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Research Paper

Evaluation of offshore wind energy zones within marine spatial planning: A case study in the Spanish Mediterranean Sea

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ABSTRACT

Offshore renewable energy is gaining attention as a vital component in the battle against climate change. This emerging use of the marine environment is poised for rapid growth, presenting new challenges for ocean management. As a result, marine spatial planning is being developed to designate potential zones for this use, however, these processes often lack important considerations for adequate decision-making. This work evaluates high-potential zones for offshore wind energy within marine spatial planning. This approach is illustrated through a case study in the Spanish territorial waters in the Mediterranean. This work considers port facilities, water depth, availability factor of wind turbines, estimated energy production and, last but not least, the impact of the wave climate on maintenance scheduling. In selecting port facilities, the decision between prioritising proximity or well-equipped infrastructure is crucial – particularly in the Levantine-Balearic subdivision. Water depth, which influences the foundation costs, presents a considerable range across the high-potential zones (100–1000 m), potentially decisive for offshore wind siting. Distinctive wave climates occur in the zones within the enclosed Alboran Sea, leading to a higher number of available windows for essential maintenance operations (~85% of the total). Finally, whereas the availability factor of wind turbines remains consistent across the high-potential zones (~75%), regions closer to the Gulf of Lyon exhibit substantially greater estimated energy production – up to 1.24 times the energy produced in other zones. Given that energy generation is the paramount objective of offshore wind farms, this aspect has the potential to make a difference. This analysis aims to identify the most favourable locations for advancing offshore wind initiatives in the Spanish territorial waters in the Mediterranean, offering valuable insight to support informed decision-making processes in marine spatial planning.

1. Introduction

Wind energy is poised to play a pivotal role in the fight against climate change. With approximately 70% of greenhouse gas emissions linked to energy production and consumption (European Commission, 2019), the urgent need to decarbonise the energy sector (Astiaso Garcia et al., 2023) has become a global priority (Aszódi et al., 2021). Consequently, there has been a notable increase in worldwide wind energy installations. However, challenges such as limited available land in developed countries, concerns about noise pollution and visual impacts have impeded further onshore wind development. This has spurred the industry to shift its focus towards harnessing offshore wind resources, with wind turbines mounted on bottom-fixed structures (monopiles (Negro et al., 2017; Perez-Collazo et al., 2019) and jackets (Bao et al., 2023; Perez-Collazo et al., 2018)) or floating platforms (semi-submersible (Lopez-Pavon and Souto-Iglesias, 2015), spar-buoy (Tomasicchio et al., 2020) and tension-legged (Sclavounos et al., 2010)). Offshore regions offer more consistent and abundant wind resources, along with fewer constraints in turbine sizing and reduced environmental constraints. Offshore renewable energy technologies also represent a valuable opportunity for achieving energy self-sufficiency in small- (Ramos and Iglesias, 2014) to medium-sized islands, e.g., in the Mediterranean (Onea and Rusu, 2022) or Australasia (Fournier et al., 2023) – studies have been widely conducted for wind, e.g., Fuerteventura (Veigas and Iglesias, 2014), Naxos (Fyrippis et al., 2010), Tenerife (Veigas and Iglesias, 2013), and wave energy (Veigas et al., 2014).

Offshore renewable energies lend themselves to co-location, i.e., to

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Nomenclature

ECMWF	European Centre for Medium-Range Weather Forecast
EEZ	Exclusive Economic Zone
LCOE	Levelised Cost of electricity
MSP	Marine Spatial Plan
O&M	Operation and maintenance
POEMs	Planes de Ordenación del Espacio Marítimo (Maritime Space Management Plans)
PV	Photovoltaic
WPS	World Port Source

the deployment of technologies exploiting different resources (wind, waves, solar radiation, tides) in the same area. This approach has many benefits, not least an improved utilisation of the marine space and the realisation of several key synergies (Veigas and Iglesias, 2015) such as shared submarine export cables, shared substations, and shared crews and vessels for operation and maintenance (O&M) tasks (S Astariz et al., 2015a; Astariz and Iglesias, 2015). Importantly, co-located renewable energy farms may contribute to reducing the variability of the power output and the system integration costs (S. Astariz et al., 2015), to maximising the power output (Rusu, 2023) and the compatibility with other uses, such as fisheries (Fayram and De Risi, 2007). A number of innovative technical solutions have been proposed for co-located farms, including, in respect of wind-wave systems (Pérez and Iglesias, 2012), solutions for monopiles (Perez-Collazo et al., 2019), jackets (Perez-Collazo et al., 2018) and novel WECs for co-location (Ramos et al., 2022). In addition, the understanding of hybrid systems has advanced regarding power extraction (Michele et al., 2019) or the viability of co-location itself. In this respect, the co-location feasibility (CLF) index (Astariz and Iglesias, 2016a, 2017) is a useful tool to rank and select areas for co-located wind and wave energy, which has been applied successfully to the North Sea (Astariz and Iglesias, 2016b). The optimum layout of co-located wind-wave farms has also been investigated (Astariz et al., 2016), including uniformly-distributed (Astariz and Iglesias, 2016c) and non-uniformly-distributed (Astariz and Iglesias, 2015) arrays. Solutions have also been proposed for co-located wind-solar farms (López et al., 2020). The combination of wind and tidal energy has been studied in different regions, including Scotland (Coles et al., 2021) and New Zealand (Majdi Nasab et al., 2020). Wave and tidal energy have been investigated in, e.g., Iran (Khojasteh et al., 2018). Finally, the combination of the three main offshore renewable energies, offshore wind, wave and tidal, has been investigated from the standpoint of both the energy production (Li et al., 2018) and the levelized cost of energy (S Astariz et al., 2015b). Given their potential, further work regarding co-location or hybrid options combining different offshore renewables is warranted.

The number of offshore wind installations is on the rise. In 2022 alone, the global capacity saw an increase of 8.8 GW (2.46 GW in Europe), leading to a total of 64.3 GW (Global Wind Energy Council, 2023). In Europe, most offshore wind installations consist of turbines mounted on bottom-fixed structures in shallow areas of the North Sea (Martinez et al., 2023). In Spain, despite its significant potential for wind and wave energy (Veigas et al., 2015), the challenging scarcity of low-depth areas has hindered the implementation of marine renewable energies (Esteban et al., 2019). Nonetheless, the Spanish government has committed to expanding the share of renewable energy in its electricity production to 74% by 2030 and achieving complete energy production from renewables by 2050, a substantial increase from the current 40% (2021). In this context, the development of floating technologies offers a promising pathway to realising these ambitious goals (Díaz and Guedes Soares, 2020). In its favour, Spain possesses a strong onshore wind capacity and a robust naval and civil engineering industry (Varela-Vázquez and Sánchez-Carreira, 2017), providing a solid foundation for offshore energy development (Colmenar-Santos et al., 2016). This, in turn, could foster the growth of local stakeholders and reduce the cost of electricity at a regional level (Roldan-Fernandez et al., 2021).

Extensive efforts have been directed towards assessing Spain's offshore energy potential, particularly in Galicia (Castro-Santos and Diaz-Casas, 2014), Asturias (Abanades et al., 2018; López et al., 2018), the Canary Islands (Díaz and Soares, 2021; Schallenberg-Rodríguez and García Montesdeoca, 2018), and through combined wind-solar PV (photovoltaic) in the Iberian Peninsula (Costoya et al., 2022). From an economic point of view (Filgueira-Vizoso et al., 2023; Sim, 2023), the levelised cost of energy (LCOE) analysis suggests that the most suitable areas for offshore wind development lie along the Atlantic coast of Galicia in north-western Spain (Castro-Santos et al., 2020a). However, the selection of viable offshore wind areas requires the consideration of numerous factors (Díaz and Soares, 2021), posing challenges for ocean management (Zhou et al., 2022). It is crucial to address potential environmental impacts (Galparsoro et al., 2022) from a life cycle perspective (Colaleo et al., 2022), such as effects on marine biodiversity (Rodríguez-Rodríguez et al., 2016) or coastal processes (Esteban et al., 2011), as well as potential conflicts with existing human activities at sea (Salvador et al., 2018a). A well-defined regulatory framework (Salvador et al., 2018b) and marine spatial planning (MSP) (Azzellino et al., 2019) from the government are essential to guide and promote the growth of offshore wind within a country.

Recently, the Spanish government made public the Maritime Space Management Plans (*Planes de Ordenacion del Espacio Maritimo* or *POEMs*) to establish a comprehensive regulatory framework for managing and utilising the country's marine waters (Ministerio de Transicion ecologica y el reto demografico, Spanish government, 2023). The *POEMs* emphasise the significance of developing marine renewable energies, with offshore occupying a prominent position among the topics covered. For the first time, the *POEMs* include a zoning regulation that designates specific areas suitable for offshore wind development (Ramos et al., 2021). Following a thorough assessment of marine activities and environmental impacts (Bush and Hoagland, 2016), areas labelled as "high-potential zones for offshore wind" have been identified for future offshore wind projects.

However, the criteria used to determine these high-potential zones for offshore wind are not sufficient for selecting final sites for offshore wind farms (Díaz and Soares, 2020). These zones in the *POEMs* are determined through a careful evaluation of factors such as biodiversity impact, protected areas and various maritime activities, including fishing efforts and shipping routes (Taoufik and Fekri, 2021). However, the same *POEMs* acknowledge the shortcomings of the zoning process and the need to reduce uncertainties in wind resources assessment – especially important given the anticipated changes in wind resources as a result of climate change (Martinez and Iglesias, 2023a). Importantly (Nezhad et al., 2022b), a deep understanding of offshore wind resources is key to selecting areas for future offshore wind development, along with an estimation of the energy production (Kokkos et al., 2021). Indeed, various techno-economic considerations will play a pivotal role in the decision-making process for selecting future offshore wind development areas (Marin et al., 2022), and thus the motivation of this work.

This work delves into and compares the areas identified as high-potential zones for the development of offshore wind in the Spanish territorial waters in the Mediterranean (hereinafter, the Spanish Mediterranean). Being the largest in size and with significant wind resources, the ambitious goals of the Spanish government would imply the installation of several wind farms in the Mediterranean waters – this development would be particularly beneficial for the Balearic Islands, included in this region. This analysis is made on the basis of various elements that will be pivotal to selecting the most suitable areas for offshore wind, thus complementing the Maritime Space Management Plans made by the Spanish Government. These elements include a study of the potential ports to service the wind farms (including the distance to the sites), water depth, wind resources availability, estimated energy production and wave climate for available maintenance windows.

In this manner, this work utilises a new approach in the context of the existing marine spatial planning (Azzellino et al., 2013) for the optimal placement of high-potential zones. Through the evaluation and comparison of the different techno-economic aspects, this study provides useful insights into the strengths and weaknesses of each of the high-potential zones, enabling well-informed decisions.

2. Materials and methods

The *POEMs* separate the Spanish territorial waters into five marine subdivisions: Canaries, Levantine-Balearic, Strait and Alboran, South Atlantic and North Atlantic marine subdivisions. The focus of this study is on the Levantine-Balearic and the Strait and Alboran marine subdivisions, which together constitute the Spanish Mediterranean (Fig. 1).

The Levantine-Balearic marine subdivision spans from the Gulf of Lyon to the North, characterised by its strong wind resources, and the Algerian Basin to the South. It extends from the eastern coast of mainland Spain to the Balearic Islands, encompassing the Balearic Sea and, thus, the biggest of its kind in Spain.

The Strait and Alboran marine subdivision encompasses the unique waters of the Spanish Mediterranean situated south of the Cape of Gata and the Strait of Gibraltar. This region holds distinctive characteristics as it acts as a natural link between the Atlantic Ocean and the Mediterranean Sea, bridging the European and African continents. This geographical significance establishes it as a vital migration route for numerous bird and marine species, as well as a crucial maritime path for ships travelling between the Atlantic and Mediterranean.

The *POEMs* identify the high-potential areas for offshore wind with the following criteria. Firstly, the potential impacts that offshore wind installations may have on biodiversity and marine habitats are accounted for (Lloret et al., 2022). Areas of high ecological value, warranting protection, are excluded from consideration. Secondly, the interactions between the offshore wind farm and the various human activities occurring at the sea are considered. These activities encompass air navigation, military exercises and marine traffic.

Based on these criteria, the *POEMs* designate five high-potential areas for offshore wind. Among these, three areas are located in the Levantine-Balearic marine subdivision, i.e., LEBA 1, LEBA 2 and LEBA 3; while the remaining are situated in the Strait and Alboran subdivision, i.e., ESAL 1 and ESAL 2 (Fig. 1). However, various techno-economic considerations must be taken into account when selecting areas for developing floating offshore wind (He et al., 2022). In the following, an in-depth exploration and comparison of these high-potential zones are undertaken, assessing various aspects.

2.1. Ports

An essential factor requiring consideration is the presence of sufficient port infrastructure capable of accommodating the demands of the offshore wind farm. The successful establishment and ongoing operation of an offshore wind farm hinge on the availability of appropriate port facilities, enabling the installation phase and subsequent operation and maintenance (O&M) activities. The distance to these facilities affects the costs of installation and accessibility of the wind farm for maintenance operations significantly.

The specific requirements of port infrastructure vary based on the technology employed by the wind farm. Given the absence of shallow-depth zones in the designated study area, floating offshore wind solutions are likely the most viable option. Within the realm of floating technologies, the constraints posed by draught requirements for spar-buoy concepts and the foundation needs of the tension-legged designs point to the semi-submersible option as the most advantageous (Castro-Santos et al., 2016). Notably, semi-submersibles impose fewer constraints in terms of draught, given the capacity for assembly within the port and subsequent transportation in barge vessels or tugged to the site. Hence, requirements on port draught for semi-submersible platforms are expected to fall within the 3–8.9 m range (Castro-Santos et al., 2020b).

Furthermore, port facilities must offer ample space to accommodate essential operations and component marshalling, which may include the operation or even the installation of cranes (if needed). Estimating the precise space required is challenging, given the absence of real-life floating offshore wind farms to reference. However, estimations indicate that 13,000 m^2 of minimum available space may be needed (Martinez and Iglesias, 2022a). Notwithstanding, recognising that significant modifications will be necessary to adapt port infrastructures to servicing the wind far, ports that possess potential available space will be considered.

The selection of suitable ports to service the wind farm is made from a list of 91 ports located in the Spanish Mediterranean and South

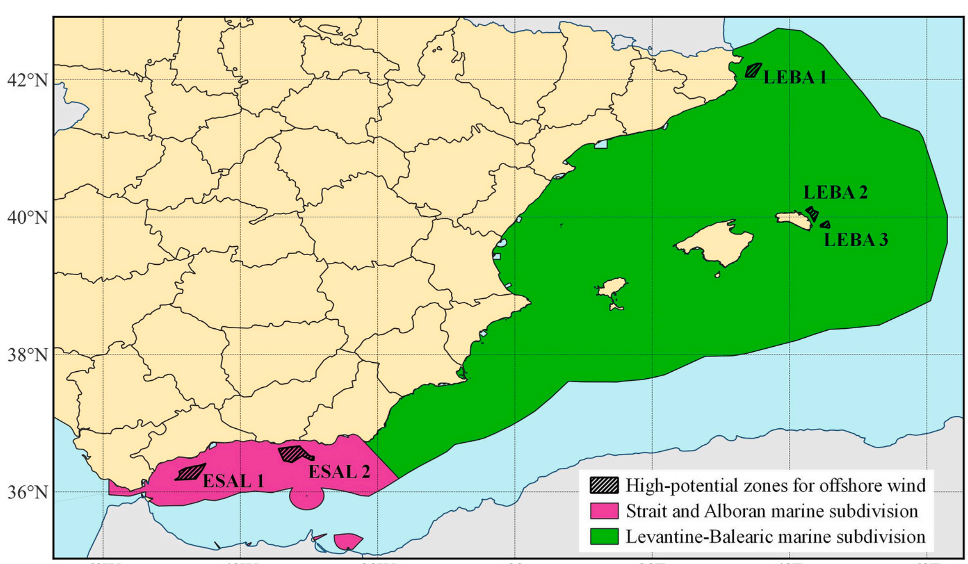

Fig. 1. Strait and Alboran and Levantine-Balearic marine subdivisions. “High-potential zones for offshore wind”, as established in the POEMs (“Visor Informacion Geografica Marina - MITECO, CEDEX,” n.d.).

Atlantic regions, with data from the World Port Source (WPS) (WPS, 2023), WikiWand (Wikiwand, 2023), Searates (SeaRates, 2023) and Ports of the State (*Puertos del Estado*) (Puertos del Estado, 2023) (Table 1). The compilation of the ports encompasses ports identified as being of general interest to the State and those labelled as small or bigger. Draughts in ports are sourced from nautical charts.

2.2. Water depth

Water depth presents a significant constraint for offshore wind installations. For instance, bottom-fixed structures can only be deployed in water depths no deeper than 70 m (Jiang, 2021) – an important limitation in Spain due to the scarcity of shallow-water areas (Colmenar-Santos et al., 2016). Hence, despite the increasing installation of bottom-fixed wind turbines in other nations (Global Wind Energy Council, 2023), this technology remains unutilised in Spain (Ministerio de Transicion ecologica y el reto demografico, Spanish government, 2023). In contrast, in scenarios involving semi-submersible concepts, the applicable range typically spans from 20 to 1000 m (Maness et al., 2017).

Furthermore, water depth plays a pivotal role in cost considerations, impacting the expenses linked to the foundations of wind devices (Castro-Santos, 2016). In instances of semi-submersible platforms, the water depth directly influences the required length of the mooring lines.

The determination of water depth within the high-potential zones is derived from bathymetry data sourced from the NOAA's ETOPO Global Relief Model, with one arc-minute spatial resolution (NOAA National Centers for Environmental Information, 2022).

2.3. Wind resource and energy production

Evaluating the viability of offshore wind farms relies on the interplay between the available wind resources and the ability to harness them, constituting a pivotal techno-economic determinant (Diaconita et al., 2022). The adequate assessment of the offshore wind climate is a key factor to developing new wind farms at the sea (Nezhad et al., 2021). The *raison d'être* of an offshore wind farm is energy generation, making it the cornerstone of economic feasibility (Castro-Santos and Diaz-Casas, 2015).

The *POEMs* consider average wind conditions for an initial evaluation of the high-potential zones. However, the same *POEMs* acknowledge the limitations of this approach, as mean conditions do not relate linearly with energy production. The efficiency of the turbine to capture wind resources over its lifetime will ultimately determine the amount of energy produced, underscoring the need for precise energy production estimations.

This work accurately estimates the energy output of a wind turbine at each high-potential zone by combining hindcast data with the power profile of a wind turbine. Data on wind speed at a 100 m altitude are sourced from the ERA-5 reanalysis database (Hersbach and Dee, 2016), developed by the European Centre for Medium-Range Weather Forecast (ECMWF), at each high-potential zone. The data employed have a temporal resolution of one hour and spans from 2000 to 2019 (20 years' worth of data, the approximate lifespan of the wind turbine) and a spatial resolution of $0.25^\circ \times 0.25^\circ$ in latitude and longitude. Data on the eastward and northward components of the wind are employed to calculate the horizontal wind speed at a height of 100 m. The ERA-5 dataset is one of the most recognised datasets, which has been reported to reproduce the wind speed spectrum at a high accuracy for any location in Europe (Molina et al., 2021), including the region of study. Regarding the turbine, the DTU 10-MW wind turbine's power curve, characterised by a cut-in 4 ms^{-1}, rated power at 11.4 ms^{-1}, and cut-out at 25 ms^{-1}, is employed (Bak et al., 2013).

Hence, the estimated energy production (E) is computed as

$$E = \int_{t1}^{t2} \eta P(u) dt \tag{1}$$

where E is the estimated energy output and $P(u)$ is the power curve of the wind turbine, which is a function of the wind speed u. The parameters $t1$ and $t2$ indicate the time interval (in this case, the twenty years spanning from 2000 to 2019).

The combination of the power profile curve of the wind turbine and wind data yields an estimate of the extracted energy. Notably, energy losses linked to turbine availability due to maintenance, electrical losses or wake-induced aerodynamical effects are omitted from consideration (Martinez and Iglesias, 2022b). These losses are assumed to be comparable across the zones, rendering them inconsequential for interzone comparisons.

Finally, the variability of wind resources significantly impacts project financing, as stability in revenue is a priority for investors. An important metric in this regard is the availability factor, defined as the ratio between the amount of time the power plant can generate electricity to the total time in the period considered. Here, the availability factor is calculated in terms of the wind resource by measuring the stoppages of the turbine due to wind speeds exceeding operational limits (under cut-in or surpassing the cut-off). Factors that may affect the availability factor, such as maintenance-related downtime, are assumed to be uniform across zones and therefore lack comparative value.

Table 1
Preliminary list of ports considered for servicing a wind famr in the Strait and Alboran and Levantine-Balearic marine subdivisions. Ports designated as of general interest to the State (left column) and other ports.

General Interest	Other ports		
Barcelona	La Selva (Marina)	Alcanar	Bonanza
Tarragona	La Selva	Vinaros	Fornells
Castellon	Roses	Benicarlo	Addaia (Marina)
Sagunto	L'Escala	Las Fuentes	Cala en Bosc
Valencia	L'Estartit	Oropesa del Mar	Pollenca
Gandia	Palamos (Marina)	Burriana	Soller
Alicante	Palamos	Canet Siles (Marina)	Andratx
Cartagena	Sant Feliu de Guixols	Denia	Adriano
Carboneras	Blanes	Javea	Portitxol (Marina)
Almería	Arenys de Mar	Moraira	Cala Gamba (Marina)
Motril	Balis	Calp	Ca'n Pastilla
Málaga	Masnou	Altea	S'Arenal
Algeciras Bay	Forum (Barcelona)	Santa Pola	Estanyol de Migjorn
Tarifa	Olimpic (Barcelona)	Torrevieja	Sa Rapita
Cadiz Bay	Ginesta	Escombreras	Colonia de Sant Jordi
Sevilla	Vilanova i la Geltru	Aguilas	Cala Figuera
Huelva	Segur-Calafell	Almerimar	Petro
Mahon	Torredembarra	Adra	Cala d'Or (Marina)
Palma	Tarragona (Marina)	Benalmadema	Portocolom
Alcudia	Cambrils	Campamento	Sant Antoni
Ibiza	L'Ametlla de Mar	Endesa	Santa Eulalia
La Savina	Marina L'Ampolla	Barbate	Ceuta
Melilla	Cemex Alcanar	Conil	

2.4. Wave climate

The wave conditions at the wind farm location can significantly impact the costs of the offshore wind project. Particularly, harsh wave conditions may hinder access to the wind farm for essential O&M tasks, including regular on-site examinations and the replacement of faulty elements.

The expenses linked to O&M activities represent a substantial portion of the overall costs throughout the offshore wind project's lifespan (Laura and Vicente, 2014). The expenditures related to hiring personnel and vessels are considerable, constituting a significant source of cost that influences the LCOE (Martinez and Iglesias, 2021). Importantly, the efficiency of maintenance operations has a crucial role in minimising wind turbine downtimes (Michler-Cieluch et al., 2009). Delays in these activities due to challenging wave conditions can profoundly impact energy generation and, consequently, the LCOE (S Astariz et al., 2015a).

Hence, it is crucial to evaluate the available maintenance windows for an offshore wind farm to reduce downtime caused by delayed maintenance procedures (Ciuriuc et al., 2022). However, estimating the required wave conditions for conducting maintenance tasks is challenging due to the lack of real-world, large-scale floating wind farms. Based on experience-derived data, it is indicated that a maximum significant wave height of 1.5 m is required for the duration of the maintenance activities (Ren et al., 2021). A time frame of 3 hours is selected following the literature (Catterson et al., 2016). While these values may be updated when floating offshore wind farms become operational, the estimation of operation windows in this work can serve for comparative analysis across zones.

Notably, the wave climate of the Spanish Mediterranean region falls within the least energetic category, known as Class I, which is associated with enclosed and semi-enclosed seas (Martinez and Iglesias, 2020). This is an advantage for offshore wind development, as it allows for more frequent maintenance windows compared to regions like the Spanish Atlantic. Nevertheless, the wave climate of the Spanish Mediterranean is marked by significant variability, potentially exerting a crucial influence on the comparison of high-potential zones.

Data on the wave climate at the high-potential zones are sourced from the Mediterranean Sea Waves Reanalysis of the Copernicus Marine Service (Korres et al., 2021). Hourly data on significant wave height from 2000 to 2019 are employed, which roughly aligns with the lifespan of the offshore wind farm.

3. Results

In the following, the considerations presented in Section 2 are evaluated and intercompared for all high-potential zones, i.e., LEBA 1–3 and ESAL 1 and 2.

3.1. Eligible ports and distances

With the above-mentioned criteria, a selection of ports suitable for servicing the wind farm is made from a list of 91 eligible ports within the area of study. In addition to the technical requirements necessary for facilitating wind farm operations, the selection process is categorised into distinct regions given the considerable distances between the high-potential zones. As a result, ports are segregated into three groups: ports capable of servicing LEBA 1, those suited for LEBA 2 and 3, and those intended for ESAL 1 and 2.

Moreover, certain ports are excluded from consideration due to their proximity to other ports of greater significance. This is the case of the Forum port in Barcelona, in favour of the port of Barcelona; and ports in the Cartagena, Algeciras and Palma Bays. As a result, a list of 16 ports is selected (Table 2) (Figs. 2 and 3).

The selected ports and their respective distances to the corresponding high-potential zones are evaluated (Table 3). Notably, ports that are located more than 250 km away from at least one potential zone are disregarded – as the Spanish Mediterranean boasts an array of port facilities with the potential to service offshore wind farms, multiple options with various characteristics can be found within the 250 km limit. It was reported in (Cavazzi and Dutton, 2016) that the speed of a vessel for the installation of the offshore wind farm is approx. 20 kmh^{-1}. A bigger distance to the coast would translate into long travel times, with the associated costs of hiring vessels and larger time windows of adequate weather.

Table 2
Port facilities eligible for servicing floating offshore wind farms.

Ports	Location	
Palamos	41° 50.4′ N	3° 7.2′ E
Barcelona	41° 19.2′ N	2° 10.0′ E
Vilanova i la Geltru	41° 12.3′ N	1° 43.6′ E
Tarragona	41° 4.6′ N	1° 12.3′ E
Cartagena Bay	37° 35.5′ N	0° 58.9′ W
Aguilas	37° 24.1′ N	1° 34.3′ W
Carboneras	36° 59.2′ N	1° 53.8′ W
Almeria	36° 49.6′ N	2° 27.6′ W
Motril	36° 42.9′ N	3° 30.8′ W
Malaga	36° 41.9′ N	4° 25.0′ W
Algeciras Bay	36° 8.2′ N	5° 25.0′ W
Cadiz Bay	36° 33.1′ N	6° 16.1′ W
Melilla	35° 17.1′ N	2° 55.2′ W
Mahon	39° 52.1′ N	4° 18.5′ E
Palma	39° 33.3′ N	2° 38.3′ E
Alcudia	39° 50.1′ N	3° 8.2′ E

Particularly, a significant number of these ports necessitate minimal expansion of their current infrastructure to accommodate requisite operations and marshalling of components. This is the case, prominently, of the ports labelled as of general interest for the State due to their substantial volumes of cargo. Such ports abound in the vicinity of LEBA 1 and ESAL 1 and 2. In this sense, a dichotomy arises in the case of LEBA 1 between the closer port of Palamos and the port of Barcelona, already equipped for a high volume of activity. A deep life-cost analysis must be undertaken to determine the optimal option.

The scenario shifts considerably when considering the Balearic Islands. Given that the high-potential zones are located on the eastern side, mainland Spanish ports are geographically distant for servicing wind farms sited in LEBA 2 or 3. Here, the proximity of the port of Mahon is decisive, making it the preferred solution. Nevertheless, substantial expansions of Mahon's port facilities would be necessary to accommodate the envisaged activities. This expansion, however, could be justified if multiple wind farms are accommodated in LEBA 2 and/or 3, given their proximity.

Finally, ESAL 1 and 2 offer several well-equipped options in terms of port infrastructure. Both the ports of Motril and Malaga emerge as prime choices in terms of proximity for wind farms located in either ESAL 1 and/or ESAL 2 – being Motril closer to ESAL 2 and Malaga to ESAL 1. Consequently, the preferred option depends on the installed capacity within ESAL 1 and/or ESAL 2.

3.2. Water depth

As previously mentioned, water depth imposes two constraints on offshore wind. Primarily, it acts as a technological limitation for the installation of the turbines. For semi-submersible platforms, this constraint typically imposes a maximum depth of 1000 m. Secondly, water depth significantly influences the costs of installation and the amount of material needed for the foundations (Castro-Santos, 2016). In the case of semi-submersible platforms, water depth has a notable effect on the length of the mooring lines, and thus the related material expenses.

The evaluation of water depth is conducted within the high-potential zones for offshore wind in the Levantine-Balearic and the Strait and Alboran marine subdivisions (Figs. 4 and 5, respectively). As seen, the selection of these zones by the *POEMs* already considers the limitation of 1000 m depth.

The spatial distribution of the high-potential zones leads to the differentiation of three distinct groups. Firstly, LEBA 1 is characterised by medium water depths in which semi-submersible platforms work best – shallower would render bottom-fixed turbines more economically viable. Secondly, LEBA 2 and 3 encompass a wide range of water depths, from 100 to 1000 m. As a result, a thorough evaluation of wind farm

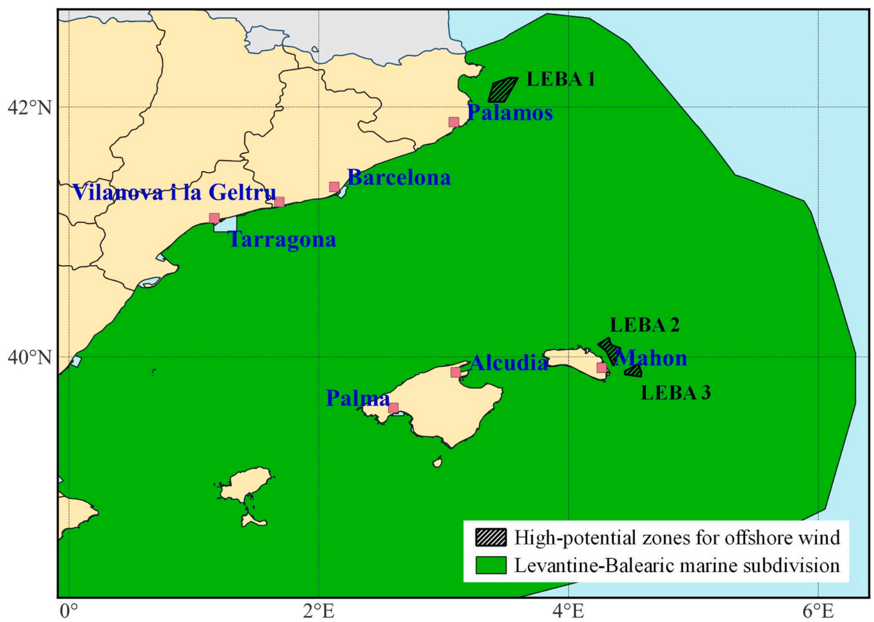

Fig. 2. Ports eligible to service wind farms located in the Levantine-Balearic marine subdivision.

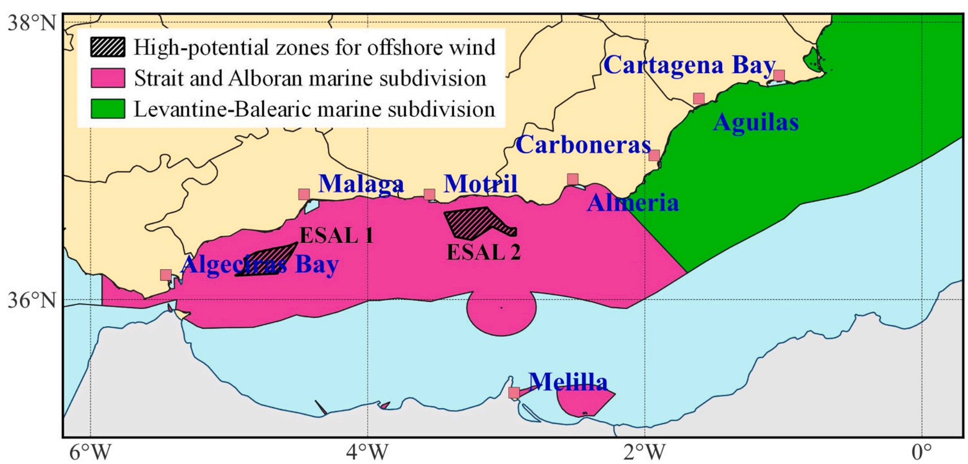

Fig. 3. Ports eligible to service wind farms located in the Strait and Alboran marine subdivision.

Table 3
Distance (km) from ports selected for servicing the floating offshore wind farms to high-potential zones.

	LEBA 1	LEBA 2	LEBA 3	ESAL 1	ESAL 2
Palamos	44.26				
Barcelona	142.97				
Vilanova i la Geltru	184.82				
Tarragona	229.09				
Cartagena Bay				391.14	247.42
Aguilas				337.80	198.90
Carboneras				285.39	148.34
Almeria				217.98	83.15
Motril				122.04	30.37
Malaga				59.26	105.37
Algeciras Bay				64.44	202.60
Cadiz Bay				182.23	320.58
Melilla				204.09	143.71
Mahon		27.96	19.07		
Palma		212.05	193.90		
Alcudia		110.37	119.40		

siting becomes imperative to minimise mooring costs and ascertain the availability of adequate space in the shallower parts. Lastly, ESAL 1 and 2 are located in deep areas (>550 m), a factor that significantly impacts mooring costs.

3.3. Energy production and availability factor

Mean wind speeds are evaluated in the Levantine-Balearic and Strait and Alboran marine subdivisions (Figs. 6 and 7). Notably, the northern region of the study area, near the Gulf of Lyon, exhibits the highest wind resources in the region of study, where LEBA 1 is located (Fig. 6) (Carvalho et al., 2014). A study using a Modern-Era Retrospective analysis for Research Applications version 2 (MERRA-2) re-analysis highlights the high potential of the wind resource in this area (Nezhad et al., 2022a).

High values of wind speed extend from the Gulf of Lyon southwards to the eastern areas of the Balearic Islands, particularly the eastern sections of Menorca, where LEBA 2 and 3 are situated. In contrast, areas near the Levantine shores of mainland Spain and Mallorca possess limited wind resources (Martinez and Iglesias, 2023b).

Moving to the southern regions of the area of study, wind resources

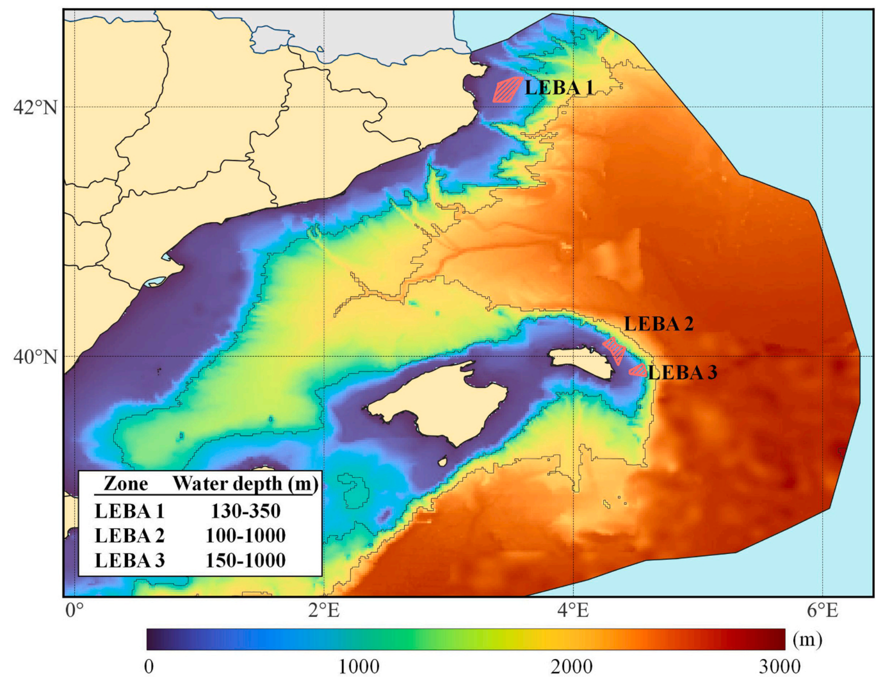

Fig. 4. Water depth in the Levantine-Balearic marine subdivision (isobaths every 1000 m). High-potential zones for offshore wind in the Levantine-Balearic marine subdivision (red).

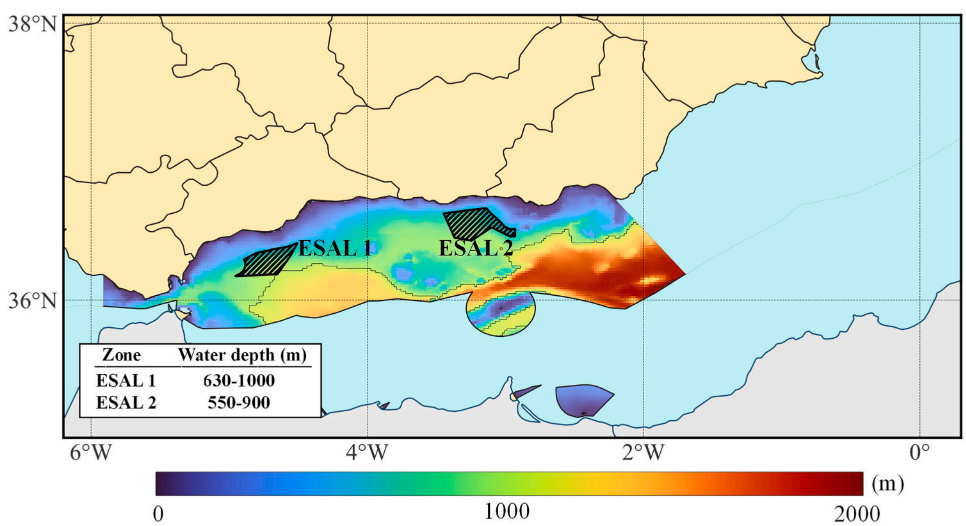

Fig. 5. Water depth in the Strait and Alboran marine subdivision (isobaths every 1000 m). High-potential zones for offshore wind in the Strait and Alboran marine subdivision (black).

are lower in nearshore areas, while more substantial wind resources occur farther away from the coast.

The estimated energy production is computed by combining wind hindcast data with the power curve of an exemplar wind turbine following Eq. (1). As the primary objective of a wind farm is electricity generation, assessing this aspect holds paramount importance (von Krauland et al., 2023). Importantly, the mapping of the estimated electricity generation (Figs. 8 and 9) shows exacerbated differences between high-potential zones in comparison with mean wind speeds. Table 4 shows the estimated energy production, calculated as a representative value of the average of the entire sector, relative to the zone with the lowest production of energy – corresponding to LEBA 2. Despite the relatively high wind resources in LEBA 2 and 3, differences from LEBA 1 are apparent. LEBA 1 emerges as the optimal choice in terms of energy production, generating 1.24 times the energy at LEBA 2. LEBA 3, ESAL 1, and 2 slightly surpass LEBA 3 in estimated energy production.

Another pivotal factor is the predictability of the wind farm power output. Variability in resources has an impact on project financing, as investors typically favour stable revenues, and supply-demand balancing. High-potential zones demonstrate a similar value of the availability factor (Table 5), with the notable exception of ESAL 2, in which the availability factor is lower. Interestingly, discrepancies between the available wind resources, estimated energy production and the availability factor are apparent. In this sense, a detailed project-specific analysis is necessary to ascertain whether relatively higher estimated energy production compensates for a lower variability factor, as seen in ESAL 1 vs 2.

Noteworthy, the spatial resolution of the wind dataset may pose some limitations to the analysis, particularly due to the proximity of LEBA 2 and 3. However, the analysis of the wind conditions showed very

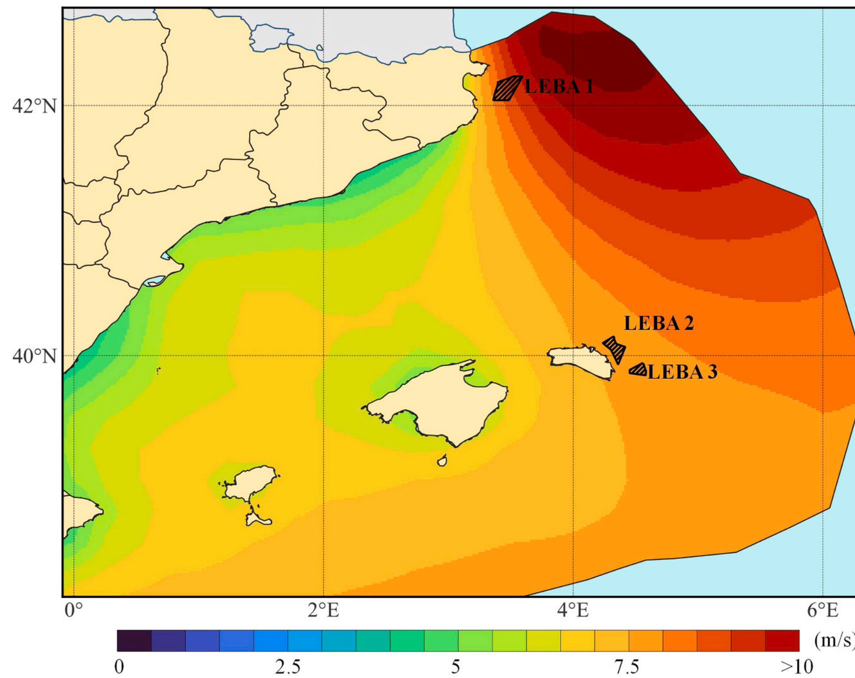

Fig. 6. Mean wind speed (ms^{-1}) in the Levantine-Balearic marine subdivision. High-potential zones for offshore wind in the Levantine-Balearic marine subdivision (black).

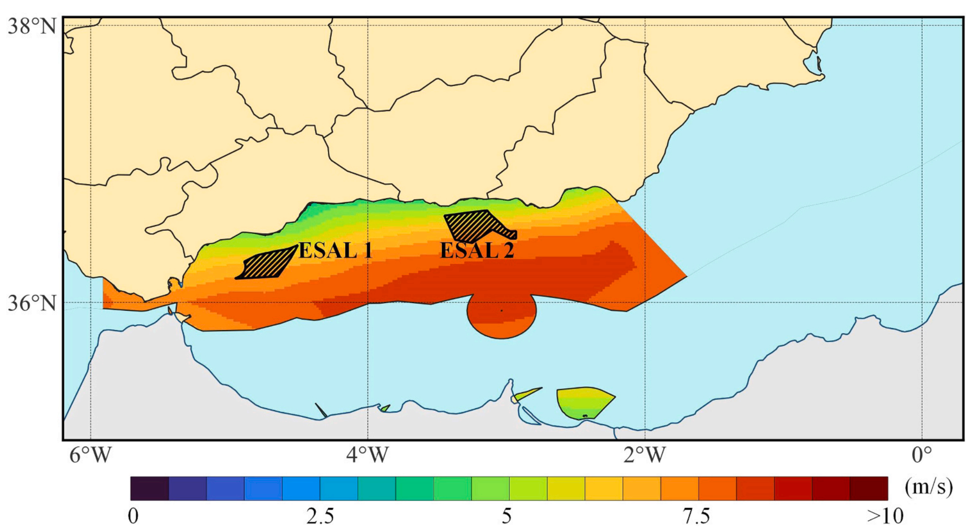

Fig. 7. Mean wind speed (ms^{-1}) in the Strait and Alboran marine subdivision. High-potential zones for offshore wind in the Strait and Alboran marine subdivision (black).

little variations in the wind conditions across these two zones – which can also be seen in the Global Wind Atlas (Badger et al., 2015). Given that the wind climate in both zones is characterised by different grid points and the small gradient of wind speeds in this direction, the spatial resolution is not a limitation.

3.4. Wave conditions for operation and maintenance

Delayed maintenance operations can lead to undesirable stoppages and thus to a loss of energy production, which ultimately translates into economic setbacks. The wave climate categorises high-potential zones into two groups. Firstly, zones within the Levantine-Balearic marine subdivision exhibit a relatively high percentage of available windows (~70% of the total) (Table 6). Conversely, high-potential zones in the Alboran Sea display notably higher values due to their enclosed location, characterised by a short fetch resulting in infrequent surpassing of the threshold.

Noteworthy, even though numbers shown in Table 6 demonstrate good, comparative value between high-potential zones, they are calculated using thresholds based on experience. However, these thresholds could evolve in the future with the installation of real-life projects. Moreover, even though the O&M stage is the longest in the lifetime of the project, the necessary wave conditions may differ at different stages, which ought to be studied when more data become available.

4. Discussion

The results presented highlight the different characterteristics of the high-potential zones designated by the Spanish Government in its Marine Spatial Planning. These attributes shed light on crucial decisions

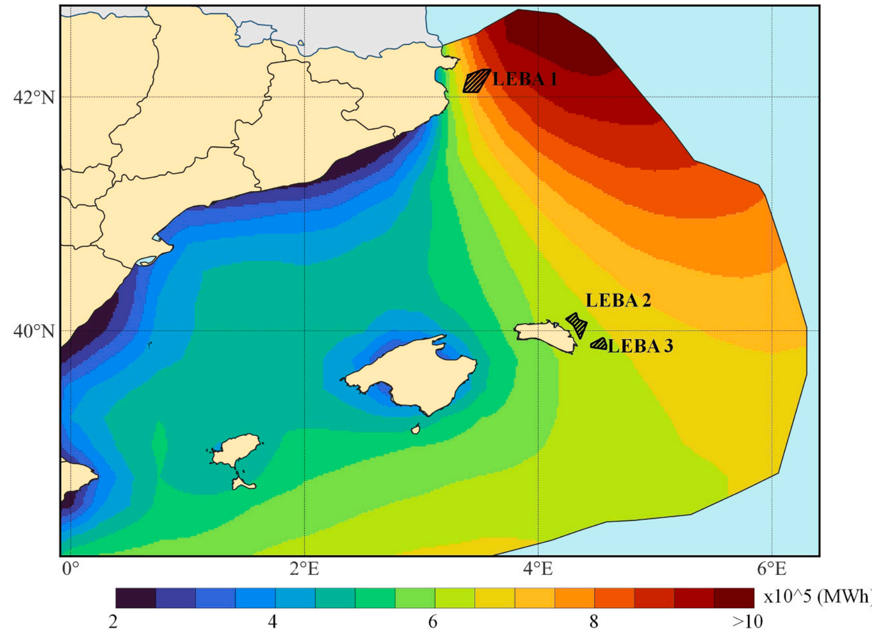

Fig. 8. Calculated output of a wind turbine in the Levantine-Balearic marine subdivision during its lifespan. In black, high-potential zones for offshore wind in the Levantine-Balearic marine subdivision.

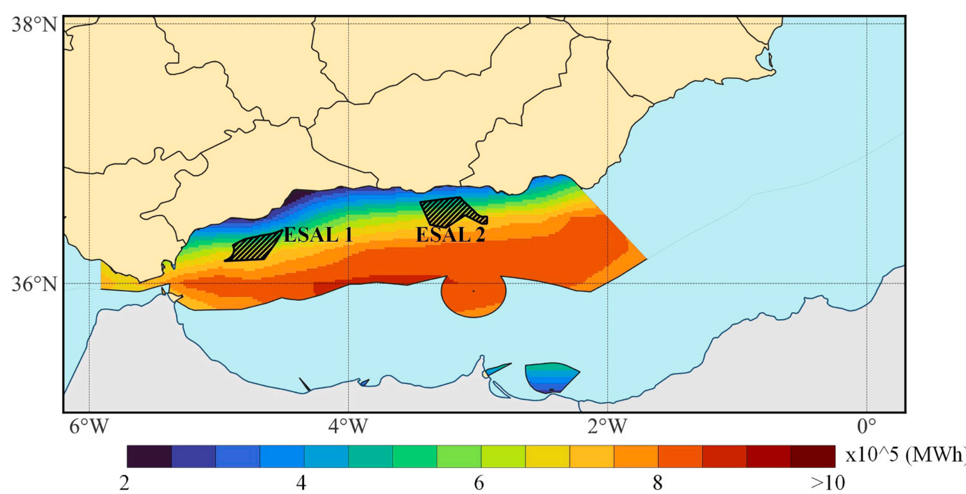

Fig. 9. Calculated output of a wind turbine in the Strait and Alboran marine subdivision during its lifespan. In black, high-potential zones for offshore wind in the Strait and Alboran marine subdivision.

Table 4
Calculated output of a single wind turbine installed at the high-potential zones, adimensionalised with respect to the lowest energy output – corresponding to LEBA 2 (~634×10^3 MWh).

Zone	Electricity production
LEBA 1	1.24
LEBA 2	1.00
LEBA 3	1.01
ESAL 1	1.02
ESAL 2	1.05

Table 5
Availability factor of a wind turbine at each high-potential zone.

Zone	Availability factor
LEBA 1	72%
LEBA 2	70%
LEBA 3	70%
ESAL 1	70%
ESAL 2	64%

that the Spanish Government, stakeholders and developers must make when selecting sites for offshore wind development. For example, the findings suggest a pivotal decision between prioritising proximity to wind farms or using better-equipped port infrastructure. Medium-sized ports closer to high-potential zones could potentially allocate the necessary activities required by the wind farm. However, they would require a greater initial investment to upgrade their facilities compared to better-equipped ports. The most significant characteristics of the high-potential zones are summarised in Table 7. All these attributes must be carefully incorporated into the decision-making process to optimise wind farm siting from a techno-economic perspective.

The techno-economic evaluation conducted in this study

Table 6
Number of estimated maintenance windows at each high-potential zone, shown relative to the total windows during the lifespan the farm.

Zone	Maintenance windows
LEBA 1	74%
LEBA 2	71%
LEBA 3	67%
ESAL 1	90%
ESAL 2	83%

Table 7
Attributes of each high-potential zone.

LEBA 1	• Highest energy production • Close to the port of Palamos (medium-sized) • Good range of water depth • High availability factor • Relatively high number of maintenance windows
LEBA 2	• Close to the port of Mahon (medium-sized) and LEBA 3 • Very wide ranges of water depth • Relatively high availability factor
LEBA 3	• Close to the port of Mahon (medium-sized) and LEBA 2 • Very wide ranges of water depth • Relatively high availability factor • Lowest number of maintenance windows
ESAL 1	• Close to multiple large ports • Very deep waters • Highest number of maintenance windows
ESAL 2	• Close to multiple large ports • Very deep waters • Lowest availability factor • Relatively high number of maintenance windows

complements the Marine Spatial Plans recently published by the Spanish Government. This approach can be applied to other plans in other countries. Given that offshore wind energy is still a nascent technology, specific areas designated for offshore wind are relatively new. Countries like Germany or Denmark, with already developed offshore wind industries, have addressed this situation first. Germany introduced its most recent Maritime Spatial Plan in 2021, following one in 2009, covering the German exclusive economic zone (EEZ) of the North Sea and Baltic Sea (European MSP Platform, 2024a). These plans designate priority areas for offshore wind, although offshore wind is not entirely limited to these areas. Similarly, Denmark adopted and launched its Maritime Spatial Plan in March 2021 (European MSP Platform, 2024b), designating special zones for offshore energies and energy islands.

Notwithstanding, offshore wind is already developed in these countries – in Germany, 8 GW of offshore wind was already installed by the end of 2022 (Norton Rose Fulbright, 2023). The research presented in this work is highly applicable to countries where decisions regarding offshore wind siting must be made. This is particularly relevant for countries where bottom-fixed turbines are not viable, and thus large-scale offshore wind is still to be developed. This includes, for example, countries located in Southern Europe, where shallow waters are scarce due to the narrow continental shelf, including Spain and Portugal, which have recently submitted their MSPs.

In Portugal, high-potential zones for renewable energies are designated in the Allocation Plan for Offshore Renewable Energy ("*Plano de Afetação para as Energias Renováveis Offshore*"), published recently (DGRM, 2024). While these plans consider factors like mean wind resources, wave conditions and water depth restrictions, they lack insights into crucial aspects like the evaluation of suitable port infrastructure for wind farm operations and their distance to the sites. In such cases, the techno-economic assessment presented in this work can aid the decision-making process for offshore wind farm siting.

Furthermore, in countries where Marine Spatial Plans are under development, the techno-economic assessment performed in this work can be directly incorporated to the designation of high-potential zones, resulting in a more informed zoning for offshore wind development. Italy and Greece are prominent examples where MSP is an ongoing process. Italy shared a draft MSP for public consultation in Autumn 2022, which is currently being finalised by a technical committee (European MSP Platform, 2024c). In Greece, the THAL-CHOR II stands out as an initiative aimed at implementing a pilot project for the preparation of MSP in certain areas of Cyprus and Greece, through cooperation between the two countries (European MSP Platform, 2024d).

Other cases in which the analysis performed can be applied are Ireland and France. In Ireland, the first Offshore Renewable Energy Development Plan I (OREDP I) currently guides the use for offshore renewable energies; however, this is going to be updated to incorporate specifically the use for large-scale offshore wind in OREDP II, currently in public consultation (Irish Government, 2023). In the case of France, four 4 MSPs were adopted in the Documents Stratégiques de Façade (DSF) in April 2022 (Direction Interrégionale de la Mer Méditerranée, 2024). While these plans do not specifically address regions for offshore wind, multiple large-scale projects are under way, including in the Gulf of Lyon, close to the areas explored in this work (Norton Rose Fulbright, 2024).

The analysis performed in this work can be extended to numerous countries where offshore wind is yet to be developed, where it can facilitate informed decisions for optimal wind farm siting. While this study evaluates techno-economic aspects of high-potential zones in the Spanish Mediterranean, the same approach can be applied in countries facing a similar situation, such as Portugal. Most importantly, this can already be incorporated into the zoning process of countries with pending MSPs, such as Italy or Greece.

5. Conclusions

This study evaluates and compares zones for the development of offshore wind in the context of marine spatial planning. This is illustrated through the high-potential zones identified by the Maritime Space Management Plans of the Spanish government in the Mediterranean. Relevant aspects to the siting of floating offshore wind farms are considered: potential port infrastructures to service the offshore wind farms, water depths, estimated energy production, wind farm availability factor, and wave climate for operation and maintenance.

Regarding port infrastructure availability, the study identifies the most suitable port facilities for each high-potential zone. Importantly, a pivotal decision must be made between prioritising proximity to the wind farm versus better-equipped port facilities, requiring a lower initial investment to expand current capabilities. In the first case, high-potential zones in the Strait and Alboran marine subdivision boast well-prepared port infrastructure. Both the ports of Motril and Malaga could service wind farms located in ESAL 1 and/or ESAL 2. Alternatively, if proximity takes precedence, Palamos port could service wind farms in LEBA 1, and Mahon wind farms in LEBA 2 and 3. However, these ports must undergo significant expansion of their current facilities to accommodate the necessary operations and marshalling of components. Economic justification for such expansions could arise if multiple wind farms are developed, for example, in LEBA 2 and 3.

Regarding water depth, LEBA 1 is evaluated as the optimal choice for minimising mooring costs. LEBA 2 and 3 exhibit a wide range of water depths, necessitating an in-depth analysis for offshore wind siting. Importantly, high-potential zones in the Alboran Sea (ESAL 1 and 2) are situated in very deep areas.

LEBA 1 stands out in terms of energy production and availability factor. Given that energy production is most relevant to the economics of an offshore wind farm, LEBA 1 emerges as the best option. It remains to be studied whether a relatively higher production of energy can compensate for a lower availability factor, e.g., when comparing ESAL 1 and 2.

Finally, substantial discrepancies arise in wave climates between the zones in the Levantine-Balearic subdivision and the more enclosed zones within the Alboran Sea, the latter being more adequate for maintenance operations.

The factors analysed herein play a pivotal role in the decision-making process for floating offshore wind development in the Spanish territorial waters in the Mediterranean. Offshore wind is rapidly growing and can pose challenges to effective ocean management, accentuating the need for well-informed marine spatial planning. Hence, the outcomes of this research work illuminate the pros and cons of establishing offshore wind farms in each location. Both developers and policy-makers must take into consideration the results of this work to produce informed decisions.

The approach employed in this work can be widely applied to the Maritime Space Management Plans of different regions. However, the importance of the aspects considered in this work must be carefully weighed in project-specific studies to arrive at definitive decisions regarding offshore wind farm siting. For example, although LEBA 1 excels in terms of wind resources, the port selection for this zone requires careful consideration. Moreover, decisions should consider other perspectives that are beyond the scope of this work – for instance, the Balearic Islands could really benefit from local energy production.

Additionally, the scope of this work cannot include important project-specific aspects that will play a role in the development of the technology, such as important aerodynamic and hydrodynamic issues, and the economic viability of the installations, such as the turbine layout. These aspects ought to be the focus of future works to advance our current knowledge on offshore wind.

CRediT authorship contribution statement

A. Martinez: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing - original draft. **G. Iglesias:** Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Writing - review & editing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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