms. An analysis of the technological and siting alternatives to and for an offshore wind farm on the island of Lampedusa, located in the Strait of Sicily, is provided, proposing a hybrid multi-criteria decision-making approach supported by a GIS tool. Adopting customised performance indicators, both technical and socio-environmental, we propose an analysis of suitable areas, in compliance with the in-force Italian regulatory framework, near the island of Lampedusa, and assess the extent to which the technical parameters are conducive to identifying the best trade-offs for offshore wind installation. Finally, we propose a methodological benchmark to support the installation of offshore energy projects in the small islands of the Mediterranean Sea. The study shows that different investigation perspectives give contradictory installation sites, highlighting that distance from the cost highly conflicts with the distribution of marine mammals taken into account in the investigation.

1 INTRODUCTION

The energy transition is the main goal to be pursued by the most industrialised and non-industrialised economies through a wide deployment of renewable energy technologies. However, although consolidated renewable technologies may in themselves be sufficient to achieve carbon neutrality, their use in contexts such as islands is difficult due to a restrictive regulatory framework and scarcity of available land, as investigated by Moscoloni et al., (2022) concerning the Mediterranean islands. In this framework, offshore renewable energy installations, such as offshore wind projects, will lead the energy transition. With the EU Offshore Renewable Energy Strategy (COM (2020)741), the European

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Community sets two main targets: 60 GW of Offshore Wind Capacity and 1 GW of Wave Energy. However, an incomplete and sometimes unfavourable regulatory framework still jeopardises the feasibility of prototypes and large-scale installations Moscoloni et al., (2023). However, the introduction of utility-scale offshore plants can be detrimental to the ecosystems that will host them.
Marine ecosystems are currently facing multiple stressors (e.g., elevated temperatures, salinity changes, organic pollution, and overfishing) caused by human activities together with global climate change (Hewitt et al., 2016; Halpern et al., 2019). For this reason, in the past years significant concerns have been raised within the scientific community regarding the installation of offshore wind farms (OWFs) in Europe (Inger et al., 2009; Degraer et al., 2013). The negative effects observed in North Sea ecosystems serve as a "cautionary tale" (Bailey et al., 2014; Lloret et al., 2023) to avoid adding stressors to the marine ecosystem with the exploitation of renewable offshore energies, usually perceived as "green", without the appropriate knowledge of its potential impacts on marine life (Abramic et al., 2022; Galparsoro et al., 2022).
Potential impacts of OWFs in the Mediterranean include increased noise levels, increased collision risks, alterations in benthic habitats, contamination risks, attraction of birds, and changes in water layer mixing (Bailey et al. 2014). The severity of these impacts varies depending on factors such as species or animal groups, seasons, and type of structure.
The Mediterranean Sea is renowned for its high biodiversity, with approximately 20-30% of species being endemic and boasting high diversity on a global scale (Coll et al., 2010; European Commission 2020). Recent studies have highlighted the Mediterranean as one of the fastest-warming oceans, attributed in part to its position and semi-enclosed nature (Vargas-Yanez et al., 2008; Ali et al., 2022). This accelerated warming further emphasizes the fragility of the Mediterranean marine ecosystems.
The establishment of protected marine areas under the Natura 2000 network is a crucial initiative by the EU to safeguard biodiversity (O'Learly et al., 2016). However, the construction proposed sites of new OWFs often overlap or are near areas of high biodiversity value (Lloret et al., 2023). There is an urgent need for comprehensive tools to accurately identify and quantify sources of impacts during Environmental Impact Assessments (EIA) to ensure the sustainability of OWF development in the Mediterranean Sea (Defingou et al., 2019; Abramic et al., 2022; Lloret et al., 2023). Effective monitoring and study are essential to mitigate potential negative impacts and promote the long-term health of marine ecosystems in the region.

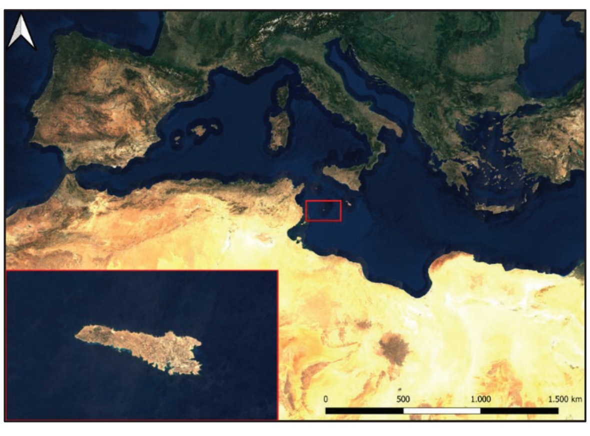

Figure 1: Area of interest

In such a complex environment, a multi-criteria approach that is able to weigh socio-environmental impacts while safeguarding the techno-economic viability of offshore installations can play a crucial role. However, many researchers include a mixed approach, based on the mixture of different performance indicators, in their siting analysis. For instance, Gkeka-Serpetsidaki and Tsoutsos, (2022) introduce the impacts on the heritages as decision criteria in the identification of optimal siting of offshore wind farms in the waters of Crete. Instead, Argin et al., (2019) propose a multicriteria method, for site selection, that includes only the mandatory constraints, both technological and environmental.

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The paper provides a multicriteria approach for the identification of suitable areas for the deployment of a floating offshore wind turbine in the area of Lampedusa Island, as shown in Figure 1, adopting a multicriteria method based on the Criteria Importance Trough Intercriteria Correlation (CRITIC) method proposed by Diakoulaki, Mavrotas and Papayannakis, (1995a) enhanced with extensive use of the QGIS environment and stressing the marine biosphere elements.

2 MATERIALS AND METHOD

This chapter is composed of two sections: A. Data collection and Key Performance Indicators, in other words, are the definition of all inputs needed, both from the socio-environmental point of view and the technological one, conducive to defining the effects of an OWF installation in a specific geographical area. B. Multicriteria Decision Method, by the application of the CRITIC method, the study assesses the influence of the socio-environmental parameters on the siting of an OWF supporting the Multicriteria Decision-Making Analysis.

2.1 Data Collection and Key Performance Indicators

The siting of an OWF interests various receptors, such as the marine biosphere, visual perception, the human activities (i.e. fisheries, ferry routes, etc.), that can be affected by the installation itself in different ways. At the same time, the techno-economic feasibility establishes minimum requirements in terms of Annual Energy Production (AEP), bathymetry, and grid connection submarine cable length. The following sections report the receptors identified and the technical parameters adopted by the study.
2.1.1 Socio-Ecological aspects: Initially, a literature review was conducted to identify the potential environmental impacts of OWFs in European waters. The aim was to identify pressures on marine ecosystems, with particular attention to vulnerable habitats and those of high ecological value within the study area, the waters off the coast of Lampedusa Island, which is part of the SCI (Site of Community Importance) "Pelagie Islands" (SIC ITA040014), an archipelago located in the heart of the Sicilian Channel, are recognized as a significant hotspot for Mediterranean biodiversity. Encompassing diverse habitats and marine species protected under the Habitat Directive, this area holds considerable ecological importance. All gathered information follows the GES (Good Envrionmental Status, MSFD) framework outlined in the Marine Strategy Framework Directive (2008/56/EC). This framework guided the identification of the most relevant ecosystem elements for assessing the potential impacts of wind energy devices on marine ecosystems. While the study approach aligns with a study by colleagues, Abramic et al. (2022), the focus was not to encompass all descriptors outlined in the Marine Strategy but rather to introduce and develop a new tool for facilitating decision-making processes regarding the development of offshore wind farms in Mediterranean areas, in line with the European plan for maintaining the good environmental status of marine environments, as advocated by Abramic et al. (2022). Therefore, the investigation focused on two main aspects deemed most susceptible to the installation of floating turbines in the study area: Biodiversity and Seafloor Integrity.
Numerous studies indicate that the installation of offshore wind farms can affect various species of marine animals, both negatively and positively, with the severity of impacts varying based on species' biology and conservation status. Marine mammals, reptiles, and birds are known to experience disturbance from the installation of OWFs Kraus et al., 2019). The development of OWFs can influence their behaviors such as migration and foraging activity, potentially leading to displacement and avoidance of the interested area (Welcker et al., 2017; Hemery et al., 2024).
Increased collision risks, directly caused by the turbines themselves (i,e., birds and bat collisions) and indirectly caused by the increase of vessel traffic (i.e., ship strikes large marine mammals), are also a concern (Desholm et al., 2005; Biehl et al., 2006). Moreover, underwater noise and electromagnetic field are also other aspects that should be considered during EIA of OWFs since they are known to be a potential source of disturbance for marine organisms (Tougaard et al., 2009; Mooney et al., 2020; Thomsen et al., 2021); for example, reptiles and some species of fish, especially elasmobranchs (i.e., sharks) are known to be sensitive to electromagnetic field and its changes (Tricas et al., 2011).
On the other hand, some positive impacts could be introduced by the development of OWFs, for example, the so-called "reef effect" could lead to the attraction of marine species to the area by improving the ecosystem complexity (Degraer et al., 2020).

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In light of what was said above, for OWF projects and site planning, Marine Protected Areas (MPA) should be considered as a priority for criteria of exclusion areas, in addition presence of important nursing, reproduction, and feeding sites for marine animals, migratory routes should be included in the analysis. For this reason, the study has included MPA "Isole Pelagie" area as an exclusion criterion in the index. Afterward, spatial data on the distribution of marine mammals, seabirds, and reptiles that inhabit the waters off the coast of Lampedusa have been consulted. Spatial data collected during "The ACCOBAMS Survey Initiative (ASI)" (ACCOBAMS Survey Initiative, 2018) were used to identify spatial concentration for the distribution of marine wildlife using a clustering approach. In addition, the study included data collected by Abaro-Morla et al., (2022), from loggerhead sea turtles (Caretta caretta) tagged in the Mediterranean Sea through telemetry technique.

Then, data on favorable habitats for fin whales (*Balaenoptera physalus*) in the Mediterranean Sea (Druon et al., 2012; 2019) have been considered. Lampedusa is one of the known foraging grounds of the Mediterranean Sea for fin whales, where they occur for feeding during March and April (Panigada et al., 2018). The study of Druon et al., (2019) modeled suitable feeding areas for the species based on ocean productivity features for each year from 1998 to 2018, the presence data have been used performing an average of the two most representative months. The higher habitat suitability for fin whales was considered negatively for the installation of the wind turbine.

Other spatial criteria to calculate the suitability areas for the construction of the wind turbine was the vicinity to AMP considered negatively, on the contrary vicinity to areas with high vessel density, obtained as the monthly mean presence for square kilometers according to the data available on EMODnet, was considered positively. Moreover, a buffer zone of about 200m from the ferry routes has been applied as a threshold, conversely, the closeness to the buffer limit has been considered beneficial.

Installation of offshore wind turbines modifies the structure of the seabed and its integrity, the degree of impact would vary with the dimension and type of fixation structure, with floating structures appearing to be the better solution for the Mediterranean Sea. However, the loss of seabed is expected with anchoring. For this reason, the selection of appropriate substrates is essential to minimize the effect and avoid irreversible negative impacts on vulnerable marine habitats and their benthic communities (Bray et al., 2016). As mentioned above, the foundations of wind turbines have the potential to create new habitats increasing benthic and pelagic communities if properly sited (Dregaer et al., 2020). Soft substrates, such as muddy and sandy seafloor are expected to have a positive effect due to the already mentioned reef effect, which basically would consist of the colonization and aggregation of species around the turbine foundation. On the contrary, hard substrates are the ones expected to be highly negatively impacted by the installation (Abramic et al., 2022). In addition, some types of benthic habitats are listed as vulnerable in the Habitat Directive (92/43/EEC) and construction in those areas should be strictly avoided to refrain from habitat loss and ecosystem degradation.

For this study, data from EMODnet on the Seabed classification (EUNIS 2007 habitat maps) and Seagrass cover were used to identify the proper siting. Areas covered by Posidonia meadows (*Posidonia oceanica*) were considered exclusion areas for construction as well as areas classified as "rocky bottom" were excluded. For instance, muddy seafloor was used as a good suitability index for the construction of the wind turbine.

Gkeka-Serpetsidaki, Papadopoulos, and Tsoutsos (2022) identify the visual impact as one of the most significant effects of the OWF on the local communities. Considering this, the current study adopts the visual impact as a performance indicator of the multicriteria analysis performing an intervisibility network analysis, within the QGIS environment, employing the plugin *Visibility Analysis*, where the visibility impact is expressed using a line-of-sight relationship between an observer, posed on the digital surface model of the Island of Lampedusa, and a target, represented by the single wind turbine. Each target can affect multiple observers; moreover, a higher value of intervisibility is intended as a detrimental effect.

The introduction of an offshore project in a specific zone requires considering, in addition to the biosphere impacts and the local community influence, the socio-political dynamics that interest the area itself. According to the European Border and Coast Guard Agency, FRONTEX, the Sicily Channel is the core of the Central Mediterranean migrants' route, which has its epicenter on the island of Lampedusa. Per personal confidential communications, localizing an offshore wind farm in the southern area of Lampedusa could act as a hotspot for the migration routes resulting in navigation and search

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and rescue safety problems. In light of this, the southern area of Lampedusa has been excluded from the investigation. Moreover, according to Minigozzi et al., (2007), the southern area of Lampedusa is well known for nesting areas of loggerhead sea turtles, hence offshore areas near sandy beaches were considered excluded for the installation of OWFs.

2.1.2 Technological parameters and exclusion criteria: the amount of energy produced by an offshore wind turbine represents a pivotal parameter in the wind farms' siting problem. For instance, Vinhoza and Schaeffer, (2021) assume the wind speed, directly related to the annual energy production (AEP), as a key parameter in their investigation. At the same time, Mahdy and Bahaj, (2018) adopt a specific level of productivity and power density as a mandatory threshold in the identification of the most suitable area for an OWF in Egypt. To assess the wind resource, the AEP has been estimated through the software WAsP, released by the DTU, simulating an OWT (Offshore Wind Turbine), characterized by a hub height of 100mt and a rated power of 2.5 MWp, located in the surrounding sea of Lampedusa Island.

The installation of offshore technologies, from a broad perspective, is highly influenced by bathymetry Pérez-Collazo, Greaves, and Iglesias, (2015). The exploitation of the bottom-fixed substructures, in the Mediterranean basin, could regard only those areas that are not so far from the coast, due to technical limitations. Contra, the floating substructure can allow it to move away from the coastline by widening the available sea areas. Moreover, the bathymetry implies the mooring length, which represents one of the most expensive voices in offshore technology's CAPEX (CAPital EXpenditure), as reported by Giglio et al., (2023). This study adopts bathymetry, obtained by the EMODnet service, both as a technological threshold, restricting the allowed bathymetry between -50m and -100m, both as technology parameters, where the positive ideal solution (PIS) is the minimum of the function. Moreover, once again Giglio et al., (2023) identify the grid connection submarine cable length as a weighty parameter in the estimation of the CAPEX for the offshore installation. Due to this, the study adopts the distance from the coastline as a representation of the cable length intending that a greater distance from the coastline results in a higher cost for the cable. For this reason, the analysis assumes that a closeness with the island would be beneficial. Alongside the bathymetry, the seabed slope, calculated within the QGIS environment, has been adopted as a feasibility constraint intending no suitable areas exceeding the 30°of slope.

Table 1 shows the key performance indicators adopted and discussed previously reporting the positive ideal solution (PIS), the negative ideal solution (NIS), i.e., respectively the best and the worst solution concerning the specific parameter, and the related threshold, when applicable.

Table 1: Key Performance Indicators

KPI	PIS	NIS	Threshold
AEP [GWh/year]	max	min	-
Intervisibility [-]	min	max	-
Bathymetry [m]	min	max	**-100 m ≤ x ≤ -50m**
Distance from coastline [m]	min	max	-
Distance from MPA [m]	max	min	-
Distance from ferry routes [m]	min	max	**≥ 200 m**
Fin whales' distribution [% of presence]	min	max	-
ACCOBAMS Survey [-]	min	max	-
Vessel density [hour/month/km^2]	max	min	**≥ 30 hour/km^2/month**

2.2 Multicriteria Decision-Making Analysis Method (MCDM)

The calculation of objective weights and the relative scores, the pivot of the proposed multicriteria method, as outlined in the CRITIC method, involves defining a multicriteria problem consisting of A alternatives assessed across m evaluation criteria. The relative score matrix x_j, which gauges the performance of each alternative across each criterion, is constructed using a mapping function x_{aj} that represents the normalized distance from the ideal solution. The introduction of the parameter Cj characterizes the contrast and conflict associated with each decision criterion. As suggested by

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Diakoulaki, Mavrotas and Papayannakis, (1995b) and Mukhametzyanov, (2021) C_j quantifies the information conveyed by the MCDM problem regarding a single evaluation criterion. This parameter is calculated using the formula:

$$C_j = \sigma_j \sum_{k=1}^{m} (1 - r_{jk}) \tag{1}$$

Where σ_j denotes a divergence index of the scores, and r_{jk} represents the correlation term. Normalizing Equation (1) yields the objective weights, denoted as w_j. Defining the objective weights allows to set a scoring equation up, as shown in the following Equation (2):

$$D_i = \sum_{j=1}^{m} w_j * x_{ij} \tag{2}$$

RESULTS AND DISCUSSION

By applying the thresholds reported in Table 1 to the area of interest represented by the red square in Figure 2 and with an extension of about 4400 km^2, the suitable area for the offshore wind installation in the investigated area is obtained and shown in Figure 2; moreover, a resolution of 200m x 200m has been adopted, which can represent properly the mooring footprint of the floating structure. Depending on the application of the MCDM method presented previously, two scenarios have been investigated to highlight how the socio-environmental parameters shift the most suitable areas for the floating offshore wind turbine installation.

Table 2: Best Sites - Key Performance Indicators

KPI	Technological Scenario	Socio-Environmental Scenario
AEP [GWh/year]	7.5	7.4
Intervisibility [%]	[-]	1.06
Bathymetry [m]	-56	-66
Distance from coastline [km]	12	6.8
Distance from MPA [km]	[-]	0.2
Distance from ferry routes [km]	[-]	7
Fin whales' [% of presence]	[-]	~0
ACCOBAMS Survey [-]	[-]	0.35
Vessel density [hour/month/km^2]	[-]	0.94
MCDM Score	**0.84**	**0.74**

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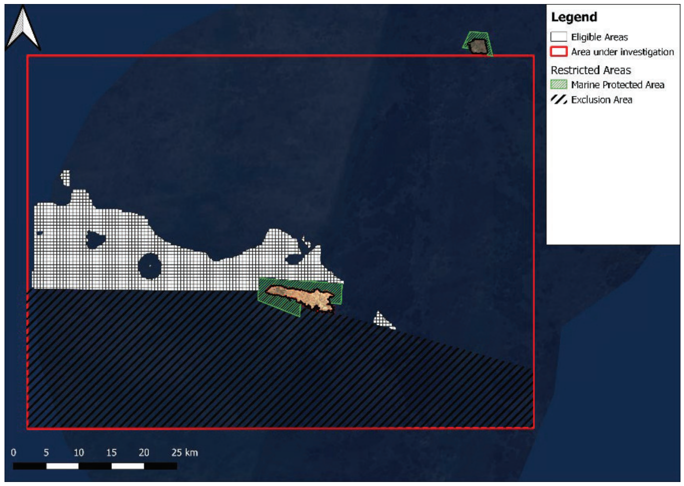

Figure 2: Eligible Areas

As shown in Figure 3, the objective weights obtained by means of Equation (2) report how in the Technological Scenario (i.e., Scenario 1), which includes only the technical parameters, the coastline distance plays a pivotal role. It depends on the extension of the suitable area, to which corresponds a high variation of the distances between the specific location and the coast. Contra, the weights of the Socio-environmental Scenario (i.e., Scenario 2) rescale the technological parameters in favor of the fin whales' distribution and intervisibility criteria.

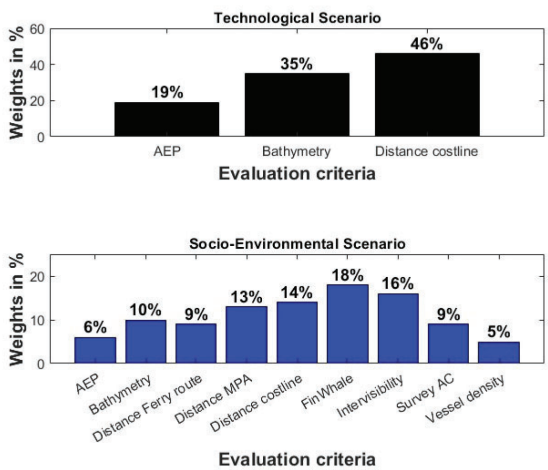

Figure 3: Weights Comparison - Multicriteria Analysis Results

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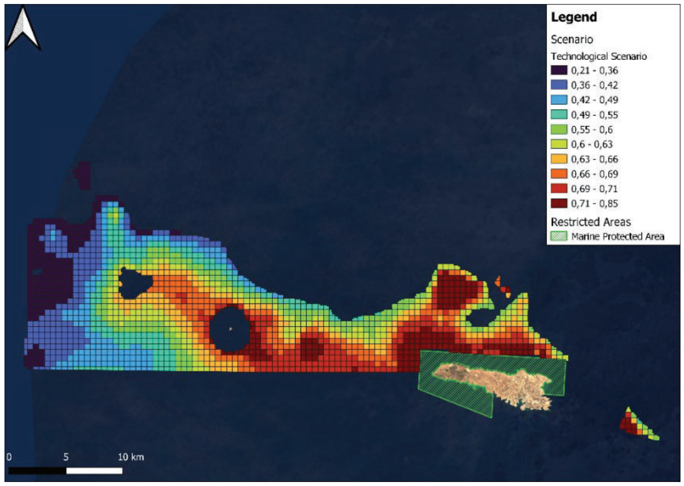

Figure 4: Technological Scenario - Multicriteria Analysis Results

The application of the objective weights reported in Figure 3 to the area of interest shows how the Technological Scenario, represented in Figure 4, rewards a higher score in the surrounding area of Lampedusa Island, especially the northern area and the northwest one. It depends mainly on the distribution of the bathymetry, which is lower near the island, and due to the minimization of the distance from the coastline. The AEP appears not to play an impactful role, as testified by the lesser magnitude of the respective weight.
Conversely, the situation exposed by the Socio-environmental Scenario, shown in Figure 5, depicts a less homogeneous distribution of the higher scores.

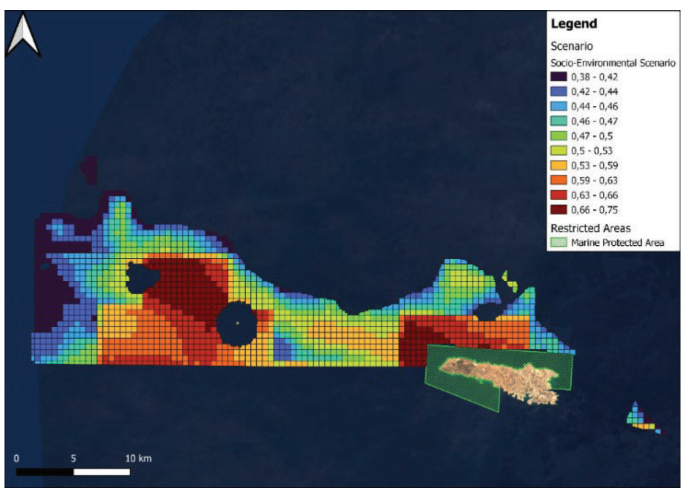

Figure 5: Socio-Environmental Scenario - Multicriteria Analysis Results

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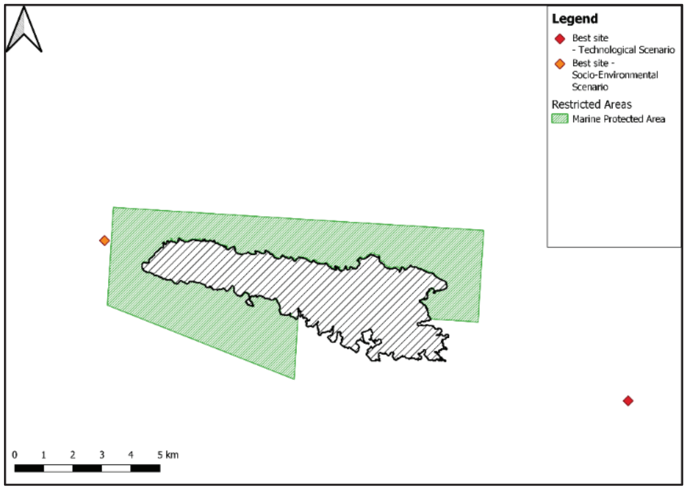

Figure 6: Scenario Comparison - Multicriteria Analysis Results

CONCLUSION

This study provides evidence that OWF developments in the Mediterranean Sea frequently coincide with areas of significant conservation value, particularly those designated under the Natura 2000 network. Consequently, this raises a critical need to establish comprehensive and customizable tools for pinpointing suitable locations for wind turbine installation.

In this regard, it is highly recommended to establish buffer zones around ecological corridors and protected areas to safeguard against potential adverse impacts. Additionally, careful consideration must be given to siting decisions to preclude any irreversible negative effects on vital habitats, such as Posidonia meadows. As underlined by previous researchers, it is highly recommended that a case-by-case analysis approach be adopted, taking into account the specific ecological characteristics of each site (Lloret et al., 2023; Bailey et al., 2016; Abramic et al., 2022). In essence, the development of such tailored tools for site selection processes is imperative to ensure the compatibility of OWF projects with conservation objectives and to mitigate potential ecological impacts in the Mediterranean Sea region.

In addition, it is important to note that collecting data on the marine environment is a costly endeavor, and the Mediterranean Sea currently lacks baseline data essential for conducting comprehensive impact assessments concerning the installation of OWFs (Defingou et al., 2019; Lloret et al., 2023). Consequently, the findings of this study regarding the best-case scenario for environmental considerations must be carefully considered. Although some information regarding species potentially affected by wind turbine construction in the study area was available, spatial data on species abundance, movement patterns, and habitat utilization were either absent or incomplete. For instance, information regarding the presence of the Sandbark shark (*Carcharhinus plumbeus*) around Lampione Island was found (Cattano et al., 2022), the distribution of this species, classified as Vulnerable according to the IUCN Red List, should be considered in the current study due to potential negative impacts of electromagnetic fields produced by OWF on sharks. However, the lack of spatial information precluded the inclusion of this data. As well as numerous species that have been reported to inhabit the study area, their spatial data remains deficient.

Nevertheless, employing data derived from niche models or habitat models, as was done for the fin whale in the study, could serve as a feasible solution for accurately identifying areas of high productivity and hotspots of food sources across different trophic levels. While the use of fin whale habitat models in the investigation provides insights into potential areas favorable for other species with similar dietary preferences, it is important to note that the scale of these models is relatively broad. Therefore, for the specific task of identifying suitable sites for OWF installation, finer-scale models are necessary.

Furthermore, when assigning weights to environmental indices, careful consideration should be given to the biological traits of the impacted area, including the types of habitats and species present, as well

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as their conservation statuses. Additionally, the degree of impact on each species involved should be taken into account to ensure a thorough assessment of the environmental implications of OWF installation.

Furthermore, adopting the GES framework proposed by Abramic et al. (2022) offers a promising approach to improving EIAs and aligning them with the standards set by environmental protection authorities. By employing this framework, stakeholders can collaborate effectively with environmental authorities, facilitating the collection of new data on installation sites based on GES criteria. This enhanced data collection process can improve GES assessments, enabling better analysis of future scenarios in light of the blue growth strategy and the climate change challenge. Consequently, this collaboration can further promote the implementation of the Marine Strategy Framework Directive (MSFD), a crucial legal instrument for preserving marine habitat ecosystems. In conclusion, the analysis underscores the importance of carefully considering the results obtained and emphasizes the necessity for ongoing observation to enhance the model's autonomy in decision-making processes.

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