npj | ocean sustainability

Article

https://doi.org/10.1038/s44183-024-00080-8

# More robust offshore wind energy planning through model ensembling

**Daniel Depellegrin**[1,2] ✉, **Maurizio Ambrosino**[3], **Sanjoy Roy**[1,4], **Javier Sanabria**[5] & **Carolina Martí Llambrich**[1]

This research performs an *ex-ante* assessment of the 19 high potential areas for offshore wind energy (HPA-OWE) allocated in four maritime spatial planning subdivisions of Spain. A 39 geo-statistical criteria pool was developed and categorized into five planning tiers (coexistence, socio-ecological, spatial-efficiency, energy-equity, technical/technological). An ensemble of three multi-criteria decision analysis (MCDA) techniques coupled with a Monte Carlo method based on a large, uniform number of randomly distributed criteria weights is applied for more robust priority rankings of HPA-OWE. The co-existence tier indicates that HPA-OWE should be prioritized in the North Atlantic and in the Levantine–Balearic planning subdivision. The application of machine learning on the MCDA results identified criteria that most influence the rank of each HPA-OWE at planning subdivision. The outcomes highlight the need to include place-based data to better take into account spatial inequalities in coastal regions and re-balance them with socio-economic and energetically privileged coastal territories.

Offshore wind energy (OWE) development belongs to the pillars of the European[1] and global Energy transition[2]. In European seas, national governments have identified potential areas for offshore wind energy deployment using maritime spatial planning (MSP). Most recent national MSP initiatives lack the analytical tools necessary to provide *ex-ante* assessments for sea areas prioritized for OWE development. *Ex-ante* assessments are crucial as they support decision-making in the early stages of developing technological systems, facilitating the sustainable deployment of infrastructure and technological innovations[3,4]. *Ex-ante* assessments of maritime spatial plans are a priority area for the European Maritime, Fishery and Aquaculture Fund (EMFAF) and have the benefit of identifying trade-offs, minimize conflicts, promote sustainable development in marine areas and reinvigorate with new knowledge future amendments and cycles of national maritime spatial plans. In the context of OWE planning, MSP appears to have multiple utilities, such as ensuring legal certainty of use of the sea space of emerging human activities such as OWE[5], it regulates co-existence of OWE with existing human activities at sea (commercial fishery, shipping, aquaculture, etc…)[6], it fosters ecosystem-based management of natural resources at multi-sectoral level[7] and facilitates coordinated actions among stakeholders.

However, MSP, together with the Blue Economy—which encompasses economic activities that depend on the sea, often associated with other economic sectors, including tourism, maritime transport, energy, and fishing[8]—receives increased criticism together with Blue Economy, because promoting a neoliberal logic centered on re-spatializing the sea space in favor of economic interests[9], leaving behind nature protection and the place-based socio-cultural characteristics of coastal territories[10,11].

European seas are experiencing significant changes in governance, particularly through the implementation of the MSP Directive. As of January 2018, 21 out of 23 EU member states have transposed the MSP Directive into their national legislation[12]. The pressing need for transitioning towards more sustainable modes of energy production is expected to increase competition for sea space of up to 80% of Europe's sea space by 2050[13] due to marine infrastructure deployment. The experience of first-cycle national maritime spatial plans provides an unprecedented opportunity to initiate *ex-ante* assessments addressing the balance of ecological, social, spatial, economic, energy-related, and technological characteristics when determining the allocation of OWE arrays at sea.

Literature on MSP has identified in multi-criteria decision analysis (MCDA)[14–17] a central technique for OWE allocation. In the last five years the approach has been subjected to an evolution as techniques shifted from single to ensembled MCDA (EnseMCDA) techniques[14,18]. Ensembling techniques involve the aggregation of multiple decision-making methods, criteria, or models to rank alternatives across multiple objectives. They leverage the strengths of individual methods, compensate for their weaknesses, and provide a more holistic, balanced, and reliable evaluation of

---

[1]Landscape Analysis and Management Laboratory, Department of Geography, University of Girona, Girona, Spain. [2]IHCantabria—Instituto de Hidráulica Ambiental de la Universidad de Cantabria, Santander, Spain. [3]Department of Science and Technology, University of Sannio, Benevento, Italy. [4]Bengal Institute—Architecture, Landscapes and Settlements, Dhaka, Bangladesh. [5]Research Group on Integrated Coastal Zone Management, Sustainable Social Development Research Institute (INDESS), University of Cádiz, Cádiz, Spain. ✉e-mail: daniel.depellegrin@unican.es

alternatives. By integrating diverse perspectives, EnseMCDA enhances the comprehensiveness of decision-making processes, enabling stakeholders to make more informed and objective decisions.

The aim of this research is the development and application of an EnseMCDA technique to support more robust ocean planning decisions based on a national case study for the high potential areas for offshore wind energy (HPA-OWE) settled in the first Spanish Maritime Spatial Plan.

The manuscript is structured as follows: The results section describes the 39 criteria database describing the ecological, social, economic, energy-related, spatial, and technical/technological performance of the 19 the HPA-OWE (Figs. 1 and 2). Then, we describe the EnseMCDA ranking and the optimal ranking results (Fig. 3; Table 1) for each HPA-OWE based on three MCDA methods (TOPSIS—technique for order of preference by similarity to ideal solution; MMOORA—multi-objective optimization by ration analysis and VIKOR—multicriteria optimization and compromise solution)[19–21]. The EnseMCDA is coupled with a non-conditioned weighting mechanism with importance weights attributed uniformly through a Monte Carlo simulation to derive a more robust decision. We describe the emerging trade-offs in the four planning subdivisions (Fig. 4) by applying a Random Forest (RM) machine-learning (ML) technique to identify the mean square error (MSE) as criteria importance indicator. The discussion section addresses the findings and outlines potential future research directions.

On February 2023 the Spanish Ministry for the Ecological Transition and the Demographic Challenge adapted the first Spanish Maritime Spatial Plan (*Planes de Ordenación del Espacio Marítimo*—POEM; BOE-A-2023-5704)[6], by the Council of Ministers by Royal Decree. It establishes plans for five planning subdivisions (Fig. 1): Canary Islands (CAN); Straight-Alborán (ESAL); Levantine-Balearic (LEBA), South-Atlantic (SUR) and North-Atlantic (NOR). There are 19 HPA-OWE covering 0.4% (5056.7 km$^2$) of the entire Spanish EEZ (Table 2). The two HPA-OWE located in the ESAL planning subdivision have highest sea space occupation 4.9% (1234 km$^2$). At the time of the release of the POEM, no HPA-OWE was defined in the South Atlantic (SUR) subdivision. The National Integrated Plan for Energy and Climate (PNIEC) foresees to install 3 GW of offshore wind capacity by 2030.

## Results

### Criteria performance

Figure 2 provides an overview of the 39 criteria and the planning tier setup. We summarize the most noticeable aspects. The *Coexistence Tier* is the overall tier ($n = 39$ criteria) that incorporates the socio-ecological tier ($n = 10$ criteria), technical/technological tier ($n = 10$ criteria); spatial-efficiency tier ($n = 11$ criteria) and the energy-equity tier ($n = 8$ criteria). *Spatial-Efficiency criteria*. NOR2 is the most extended HPA-OWE development, it is the most constrained area as located in military areas and shipping lanes and has highest intensity of interactions with commercial fishery (27,997 h of displacement in 2021). NOR3 is the area with the highest collision risk potential in the North Atlantic subdivision and ESAL1 in the Mediterranean. Eight HPA-OWE fully overlap with restricted areas (Gov_perc) for offshore wind energy development. There are three HPA-OWE that fully or partially overlap with marine protected areas in the Canary Islands (CANFV1, CANFV2, and CANLANZ1), the Straight-Alborán (ESAL2) and North Atlantic (NOR8). *Socio-Ecological criteria*. HPA-OWE located in the North Atlantic subdivision shows higher distance from shore (28–13 km). Mediterranean HPA-OWE are mostly located in high population areas such as

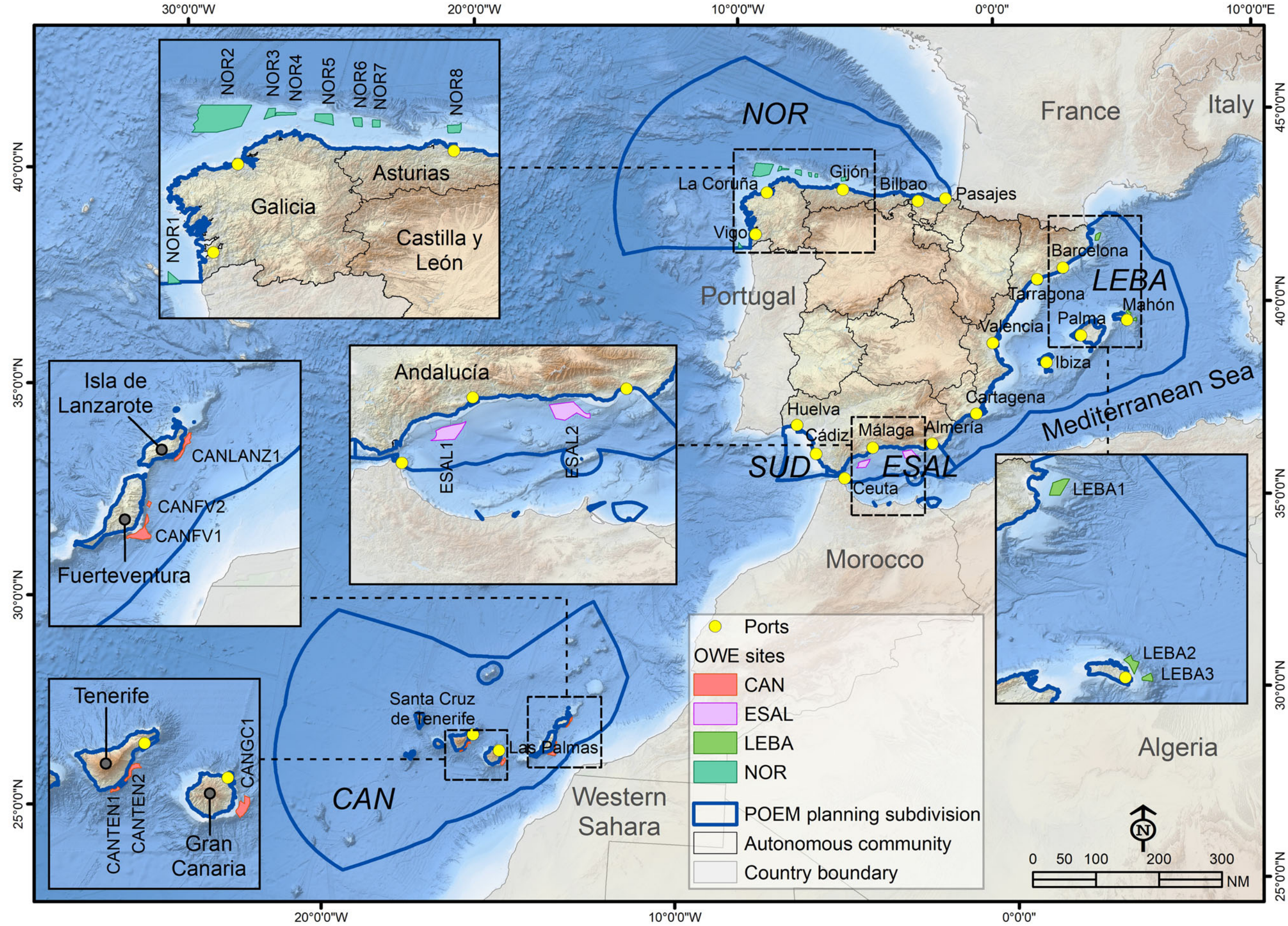

**Fig. 1 | The map represents the five planning subdivisions of the Spanish Maritime Spatial Plan including 19 high-potential areas for offshore wind energy (HPA-OWE) development.** Source: BOE-A-2023-5704.

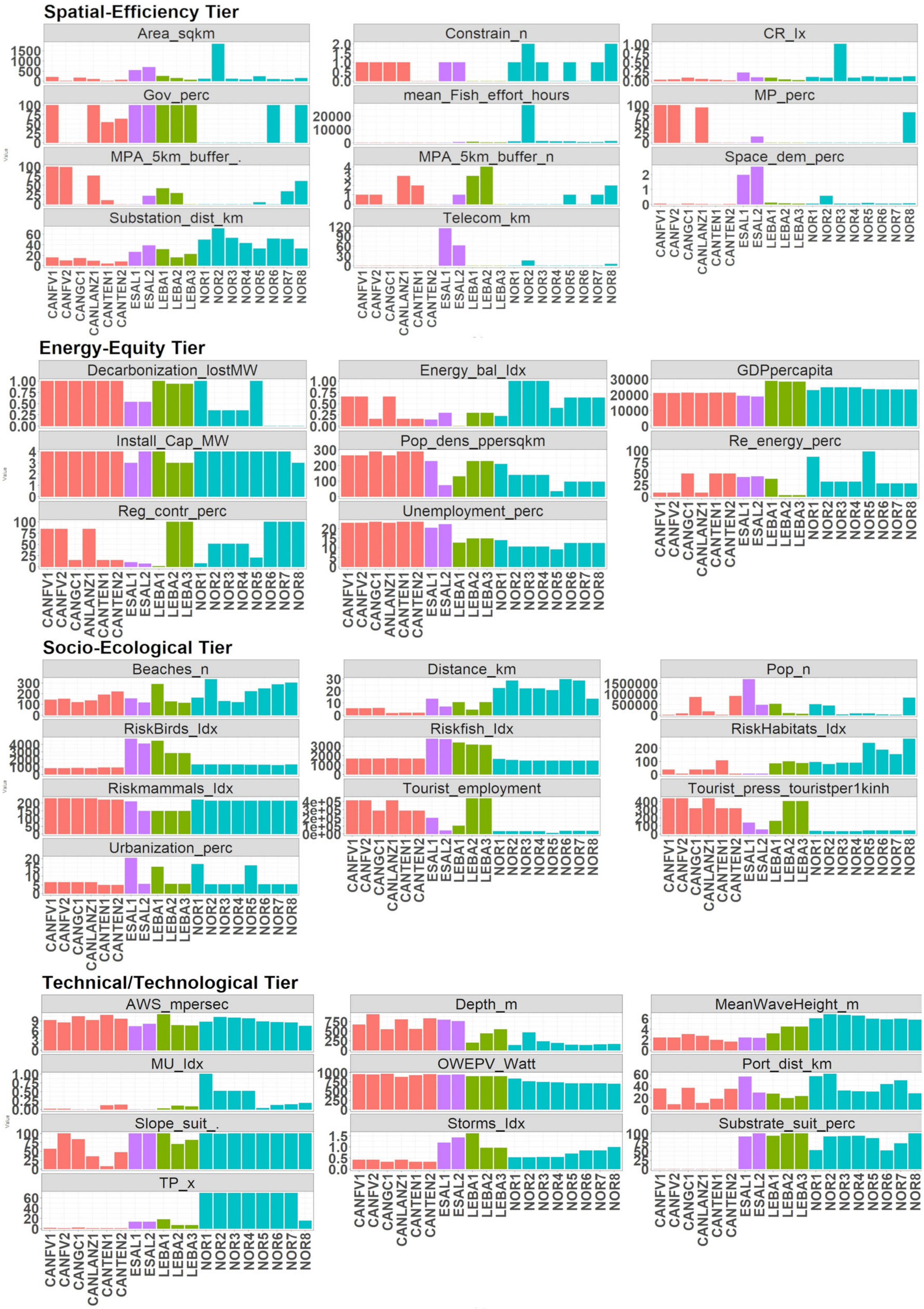

**Fig. 2 | Performance of the 39 criteria for each of the 19 HPA-OWE development.** Table 1 provides the abbreviations and methodological description of each criteria.

ESAL1 and 2. Highest urbanization patterns are in ESAL1 (20.5%), NOR1 (16.9%) and LEBA1 (15.3%). Ecological risks to birds and fish resources are higher in Mediterranean HPA-OWE compared to the North Atlantic subdivision. *Energy-Equity criteria*. Coastal provinces of LEBA1 to 3 have the highest GDP per capita (2021) compared to coastal provinces. Renewable energy percentage is highest in NOR5 and lowest in the LEBA2 and 3 located in the Balearic Islands. Unemployment rates are high in the Canary Islands and the ESAL1 and 2. *Technical/Technological criteria*. Multi-use potentials (MU_Idx) with offshore wind energy—aquaculture MU are NOR1 (score 1) and NOR 2–4 (score 0.52)

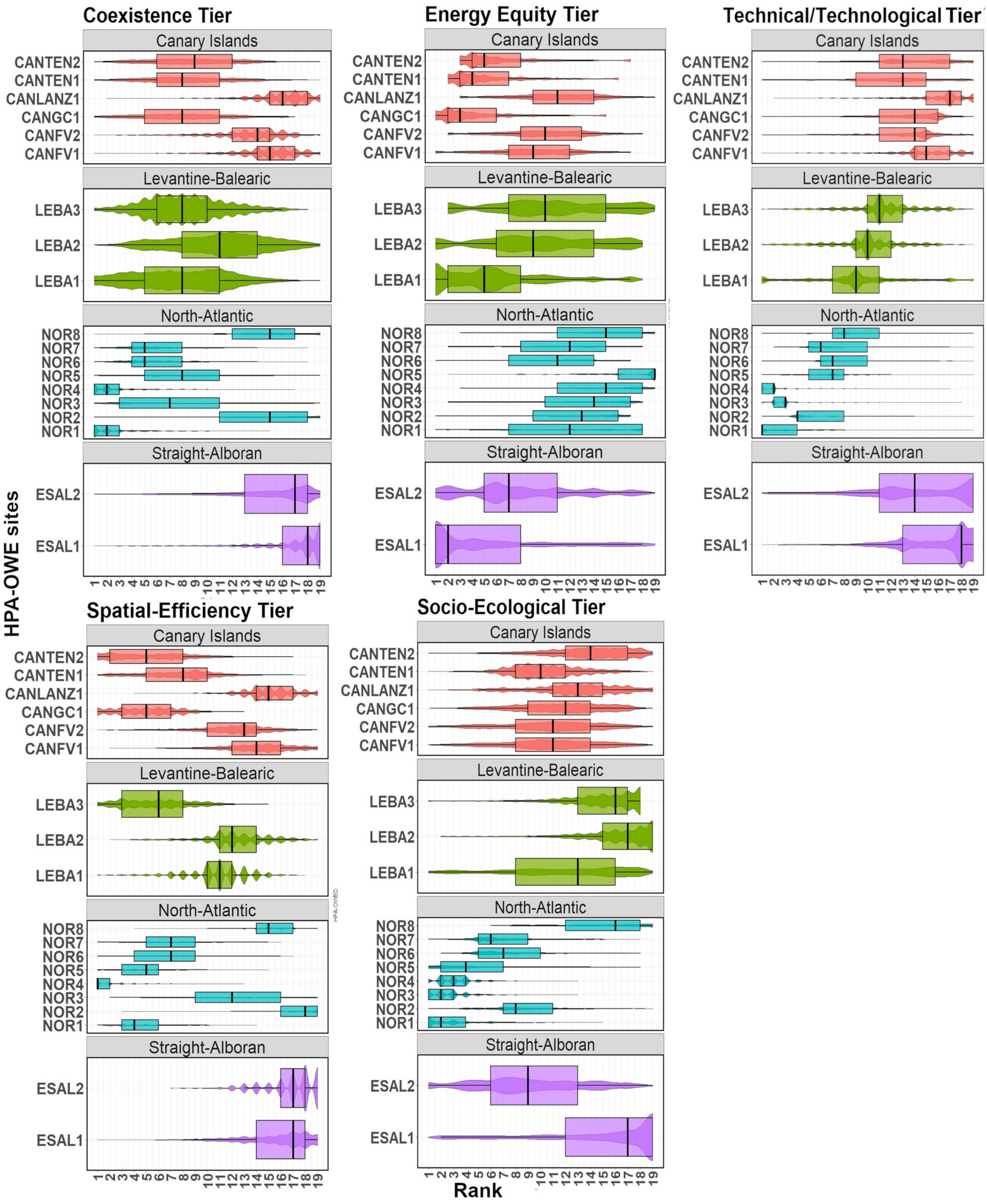

**Fig. 3 | Ranking results of HPA-OWE for each planning subdivision and planning tier.** The x-axis defines the rank from 1 to 19 of the HPA-OWE, the y-axis defines the assessed HPA-OWE site.

in the North Atlantic. Multi-use potentials with Photovoltaic power are highest in the Canary Island, Straight-Alborán, and Levantine Balearic subdivisions. Increased storm frequency due to climate change can cause damage to infrastructure and to the operational safety of the site is most relevant in the Mediterranean HPA-OWD (LEBA1, ESAL2, and 1).

### Ranking of HPA-OWE

Results for the ranking of the HPA-OWE were presented for a data frame of 390,000 weights and 30,000 ranking results. They were graphically presented as boxplots (Fig. 3) in terms of median rank ($\tilde{x}$) and as interquartile range of ranks (IQR). We synthesize the results for the first ranked HPA-

**Table 1 | Optimal ranking for HPA-OWE for each planning subdivision and planning tier**

| | **Subdivisions** | **HPA-OWE** | **Planning Tiers** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Coexistence** | **Spatial-ēfficiency** | **Energy-equity** | **Socio-ecological** | **Technical/ technological** |
| Atlantic | Canary Islands | CANTEN1 | *8* | *9* | **2** | *9* | *11* |
| | | CANTEN2 | *11* | *5* | **3** | *17* | *16* |
| | | CANLANZ1 | *19* | *17* | 11 | *14* | *18* |
| | | CANGC1 | *6* | **3** | **1** | *13* | *14* |
| | | CANFV1 | *17* | *14* | *7* | *10* | *17* |
| | | CANFV2 | *14* | *12* | *9* | *11* | *13* |
| | North-Atlantic | NOR1 | **1** | *4* | *13* | **3** | **3** |
| | | NOR2 | *13* | *16* | *16* | *7* | *5* |
| | | NOR3 | *10* | *11* | *15* | **2** | **2** |
| | | NOR4 | **2** | **1** | *17* | **1** | **1** |
| | | NOR5 | *7* | **2** | *19* | *5* | *4* |
| | | NOR6 | *4* | *8* | *12* | *6* | *7* |
| | | NOR7 | **3** | *7* | *14* | *4* | *6* |
| | | NOR8 | *16* | *18* | *18* | *16* | *8* |
| Mediterranean | Levantine-Balearic | LEBA1 | **9** | **10** | **4** | **12** | **9** |
| | | LEBA2 | **12** | **13** | *8* | *19* | **10** |
| | | LEBA3 | **5** | **6** | *10* | *18* | **12** |
| | Straight- Alboran | ESAL1 | *18* | *15* | **5** | **15** | *19* |
| | | ESAL2 | *15* | *19* | **6** | **8** | *15* |

Bold values represent the top ranked HPA-OWE within the Atlantic (CAN and NOR) and Mediterranean (LEBA and ESAL) sea-basin. Italic values refer to non-top ranked HPA-OWE within sea-basins

OWE for each planning tier in the Atlantic (NOR and CAN) and for the Mediterranean subdivisions (LEBA and ESAL):

- *Coexistence Tier*. In the Atlantic subdivision NOR1 ($\tilde{x} = 2$; *IQR* = *1–3*) and NOR4 ($\tilde{x} = 2$; *IQR* = *1–3*) and in the Mediterranean subdivisions LEBA3 ($\tilde{x} = 8$; *IQR* = *6–10*) and LEBA1 ($\tilde{x} = 8$; *IQR* = *5–11*).
- *Spatial-Efficiency Tier*. In the Atlantic subdivisions NOR4 ($\tilde{x} = 1$; *IQR* = *1–2*) and NOR1 ($\tilde{x} = 4$; *IQR* = *3–6*) and in the Mediterranean subdivisions LEBA3 ($\tilde{x} = 6$; *IQR* = *3–8*) and LEBA1 ($\tilde{x} = 11$; *IQR* = *10–12*).
- *Energy-Equity Tier*. In the Atlantic subdivision CANGC1 ($\tilde{x} = 3$; *IQR* = *2–6*) and CANTEN1 ($\tilde{x} = 4$; *IQR* = *3–7*) and in the Mediterranean subdivisions ESAL1 ($\tilde{x} = 1$; *IQR* = *1–8*) and LEBA1 ($\tilde{x} = 5$; *IQR* = *2–8*).
- *Socio-Ecological Tier*. In the Atlantic subdivision NOR1 ($\tilde{x} = 2$; *IQR* = *1–4*) and NOR3 ($\tilde{x} = 2$; *IQR* = *1–3*) and in the Mediterranean subdivisions ESAL1 ($\tilde{x} = 17$; *IQR* = *12–19*) and ESAL2 ($\tilde{x} = 9$; *IQR* = *5–13*).
- *Technical/Technological Tier*. In the Atlantic subdivision 8 HPA-OWE are within the first 10 ranks: e.g., NOR1 ($\tilde{x} = 1$; *IQR* = *1–4*) and NOR4 ($\tilde{x} = 2$; *IQR* = *1–2*) and in the Mediterranean subdivisions LEBA1 ($\tilde{x} = 9$; *IQR* = *7–11*) and LEBA2 ($\tilde{x} = 10$; *IQR* = *9–12*). To notice is that ESAL1 performance is the weakest ($\tilde{x} = 18$; *IQR* = *13–19*).

## Optimal ranking of HPA-OWE

The optimal ranking (Table 1) provides a definitive rank ($R$) on how often a specific HPA-OWE alternative ranks within the top-10 ($n_{top\text{-}10}$). In the supplementary information (Fig. 1), a detailed graphical overview of optimal rankings is available. We synthesize the results for the optimal ranking for the best-ranked HPA-OWE in the Atlantic (NOR and CAN) and in the Mediterranean subdivisions (LEBA and ESAL):

- *Coexistence Tier*. In the Atlantic subdivisions NOR1 ($R = 1$; $n_{top\text{-}10} = 29{,}776$), NOR4 ($R = 2$; $n_{top\text{-}10} = 29{,}709$) and in the Mediterranean subdivisions LEBA3 ($R = 5$; $n_{top\text{-}10} = 22{,}869$) and LEBA1 ($R = 7$; $n_{top\text{-}10} = 21{,}217$).
- *Spatial-Efficiency Tier*. In the Atlantic subdivisions NOR4 ($R = 1$; $n_{top\text{-}10} = 29{,}956$); CANGC1 ($R = 3$; $n_{top\text{-}10} = 29{,}395$) and in the Mediterranean subdivision LEBA3 ($R = 5$; $n_{top\text{-}10} = 28{,}252$) and LEBA1 ($R = 10$; $n_{top\text{-}10} = 12{,}055$).
- *Energy-Equity Tier*. In the Atlantic subdivisions CANGC1 ($R = 1$; $n = 27{,}383$), CANTEN1 ($R = 2$; $n_{top\text{-}10} = 26{,}710$) and for the Mediterranean LEBA1 ($R = 4$; $n_{top\text{-}10} = 25{,}422$) and ESAL1 ($R = 5$; $n_{top\text{-}10} = 24{,}690$).
- *Socio-Ecological Tier*. In the Atlantic subdivisions (e.g., NOR4: $R = 1$; $n_{top\text{-}10} = 29{,}964$; NOR3: $R = 2$; $n_{top\text{-}10} = 29{,}939$) and in the Mediterranean subdivisions ESAL2 ($R = 8$; $n_{top\text{-}10} = 19074$) and LEBA1 ($R = 12$; $n_{top\text{-}10} = 11{,}558$).
- *Technical/Technological Tier*. In the Atlantic subdivisions NOR4 ($R = 1$; $n_{top\text{-}10} = 29{,}109$) and in the Mediterranean subdivisions LEBA1 ($R = 9$; $n_{top\text{-}10} = 20{,}706$).

## Cost-benefit analysis at planning subdivision scale

The 13 most important criteria for each planning subdivision are represented as costs and benefits in form of cumulative mean square error (*C-MSE*; Fig. 4A) and in detail as single criterion (Fig. 4B). On overall, the *C-MSE* shows that the *Spatial-Efficiency Tier* has most importance in ESAL ($C\text{-}MSE_{ESAL} = 233.51\%$) and LEBA ($C\text{-}MSE_{LEBA} = 173.75\%$). While the *Technical/Technological Tier* has more relevance in the North Atlantic ($C\text{-}MSE_{NOR} = 198.03\%$) and CAN ($C\text{-}MSE_{CAN} = 244.96\%$).

In the *Socio-Ecological Tier* ($C\text{-}MSE_{LEBA} = 162.74\%$) and the NOR ($C\text{-}MSE_{LEBA} = 165.63\%$). Tier-specific results indicate that the Energy-Equity Tier shows that recurrent costs are associated provincial contribution to the energy balance for Levantine-Balearic ($\mathrm{MSE}_{LEBA} = 42\%$) and North Atlantic ($MSE_{NOR} = 41\%$) and loss of MW due to national decarbonization policies ($MSE_{NOR} = 37\%$).

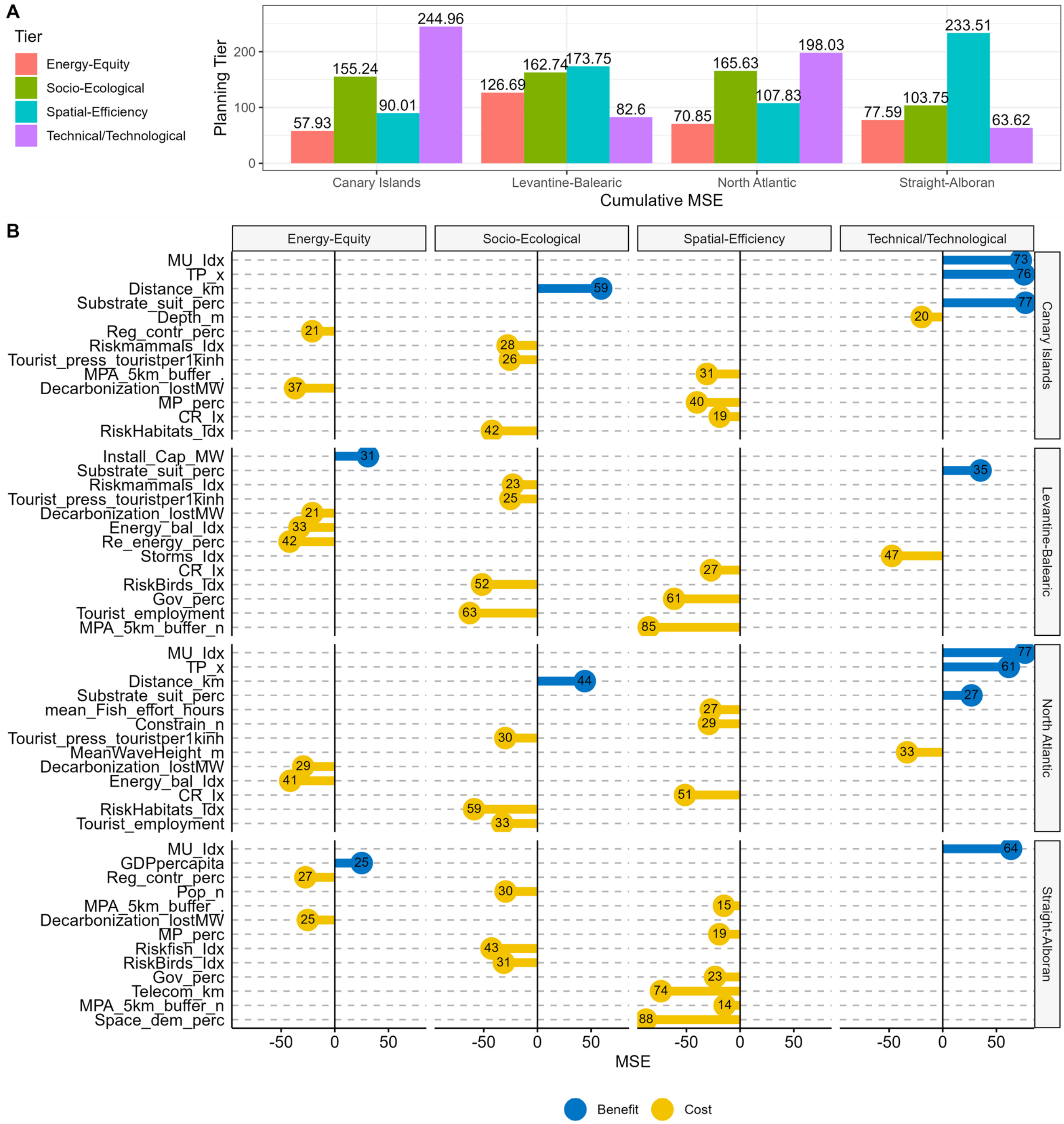

**Fig. 4 | Overview of 13 most important criteria for each planning subdivision expressed as costs and benefits.** **A** Cumulative-MSE (*C-MSE*) for each planning subdivision and **B** specific *MSE* score for 13 highest costs and benefits in the 39 criteria database according to four different planning tiers.

**Table 2 | Planning subdivisions and space occupation of the HPA-OWE in square kilometers (km$^2$) and percentage (%)**

| POEM -subdivisions | Nr. of HPA-OWE | Area in km$^2$ (%) | Mean Depth (m) | HPA-OWE (km$^2$) | HPA-OWE space demand per subdivision (%) |
|---|---|---|---|---|---|
| Canary Islands (CAN) | 6 | 536,776 (47.6) | −3574.3 | 605.1 | 0.1 |
| Straight y Alborán (ESAL) | 2 | 25,200.3 (2.2) | −867.1 | 1234 | 4.9 |
| Levantine-Balearic (LEBA) | 3 | 231,547 (20.5) | −1661.1 | 475 | 0.2 |
| North-Atlantic (NOR) | 8 | 320,221 (28.4) | −3698.4 | 2742.6 | 0.9 |
| South-Atlantic (SUD) | 0 | 14.299.4 (1.3) | −353.4 | / | / |
| **TOTAL** | **19** | **1,128,043.7 (100%)** | | **5056.7 (0.4%)** | |

Total values are represented in bold

The *Spatial-Efficiency Tier* is related to the proximity of HPA-OWE development to marine protected areas ($MSE_{LEBA} = 85\%$), space demands ($MSE_{ESAL} = 88\%$), and the presence of telecommunication subcables ($MSE_{ESAL} = 74\%$) are relevant for the Straight-Alborán subdivision. In the *Socio-Ecological Tier,* habitat risks ($MSE_{NOR} = 59\%$), risks to birds ($MSE_{LEBA} = 52\%$), and risks to fish ($MSE_{ESAL} = 43\%$) and mammals ($MSE_{CAN} = 28\%$). The *Technical/Technological Tier* include Storm Frequency ($MSE_{LEBA} = 47\%$), wave height ($MSE_{NOR} = 33\%$), and depth ($MSE_{CAN} = 20\%$).

## Discussion

In addressing the fundamental challenge of transitioning towards sustainable use of marine resources and sea space utilization, our study aims to strategically re-analyze proposed HPA-OWE sites of a national maritime spatial plan through balancing ecological, social, spatial, energy-related, and technical/technological characteristics. To respond to this challenge, we develop a 39-criteria dataset and apply an ensemble MCDA based on three algorithms, resulting in a database of 30,000 ranking results. The optimal prioritization of HPA-OWE development (Table 1 and Supplementary Figure 1) based on the coexistence planning tier are:

Atlantic subdivisions:

NOR1 ($n_{top\text{-}10} = 29{,}776$); NOR7 ($n_{top\text{-}10} = 27{,}475$) and NOR4 ($n_{top\text{-}10} = 29{,}709$);

Mediterranean subdivisions:

LEBA3 ($n_{top\text{-}10} = 22{,}869$); LEBA1 ($n_{top\text{-}10} = 21{,}217$) and LEBA2 ($n_{top\text{-}10} = 12{,}217$).

Our method can be extended to other geographic areas and handle decision-making problems of any other sectors of the Blue Economy: For instance to reach protection targets of 30% of sea space by the Biodiversity Strategy 2030, the method can be used for optimal allocation of new protected sites as well as for aquaculture development, ports or any other emerging marine renewables technology (e.g., wave energy converters, tidal energy etc…). The EnseMCDA modeling protocol is fully open source, using R-programming and a database of regional, national, European and global open data repositories (see Table 3). The adaptation of an ensembled MCDA technique and the use of uniformly machine-generated weights through Monte Carlo simulation have several advantages compared to traditional MCDA applications:

i. Our technique has an enhanced robustness by combining multiple individual algorithms and mitigating the weaknesses of any single method[22–25].
ii. Our technique promotes a more objective and transparent method for criteria weighting, relying on empirical data rather than subjective, sector-specific or expert-based knowledge usually used in offshore infrastructure suitability analysis[24,26].
iii. The EnseMCDA technique is more effective in exploring different planning options through the generation of a large number of weight combinations.
iv. The technique is more adaptable to evolving environmental, economic, policy, energy security, and social conditions. This adaptability is crucial for the design of MSP scenarios that have to respond to transition strategies, such as the European Green Deal (COM/2019/640), the EU Nature Restoration Law (2022/304 final), or the Just Transition Mechanism (2021/1056).
v. The method is highly flexible and can be applied to any high-potential ocean technologies relevant to future maritime spatial plans, including the identification of nature-inclusive designs, nature-based solutions, vessel electrification potentials, ocean clean-up systems, etc…
vi. The EnseMCDA model can make stakeholder engagement within MSP processes more dynamic, by testing planning proposals and measures for different Blue Economy activities and emerging technological solutions. This dynamism stems from the ability of the model to explore how different stakeholder perception and societal values and behaviours influence resources use, ensuring a more responsive and inclusive decision-making process.

In Europe, maritime spatial planners and decision-makers face challenges in implementing decarbonization policies. Our method is concrete and transparent as it enables the testing of different OWE planning scenarios under different social, ecological, economic, energy-related, and technological marine-coastal settings. The trade-off analysis based on the ML technique (Fig. 4) identified the cost-benefits in different planning subdivisions providing novel insights for future designs of maritime spatial plans that should aim to minimize the identified costs. For instance in the ESAL subdivision planning measures are required to ensure spatial-efficiency of allocation of HPA-OWE, in the LEBA technological solutions are required to reduce damage from increasing storm events and in the NOR, OWE-aquaculture multi-use potentialities should be further explored. Overarching to every subdivision remain the ecological risks from the interaction of the infrastructure with the ecological features that appear to be different in every subdivision (Fig. 4B): risks to habitats (NOR and CAN), to birds (ESAL, LEBA), to mammals (LEBA and CAN) and to fish (ESAL). Our model informs planners on the ecological risks in each planning subdivision that can, in the future, be used to provide recommendations for the design of the HPA-OWE, explore nature-inclusive solutions designed for specific HPA-OWE or based on precautionary principles recommend no-development areas.

Our study incorporates a fully novel indicator set on the energy-equity highlighting that there are spatial disparities in coastal provinces where HPA-OWE are planned. OWE allocation within MSP process needs to be integrated with distributional equity principles when defining HPA-OWE. The indicators include energy production-consumption balance, renewable energy production, provincial contribution to regional energy production, decarbonization policies aimed at coal plants closure or repurposing (CRiT—Coal Regions in Transition, 2017)[27] and social conditions, including unemployment rate (in %) and GDP per capita (see Table 3). Between 2019 and 2023, in coastal regions and provinces of Spain, there are at least 10 coal power plants shut down totaling about 7452 MW of lost energy production (Supplementary Table 2). Our ML results (Fig. 4) show that energy-equity aspects are important within the multi-criteria technique: applying National Statistics data (2021) shows that socio-economic wealthy coastal provinces are, in some cases, "*energy privileged*" areas (Supplementary Tables 1 and 2): For instance coastal provinces of the Levantine-Balearic subdivision (LEB1—Girona province and LEBA2&3-Las Palmas province) have highest GDP per capita (€28,666–€28,325 per year), comparably low unemployment rates (12.7%-14.9%) in respect to Canary Island (€21,344–€21,164; 23–23.5%) or Straight-Alborán (€18,861–€19,276; 20.4–22.2%) subdivision and their coastal regions are little affected by decarbonization policies aimed at coasl plants closure or repurposing. However, the Girona province in front of LEBA1 HPA-OWE is the most energy-reliant coastal province with the most negative energy balance of −3921 GWh (produced vs. consumed ratio) among the 9 coastal provinces and the Principality of Asturias.

The proposed socio-ecological dataset is composed of four risk indicators (risk to habitats, marine mammals, birds, and fish; Fig. 2). Particularly relevant in this context is the application of cross-seabasin datasets of fish, birds, and mammals at the scale relevant for strategic environmental assessment with a common methodology applicable at Mediterranean (LEBA and ESAL) and Atlantic seabasin level (NOR and CAN). The results indicate the need for techniques in cumulative effects assessment that can be coupled with species distribution models adequate for addressing the multiple interactions of the infrastructures with the ecological receptors. The ML results for the socio-ecological tier indicate that the LEBA planning subdivisions with the highest importance for impacts on the coastal tourism sector (Fig. 4): areas show to be highly dependent on coastal tourism employment (between 102,680 and 438,976 jobs; $MSE_{LEBA} = 63\%$) and tourism pressures (161.1–404.6 tourist/inhabitant; $MSE_{LEBA} = 63\%$). The ecological risks are predominant for birds ($MSE_{LEBA} = 52\%$) and marine mammals ($MSE_{LEBA} = 23\%$), for fish in the ESAL ($MSE_{ESAL} = 28\%$), and for marine habitats in the Canary Islands ($MSE_{CAN} = 42\%$).

**Table 3 | Overview, description and unit of the integrated geospatial database development for the analysis of decision dimensions**

| # | Criteria (C) | Abbreviations | C/B | Methodological description |
|---|---|---|---|---|
| *Spatial-Efficiency* | | | | |
| $C_1$ | Area | Area_sqkm | B | *[km$^2$]*. Area occupied by HPA-OWE.<br>**Source:** https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/costas-medio-marino/poem.html |
| $C_2$ | Constrained zones[15,16,55] | Constrain_n | C | *[Number of constrained areas inside the OWE site]*. .Shipping lanes, MPAs and military areas are considered as "*constrained areas*" where any other activity is excluded. The value can range from 0 (no constrain) to 3 (high constrain). **Source:** https://emodnet.ec.europa.eu/geoviewer/; https://www.protectedplanet.net/en. |
| $C_3$ | Collision Risk[55,56] | CR_Ix | C | *[Mean Vessel Density within 6482 m safety buffer from the OWE perimeter]*. The maximum safety buffer identified in literature for OWE sites. Vessel density is considered for Tankers, Cargo, Passenger and Sailing vessels. If it is between 0.5 nm – 3.5 nm (926 m – 6482 m) this is deemed tolerable if the risk is being reduced to as low as reasonably practicable; The Route Density Maps are produced and provided to EMODnet by the European Maritime Safety Agency (EMSA) solely for the purposes of EMODnet. EMODnet shall ensure the storage of the received the data and prepare and distribute maps via the EMODnet portal using its own data conversion and presentation tools and methodologies. The data made available through EMODnet portal and the maps produced by EMODnet from the data shall have reference to EMSA as the source of data. Users shall make reference to EMSA as the source of data when using them, promoting them or generating related publications, whatever the purpose. EMODnet Human Activities accepts no responsibility or liability whatsoever for the re-use of content accessible on its website.<br>**Source:** https://emodnet.ec.europa.eu/geoviewer/. |
| $C_4$ | Restricted vs prohibited sites | Gov_perc | C | *[%]*. This criterion describes if the *HPA-OWE* site is fully or partially located inside a restricted area.<br>**Source:** https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/costas-medio-marino/poem.html. |
| $C_5$ | Fishery Displacement[57] | Mean_Fish_effort_hours | C | *[Sum of hours in fishing effort (FE) foregone within the perimeter of the OWE site]*. The Displacement for the years 2022-2023 is calculated using the Spatial Statistics as Table toolbox available in ArcGIS 10.7. The higher *FE*, the higher the number of fishing hours inside the HPA-OWE site and therefore the displacement score:<br>$FE = R_{OWE} \cap F_{GFW}$<br>**Source:** https://globalfishingwatch.org/map/index |
| $C_6$ | Overlay of MPAs | MP_perc | C | *[Number of protected areas within 5 km buffer]*. MPA usually include already a protection buffer, however it is unclear whether in this case if they include. We use safety buffer to enhance the precautionary approach in this study. **Source:** https://www.protectedplanet.net/en. |
| $C_7$ | Adjacency to MPA | MPA_5km_buffer | C | *[%]*. Percentage of protected areas within 5 km buffer from the HPA PWE perimeter.<br>**Source:** https://www.protectedplanet.net/en. |
| $C_8$ | Distance from MPAs | MPA_5km_buffer_n | C | *[Number of protected areas within 5 km buffer]*. MPA usually include already a protection buffer, however it is unclear whether in this case if they include. We use safety buffer to enhance the precautionary approach in this study. **Source:** https://www.protectedplanet.net/en. |
| $C_9$ | Space demand | Space_dem_perc | C | *[%]*. Percentage of area occupied by HPA-OWE inside the respective planning subdivision.<br>**Source:** https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/costas-medio-marino/poem.html (HPA-OWE); |
| $C_{10}$ | Distance to electricity substastion | Substation_dist_km | C | *[km]*. Calculated from the center point of OWE polygon to the closest substations, according to national electricity map *(mapa red electrica, 2016)*.<br>**Source:** https://eepublicdownloads.entsoe.eu/clean-documents/Publications/maps/2019/ Map_ENTSO-E-4.000.000.pdf. |
| $C_{11}$ | Telecommuncation cables[55] | Telecom_km | C | *[km]* Length of telecommunication cables inside the HPA-OWE sites.<br>**Source:** https://emodnet.ec.europa.eu/geoviewer/ |
| *Energy-Equity* | | | | |
| $C_{12}$ | Decarbonization policies | Decarbonization_lostMW | C | *[Index]*. Lost MegaWatt (MW) production due to closure of coal plain coastal regions in front of HPA-OWE sites in the period 2019-2023. The index is normalized on a scale from 0 to 1. See Supplementary Table 2 for further details on decommissioned power plants.<br>**Source:** https://www.boe.es/buscar/act.php?id=BOE-A-2020-6621&p=20230629&tn=1#an |
| $C_{13}$ | Energy Balance[58] | Energy_bal_Idx | C | *[Index]*. Net provincial energy generation and provincial energy consumed ($E_{generation} - E_{production}$).<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm |

**Table 3 (continued) | Overview, description and unit of the integrated geospatial database development for the analysis of decision dimensions**

| # | Criteria (C) | Abbreviations | C/B | Methodological description |
|---|---|---|---|---|
| $C_{14}$ | GDP per capita[58] | GDPpercapita | C | *[€/inhabitant]*. Annual GDP per inhabitant in a given coastal province.<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{15}$ | Installation_Capacity[59] | Install_Cap_MW | B | *[MW/km$^2$]*. The technical potential for each opportunity zone is retrieved from the Energy System Management Assistance Program (ESMAP) for Spain. It has been computed by assuming a density of 3 MW per km$^2$ for wind speeds between 7–8 m/s and 4 MW per km$^2$ for wind speeds greater than 8 m/s.<br>**Source:** https://www.esmap.org/esmap_offshorewind_techpotential_analysis_maps. |
| $C_{16}$ | Population density | Pop_dens_ppersqkm | C | *[inhabitant/km$^2$]*. Population density per coastal province in front of HPA-OWE sites for 2021.<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{17}$ | Contribution to regional renewable energy production[58] | Re_energy_perc | B | *[%]*. Provincial production of energy from renewable resources (hydropower, wind, nuclear, solar) for the year 2019. **Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{18}$ | Contribution to regional energy production[58] | Reg_contr_perc | B | *[%]*. Contribution of the province to regional energy production in 2019, including combustibles, solar energy (photovoltaic and thermic), wind energy and nuclear.<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{19}$ | Unemployment[58] | Unemployment_perc | C | *[%]*. Percentage of unemployment for the year 2021. **Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| *Socio-Ecological* | | | | |
| $C_{20}$ | Coastal tourism | Beaches_n | C | *[number of beaches]*. Coastal tourism was taken into consideration by defining the number of beach within a buffer area of 82 km from the OWE site. 82 km is considered the visibility limit of a turbine of 250 m height. Dataset on beaches was collected from GeoFabrik 2022.<br>**Source:** https://www.geofabrik.de/. |
| $C_{21}$ | Distance from shore | Distance_km | B | *[km]*. Shortest distance from shore to OWE site. This was mapped with ArcGIS.<br>**Source:** https://emodnet.ec.europa.eu/geoviewer/. |
| $C_{22}$ | Population density | Pop_n | C | *[Population/km$^2$]*. Density of population in coastal provinces for the year 2017.<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm |
| $C_{23}$ | Ecological risks—birds | RiskBirds_Idx | C | *[Index]*. Ecological risk[60,61] assessment was performed as the product of the Sensitivity *S* of the *i-th* ecological feature (marine mammals, fish species, birds and habitats), that are exposed *Exp* to the *j-th* stressor exerted by an OWE installation:<br>$R_{HPA-OWE} = S_i \, x \, Exp_j$<br>whereas,<br>$Exp_j = Ef_j \, x \, d_j$<br>$Ef_j$= *number of ecological features in terms of species (marine mammals, fish species, birds) or number of different habitats (Circalittoral sand, Infralittoral rock and biogenic reef, Infralittoral sand, Offshore circalittoral coarse sediment, Offshore circalittoral mixed sediment, Offshore circalittoral mud, Offshore circalittoral rock and biogenic reef, Offshore circalittoral sand, Bathyal).*<br>$d_j$= *propagation distance of pressure j in km (0 to maximum 50 km).*<br>The exposure (*Exp*) includes the following stressors according to the sea-basin wide harmonized pressure and sensitivity score available in Supplementary Table 3 and 4 of the European Information Network (EIONET) Technical Report: *i*) Introductions of non indigenous species; *ii*) Physical loss of seabed; *iii*) Physical disturbance to seabed; *iv*) Changes to hydrological conditions; *v*) Input of hazardous substances; *vi*) Input of continuous anthropogenic sound. **Source:** https://emodnet.ec.europa.eu/geoviewer/ (*marine habitats*); https://www.iucnredlist.org/resources/spatial-data-download (*marine mammals, fish and birds*). |
| $C_{24}$ | Ecological risks—-fish | Riskfish_Idx | C | |
| $C_{25}$ | Ecological risks—habitats | RiskHabitats_Idx | C | |
| $C_{26}$ | Ecological risks—marine Mammals | Riskmammals_Idx | C | |
| $C_{27}$ | Employment in tourism sector[58] | Tourist_employment | C | *[number of person]*. Number of employees in hotelier, camping and tourist apartments sector per coastal province in front of HPA-OWE sites for the year 2021. **Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{28}$ | Tourism pressure | Tourist_press_touristper1kinh | C | *[number of arrivals per 1000 inhabitants]*. Tourism pressure: number of arrivals per 1000 inhabitants in coastal province for the year 2021. **Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |

**Table 3 (continued) | Overview, description and unit of the integrated geospatial database development for the analysis of decision dimensions**

| # | Criteria (C) | Abbreviations | C/B | Methodological description |
|---|---|---|---|---|
| $C_{29}$ | Urbanization | Urbanization_perc | B | *[%]*. Percentage of urbanized coastal municipalities within 50 km from the HPA-OWE based on CORINE Land Cover 2018. The land uses include: airports, construction sites, continuous urban fabric, discontinuous urban fabric, dump sites, industrial or commercial units, mineral extraction sites, port areas, road and rail networks and associated land and sport and leisure facilities.<br>**Source:** https://doi.org/10.2909/960998c1-1870-4e82-8051-6485205ebbac (raster 100 m) |
| *Technical/ technological* | | | | |
| $C_{30}$ | Average wind speed[62] | AWS_mpersec | B | *[m/s]*. Average wind speed at 200 meter height derived from the Global Wind Atlas (2021), calculated with ArcGIS 10.7 zonal Statistics. **Source:** https://globalwindatlas.info/en |
| $C_{31}$ | Depth[55] | Depth_m | C | *[m]*. Average depth of the OWE site polygon calculated using EMODNet (2020) Bathymetry with ArcGIS 10.7 zonal Statistics. **Source:** https://emodnet.ec.europa.eu/geoviewer/. |
| $C_{32}$ | Wave height | MeanWaveHeight_m | C | *[meters]*. The mean wave height inside a HPA-OWE was calculated with ArcGIS 10.7 zonal statistics using Iberia Biscay Ireland Significant Wave Height extreme from Reanalysis of the Copernicus Marine Services.<br>**Source:** https://data.marine.copernicus.eu/product/IBI_OMI_SEASTATE_extreme_var_swh_mean_and_anomaly/description |
| $C_{33}$ | Ocean Multi-Use[25,55] | MU_Idx | B | *[Index]*. This index describes the MU potential for each OWE site in relation with the aquaculture sector. The index reflects the industrial agglomeration, which is a form of spatial organization in which the same industry or related enterprises are relatively concentrated within a specific geographical scope[63]. Level of commercial specialization of the coastal province to aquaculture development was defined by the number of companies active in the finfish, mussel and algae sector ($C_{aquaculture}$). The level of specialization of coastal regions to the OWE sector was calculated by the number of companies in OWE in Spain ($C_{owe}$) using information derived from JRC's Low Carbon Observatory Report (2019)[64]. Distance ($d_{ports}$; in km) from the center point of the OWE infrastructure from major regional industrial ports in Spain according to Filgueira-Vizoso[65]. using distance toolbox in ArcGIS.<br>$MU_{potential} = (C_{aquaculture} + C_{owe})d_{ports}$<br>**Source:** https://emodnet.ec.europa.eu/geoviewer/ |
| $C_{34}$ | Photo Voltaic potential[30] | OWEPV_Watt | B | *[Watt/m²]*. Photovoltaic Resource calculated for June, July, and August of 2022. Data used to calculate PV resource: 1. ERA5 10 m Wind Speed (m/s); 2. ERA5 2 m Air Temperature (K); 3. Meteosat Surface Solar Irradiance (Watt/m²)[30]<br>**Source:** https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview**;** https://osi-saf.eumetsat.int/products/osi-304-a. |
| $C_{35}$ | Distance to ports | Port_dist_km | C | *[km]*. Shortest distance from shore to HPA-OWE site calculated with distance tool of ArcGIS 10.7<br>**Source:** https://emodnet.ec.europa.eu/geoviewer/. |
| $C_{36}$ | Slope suitability | Slope_suit | C | *[%]*. Percentage of highly suitable slope (0-4 degrees) for floating offshore wind energy infrastructure within the HPA-OWE sites. **Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{37}$ | Thunderstorms[66] | Storms_Idx | C | *[frequency of thunderstorms]*. This indicator defines the number of Thunderstorms within the period from 2021-2050 based on 14 regional climate models (EURO-CORDEX). The datasets is made available through Rädler et al. 2019. The dataset is aggregated as wind, lighting and hail.<br>$S_{2021-2050} = f_{wind} + f_{lighting} + f_{hail}$<br>**Source:** Rädler et al.[66]. |
| $C_{38}$ | Substrate suitability | Substrate_suit_perc | C | *[%]*. Percentage of highly suitable substrate (sand, fine mud, sandy mud, muddy sand) for floating offshore wind energy infrastructure within the HPA-OWE sites.<br>**Source:** https://www.ine.es/dyngs/INEbase/listaoperaciones.htm. |
| $C_{39}$ | Technical Potential[59] | TP_x | B | *[Index]*. Total installation capacity estimated by the technical capacity calculated using Wind Atlas datasets and ESMAP (Energy Sector Management Assistance Program). The technical potential for each HPA-OWE site is computed assuming a density of 3 MW per km² for wind speeds between 7–8 m/s and 4 MW per km² for wind speeds greater than 8 m/s. The indicator is normalized from 1 (high potential opportunity area) to 0 (low potential opportunity area) defines the overlay with the opportunity area.<br>**Source:** https://www.esmap.org/esmap_offshorewind_techpotential_analysis_maps |

*Note:* C-Cost, B-Benefit

Spatial efficiency in the HPA-OWE allocation shows that the ESAL1 and 2 in the Straight-Alborán subdivision face the highest planning-efficiency challenges. The *C-MSE* (Fig. 4A) is the highest among all planning subdivisions ($C\text{-}MSE_{ESAL} = 233.81\%$). ESAL1 and 2 are the HPA-OWE that have the highest space demand (Fig. 4; $MSE_{ESAL} = 88\%$). In the ESAL, the installation of OWE also requires planning measures associated with submerged cable protection and intersection in the area ($MSE_{ESAL} = 74\%$). Our model evidence that spatial compatibility of HPA-OWE with MPAs is an important planning conundrum in LEBA ($MSE_{LEBA} = 85\%$) and the ESAL ($MSE_{ESAL} = 14\%$) due to spatial adjacency and in CAN ($MSE_{CAN} = 40\%$) due to overlay of HPA-OWE and MPA. To analyze the interaction with commercial fishery activities we analyze the overlay of HPA-OWE with fishing hours in the year 2021. The highest displacement is caused within the North Atlantic Demarcation ($MSE_{NOR} = 27\%$; 34,368 h of displacement).

About 14.6% of the study area is covered by military areas, so that exploring wind energy potentials in military areas as envisioned in the DG ENER's SYMBIOSIS Program[28] can promote co-location of military area with HPA-OWE and alleviate spatial competition with sectors omitted from military areas. Particularly relevant is this aspect in the Southern Atlantic subdivision (see Fig. 1) where presence of military areas is particularly pronounced.

In terms of technical/technological tiers, there is an increasing interest on a European level (European Maritime, Fishery and Aquaculture Fund 2023) to promote multi-use as synergic use of infrastructure in maritime spatial plans (e.g., Italian MSP proposal for the Tyrrhenian Sea) and identify regulatory mechanisms for multi-use licensing. Our model takes into consideration OWE combination with aquaculture[29] and hybrid energy infrastructure with solar energy[30]. Figure 4 shows that OWE-aquaculture is one of the important technical/technological solutions in the North-Atlantic ($MSE_{NOR} = 77\%$), Canary Islands ($MSE_{CAN} = 73\%$), and the Straight-Alborán ($MSE_{ESAL} = 64\%$).

The cross-seabasin nature of the study (Atlantic Ocean and Mediterranean) poses substantial challenges in the data collection, criteria preparation, and analysis phase. Currently, for Spain, there are very few comprehensive studies on biodiversity distribution applicable to the entire Spanish maritime spatial plan. Studies are either sea-basin focused, such as for the Mediterranean (Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea, and contiguous Atlantic—Accobams[31]) or some regions of the North Atlantic planning subdivision Basque Country[32] and OSPAR level[33]. This required in our study a fit-for-purpose mapping approach through the design of a spatial-ecological dataset required as input for the ecological risk analysis (birds, fish, and mammals). A cross-seabasin mapping exercise was the use of the species abundance maps from the IUCN Spatial Data Portal[34] that were scaled on a 5 km$^2$ grid[35]. In contrast, marine habitats were represented through EUNIS maps that are scalable across the European seas. Similarly, the sensitivity scores of habitat types (0–5) and ecological features were derived from sensitivity look-up tables from EIONET[36] for the Atlantic Ocean and the Mediterranean, enabling the development of a scalable approach to cumulative ecological risk mapping for the study area that can also be used in other European seas.

We applied a 5 km buffer to survey the number of marine protected areas in the surroundings of each OWE site and to address the km$^2$ of marine protected areas within 5 km distance from each HPA-OWE (see Supplementary Table 1). Buffer zones as distance-based tools can be an important instrument to enforce precautionary principles within a wider combination of spatial indicators that could be implemented, such as technical solutions, avoidance of sensitive areas and of sensitive periods, pollutant-specific mitigation measures (Methodological Guidance 2021/C 437/01)[37]. We also refer to EU nature legislation (Commission Notice 2020)[38] that expresses the need for caution on the use of buffer zones in wildlife sensitivity mapping, especially when defining zero-development areas in recognition of the uncertainty associated with the spatial data and knowledge.

Another limitation is that small-scale fishery (SSF; vessel length < 15 meters) data is not included in our analysis, but it is a fundamental contributor to local economies in Spain[39–41] and globally[42], so that data collection techniques to better take into account interactions of SSF with HPA-OWE are needed in the near future. To our knowledge, only the Polish Maritime Spatial Plan[43] provides an operational integration of SSF into a national ocean plan.

Building on this work, we argue that incorporating place-based datasets can provide important insights into the energy performance of the study area and offer knowledge for more balanced decisions of future marine energy infrastructure allocation. Maritime spatial plans need to contribute to reducing spatial inequalities by balancing environmental, social, spatial, energy-related, and technological characteristics of a territory. This means that planning approaches aimed at locating offshore wind energy infrastructure in degraded sea areas or urbanized coasts without taking into consideration the social conditions can increase spatial inequalities and further impair environmental resources. Particularly important in this case are social conditions in coastal territories with low income, territories affected by decarbonization policies or high unemployment.

Moreover, knowledge of place-based socio-economic conditions is fundamental for next-generation maritime spatial plans and for a just energy transition. A better understanding of the marine ecosystem services[44]

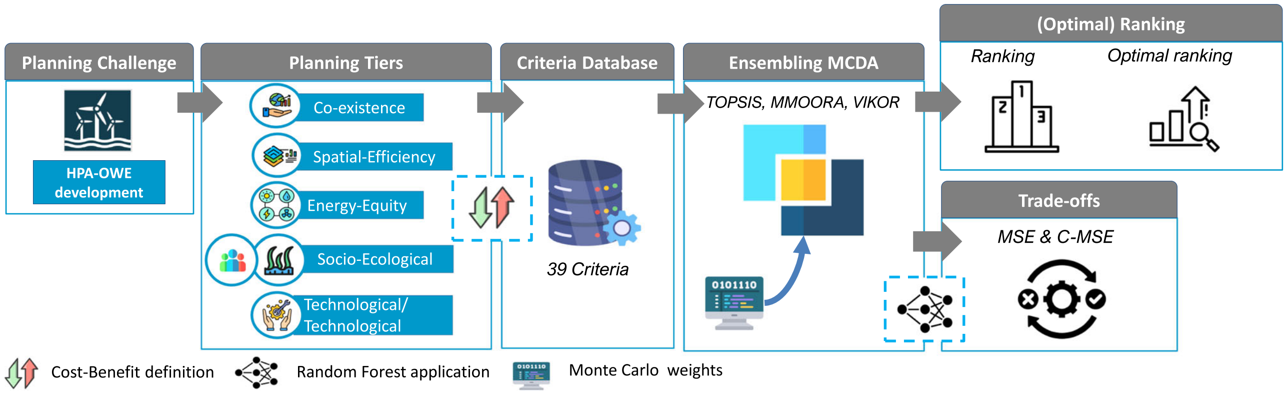

**Fig. 5 | The implementation of the study included the development of a database of 39 criteria and their preparation for analysis.** The Ensemble Multi-Criteria Decision Analysis (EnseMCDA) approach incorporates three distinct multi-criteria methodologies: TOPSIS, MMOORA, and VIKOR. Each of these techniques was executed using a set of 10,000 unique weights for each criterion (39 criteria × 10,000 weights = 390,000 weights). These weights were derived through a Monte Carlo simulation process. Consequently, a total of 30,000 rankings were generated, with each methodology contributing 10,000 ranks. These rankings were then consolidated and presented in the form of priority ranks and optimal priority rankings. This comprehensive approach ensures a robust and reliable decision-making process. Machine Learning Technique based on Random Forest was applied for the identification of trade-offs using a C-MSE—cumulative means standard error (Fig. 3A) and the MSE for single criteria (Fig. 3B).

**Table 4 | Planning tiers applied to EnseMCDA**

| Planning Tiers | Description |
|---|---|
| Coexistence[6] | Allocation of HPA-OWE follows *recital 8* of the EU MSP Directive (2014/89/EU)[67] and the methodological approach of the Spanish Maritime Spatial Plan (Section 2.1.1b)[6] by promoting coexistence among different uses of the sea. |
| Socio-Ecological[68] | HPA-OWE should be allocated in areas where ecological and social costs are minimized, such as distance from coast to avoid visual impacts and in sea areas where cumulative ecological risks to habitats, birds, marine mammals and fish are minimized. |
| Spatial-Efficiency[67] | HPA-OWE should be developed in areas where interactions and conflicts (recital 19; 2014/89/EU)[67] with other uses of the sea are minimized, such as with nature protection, commercial fishery, shipping, cabling, military areas and coastal tourism. |
| Energy-Equity[69,70] | Allocation of HPA-OWE follow distributional equity by considering fair distribution of benefits and burdens to coastal communities, this includes taking into account economic and social disadvantaged coastal regions/provinces, just transition towards low-carbon energy systems and sharing of burden with energetically "*privileged*" provinces. |
| Technical/technological[29,30,66,71] | HPA-OWE should be allocated in sea areas where technical/technological feasibility is maximized, where potentials for multi-use combinations with OWE infrastructure are maximized (with aquaculture and solar energy), weather conditions do not harm infrastructure and where capacity of energy production can be maximized. |

**Table 5 | EnseMCDA decision matrix**

| HPA-OWE alternatives | $C_1$ | $C_2$ | … | $C_{39}$ |
|---|---|---|---|---|
| $HPA\text{-}OWE_1$ | $x_{11}$ | $x_{12}$ | … | $x_{1n}$ |
| $HPA\text{-}OWE_2$ | $x_{21}$ | $x_{22}$ | … | $x_{2n}$ |
| … | … | … | $x_{ij}$ | … |
| $HPA\text{-}OWE_{19}$ | $x_{m1}$ | $x_{m2}$ | … | $x_{mn}$ |

requires the integration of Blue Economy datasets[45–47] (sectorial jobs, revenue), as they enable to understanding the costs and benefits of interactions of offshore wind energy with other sectors (especially commercial fishery, tourism, and shipping) of the Blue economy and can help to produce more informed planning outcomes for society.

Through the five planning tiers, we explore stereotypical dimensions of planning choices and the essential need for interdisciplinary knowledge and data for their implementation. Our method provides a relevant starting point for the definition of new generation of MCDA methods for more transparent and robust exploration of planning decisions in OWE development that however can be extended to any other offshore infrastructure, to conservation planning or any other coastal and maritime activities allocation.

## Methods

Figure 5 lays out the methodological framework adopted in this study, exemplified for planning challenge of HPA-OWE development. In the following materials and method section and in the supplementary information a detailed description of each methodological step and data sources is provided.

### Defining planning tiers

In order to formulate planning relevant outcomes we define five exploratory planning tiers. Planning tiers can provide a set of plausible spatial planning rationales applicable to sectorial MSP challenges such as OWE development[15,48]. Each of the five planning tiers consists of a descriptive planning narrative (Table 4) derived from the MSP Directive (2014/89/EU), the national plan (BOE-A-2023-5704) and planning research theory. In the EnseMCDA model each tier gets unpacked by a group of criteria. To note is that the coexistence tier is the overall tier and incorporates all 39 criteria displayed in Fig. 2 and described in Table 3.

### Criteria database and preparation

The criteria were developed using a comprehensive open-source database of indicators. In total 39 indicators were developed (Table 3) and organized into four categories (ecological, social, spatial/technical, and energy-equity; see Supplementary Table 1). Table 3 provides an overview of the criteria including the cost or benefit attribution ($n = 29$ are costs and $n = 10$ are benefits), a methodological description and the data sources. The preparation of the spatial layers was performed with ArcGIS 10.7 (ESRI, 2022). The 19 HPA-OWE (high potential areas for offshore wind energy areas - "*Zonas de alto potencial para el desarrollo de la energía eólica marina*") and the 5 planning subdivisions of the Spanish Maritime Spatial Plan ("*Ámbito espacial del POEM*") were downloaded from MITECO, 2023 (see Fig. 1).

The indicators were then categorized based on a literature review[49] into costs and benefits. We apply a precautionary principle in the cost and benefit attribution selection so that in case a criterion is used in an ambiguous way in different literature, it is defined as cost in our model. Costs refer to anti-ideal solutions that reflect the worst possible value for a specific indicator (e.g., *collision risk, distance to coast, overlay with protected areas*). Benefits refer to ideal solutions that reflect the best possible value for a specific indicator (e.g., *average wind speed, distance from ports*).

### Creating a decision matrix

After the development of the indicator database, a decision matrix (Table 5) is set up with $HPA\text{-}OWE_{1\text{-}19}$ being the 19 alternative HPA-OWE defined within the Spanish Maritime Spatial plan. The alternatives are characterized by a total of 39 criteria ($C_1$–$C_{39}$) described in Table 3.

### Ensembled multi-criteria decision analysis

We apply an ensembled multi-criteria decision analysis (*EnseMCDA*) technique based on the "MCDM" (multi-criteria decision modeling) library available in R programming language[50]. The library has the advantage that it can rank alternatives using three MCDM techniques as follows (Table 6): (i) TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)[19]; (ii) Multi-MOORA (Multi-Objective Optimization by Ration Analysis (MOORA)—Full Multiplicative Form)[21]; (iii) VIKOR (Multicriteria Optimization and Compromise Solution)[20]. Once the cost or benefit of the criteria used and their relative weight have been defined, the algorithms will assign a score for each alternative. However, although it is objective to decide whether the criterion represents a cost or a benefit, the weight attributed to each criterion varies based on the opinions of experts. In order to overcome the expert-based weighting, we apply a non-conditioned weighting mechanism with weights attributed via Monte Carlo simulation, using a continuous uniform distribution. Namely, 10,000 uniformly distributed weights were generated for each criterion in a range between 0.1 (low importance) and 0.99 (very important), as shown in Table 7. The uniform distribution represents an optimal choice in the Monte Carlo simulation when a certain variable is contained in a certain interval, but there is no reason to consider some values more plausible than others[51]. In this way, the alternatives will be evaluated for a wide range of weights. Compared to the traditional method, there are two main advantages: i) The most robust alternatives can be highlighted, whose score varies little as the weights vary and ii) The criteria that most influence the score of the alternatives can be recognized. The adopted approach generates 10,000 rankings for each MCDA method. These results in a total of 30,000 rankings, corresponding

**Table 6 | Normalization methods and three EnseMCDA were applied**

| MCDM Methods | Algorithm | |
|---|---|---|
| Normalization | TOPSIS and MMOORA normalization of the $x_{ij}$ values:<br>$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} (x_{ij})^2}}$ | VIKOR normalization of the $x_{ij}$ values:<br>$n_{ij} = \frac{f_j^* - x_{ij}}{f_j^* - f_j^-}$ |
| TOPSIS—Technique for Order of Preference by Similarity to Ideal Solution[19] | Calculate the ideal or reference solutions, which are the Positive Ideal Solution (PIS), $A^+$, and the Negative Ideal Solution (NIS), $A^-$, as follows:<br>$(PIS) = A^+ - \left\{v_1^+, v_2^+, \ldots, v_j^+\right\}$<br>$(NIS) = A^- - \left\{v_1^-, v_2^-, \ldots, v_j^-\right\}$<br>where $v_j^+ = max_i(v_{ij})$ and $v_j^+ = \min_i(v_{ij})$ if the $j^{th}$ criterion is benefit; and $v_j^+ = \min_i(v_{ij})$ and $v_j^- = \max_i(v_{ij})$ if the $j^{th}$ criterion is cost, $i = 1,2,\ldots,m$ and $j = 1,2,\ldots,n$.<br>Calculate the distances from every alternative to the ideal solution, being $d_i^+$ the distance to $A^+$ and $d_i^-$ the distance to $A^-$.<br>Best<br>$d_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^+)^2}, i = 1, 2, \ldots m; j = 1, 2, , \ldots, \mathrm{n},$<br>Worst<br>$d_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, i = 1, 2, \ldots m; j = 1, 2, , \ldots, \mathrm{n},$<br>which corresponds to the m-dimensional Euclidean distance.<br>Calculate the relative Closeness:<br>$R_i = \frac{d_i^-}{d_i^+ + d_i^-}$ | |
| MMOORA—Multi-Objective Optimization by Ration Analysis[21] | $u(y, z) = k_y u_{y(y)} + k_z u_z(z) + k_{yz} u_y(y) u_z(z)$<br>If $k_{yz} = 0$ we return to the additive form. For Keeney the additive form is rather a limiting case of the multiplicative utility function (Keeney 1973: 110)[1].<br>If $k_{yz} \neq 0$, then the utility function possesses a multiplicative part:<br>if $k_{yz} > 0$, then the mutual influence is positive,<br>if $k_{yz} < 0$, then the mutual influence has a negative effect on the utility function.<br>$U_j = \prod_{i=1}^{n} X_{ij}$ | |
| VIKOR—Multicriteria Optimization and Compromise Solution (in Serbian VIseKriterijumska Optimizacija I Kompromisno Resenje)[20] | Determine the best $f_j^*$ and worst $f_j^-$ values of each criterion as $f_j^* = \max_i(x_{ij})$ and $f_j^- = \min_i(x_{ij})$ if the $j^{th}$ criterion is benefit, and as $f_j^* = \min_i(x_{ij})$ and $f_j^- = \max_i(x_{ij})$ if the $j^{th}$ criterion is cost, $i = 1,2,\ldots,m$ y $j = 1,2\ldots,n$.<br>Calculate value $S_i$ and $R_i$ $i = 1,2,\ldots,m$ and $j = 1,2,\ldots,n$:<br>$S_i = \sum_{j=1}^{n} w_j * n_{ij}$<br>$R_i = \max[w_j * n_{ij}]$<br>$Q_i = v + \frac{(S_i - S^*)}{S^- + S^*} + (1 - v)\frac{(R_i - R^*)}{R^- + R^*}$<br>where $\mathrm{S}^* = \min_i\left(S_i\right), S^- = \max_i(S_i), R^* = \min_i(R_i), R^- = \max_i\left(R_i\right)$, and $v \in [0,1]$.<br>Parameter $v$ balances the relative importance of indexes $S$ and $R$. | |

All algorithms were retrieved from R MCDM Package documentation[50].

**Table 7 | Summary of uniformly distributed weights matrix, defined for the 39 criteria ($C_1$–$C_{39}$)**

| *Weights* | $C_1$ | $C_2$ | $C_3$ | … | $C_{39}$ | $\sum W_i$ |
|---|---|---|---|---|---|---|
| $W_1$ | 0.12 | 0.08 | 0.53 | $W_{Ci}$ | 0.24 | 1 |
| $W_2$ | 0.51 | …. | 0.21 | …. | …. | 1 |
| $W_3$ | …. | 0.32 | …. | …. | …. | 1 |
| …. | 0.02 | …. | 0.03 | …. | 0.89 | 1 |
| $W_{10000}$ | …. | 0.21 | …. | …. | 0.09 | 1 |

to the number of weights produced through the Monte Carlo simulation. The results were visually represented using boxplots (Fig. 3) to display all the scores acquired from each HPA-OWE.

## Optimal ranking

Reducing complexity in spatial decision-making is pivotal as it helps build consensus and agreement among stakeholders with diverse backgrounds and perspectives. For this purpose we synthesize results with an optimal ranking. The optimal ranking is the definitive rank ($R$) that calculates how often a HPA-OWE falls within the top-10 ranks ($n_{top\text{-}10}$) of the ranking database generated. Table 1 provides a synthesis of the results for the Atlantic (CAN and NOR) and the Mediterranean subdivisions (ESAL and LEBA). In Supplementary Figure 1, a graphical representation of $n_{top\text{-}10}$ is provided.

## Trade-off analysis

Trade-off analysis is the process of evaluating the costs (disadvantages) and benefits (advantages) associated with different decisions, actions, or allocations of resources within maritime areas. In ocean planning, trade-off analysis can be important because it helps choose the optimal location of wind farms and minimizes conflicts among the multiple sectors, resources, and values. This improves transparency in the decision-making process, promotes efficient solutions, and maximizes sector values. In ocean planning, a limitation of trade-off analysis is the local geographic scope and its dual or triple sector analysis (e.g., offshore wind energy—fishery—marine protection)[52,53] often settled into the ecosystem services domain[49].

To identify the costs and benefits that significantly impact the scores of the 19 HPA-OWE alternatives examined in this study, we employed the random forest machine learning (ML) algorithm from the "*randomForest*" R package[54]. This algorithm is suitable for both classification and regression tasks and assesses the importance of variables involved in the model by calculating the increase in the model's mean square error ($MSE$) when a variable is omitted. The algorithm was trained using the weight matrix, which was assigned to the 39 criteria, as predictors (e.g., $W_1$, $W_2$,…,$W_{10,000}$) and the average score derived from the EnseMCDA for a specific HPA-OWE alternative (e.g., $\tilde{x}$ Scores-$W_1$, $\tilde{x}$ Scores-$W_2$, …, $\tilde{x}$ Scores-$W_{10,000}$) as response variable. This training process enabled the algorithm to discern how score variations for each HPA-OWE are influenced by the weights assigned to the different criteria. To characterize the importance of the planning tiers at the planning subdivision level we formulate a cumulative MSE (*C-MSE*) for each planning subdivision. The results (Fig. 4B) unveil what costs and benefits affect most significantly the average score obtained from the four planning subdivisions, providing a robust trade-off analysis at the relevant planning scale. Supplementary information (Table 5) provides a look-up table with the MSE scores for each planning subdivision and planning tier.

## Data availability

The dataset composing the criteria used in this study is available in the supplementary material and upon request to the corresponding author for reasonable use in research.

Received: 7 May 2024; Accepted: 2 September 2024;

## References

1. EC (European Commission). *Offshore Renewable Energy*. https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en. (2024). Accessed 23/04/2024.
2. IRENA (International Renewable Energy Agency). *Enabling Frameworks for Offshore Wind Scale Up: Innovations in Permitting*. https://www.irena.org/Publications/2023/Sep/Enabling-frameworks-for-offshore-wind-scale-up. (2023). Accessed 24/05/2024.
3. Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A. & Cucurachi, S. Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *J. Clean. Prod.* **299**, 126866 (2021).
4. Andrade, J. F. et al. A spatial framework for *ex-ante* impact assessment of agricultural technologies. *Glob. Food Secur.* **20**, 72–81 (2019).
5. Schultz-Zehden, A., Weig, B. & Lukic, I., 2019. Maritime Spatial Planning and the EU's Blue Growth Policy: Past, Present and Future Perspectives. in *Maritime Spatial Planning: past, present, future* (eds Zaucha, J. & Gee, K.) 121–149 (Springer International Publishing, Cham, 2019). https://doi.org/10.1007/978-3-319-98696-8_6.
6. BOE-A-2023-5704 Real Decreto 150/2023, de 28 de febrero, por el que se aprueban los planes de ordenación del espacio marítimo de las cinco demarcaciones marinas españolas. https://www.boe.es/diario_boe/txt.php?id=BOE-A-2023-5704.
7. Ehler, Charles, and Fanny Douvere. Marine spatial planning: a step-by-step approach toward ecosystem-based management—UNESCO Digital Library. https://unesdoc.unesco.org/ark:/48223/pf0000186559 (2009).
8. Martínez-Vázquez, R. M., Milán-García, J., & de Pablo Valenciano, J. Challenges of the Blue Economy: evidence and research trends. *Environ. Sci. Eur.* **33**, 61 (2021).
9. Tafon, R., Saunders, F. & Gilek, M. Re-reading marine spatial planning through Foucault, Haugaard and others: an analysis of domination, empowerment and freedom. *J. Environ. Policy Plan.* **21**, 754–768 (2019).
10. Flannery, W., Clarke, J. & McAteer, B. Politics and Power in Marine Spatial Planning. in *Maritime Spatial Planning: past, present, future* (eds. Zaucha, J. & Gee, K.) 201–217 (Springer International Publishing, Cham, 2019). https://doi.org/10.1007/978-3-319-98696-8_9.
11. Harris, J. L. & Thompson, B. S. Supporting places left to the sea: a place-based research agenda for regional coastal transformations in the blue economy. *Prog. Environ. Geogr.* **2**, 266–288 (2023).
12. Friess, B. & Grémaud-Colombier, M. Policy outlook: recent evolutions of maritime spatial planning in the European Union. *Mar. Policy* **132**, 103428 (2021).
13. Pettersen, S. S. et al. Offshore wind in the race for ocean space: a forecast to 2050. *J. Phys. Conf. Ser.* **2507**, 012005 (2023).
14. Díaz, H. & Soares, C. G. A multi-criteria approach to evaluate floating offshore wind farms siting in the Canary Islands (Spain). *Energies* **14**, 865 (2021).
15. Virtanen, E. A. et al. Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design. *Renew. Sustain. Energy Rev.* **158**, 112087 (2022).
16. Argin, M., Yerci, V., Erdogan, N., Kucuksari, S. & Cali, U. Exploring the offshore wind energy potential of Turkey based on multi-criteria site selection. *Energy Strategy Rev.* **23**, 33–46 (2019).
17. Solbrekke, I. & Sorteberg, A. Norwegian offshore wind power—spatial planning using multi-criteria decision analysis. *Wind Energy* **27**, 5–32 (2023).
18. Ziemba, P. Uncertain multi-criteria analysis of offshore wind farms projects investments—-case study of the Polish Economic Zone of the Baltic Sea. *Appl. Energy* **309**, 118232 (2022).
19. Hwang, C.-L. & Yoon, K. *Multiple Attribute Decision Making*. vol. 186 (Springer, Berlin, Heidelberg, 1981).
20. Opricovic, S. & Tzeng, G.-H. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. *Eur. J. Oper. Res.* **156**, 445–455 (2004).
21. Brauers, W. K. M. & Zavadskas, E. K. Project management by multimoora as an instrument for transition economies. *Ukio Technol. Ir. Ekon. Vystym.* **16**, 5–24 (2010).
22. Gavériaux, L., Laverrière, G., Wang, T., Maslov, N. & Claramunt, C. GIS-based multi-criteria analysis for offshore wind turbine deployment in Hong Kong. *Ann. GIS* **25**, 207–218 (2019).
23. Gkeka-Serpetsidaki, P. & Tsoutsos, T. A methodological framework for optimal siting of offshore wind farms: a case study on the island of Crete. *Energy* **239**, 122296 (2022).
24. Mytilinou, V., Lozano-Minguez, E. & Kolios, A. A framework for the selection of optimum offshore wind farm locations for deployment. *Energies* **11**, 1855 (2018).
25. Weiss, C. V. C. et al. Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago. *Ocean Coast. Manag.* **166**, 62–71 (2018).
26. Novgorodcev Jr, A. R. & Jarquín-Laguna, A. Multi-criteria analysis to rank offshore renewable technologies to support deep-water oil and gas production. in *Developments in Renewable Energies Offshore* (ed. Guedes Soares, C.) 771–778 (CRC Press, 2020). https://doi.org/10.1201/9781003134572-88.
27. EU coal regions in transition—European Commission. https://energy.ec.europa.eu/topics/carbon-management-and-fossil-fuels/eu-coal-regions-transition_en. Accessed 05/05/ 2024.
28. European Defence Agency. Offshore energy and defence require better synergy - EDA Symbiosis conference hears. https://eda.europa.eu/news-and-events/news/2023/06/28/greater-synergies-between-offshore-energy-and-defence-needed-hears-eda-conference. (2023). Accessed 01/05/2024.
29. Depellegrin, D. et al. Exploring multi-use potentials in the Euro-Mediterranean sea space. *Sci. Total Environ.* **653**, 612–629 (2019).
30. Costoya, X., deCastro, M., Carvalho, D., Arguilé-Pérez, B. & Gómez-Gesteira, M. Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: a case study on the western Iberian Peninsula. *Renew. Sustain. Energy Rev.* **157**, 112037 (2022).
31. Panigada, S. et al. The ACCOBAMS survey initiative: the first synoptic assessment of cetacean abundance in the Mediterranean Sea through aerial surveys. *Front. Mar. Sci*. **10**, 1–15 (2024).
32. Pınarbaşı, K. et al. A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning. *Sci. Total Environ.* **667**, 306–317 (2019).

33. Geelhoed, S. C. V., Authier, M., Pigeault, R., Gilles, A. Abundance and Distribution of Cetaceans. In: OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic. *OSPAR Comm. Lond*. (2022).
34. IUCN. *The IUCN Red List of Threatened Species*. https://www.iucnredlist.org/en (2024). Accessed 23/04/2024.
35. Roy, S. et al. Development and analysis of a geospatial database for maritime spatial planning in Bangladesh. *J. Environ. Manag.* **317**, 115495 (2022).
36. Korpinen, S. et al. Combined effects of human pressures on Europe's marine ecosystems. *Ambio* **50**, 1325–1336 (2021).
37. *Commission Notice Assessment of Plans and Projects in Relation to Natura 2000 Sites—Methodological Guidance on the Provisions of Article 6(3) and (4) of the Habitats Directive 92/43/EEC 2021/C 437/01*. (2021).
38. Directorate-General for Environment (European Commission). *Guidance Document on Wind Energy Developments and EU Nature Legislation*. (Publications Office of the European Union, 2020).
39. Murillas-Maza, A., Mugerza, E., Bachiller, E., Errazkin, L. A. & Louzao, M. Participatory-based bio-economic activity mapping of small-scale fisheries: towards holistic management in the Bay of Biscay. *ICES J. Mar. Sci.* **80**, 1202–1217 (2023).
40. Romero Manrique de Lara, D. & Corral, S. Local community-based approach for sustainable management of artisanal fisheries on small islands. *Ocean Coast. Manag.* **142**, 150–162 (2017).
41. Márquez Escamilla, A., Herrera-Racionero, P., Pastor Gimeno, J. & Miret-Pastor, L. The artisanal fishing sector in the Spanish mediterranean: a sector with a long history and an uncertain future. *J. Mar. Sci. Eng.* **10**, 1662 (2022).
42. FAO. *El estado mundial de la pesca y la acuicultura 2020: La sostenibilidad en acción*. (FAO, Rome, Italy, 2020).
43. Psuty, I., Kulikowski, T. & Szymanek, L. Integrating small-scale fisheries into Polish maritime spatial planning. *Mar. Policy* **120**, 104116 (2020).
44. Burgess, M. G., Clemence, M., McDermott, G. R., Costello, C. & Gaines, S. D. Five rules for pragmatic blue growth. *Mar. Policy* **87**, 331–339 (2018).
45. Depellegrin, D. et al. Innovating the blue economy: a novel approach to stakeholder landscape mapping of the Atlantic Area Sea Basin. *Front. Mar. Sci.* **9**, 1–14 (2022).
46. Hamdy, N. & Bevilacqua, C. Assessing the Role of the Blue Economy in the Comprehensive Development of Lagging Coastal Areas. A Case Study of Calabria. in *New Metropolitan Perspectives* (eds Bevilacqua, C., Balland, P.-A., Kakderi, C. & Provenzano, V.) 21–45 (Springer International Publishing, Cham, 2023). https://doi.org/10.1007/978-3-031-34211-0_2.
47. McGowan, L., Jay, S. & Kidd, S. Scenario-building for marine spatial planning. in *Maritime Spatial Planning: Past, Present, Future* (eds Zaucha, J. & Gee, K.) 327–351 (Springer International Publishing, Cham, 2019). https://doi.org/10.1007/978-3-319-98696-8_14.
48. Gusatu, L. F., Yamu, C., Zuidema, C. & Faaij, A. A spatial analysis of the potentials for offshore wind farm locations in the North Sea region: challenges and opportunities. *ISPRS Int. J. Geo-Inf.* **9**, 1–35 (2020).
49. Lester, S. E. et al. Evaluating tradeoffs among ecosystem services to inform marine spatial planning. *Mar. Policy* **38**, 80–89 (2013).
50. Ceballos, B., Lamata, M. T. & Pelta, D. A. *MCDM: Multi-Criteria Decision Making Methods with R*. https://www.imsbio.co.jp/RGM-files/R_CC/download/MCDM/vignettes/MCDM.pdf.
51. Harrison, R. L. Introduction to Monte Carlo simulation. *AIP Conf. Proc.* **1204**, 17–21 (2010).
52. Smythe, T., Bidwell, D., Moore, A., Smith, H. & McCann, J. Beyond the beach: tradeoffs in tourism and recreation at the first offshore wind farm in the United States. *Energy Res. Soc. Sci.* **70**, 101726 (2020).
53. White, C., Halpern, B. S. & Kappel, C. V. Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. *Proc. Natl. Acad. Sci. USA* **109**, 4696–4701 (2012).
54. Liaw, A. & Wiener, M. Classification and Regression by random Forest. *R. N.* **2**(3), 18–22 (2002).
55. EMODnet Map Viewer. https://emodnet.ec.europa.eu/geoviewer/ (2024). Accessed 04/05/2024.
56. Fetissov, M. et al. Towards navigational safety of ecosystem based Maritime Spatial Planning solutions. *SHS Web Conf.* **58**, 01008 (2018).
57. Chollett, I., Box, S. J. & Mumby, P. J. Quantifying the squeezing or stretching of fisheries as they adapt to displacement by marine reserves. *Conserv. Biol.* **30**, 166–175 (2016).
58. Spanish Statistical Office. *INE*. https://www.ine.es/en/. Accessed 03/02/2024.
59. ESMAP (Energy Sector Management Assistance Program), 2019. OFFSHORE WIND TECHNICAL POTENTIAL | ANALYSIS AND MAPS. 1–12 (2019). Web: https://www.esmap.org/esmap_offshore-wind, accessed 02/06/2024.
60. IUCN. Spatial data download for marine species. (2022).
61. Korpinen, S. et al. *Multiple Pressures and Their Combined Effects in Europe's Seas*. ETC/ICM Technical Report 4/2019: European Topic Centre on Inland, Coastal and Marine waters,164 (2019).
62. Global Wind Atlas. https://globalwindatlas.info. Accessed 04/08/2023.
63. Zheng, Z., Zhu, Y., Pei, Y. & Wang, L. Spatial–temporal heterogeneity and influencing factors of the coupling between industrial agglomeration and regional economic resilience in China. *Environ. Dev. Sustain.* **25**, 12735–12759 (2023).
64. Telsnig, T. et al. *Clean Energy Technology Observatory: Wind Energy in the European Union—2022 Status Report on Technology Development, Trends, Value Chains and Markets* (2022).
65. Filgueira-Vizoso, A. et al. How important are ports for the offshore wind industry?: the case of Spain. *Renew. Energy Power Qual. J.* **19**, 121–125 (2021).
66. Rädler, A. T., Groenemeijer, P. H., Faust, E., Sausen, R. & Púčik, T. Frequency of severe thunderstorms across Europe expected to increase in the 21st century due to rising instability. *Npj Clim. Atmos. Sci.* **2**, 1–5 (2019).
67. *Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 Establishing a Framework for Maritime Spatial Planning*. *OJ L* vol. 257 (2014).
68. Galparsoro, I. et al. Operationalisation of ecosystem services in support of ecosystem-based marine spatial planning: insights into needs and recommendations. *Mar. Policy* **131**, 104609 (2021).
69. Stokes, L. C., Franzblau, E., Lovering, J. R. & Miljanich, C. Prevalence and predictors of wind energy opposition in North America. *Proc. Natl. Acad. Sci. USA* **120**, e2302313120 (2023).
70. Barlow, J., Tapio, R. & Tarekegne, B. Advancing the state of energy equity metrics. *Electr. J.* **35**, 107208 (2022).
71. Schupp, M. F. et al. Toward a common understanding of ocean multi-use. *Front. Mar. Sci.* **6**, 1–12 (2019).

## Acknowledgements

This research was funded by 1) *Blue-Paths—Addressing Sustainability Transition Pathways in the Blue Economy* (https://blue-paths.eu/) funded by the European Commission (Grant Agreement: 101062188) under the HORIZON—Marie Skłodowska-Curie Actions 2021 of the Horizon Europe program and by 2) the Ramón y Cajal grant RYC2022-035260-I, awarded by the Spanish Ministry of Science and Innovation (MCIN/AEI/10.13039/501100011033) and by the European Social Fund Plus (ESF+).

## Author contributions

D.D. led the research project, conceived the research idea, defined the analysis principles, collected and prepared the datasets, drafted and tested the code, prepared the paper and the figures and tables (except Fig. 1); M.A. prepared and revised the R-code, supplied and revised the methodological description of the ensemble MCDA and random forest; S.R. prepared the versioning of Fig. 1, oversaw the preparation of indicators and the collection and preparation of the socio-ecological data and technical/technological data; J.S. contributed to the analysis principles and reviewed and

commented on the paper; C.M.L. co-led the research project, contributed to the definition of the analysis principles, and reviewed the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s44183-024-00080-8.

**Correspondence** and requests for materials should be addressed to Daniel Depellegrin.

**Reprints and permissions information** is available at http://www.nature.com/reprints

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2024