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Assessing the potential impacts of floating Offshore Wind Farms on policy-relevant species: A case study in the Gulf of Roses, NW Mediterranean

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ABSTRACT

Our study investigates for the first time how floating Offshore Wind Farms (OWFs) technologies could impact policy-relevant Mediterranean species, focusing on planned OWFs in the Cape Creus/Gulf of Roses (Spain, NW Mediterranean). Using the Generalized Impact Assessment framework, we identified pressure on diverse taxonomic groups. Our species selection prioritized species under European policy (Birds and Habitats Directives) and international/local conventions protecting flora and fauna, as they are vital biodiversity indicators. Our analysis identified 135 policy-relevant species susceptible to OWF-induced stressors, notably marine mammals, seabirds, elasmobranchs, and benthic macroinvertebrates at the highest risk. Among the different stressors, noise and vibration, along with habitat loss, pose the greatest potential impacts. While decarbonizing energy production is crucial for addressing climate change, preserving ocean biodiversity is equally vital. Our study pioneers the assessment of emerging OWFs potential impacts on Mediterranean species, offering valuable insights for decision-makers during OWF planning.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has highlighted the crucial role of transitioning towards renewable energy sources, such as Offshore Wind Farms (OWFs), in limiting global warming [123]. This urgent need for renewable energy sources in the face of the climate crisis is widely acknowledged, as they have the potential to significantly reduce greenhouse gas emissions [100]. However, as we develop and expand these technologies, it is imperative to consider their potential impacts on marine biodiversity, in front of the biodiversity crisis we are also facing. As essential outcomes of COP Climate Change Conferences, we need to ensure that climate adapted solutions also co-deliver to Nature [126]. The biodiversity crisis has brought to the forefront the critical need to protect and conserve marine ecosystems and their biodiversity [139]. OWFs have been shown to have the potential to disrupt marine ecosystems and harm vulnerable species and habitats [76]. Therefore, striking a balance between our energy needs and the health and vitality of our oceans is essential [35]. By conducting thorough evaluations of the potential impacts of OWFs on marine biodiversity, we can help avoid or mitigate negative effects and ensure that marine renewable energy production can be delivered in a sustainable manner that also safeguards marine ecosystems [46].

The Mediterranean region has potential for the development of offshore wind energy, but the industry is still in its early stages. In contrast to other parts of Europe, such as the North Sea and the Baltic Sea, where offshore wind has been operating for more than a decade, the Mediterranean is lagging behind [84]. However, the abundant wind resources present in some regions and proximity to high-energy demand areas make it an attractive location for the development of floating OWFs [120,129]. It is worth noting that floating offshore wind technology is a new development compared to fixed offshore turbines [7], which have been operating for more than a decade in northern European seas. As the urgency to transition to a low-carbon economy grows, there is an opportunity for the Mediterranean region to accelerate the development of its offshore wind energy potential using the latest technologies, such as floating offshore wind, contributing to the decarbonization

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of the economy.

This paper conducts an impact assessment of floating OWF technologies within the Mediterranean Sea, with a specific focus on their potential implications for policy-relevant species. In the context of this study, policy-relevant species are defined as those of high conservation priority due to their vulnerability and population status. These species are explicitly covered by international, national, or regional regulations, specifically European, Spanish, and Catalan laws, as well as non-binding agreements such as conventions aimed at species protection. Policy-relevant species play a crucial role in conservation efforts, as they are central to legal and regulatory frameworks [74]. Recognizing and addressing their significance is essential for the formulation of effective and sustainable environmental policies. By comprehensively understanding how different OWF technologies impact the response and vulnerabilities of these species, we can develop a holistic perspective that facilitates the assessment of OWF impacts on marine biodiversity. This knowledge becomes particularly pivotal in strategic planning for the development of OWFs, especially when these infrastructures have the potential to affect marine protected areas (MPAs) that harbor policy-relevant species [76].

To illustrate these impacts, the paper uses the example of a large floating OWF proposed to be built in the Costa Brava region of the northern Catalan Sea, in the waters of Cape Creus/Gulf of Roses (Spain, NW Mediterranean). This region is known for its high biodiversity and the presence of vulnerable species [24], and the development of an OWF in this area could have significant environmental impacts on it [76]. The paper reviews relevant literature and scientific studies to evaluate the existing knowledge and research on the topic, and to identify potential gaps in our understanding of the impacts of OWFs on policy-relevant species in the Mediterranean.

The outcomes of this research are poised to enhance our comprehension of how OWF development may impact the Mediterranean's environment. They will play a crucial role in devising effective strategies to manage and alleviate these effects, safeguarding the long-term well-being of the region's marine ecosystems. These insights carry significant weight within the contemporary conservation landscape. The Kunming-Montreal Global Biodiversity Framework [22] aspires to expand marine protected areas to 30 % by 2030. Correspondingly, the European Union's Nature Restoration Law [39] aims to restore 20 % of degraded habitats by 2020, with a focus on recovering Natura 2000 protected areas by 2050. These commitments underscore the pressing need to counteract human-induced damage to ecosystems and biodiversity. However, these aspirations might collide with the development of offshore wind energy unless meticulous planning minimizes adverse impacts on the delicate Mediterranean habitats and species [87]. Notably, the joint conclusions of the IPCC and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) emphasize the imperative need to address both climate and biodiversity crises concurrently, ensuring that the solutions implemented do not exacerbate the issues they aim to resolve [108]. It is imperative to adopt measures that harmonize OWFs with the conservation of vital Mediterranean ecosystems.

2. Methodology

2.1. Case study

There are currently no operational commercial OWFs in the Mediterranean Sea. However, the European Union's energy policy advocates the installation of OWFs and has established targets for 2030 in collaboration with member countries. Additionally, the Spanish government, in its Maritime Plan Ordination of 2023 [91], has identified specific "Zones of high potential for offshore wind energy" (ZAPER - *Zonas de alto potencial para el desarrollo de la energía eólica marina*). These zones are deemed suitable for the development of commercial offshore wind energy infrastructure. Our study has been conducted in one such area, known as LEBA 1 (or LEvantino BAlear 1) in Cape Creus/Gulf of Roses (Spain, NW Mediterranean, Fig. 1), which is characterized by its high biodiversity and the presence of several MPAs of different categories including Natura 2000 sites [76]. Additionally, this area is classified as "High-potential zone for biodiversity conservation" [91]. This region, along with the proposed floating OWF, serves as a case study to assess potential ecological impacts of such facilities in the Mediterranean Sea.

In the LEBA 1 area, there are six proposed commercial projects and one proposed experimental platform designated for research purposes. Our analysis of the documentation submitted during their Environmental Impact Assessment procedures by the developers has enabled us to identify the technologies and components planned for installation. For clarity, we have categorized them based on different phases of the OWF's life cycle, including exploration and planning, installation and commissioning, and operation and maintenance. Decommissioning and repowering stages were not specifically assessed, given limited research available on these phases. This is particularly true for floating OWFs due to their relatively recent development. Consequently, there is a significant knowledge gap regarding the environmental impacts associated with these stages, necessitating more long-term studies and data.

2.2. Species selection

We first identified the macro-species within our study area through the utilization of the Spanish Node of the Global Biodiversity Information Facility (GBIF.ES, https://www.gbif.es/). This process involved documenting all observed species within the marine region of our study.

Next, we adapted the species selection process detailed in Lloret et al. [75] to identify policy-relevant species susceptible to the impacts of OWFs in an European framework. This approach comprised three main steps. Initially, we encompassed all species protected by the Habitats and Birds Directives (Habitats 92/43/EEC Directive, Birds 2009/147/EC Directive). Then, we included species classified as Critically Endangered (CR), Endangered (EN), Vulnerable (VU), and Near Threatened (NT)

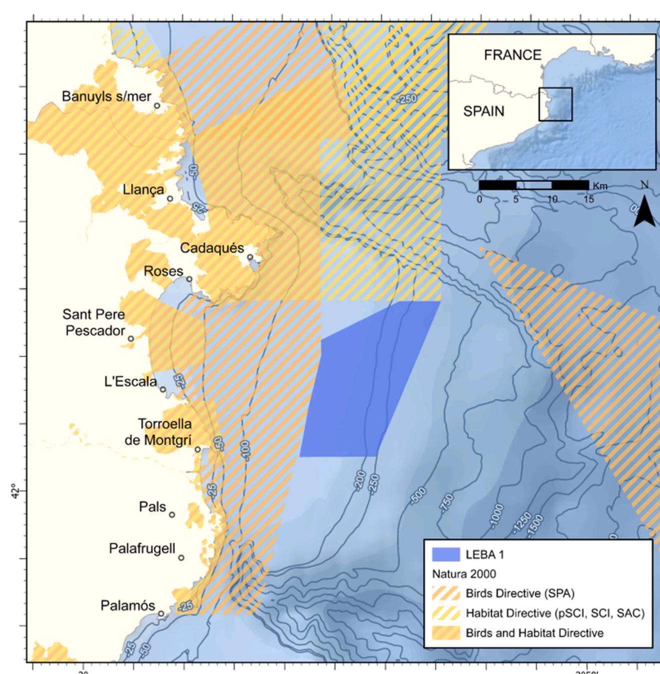

Fig. 1. Study area map. Map displaying the study area of Cape Creus/Gulf of Roses area (Spain, NW Mediterranean) with the location of the LEBA 1 (zone of high potential for offshore wind energy), and Natura 2000 sites (SPA, SCI, and pSCI). SPA: special protection area; SCI: site of community importance; pSCI: proposed sites of community importance.

following the IUCN Red List's Mediterranean regional assessment (www.iucnredlist.org), resorting to the global assessment when regional data were absent. Finally, our selection extended to species protected by international agreements (Barcelona, Bern, Bonn, and CITES conventions) and those with local safeguarding status, documented in the Spanish List of Wild Species under Special Protection Regime, Spanish Catalog of Threatened Species, and Catalan List of protected and threatened species of the native fauna.

We pinpointed 135 policy-relevant species from the 1188 macro-species inhabiting the study area (Table 1, Table A). These species span diverse taxa, with the most prominent concentrations in Aves (33 species), Mammalia (26 species, comprising 7 Cetacea and 18 Chiroptera), and Actinopterygii (18 species). Of these 135 policy-relevant species, 58 enjoy protection under either the Birds or Habitats Directives, with Aves and Mammalia encompassing 25 protected species each under both directives (Table 1).

In this study, we analyze policy-relevant species at the taxonomic group level to capture broad patterns and trends essential for informing conservation and policy measures. By focusing on taxonomic groups, we can address broader ecological implications of floating OWFs while maintaining relevance to policy and conservation priorities.

2.3. Impact assessment

To comprehensively assess the biological effects of floating OWFs, a rigorous literature review protocol was implemented. Initially, generic term like "floating offshore wind farm environmental impact" were used across standard search tools, including Google Scholar,[1] Web of Science,[2] and specialized wind energy environmental databases such as Tethys.[3] Following the identification of primary stressors, focused searches using specific keywords (e.g., "floating offshore wind farm noise and vibrations") were conducted. Moreover, the snowball method [143] was employed to broaden the scope, delving into the references cited within the retrieved studies. A total of 138 studies were selected for inclusion in this comprehensive assessment.

We individually examined identified stressors (pressures) and linked each one to the corresponding technology (driver) responsible for its occurrence and the affected taxa (receptors). The retained stressors for evaluation include collision, noise and vibrations, barrier effect, entanglement, sediment resuspension, spatial behavior perturbation, electromagnetic fields, heat emission, and habitat modifications. To assess the biological impact, we adopted the Generalized Impact Assessment methodology proposed by Bergström et al. [12]. This methodology considers the temporal and spatial extent of the stressor, as well as the sensitivity of the receptor species. We provided detailed information on the spatial and temporal extent of each driver creating the stressor based on the literature review. We then calculated the mean value of these extents for each stressor, resulting in a single value for each stressor.

We assessed the magnitude of impact using scores ranging from 1 to 3, where higher scores indicate a greater level of impact. We employed the categorization criteria described in Table 2 to assign these scores. The overall impact was determined by summing all the scores by receptors. A total score of 3–4 indicated a low overall impact, characterized by mainly low scores and no high scores for any specific aspect. A total score of 5–6 indicated a moderate overall impact, consisting of predominantly moderate scores or a combination of one high score for one aspect and at least one low score for the other aspects. A total score of 7–9 indicated a high overall impact, with moderate to high scores for all aspects or multiple high scores for different aspects. In the results, these impact levels will be color-coded: yellow for low impact (3–4), orange for moderate impact (5–6), and red for high impact (7–9).

Furthermore, the level of certainty in the assessment was evaluated separately for the temporal and spatial extent of the drivers and the sensitivity of the receptors. This evaluation considered the extent to which the conclusions were supported by peer-reviewed literature.

3. Results and discussion

Our literature review enabled us to link the technologies (drivers) proposed in various floating OWF projects in our study area with the pressures (stressors) affecting the policy-relevant species under investigation. Table 3 categorizes these associations based on the OWF life cycle phase. Subsequently, we will present detailed assessments of each stressor and their potential impact on policy-relevant species.

Table 1
Number of species considered as policy-relevant in our study area, ordered by phylum and class showing the count of species protected under the Birds and Habitats Directives, those meeting our criteria but not protected under these directives, and the total number of policy-relevant species.

Phylum	Class	Birds and Habitats Directives species	Other policy-relevant species	Total policy-relevant species
Annelida	**Polychaeta**		1	1
Arthropoda	**Branchiopoda**		2	2
	Malacostraca	1	5	6
Chordata	**Actinopterygii**	1	17	18
	Aves	25	8	33
	Chondrichthyes		8	8
	Elasmobranchii		4	4
	Mammalia[1]	25	1	26
	Reptilia	3		3
Cnidaria	**Anthozoa**	1	15	16
Echiodermata	**Echinoidea**		1	1
Mollusca	**Bivlavia**	2	1	3
	Gastropoda		3	3
Ochrophyta	**Phaeophycae**		2	2
Porifera	**Desmospongiae**		5	5
Rhodophyta			1	1
Tracheophyta	**Liliopsida**		3	3

[1] **7 Cetacea, 18 Chiroptera**

Table 2
Assessment criteria for potential impact on marine life from floating OWFs stressors. Spatial extent was defined as the expected dispersal of the stressor from its source, temporal extent as its expected duration. Sensitivity was assessed in relation separately for each taxa (receptor). Certainty levels were determined based on peer-reviewed literature documentation.

Score	Spatial extent	Temporal extent	Sensitivity	Certainty
1 (low)	<100 m	During survey and/or construction phase	Minor effects on the abundance and distribution of local species	Limited or no empirical documentation
2 (moderate)	<1000 m	Throughout operational phase	Effects on the abundance and distribution of local species, no effects on food web	Documentation available, but results of different studies may be contradictory
3 (high)	>1000 m	Permanent	Effects on the abundance and distribution of local species, effects on food web	Documentation available, relatively high agreement among studies

[1] https://scholar.google.com/
[2] http://login.webofknowledge.com/
[3] https://tethys.pnnl.gov/

Table 3
Associations between stressors and technologies/components in floating OWF development. This table showcases the connections between different stressors and the specific drivers (technologies or components) linked to OWF development.

Phase	Technology Component	Stressors												
		Collision	Noise and vibration	Barrier effect	Entanglement *primary*	Sediment resuspension	Spatial behavior *attraction*	Spatial behavior *avoidance*	Chemical pollution	Electromagnetic fields	Heat emission	Habitat modification *loss and damage*	Habitat modification *creation*	Oceanographic processes
Survey	**Marine traffic**	X	X				X	X	X			X		
	Geophysical survey		X											
	Meteorological buoy				X	X	X		X					
Installation	**Marine traffic**	X	X				X	X	X			X		
	Cable installation		X			X			X			X		
	Anchoring line installation					X			X			X		
	Anchors installation		X			X			X			X		
	Substation foundation		X			X			X			X		
Operation	**Marine traffic**	X	X				X	X	X			X		
	Lighting						X							
	Wind turbine		X	X				X	X					X
	Wind turbine platform						X		X				X	
	Wind turbine blades	X												
	Wind turbine tower	X							X			X	X	
	Anchoring lines		X	X	X	X				X	X		X	X
	Dynamic power cables			X	X					X	X		X	X
	Power cables									X	X			
	Electrical substation						X			X			X	X

3.1. Collision

3.1.1. Above water

The risk of collision mortality is a significant concern for birds in wind energy facilities [33]. Although collisions with wind turbines can be deadly [26], their occurrence in OWFs is relatively rare compared to onshore wind farms due to birds' ability to perceive OWFs as obstacles and avoid them (see 3.6.2) [117]. However, the risk of collision increases in low light conditions, especially at night and during poor visibility [83], with seabirds facing heightened vulnerability due to their long lifespan and low fecundity [122]. Migrating birds are also at risk [117], although data on migration paths in the study area are limited.

For bats, the primary risk associated with floating OWFs is collision with fast-moving turbine blades [2,65], given that bats generally avoid collisions with stationary structures [36].

3.1.2. Below water

Wind energy facilities, including OWF, can lead to increased marine traffic throughout their different stages, increasing the potential for collisions with large cetaceans and turtles [10]. The risk of collision with submerged components of offshore wind turbines, such as platforms, is generally considered low or non-existent, although limited structured research is available on this aspect, there is a wealth of practical experience that has been accumulated over time [140,141].

Based on the literature, marine birds and bats are expected to be the most affected by collisions, with a moderate potential impact (Table 4 and Table B.1).

3.2. Noise and vibration

The impact of noise from OWFs on marine life is a key concern that varies across the wind farm's life cycle and weather conditions. During all phases of OWF operations, ships are essential, contributing to noise generation. This ship noise can disrupt communication among various fish species and induce physiological stress in fish and invertebrates [130]. Particularly, during survey and maintenance activities, the intermittent nature of vessel noise is a significant factor that can elevate stress responses in marine organisms [144]. Moreover, the increased marine traffic associated with OWFs may disturb and displace marine mammals and turtles from crucial habitats due to elevated noise levels and the disturbance created by vessel activities [61].

The geophysical site surveys conducted for OWFs have the potential to affect marine life. Some fish species, like clupeids, can detect mid-frequency sonar ranges [93]. However, the exact impact of these survey technologies on marine life remains not fully understood, and limited studies have been conducted on their effects [93]. Although

Table 4
Potential impact of floating OWFs on Mediterranean marine policy-relevant species from various pressures. Scores represent the cumulative impact of each pressure, combining the mean spatial extent of the pressure, mean temporal extent of the pressure, and sensitivity for each group. Color-coded: 3–4 (yellow) for low impact, 5–6 (orange) for moderate impact, and 7–9 (red) for high impact. See Section 2.3 for definitions and methodology.

Receptors (taxa)	Stressors													
	Collision	Noise and vibration	Barrier effect	Entanglement *primary*	Entanglement *secondary*	Sediment resuspension	Spatial behavior *attraction*	Spatial behavior *avoidance*	Chemical pollution	Electromagnetic fields	Heat emission	Habitat modification *loss and damage*	Habitat modification *creation*	Oceanographic processes
Marine mammals	4	6-8	5-6	4	5-6	-	-	-	3-9	4	-	5-7	-	6-9
Marine turtles	4	5-7	-	-	5	-	-	-	3-9	4	-	-	-	6-9
Marine birds	6	4-6	7-8	-	5	n.a.	8	7	3-9	n.a.	n.a.	6-8	-	6-9
Seagrasses and algae	n.a.	n.a.	n.a.	n.a.	n.a.	7-8	n.a.	n.a.	3-9	n.a.	-	7-9	5-6	6-9
Sharks	-	5-7	-	-	5-6	-	-	-	3-9	6	-	-	-	6-9
Rays	-	5-7	-	-	-	-	-	-	3-9	6	-	6-8	-	6-9
Pelagic fish	-	5-7	-	-	5-6	5-6	7-8	-	3-9	4	-	-	-	6-9
Benthic fish	-	5-7	-	-	-	5-6	7-8	-	3-9	4	-	6-8	-	6-9
Benthic invertebrates	-	5-7	-	-	-	7-8	-	-	3-9	5	4	7-9	6-7	6-9
Bats	6	n.a.	-	n.a.	n.a.	n.a.	8	-	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

direct mortality or damage to internal tissues is not anticipated, certain fish have exhibited signs of hearing loss. Invertebrates, often less motile and benthic, are also exposed to these survey technologies, but there is a lack of documented studies addressing their specific effects.

According to Nedwell et al. [95], trenching activities to bury cables are expected to have a significant impact on harbor porpoises, with greater estimated impacts on marine mammal species compared to fish. Taormina et al. [134] stated that there is currently no clear evidence demonstrating the effects of underwater noise emitted during cable installation on marine mammals or other marine animals. This may be due to the lack of studies specifically evaluating the impact of this technology on underwater noise, with existing research primarily based on modeling. For the final connection of the cable to the shore, Horizontal Directional Drilling is recommended in areas with seagrass meadows. Although this activity could potentially generate significant noise, there is a lack of available studies specifically addressing this aspect. Overall, the construction phase of OWFs is characterized by a higher level of noise, but it occurs over a relatively short period of time, and it is not expected to have population-level impacts.

Studies comparing the noise generated by operating OWFs with that of large commercial ships have pointed out that wind farms are stationary and represent local sources of noise, which marine animals may find challenging to evade [93]. During the operational phase, continuous noise from OWFs is not expected to cause physiological harm to marine animals [138,80,82,93]. However, continuous noise from OWFs can have a significant masking effect as it coincides in frequency with the hearing and vocalization ranges of numerous fish species [93]. Unlike fixed foundations, the noise from floating offshore turbines does not propagate into the seafloor, leading to a more confined spatial impact on benthic species [102]. During the operational phase of floating offshore turbines, mooring-related noise is produced in addition to continuous noise [118]. This mooring-related noise includes impulsive sounds or transients, which become more pronounced during higher wind speeds and correspondingly higher waves. These sounds may occur individually or in quick succession [118,19]. It is therefore crucial to consider the cumulative noise output of large turbine arrays because the distances over which OWF array noise can be detected under ambient conditions may increase [118].

Underwater noise is expected to impact all marine species (Table 4 and Table B.2). Marine mammals, especially, due to their reliance on sound for communication and navigation, are likely the most affected [102]. Fish, which rely on hearing and particle motion for communication and environmental awareness, might experience relocation due to construction-related noise, despite they generally do not respond to continuous operational noise [140]. Marine macroinvertebrates, like decapods and cephalopods, can detect sound and particle motion but have less sensitivity to loud noises. However, the specific effects of anthropogenic sound on these species at individual and population levels remain largely unknown [127,131]. The effects of anthropogenic sound on sea turtles are not thoroughly studied. Nonetheless, loud noises generated during OWF construction are expected to impact their behavior and displacement [61]. The recent attention to the ability of elasmobranchs to detect sound has revealed mixed responses depending on the species. Due to their capability to react to anthropogenic underwater sound, sharks may be affected by construction activities [124,88]. Certain seabirds can hear underwater, detecting low frequencies and displaying avoidance responses to human-generated noise. However, the impact of underwater noise during construction and operation is not considered significant [6].

3.3. Barrier effect

3.3.1. Above water

The above-water part of OWFs can act as a barrier for certain species of seabirds [64,85] and migrating birds [44]. Seabirds might alter their flight paths to avoid collisions with the infrastructure, incurring added energy costs [85]. The effect is expected to intensify with the scale of the OWF; larger installations are anticipated to present more pronounced barriers to avian species.Habitat fragmentation from these physical barriers may cause the avoidance of previously utilized foraging areas [28] and the impact on migrating birds varies by species and location [57]. While individual OWFs have minimal effects on large-scale birds migration, cumulative impacts may become significant if wind power expansion does not consider migration routes [20].

3.3.2. Below water

Animals may perceive barriers acoustically or visually, potentially influencing their impact extent [102]. To date, no study has reported physical barriers from OWFs on marine mammals or large aquatic animals. Yet, it is vital to consider that floating OWFs, due to their design with moorings and cables, occupy a more extensive dynamic space in the water column than fixed-bottom turbines, potentially yielding different outcomes. Although no evidence of a barrier effect on marine mammals currently exists, concerns are significant in North America, where operational OWFs have not yet been deployed, especially for North Atlantic right whales [111]. Given the complex movement patterns of many marine species, characterized by site fidelity in some cases, assessments of local marine ecosystems before OWF implementation are essential to establish baselines and evaluate potential changes upon OWF activation [102].

Concerning fish, OWFs and submerged components are unlikely to significantly affect their movement [102]. Floating platforms can even function as fish aggregating devices, providing foraging opportunities and shelter [21]. Elasmobranchs are also not expected to be impacted in their movement and might be attracted to fish aggregations around OWFs [43].

In summary, based on our findings and the literature review, underwater barrier effects on fish, sharks, and rays can be discounted, and a low impact on marine mammals is indicated (Table 4 and Table B.3). However, the outer portions of OWFs may act as barrier effects for birds, potentially resulting in a significant impact (Table 4 and Table B.3).

3.4. Entanglement

Entanglement, associated with mooring lines and cables suspended underwater, represents a key difference between fixed and floating OWFs [132,86]. Entanglement can be classified into two main types: primary (direct) and secondary/tertiary (indirect) entanglement [42]. Primary entanglement involves species getting directly caught in OWF components, such as mooring lines and power cables. In contrast, secondary/tertiary entanglement occurs when species become ensnared in fishing gear before or after the gear interacts with OWF components [42].

Primary entanglement risks in OWFs are predominantly associated with mooring lines and cables suspended in the water, particularly for marine mammals. However, the likelihood of primary entanglement is considered low, as the tension in mooring lines generally prevents loop formation for entanglement [11]. Nonetheless, the potential consequences are significant, especially for vulnerable marine mammals [11,60]. While no primary entanglement incidents have been reported with floating offshore structures, the risk may increase with the growing number of OWF projects featuring multiple turbines, each equipped with mooring lines and power cables [134]. The risk associated with primary entanglement depends on the mooring system design, with catenary mooring systems posing higher risks due to larger swept volumes and areas compared to taut mooring systems [11]. Power cables, on the other hand, generally present a lower risk, as they are designed to be less resistant and capable of breaking if large animals become entangled, allowing for easier escape [102].

Secondary and tertiary entanglement, often termed ghost fishing, is mainly linked to marine litter, especially derelict fishing gear. This form of entanglement poses risks to a broader range of marine life, including marine mammals [94], marine turtles [34], sharks [104], fish, and diving seabirds [94]. Once entangled, these smaller animals lack the ability to free themselves, and the majority of them perish without human intervention [34]. While no documented incidents have occurred with floating offshore turbines, fishing gear has been found in the mooring lines of offshore oil and gas platforms, indicating the potential for ghost fishing [102]. Secondary entanglement can have significant population-level effects, underscoring the importance of addressing this issue [86].

In assessing the potential impact of entanglement, a distinction was made between primary and secondary/tertiary entanglement, as their mechanisms and species affected vary. Primary entanglement primarily concerns large swimming-bodied species, specifically marine mammals, with a low potential impact (Table 4 and Table B.4). Secondary entanglement, on the other hand, poses moderate risks to marine mammals, sharks, pelagic fish, marine turtles, and diving seabirds, as they are all exposed to entanglement hazards (Table 4 and Table B.4).

3.5. Sediment resuspension

Sediment entering the water column during various phases of an OWF's life cycle can significantly impact different marine species. While individual turbine footprints may seem small, they can collectively have a significant impact when considering large-scale arrays [86]. This can reduce water transparency, affecting primary producers and leading to changes in algae communities [137]. It can also affect visually oriented fish species that rely on sight for feeding [136]. Furthermore, sediment resuspension can specifically impact the early life stages of fish. The burial of eggs or damage to gills can affect the survival and development of fish embryos and larvae [23,58,8]. Filter-feeding invertebrates, dependent on clear water for capturing food particles, may experience negative effects [28,73].

Considering these findings, both pelagic and benthic fish are at a moderate risk of impact (Table 4 and Table B.5). Notably, flora, including seagrasses and algae, and nonmotile organisms such as benthic invertebrates (particularly benthic feeding ones), are highly vulnerable to sediment plumes due to their inability to escape, resulting in a high potential impact (Table 4 and Table B.5)

3.6. Spatial behavior

3.6.1. Attraction

3.6.1.1. Above water. The attraction of sensitive species to OWFs is a behavioral concern mainly linked to the presence of artificial lighting on the infrastructure. Bird attraction to artificial light, a well-documented phenomenon, poses particular risks to OWFs [107,113,119,81,92]. OWFs are mandated to incorporate lighting for safety, both on turbines and structures during installation and maintenance [61]. In terms of bird behavior, OWF lighting can result in attraction and disorientation [27]. Bird attraction to OWF lights can extend over several kilometers, diverting birds from their original flight paths toward illuminated areas. Disorientation occurs when birds alter their flight paths near the light source, often circling the light source for extended periods [48]. This behavior increases the collision risk with wind turbines. It is noteworthy that traditional collision risk models, assuming straight flight paths, may not fully account for circling behavior near light sources [27]. While various factors like weather conditions [48,68,92], nocturnal species vulnerability [89], and moon phase Montevecchi [92]; Miles et al. [89] can influence this attraction to OWF artificial light, literature consistently indicates increased collision risk for birds due to artificial light [64]. Bats are known to be attracted to coastal lighting sources, such as lighthouses [106], due to increased insect prey presence [3]. However, offshore attraction patterns might differ [99]. Offshore bat attraction to lighting sources has been reported [106,2,59], yet specific factors and responses remain unclear. Recent work on onshore wind energy facilities suggests that artificial lights are not the primary cause of bat attraction to wind turbines [55] and research is needed to determine if bats exhibit similar behaviors offshore.

The attraction of seabirds to OWFs can lead to population-level impacts due to increased collision risks. The availability of resting sites on offshore structures and changes in prey distribution are contributing factors. A review by Dierschke et al. [32] sheds light on seabird attraction and avoidance behaviors. Cormorants, for instance, are strongly attracted to OWFs because they provide roosting sites, enabling them to extend their foraging range further offshore. Ship traffic at wind farms can have mixed effects on seabirds; while it may disturb some species, it can attract others. Gulls, for example, are known to associate ships with fishing vessels and the feeding opportunities they offer [47]. Moreover, the introduction of new hard substrate through OWF structures enhances habitat complexity, attracting species and increasing diversity and abundance. This, in turn, provides more foraging opportunities for diving seabirds [32]. The attraction of bats to offshore wind turbines may increase collision risks, similar to observations with onshore turbines [55]. Extensive research on onshore turbines has identified factors like landscape features, roosting opportunities, prey aggregation, and physiological features as contributors to this attraction [55,71]. Whether these attraction patterns will hold offshore remains uncertain.

3.6.1.2. Below water. OWFs can impact marine species in multiple ways, both through artificial lighting and the addition of hard substrates that introduce new habitats. Artificial lighting negatively impacts sea turtles, disrupting natural behaviors and leading hatchlings astray [121, 142]. However, the response of sea turtles to offshore wind farm lighting is not well understood. Studies present varying views on the matter, with some calling for further investigation [52] while others suggest minimal impact [101]. Marine mammals, apart from pinnipeds absent in our study area, do not rely on light for navigation, mainly using echolocation [101]. However, artificial lighting's indirect effects may impact prey availability by altering zooplankton and fish distribution patterns during diel vertical migration, affecting marine mammals' foraging habits [31]. Nevertheless, the overall understanding of artificial lighting's effects on marine mammals remains incomplete, with some comprehensive reviews dismissing its impact [101,49]. Regarding fish, light intensity can affect diel migration patterns. Effects like altered migratory patterns, disorientation, temporary blindness, and increased predation due to artificial lighting have been observed [98]. However, studies have mainly focused on direct water surface lighting, and it is unlikely that wind turbine associated lighting significantly affects fish communities [101]. More detailed studies are needed to assess OWF lighting's potential effects on fish. A study by Ramasco [112] suggests increased cod presence near the Hywind Scotland floating OWF during nighttime, possibly due to the platform's attractive lighting effect.

In addition to artificial lighting, the introduction of hard substrates by floating OWFs acts as an artificial reef (see Section 3.10.2), attracting species due to the new habitat and foraging opportunities created by biofouling and habitat-forming organisms colonizing the structures. Floating platforms act as aggregating devices (Wilhelmsson et al., 2006), enhancing foraging possibilities and providing shelter for higher trophic level mobile species, such as fish, seabirds, and marine mammals [21,30, 29]. This reef effect is notable with floating OWFs, which introduce hard substrates at multiple depths where no structures previously existed. The diversity of species attracted to these new habitats may depend on the depth and complexity of the structures [30,70]. Even if this is beneficial, the introduction of new hard substrates can displace existing species, thereby affecting ecosystem functions and food web dynamics [54]. In newly constructed OWFs (i.e., degraded environment), this attraction to suboptimal habitats, known as an ecological trap, can deteriorate the condition of fish stocks [114] and have negative ecological consequences [115]. Floating OWFs may act as fish aggregating devices that, despite having the potential to improve the condition and reproductive outcomes of fish, can still function as ecological traps [115]. The shelter effect of this structure can extend beyond the immediate turbine area and impact higher trophic level species [62]. However, it is essential to clarify the balance between attraction, production, and ecological trap effects at a regional scale, rather than relying solely on local observations. The increased complexity of the ecosystem could have energetic implications beyond the OWF, depending on the site fidelity, mobility, and migration of attracted species [62]. Additionally, the results for floating OWFs may differ from those in the literature, which primarily focus on fixed OWFs. Unlike birds and bats, which directly face collision risks with turbine blades, the attraction of marine species to OWFs does not present an immediate threat. Instead, the potential impact primarily involves an increased risk of secondary entanglement, as discussed earlier (see Section 3.4).

Marine species are attracted to OWFs due to artificial lighting and the introduction of hard substrates that create artificial reefs. While sea turtles, marine mammals, and fish may be drawn to lighting without facing direct risks, birds and bats are at a heightened risk of collision. The hard substrates enhance habitat complexity, providing improved foraging opportunities but potentially leading to ecological traps. Overall, birds and bats are expected to be the most affected groups, with significant impacts from lighting. Additionally, pelagic and benthic fish are also highly affected by the introduction of new substrates (see Table 4 and Table B.6).

3.6.2. Avoidance

3.6.2.1. Above water. Avoidance is a critical aspect of spatial behavior to consider when evaluating OWF impacts. Avoidance behavior involves species actively staying away from or avoiding specific areas, like wind farm sites, due to various factors.

Seabird avoidance of OWFs is well-documented [105]. The presence of tall wind turbine structures in open seascapes appears to be a significant reason for this behavior, disrupting seabirds' natural visual cues and navigation patterns [32]. Increased marine traffic near OWFs can further contribute to seabird avoidance, as some species tend to avoid vessel interactions, which may be more prevalent in OWF areas [32]. This avoidance can have significant energetic costs, especially if wind farms disrupt the path between seabird roosting/nesting sites and foraging grounds [85]. This fragmentation of ecological units due to wind farms can disrupt seabird populations and their overall dynamics [44,64]. The extent of avoidance impacts on seabird populations depends on the spatial relationship between wind farms, breeding colonies, and foraging areas, along with the behavioral characteristics of different seabird species [56].

3.6.2.2. Below water. In marine species, avoidance behavior is primarily driven by factors such as noise and electromagnetic fields (EMFs) from wind farm operations. Seabird avoidance indicates that birds are highly impacted by avoidance behaviors (Table 4 and Table B.6).

3.7. Chemical pollution

Chemical pollution is a significant concern, especially for sensitive species. Species with long lifespans and high trophic levels are particularly vulnerable due to the potential for bioaccumulation and biomagnification [53].

Antifouling paints are commonly used in OWF development to prevent marine organism buildup [42]. These paints, containing copper and booster biocides, can be harmful to marine life in semi-closed environments like marinas, ports, and harbors [133]. Their specific impact in open-seas where OWFs are typically located requires further investigation [42]. Corrosion protection systems are essential for OWFs [110] and associated vessels but can release organic compounds and metals into the marine environment. Current research indicates low impacts on marine life from these systems [69]. Marine sediments play a crucial role as repositories for various chemicals trapped within undisturbed layers. Disturbing marine sediments during OWF installation, dismantling, and mooring line movement (see 3.5) may release sediment contaminants, impacting water quality and marine species [37]. The impact is generally lower during OWF operation compared to installation and dismantling [63]. The expansion of offshore facilities, including OWFs, raises the risk of accidental pollution through factors like marine traffic and machinery leaks. Routine operation and maintenance activities, including hydraulic fluid or lubricant oil use, can pose a chemical spill risk [15].

Estimating the specific taxonomic groups affected by chemical release is challenging (Table 4 and Table B.7). Chemical releases can diffuse in the water column and potentially impact all taxonomic groups through processes like bioaccumulation and biomagnification. Accidental spills, depending on factors like spill scale and chemical type could have a more significant impact, with sensitivity of affected organisms playing a crucial role.

3.8. Electromagnetic fields (EMFs)

Certain marine mammals possess magneto-receptive capabilities for navigation, making EMFs a potential concern for them [102]. Nevertheless, the risk of EMFs from OWFs significantly affecting marine mammals is considered low due to their high mobility and the fact that they primarily detect the magnetic field in close proximity [135]. It is important to note that marine mammals in our case study are not electroreceptive and thus do not pose a risk.

Similarly, sea turtles, while lacking electroreceptive abilities, rely on the Earth's geomagnetic field for navigation [78]. The installation of cables near nesting areas should be avoided to mitigate potential risks [135]. However, sea turtle migration in the open ocean is not anticipated to be significantly impacted by the EMFs generated by OWFs.

Elasmobranchs are acknowledged for their capacity to detect EMFs [135,97]. The primary concern with artificial EMFs and elasmobranchs is potential behavioral impacts, particularly in feeding and predator detection, as limited direct studies have explored the physiological effects of prolonged exposure within this group [102]. While responses to EMFs vary among species, elasmobranchs have demonstrated the ability to detect extremely low electric fields [134]. These fields are challenging to shield effectively within the industry, potentially resulting in behavioral effects which could have biological consequences for the species [66]. Nonetheless, the impact of EMFs on the behavior and population-level effects of highly mobile elasmobranch species remains unclear. This impact is influenced by various factors, including species distribution (encompassing spatial range and vertical distribution in the water column), cabling distribution, migratory patterns, and proximity to cables [102,135]. Elasmobranchs have demonstrated magneto-receptive abilities, although the precise mechanism of their response to magnetic fields remains incompletely understood [5,96].

Understanding the electromagnetic sensitivity of marine and diadromous fish species, especially concerning cable signatures in natural conditions, remains a challenge [25]. Coastal and demersal species, in close proximity to seabed cables, are likely more affected than pelagic fish [102,25]. Existing research primarily investigates fish's early life stages, revealing potential genetic, physiological, and developmental alterations due to high magnetic field values during extended exposure in lab conditions [50]. However, these lab conditions may not replicate the real-life exposure of fish. Studies on EMF effects on migratory behavior have not indicated significant reductions in migratory success [102]. So far, no notable effects on fish abundance, species diversity, composition, or fisheries have been observed.

Studying the impact of EMFs on benthic species, including marine invertebrates, is vital due to their heightened EMF exposure. Existing research have been confined to a few species [135] and mainly address individual-level effects. Unfortunately, individual-scale research does not provide conclusive evidence for significant impacts, particularly at the population, community, or ecological process levels [14]. So far, arthropods, mollusks, echinoderms, and possibly annelids have been recognized as EMF-sensitive species [102]. However, it is essential to note that direct evidence of offshore wind EMF impacts is lacking, and any potential effects remain speculative [135]. Invertebrate species sensitive to electric fields have thresholds above levels produced by undersea cables, suggesting they would not be significantly affected [102,50]. Magneto-sensitive species might be impacted when encountering cable-induced magnetic fields, especially if they depend on geomagnetic fields for navigation. This effect is more likely when the magnetic sense is used within a small local range containing a cable system [135]. Presently, it is unclear whether EMFs from OWFs will directly affect marine invertebrates, as the literature is limited and primarily based on lab studies rather than field observations [4].

Based on the reviewed literature, marine mammals, sea turtles, pelagic and benthic fishes are expected to experience low impacts from EMFs. Conversely, benthic invertebrates and elasmobranchs might be more susceptible, with a moderate anticipated impact (see Table 4 and Table B.8).

3.9. Heat emission

The warming of submarine cables could indirectly disturb benthic fauna by causing changes in physicochemical and bacteriological balances [103]. Temperature radiation has the potential to induce small spatial changes in benthic community structure [134].

However, considering the narrowness of the cable corridor and the expected weak thermal radiation, the impacts are not considered significant [116,134,37] and a low expected impact was attributed to benthic invertebrates (Table 4 and Table B.9).

3.10. Habitat modification

3.10.1. Loss and damage

3.10.1.1. Above water. Habitat changes also affect avian species [45, 85], impacting their sensitivity to turbines and habitat use for spawning, resting, feeding, and migration. Wind farm avoidance can lead to habitat loss in the OWF and surrounding areas [128]. Furthermore, changes in food availability can also influence the habitat use patterns of seabirds.

3.10.1.2. Below water. The construction of OWFs inevitably alters seafloor habitats and impacts marine organisms. The installation and burying of electric cables, mooring lines, anchors, and offshore substations interact with the seabed, affecting its availability and utilization by benthic organisms. Vessel anchoring, especially during cable installation, further impacts seabed habitats and benthic communities [28].

Conventional catenary moorings continuously interact with the seabed throughout the operational phase. The design includes a tangent to the bottom at the lower end of the mooring line, resulting in continuous contact with the seabed. The movement of the floating platform, induced by wind and waves, creates a mooring footprint, where the mooring line continuously moves on the seabed, damaging bottom habitats and associated species and producing sediment resuspension that can affect nearby habitats (see Section 3.5). In contrast taut mooring line designs can reduce this impact. While motile benthic species can relocate, sessile species may face direct harm [63]. Sensitive habitats formed by vulnerable species with slow growth rates, such as deep-sea coral reefs, maërl beds and rocky outcrops [28,9], are at risk of disturbance from this continuous mooring interaction. The bottom habitat damage is considered of permanent temporal extent due to the extended recovery period required for affected seafloor areas, which may need decades or more to return to their original, pre-exposition state.

Habitat loss extends to the water column, affecting habitat for marine mammals, sea turtles, fish, and elasmobranchs. Nevertheless, the amount of pelagic habitat loss compared to the remaining benthic habitat within and surrounding an OWF is relatively small, resulting in minimal effects [63].

Habitat loss is expected to have a higher impact on sessile and benthic organisms, with potential risks to marine mammals (Table 4 and Table B.10).

3.10.2. Creation

OWFs introduce new hard substrates that modify habitats. This phenomenon commonly referred to as "reef effect" [72] occurs as OWF components like platforms, cables, and mooring lines get colonized by biofouling and habitat-forming species, enhancing habitat complexity and attracting species (see Section 3.6.1), potentially increasing diversity and abundance [67]. While this benefits some species, the extent and nature of the effect depend on the artificial reefs characteristics and the indigenous populations present during introduction [28]. The risk of invasive species colonization is also increased with the presence of OWF structures [51]. The Mediterranean region is particularly susceptible to non-indigenous and alien species [17], and OWF structures can act as stepping stones, facilitating the range extension of these species within the Mediterranean environment [1]. Biofouling also affect benthic and pelagic communities surrounding the OWFs. Colonizing organisms can alter the seabed conditions by the ejection of fecal pellets that deposit and enrich sediment around the turbines [79]. But doing so, the fouling communities make pelagic food sources available to benthic communities [125]. However, studies reporting this effect were, to date, conducted on fixed OWFs, and so, on shallow water OWFs, the results in deeper waters with floating OWFs may differ with the diffusion of the pellets in the water column, thus resulting in a lower effect on benthic communities but with the possibility to affect pelagic environment. Another effect of the biofouling on food web dynamic is the local depletion of concentration of phytoplankton and macro- and mesozooplankton from pelagic zones due to the filtering of suspension feeders [125] thus potentially affecting available primary productivity and the marine food web and biogeochemical cycle near OWFs. However, these new habitats and the associated consequences they bring may be disrupted during cleaning, removal, or the eventual dismantling phase of OWFs.

Loss of habitat primarily impacts benthic species, particularly sessile organisms, like seagrasses, algae, and benthic invertebrates. This loss can extend to the water column, potentially affecting large marine mammals and above-water areas, which can impact seabirds. Additionally, the creation of new habitats may negatively impact existing communities by increasing organic carbon in the sea bottom and reducing available primary productivity, potentially affecting sessile benthic organisms and plankton feeders (Table 4 and Table B.10).

3.11. Oceanographic processes

OWFs can significantly affect oceanographic processes [90], which are crucial for ecological dynamics as they influence nutrient availability and thermal habitats. The principal ways this impact occurs are: 1. wind extraction, reducing surface wind stress and altering water column turbulence; 2. wind farm wake-driven divergence and convergence, leading to upwelling and downwelling; 3. turbulence generated by turbine underwater structures, affecting local water movement [62].

Changes in hydrodynamics and wind wake effects may influence larval transport, connectivity, and recruitment [62], impacting both demersal and benthic species. These impacts, though difficult to assess, can be significant, especially if OWFs overlap with fish spawning habitats. Additionally, alterations in hydrodynamics can affect food availability for zooplanktivorous species, such as small pelagics, by changing the vertical stratification of the water column. This can impact primary and secondary production, with cascading effects on higher trophic levels [62].

The ecological consequences of changes in oceanographic processes due to OWFs, particularly floating ones, are understudied and warrant further investigation. Additionally, these impacts are highly dependent on OWF layout and characteristics such as turbine size, foundation type, turbine spacing, and spacing between OWFs [18]. Thus, estimating the specific taxonomic groups affected by changes in oceanographic processes is challenging, as the entire trophic web can be influenced by such changes (Table 4 and Table B.11).

3.12. Stressor summary

Table 4 provides a comprehensive overview of the potential impacts on biodiversity resulting from various floating OWF pressures. It is evident from the table that every taxonomic group can potentially be affected by the installation of a floating OWF. Notably, when the pressure extends to the sea bottom, sessile benthic organisms face a higher risk compared to their motile counterparts, warranting special attention to their conservation.

Long-lived species, such as marine mammals, elasmobranchs (sharks and rays) and seabirds, are particularly vulnerable to these impacts, as even minor modifications can have significant population-level consequences. The primary stressors with the potential for the greatest impact are noise and vibration, along with habitat loss. Additionally, the degree of impact from chemical pollution depends on the scale of the pollution event and the consequences of changes in oceanographic processes are uncertain, as they can affect the entire ecological dynamics but remain understudied.

4. Conclusions

Taking the example of the Gulf of Roses/Cap de Creus, our study provides a first assessment of the impacts of various floating OWF technologies on policy-relevant species of the Mediterranean Sea. The selection of these species, necessitating specific conservation efforts due to their vulnerability and/or population status, is based on their crucial role as indicators of the good environmental status (GES) of marine waters defined by the Marine Strategy Framework Directive (MSFD) and the objectives set by the EU biodiversity strategy for 2030. Our assessment framework is particularly valuable for conducting Appropriate Assessments required for offshore wind plans impacting Natura 2000 sites designated under the Habitats and Birds Directives, and for Environmental Impact Assessments [77]. This framework enhances the evaluation of potential impacts from floating OWFs on policy-relevant species critical for achieving the GES of Mediterranean Natura 2000 sites and the goals outlined in the EU biodiversity strategy for 2030. The EU maintains a robust environmental legislative framework to safeguard Natura 2000 sites from human activities that could undermine their integrity, including offshore wind development. According to the European Commission [40], designated areas for marine offshore energy projects must align with biodiversity conservation objectives and preserve the GES of marine waters. In this context, Lloret et al. [77] proposed a structured procedure for wind farm projects potentially affecting Natura 2000 sites, guided by Articles 6(3) and 6(4) of the Habitats Directive and EU recommendations [41].

In our assessment, we identified a total of 135 policy-relevant species, belonging to 16 classes, susceptible to different stressors arising from various floating OWF technologies. Notably, marine mammals, seabirds, elasmobranchs and benthic macro-invertebrates emerge as the taxonomic groups most likely to be affected. Among the various stressors, noise and vibration as well as habitat loss and damage exhibit the greatest potential to impact these vulnerable species.

A growing global imperative revolves around decreasing our reliance on fossil fuels. This drive is reflected in various initiatives aimed at decarbonizing our energy production, particularly through the escalating objectives to install OWFs [38]. Simultaneously, we confront a pressing biodiversity crisis [109]. The policy-relevant species we have selected exemplify the significance of this matter, as they are pivotal in characterizing the good environmental status of ecosystems [16]. Our study employed the Generalized Impact Assessment framework [13] as a fundamental method to evaluate the potential effects of floating OWFs on Mediterranean biodiversity. Our findings indicate that floating OWF technologies can exert pressure across multiple life stages and taxonomic groups, which are crucial to conservation policies. The anticipated impacts are expected to critically affect several policy-relevant groups across diverse spatial and temporal scales. These include species protected by the European Habitats and Birds Directives, as well as those listed in the IUCN Red List, international agreements such as the Barcelona, Bern, Bonn, and CITES conventions, and national and regional safeguarding legislation.

Many studies on floating OWFs rely on modeling due to the technology's novelty, limiting access to extensive in-situ data. While modeling provides valuable insights, it carries uncertainties from assumptions and extrapolations. Specific taxonomic groups, such as marine mammals, turtles, seabirds, and economically important fish, receive more attention due to their higher vulnerability or significance. However, thorough impact assessment requires evaluating not only the specific ecosystem hosting the OWF but also adjacent ecosystems. This includes lesser-studied groups and their interactions to ensure a comprehensive understanding of OWF effects. To mitigate biases, future research should prioritize increased in-situ data collection, species-specific studies, and broader ecological investigations. Additionally, future studies should explore how stressors variably impact species under different weather conditions, enhancing the precision and comprehensiveness of impact assessments.

Decarbonizing our energy production is an urgent priority in light of the persistent challenge of climate change. Equally important is the preservation of our ocean's biodiversity. Our study represents a pioneering effort to comprehensively evaluate the potential effects of floating OWFs, an emerging technology, on policy-relevant species in the Mediterranean Sea. These effects may have long-term and far-reaching consequences and therefore, subsequent research endeavors will be vital in defining the regional impacts of specific stressors on individual species within this ecosystem.

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CRediT authorship contribution statement

Josep Lloret: Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Climent Molins:** Writing – review & editing. **Paul Wawrzynkowski:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization, Visualization, Writing – review & editing.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106518.

Data availability

Data will be made available on request.

References

[1] T.P. Adams, R.G. Miller, D. Aleynik, M.T. Burrows, Offshore marine renewable energy devices as stepping stones across biogeographical boundaries, J. Appl. Ecol. 51 (2) (2014) 330–338.

[2] I. Ahlén, H.J. Baagøe, L. Bach, Behavior of Scandinavian bats during migration and foraging at sea, J. Mammal. 90 (6) (2009) 1318–1323.

[3] I. Ahlén, L. Bach, H.J. Baagøe, J. Pettersson, Bats and offshore wind turbines studied in southern Scandinavia, Nat. årdsverket (2007).

[4] L. Albert, F. Deschamps, A. Jolivet, F. Olivier, L. Chauvaud, et al., A current synthesis on the effects of electric and magnetic fields emitted by submarine power cables on invertebrates, Mar. Environ. Res. 159 (2020) 104958.

[5] J.M. Anderson, T.M. Clegg, L.V. Véras, K.N. Holland, Insight into shark magnetic field perception from empirical observations, Sci. Rep. 7 (1) (2017) 11042.

[6] K. Anderson Hansen, A. Hernandez, T.A. Mooney, M.H. Rasmussen, K. Sørensen, et al., The common murre (*Uria aalge*), an auk seabird, reacts to underwater sound, J. Acoust. Soc. Am. 147 (6) (2020) 4069–4074.

[7] M. Atcheson, A. Garrad, L. Cradden, A. Henderson, D. Matha, et al., Floating offshore wind energy. *by Joao Cruz and Mairead Atcheson*, Springe Int. Publ. Chap. Look. back. doi 10 (1007) (2016), 978–3.

[8] D. Au, C. Pollino, R. Wu, P. Shin, S. Lau, et al., Chronic effects of suspended solids on gill structure, osmoregulation, growth, and triiodothyronine in juvenile green grouper *Epinephelus coioides*, Mar. Ecol. Prog. Ser. 266 (2004) 255–264.

[9] C. Barbera, C. Bordehore, J.A. Borg, M. Glémarec, J. Grall, et al., Conservation and management of north east Atlantic and Mediterranean maërl beds, Aquat. Conserv.: Mar. Freshw. Ecosyst. 13 (S1) (2003) S65–S76.

[10] M. Barkaszi, M. Fonseca, T. Foster, A. Malhotra, K. Olsen, Risk assessment to model encounter rates between large whales and vessel traffic from offshore wind energy on the Atlantic OCS, in: Sterling (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM, 34, 2021, p. 54.

[11] Benjamins, S., Harnois, V., Smith, H., Johanning, L., Greenhill, L., *et al.*, 2014. *Understanding the potential for marine megafauna entanglement risk from renewable marine energy developments.* Scottish Natural Heritage Commissioned Report, No 791.

[12] L. Bergström, L. Kautsky, T. Malm, R. Rosenberg, M. Wahlberg, et al., Effects of offshore wind farms on marine wildlife—a generalized impact assessment, Environ. Res. Lett. 9 (3) (2014) 034012.

[13] Bergström, L., Lagenfelt, I., Sundqvist, F., Andersson, I., Andersson, M.H., *et al.*, 2013. Study of the fish communities at Lillgrund wind farm: Final report from the monitoring programme for fish and fisheries 2002–2010.

[14] G.W. Boehlert, A.B. Gill, Environmental and ecological effects of ocean renewable energy development: a current synthesis, Oceanography 23 (2) (2010) 68–81.

[15] P.A. Bonar, I.G. Bryden, A.G. Borthwick, Social and ecological impacts of marine energy development, Renew. Sustain. Energy Rev. 47 (2015) 486–495.

[16] A. Borja, M. Elliott, J.H. Andersen, A.C. Cardoso, J. Carstensen, et al., Good environmental status of marine ecosystems: what is it and how do we know when we have attained it? Mar. Pollut. Bull. 76 (1-2) (2013) 16–27.

[17] L. Bray, S. Reizopoulou, E. Voukouvalas, T. Soukissian, C. Alomar, et al., Expected effects of offshore wind farms on Mediterranean marine life, J. Mar. Sci. Eng. 4 (1) (2016) 18.

[18] Brodie, J., Manhard, R., Krebs, J., Lozano, C., Morales, L., *et al.*, 2023. Oceanographic Effects of Offshore Wind Structures and Their Potential Impacts on the North Atlantic Right Whale and Their Prey. Report by AKRF (Allee King Rosen & Fleming).

[19] Burns, R.D., Martin, S.B., Wood, M.A., Wilson, C.C., Lumsden, C.E., *et al.*, 2022. *Hywind Scotland Floating Offshore Wind Farm: Sound Source Characterisation of Operational Floating Turbines*. Document 02521, version 3.0 FINAL. Technical report by JASCO applied sciences for Equinor Energy AS.

[20] M. Busch, A. Kannen, S. Garthe, M. Jessopp, Consequences of a cumulative perspective on marine environmental impacts: offshore wind farming and seabirds at North Sea scale in context of the EU marine strategy framework directive, Ocean Coast. Manag. 71 (2013) 213–224.

[21] J.J. Castro, J.A. Santiago, A.T. Santana-Ortega, A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis, Rev. Fish. Biol. Fish. 11 (2002) 255–277.

[22] CBD, 2022. Convention on Biological Diversity. Kunming-Montreal global biodiversity framework. Montreal, Canada, 7-19 December 2022.

[23] Clarke, D., Engler, R.M., Wilber, D., 2000. *Assessment of potential impacts of dredging operations due to sediment resuspension*. DOER Technical Notes Collection (ERDC TN-DOER-E9), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

[24] M. Coll, C. Piroddi, J. Steenbeek, K. Kaschner, F. Ben Rais Lasram, et al., The biodiversity of the Mediterranean Sea: estimates, patterns, and threats, PloS One 5 (8) (2010) e11842.

[25] A.E. Copping, L.G. Hemery, H. Viehman, A.C. Seitz, G.J. Staines, et al., Are fish in danger? a review of environmental effects of marine renewable energy on fishes, Biol. Conserv. 262 (2021) 109297.

[26] D.A. Croll, A.A. Ellis, J. Adams, A.S. Cook, S. Garthe, et al., Framework for assessing and mitigating the impacts of offshore wind energy development on marine birds, Biol. Conserv. 276 (2022) 109795.

[27] Deakin, Z., Cook, A., Daunt, F., McCluskie, A., Morley, N., *et al.*, 2022. *A review to inform the assessment of the risk of collision and displacement in petrels and shearwaters from offshore wind developments in scotland*. The Scottish Government Technical report, 138pp.

[28] M. Defingou, F. Bils, B. Horchler, T. Liesenjohann, G. Nehls, Pharos4mpas-a review of solutions to avoid and mitigate environmental impacts of offshore windfarms, BioConsult SH WWF Fr. (2019) 264.

[29] S. Degraer, R. Brabant, B. Rumes, L. Vigin, Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Getting ready for offshore wind farm expansion in the North Sea (eds).. Memoirs on the Marine Environment, Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management, Brussels, 2022, p. 106 (eds).

[30] S. Degraer, D.A. Carey, J.W. Coolen, Z.L. Hutchison, F. Kerckhof, et al., Offshore wind farm artificial reefs affect ecosystem structure and functioning, Oceanography 33 (4) (2020) 48–57.

[31] M.H. Depledge, C.A. Godard-Codding, R.E. Bowen, Light pollution in the sea, Mar. Pollut. Bull. 60 (9) (2010) 1383–1385.

[32] V. Dierschke, R.W. Furness, S. Garthe, Seabirds and offshore wind farms in european waters: Avoidance and attraction, Biol. Conserv. 202 (2016) 59–68.

[33] A.L. Drewitt, R.H. Langston, Assessing the impacts of wind farms on birds, Ibis 148 (2006) 29–42.

[34] E.M. Duncan, Z.L. Botterell, A.C. Broderick, T.S. Galloway, P.K. Lindeque, et al., A global review of marine turtle entanglement in anthropogenic debris: a baseline for further action, Endanger. Species Res. 34 (2017) 431–448.

[35] P. Ehlers, Blue growth and ocean governance—how to balance the use and the protection of the seas, WMU J. Marit. Aff. 15 (2016) 187–203.

[36] Ellison, L.E., 2012. *Bats and wind energy: A literature synthesis and annotated bibliography*. US Department of the Interior, US Geological Survey Open-File Report 2012–1110, 57 p.

[37] English, P., Mason, T., Backstrom, J., Tibbles, B., Mackay, A., *et al.*, 2017. *Improving efficiencies of national environmental policy act documentation for offshore wind facilities-case studies report*. US Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling. OCS Study BOEM 2017-026, 217pp.

[38] EU, 2020. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future*. COM (2020) 741 final.

[39] EU, 2022. European Commission, Directorate-General for Environment, *Restoring nature – For the benefit of people, nature and the climate*. Publications Office of the European Union.

[40] European Commission. 2020a. An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future. ICES Document COM/2020: 741 final. ⟨https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN⟩.

[41] European Commission. 2020b. Commission Notice. Brussels. 18.11.2020C(2020) 7730 final. ⟨https://ec.europa.eu/environment/nature/natura2000/management/docs/wind_farms_en.pdf⟩.

[42] H. Farr, B. Ruttenberg, R.K. Walter, Y.-H. Wang, C. White, Potential environmental effects of deepwater floating offshore wind energy facilities, Ocean Coast. Manag. 207 (2021) 105611.

[43] J. Filmalter, P. Cowley, F. Forget, L. Dagorn, Fine-scale 3-dimensional movement behaviour of silky sharks *Carcharhinus falciformis* associated with fish aggregating devices (fads), Mar. Ecol. Prog. Ser. 539 (2015) 207–223.

[44] A. Fox, M. Desholm, J. Kahlert, T.K. Christensen, I. Krag Petersen, Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds, Ibis 148 (2006) 129–144.

[45] R.W. Furness, H.M. Wade, E.A. Masden, Assessing vulnerability of marine bird populations to offshore wind farms, J. Environ. Manag. 119 (2013) 56–66.

[46] Galparsoro, I. Menchaca, I. Garmendia, J.M. Borja, Á. Maldonado, et al., Reviewing the ecological impacts of offshore wind farms, npj Ocean Sustain. 1 (1) (2022) 1.

[47] S. Garthe, O. Hüppop, Effect of ship speed on seabird counts in areas supporting commercial fisheries (el efecto de la velocidad del bote en conteos de aves marinas en areas que sostienen pescacomercial), J. Field Ornithol. (1999) 28–32.

[48] S.A. Gauthreaux Jr, C.G. Belser, C. Rich, T. Longcore, Effects of artificial night lighting on migrating birds, Ecol. Conséq. Artif. night Light. (2006) 67–93.

[49] G. Gerdes, A. Jansen, K. Rehfeldt, S. Teske, Offshore wind energy– implementing a new powerhouse for Europe, Grid Connect., Environ. Impact Assess. (2005).

[50] A.B. Gill, M. Desender, Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices, in: A.E. Copping, L. G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World, Report for Ocean Energy Systems (OES), 2020, pp. 86–103, doi:10.2172/1633088.

[51] T.M. Glasby, S.D. Connell, M.G. Holloway, C.L. Hewitt, Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar. Biol. 151 (2007) 887–895.

[52] M.W. Goodale, A. Milman, Cumulative adverse effects of offshore wind energy development on wildlife, J. Environ. Plan. Manag. 59 (1) (2016) 1–21.

[53] J.S. Gray, Biomagnification in marine systems: the perspective of an ecologist, Mar. Pollut. Bull. 45 (1-12) (2002) 46–52.
[54] Green, R., Hein, C., Oteri, F., Severy, M., Alicia, M., *et al.*, 2022. Environmental effects of U.S. offshore wind energy development: Compilation of educational research briefs [booklet]. Report by National Renewable Energy Laboratory and Pacific Northwest National Laboratory for the U.S. Department of Energy, Wind Energy Technologies Office.
[55] E.E. Guest, B.F. Stamps, N.D. Durish, A.M. Hale, C.D. Hein, et al., An updated review of hypotheses regarding bat attraction to wind turbines, Animals 12 (3) (2022) 343.
[56] R. Hall, E. Topham, E. João, Environmental impact assessment for the decommissioning of offshore wind farms, Renew. Sustain. Energy Rev. 165 (2022) 112580.
[57] L. Hammar, D. Perry, M. Gullström, Offshore wind power for marine conservation, Open J. Mar. Sci. 6 (1) (2015) 66–78.
[58] L. Hammar, A. Wikström, S. Molander, Assessing ecological risks of offshore wind power on Kattegat cod, Renew. Energy 66 (2014) 414–424.
[59] A. Haquart, Référentiel d'activité des chiroptères, éléments pour l'interprétation des dénombrements de chiroptères avec les méthodes acoustiques en zone méditerranéenne française, Biotope, École Prat. Des. Hautes Études (2013).
[60] V. Harnois, H.C. Smith, S. Benjamins, L. Johanning, Assessment of entanglement risk to marine megafauna due to offshore renewable energy mooring systems, Int. J. Mar. Energy 11 (2015) 27–49.
[61] S.K. Henkel, R.M. Suryan, B.A. Lagerquist, Marine renewable energy and environmental interactions: baseline assessments of seabirds, marine mammals, sea turtles and benthic communities on the Oregon shelf, Mar. Renew. Energy Technol. Environ. Interact. (2014) 93–110.
[62] Hogan, F., Hooker, B., Jensen, B., Johnston, L., Lipsky, A., *et al.*, 2023. Fisheries and Offshore Wind Interactions: Synthesis of Science.
[63] E.S. Horwath, J. Hassrick, R. Grismala, E. Diller, J. Krebs, et al., Comparison of environmental effects from different offshore wind turbine foundations, in: Rep. ICF Int. Rep. ICF Int., no. OCS Study BOEM, 41, 2020, p. 53.
[64] O. Hüppop, J. Dierschke, K.-M. Exo, E. Fredrich, R. Hill, Bird migration studies and potential collision risk with offshore wind turbines, Ibis 148 (2006) 90–109.
[65] O. Hüppop, B. Michalik, L. Bach, R. Hill, S. Pelletier, Migratory birds and bats, Wildl. Wind Farms, Confl. Solut. 3 (2019) 142–173.
[66] Z. Hutchison, P. Sigray, H. He, A. Gill, J. King, et al., Electromagnetic field (EMF) impacts on elasmobranch (shark, rays, and skates) and American lobster movement and migration from direct current cables, US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM, Sterling (VA), 2018, 2018-003.
[67] R. Karlsson, M. Tivefälth, I. Duranovic, S. Martinsson, A. Kjølhamar, et al., Artificial hard-substrate colonisation in the offshore Hywind Scotland pilot park, Wind Energy Sci. 7 (2) (2022) 801–814.
[68] P. Kerlinger, J.L. Gehring, W.P. Erickson, R. Curry, A. Jain, et al., Night migrant fatalities and obstruction lighting at wind turbines in north America, Wilson J. Ornithol. 122 (4) (2010) 744–754.
[69] T. Kirchgeorg, I. Weinberg, M. Hörnig, R. Baier, M. Schmid, et al., Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment, Mar. Pollut. Bull. 136 (2018) 257–268.
[70] R. Krone, L. Gutow, T. Brey, J. Dannheim, A. Schröder, Mobile demersal megafauna at artificial structures in the German Bight–likely effects of offshore wind farm development. Estuar., Coast. Shelf Sci. 125 (2013) 1–9.
[71] T.H. Kunz, E.B. Arnett, W.P. Erickson, A.R. Hoar, G.D. Johnson, et al., Ecological impacts of wind energy development on bats: questions, research needs, and hypotheses, Front. Ecol. Environ. 5 (6) (2007) 315–324.
[72] O. Langhamer, Artificial reef effect in relation to offshore renewable energy conversion: state of the art, Sci. World J. 2012 (2012).
[73] Last, K.S., Hendrick V.J., Beveridge C.M., Davies A.J., 2011. Measuring the effects of suspended particulate matter and smothering on the behaviour, growth and survival of key species found in areas associated with aggregate dredging. Report for the Marine Aggregate Levy Sustainability Fund, Project MEPF 08/P76, 69 pp.
[74] Lengkeek, W., Didderen, K., Teunis, M., Driessen, F., Coolen, J.W.P., *et al.*, 2017. Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms: Towards an implementation guide and experimental set-up (No. 17-001). Bureau Waardenburg.
[75] J. Lloret, S. Biton-Porsmoguer, A. Carreño, A. Di Franco, R. Sahyoun, et al., Recreational and small-scale fisheries may pose a threat to vulnerable species in coastal and offshore waters of the western Mediterranean, ICES J. Mar. Sci. 77 (6) (2020) 2255–2264.
[76] J. Lloret, A. Turiel, J. Solé, E. Berdalet, A. Sabatés, et al., Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea, Sci. Total Environ. 824 (2022) 153803.
[77] J. Lloret, P. Wawrzynkowski, C. Dominguez-Carrió, R. Sardá, C. Monlins, et al., Floating offshore wind farms in Mediterranean marine protected areas: a cautionary tale, ICES J. Mar. Sci. 0 (2023) 1–14. DOI: 10.1093/icesjms/fsad131.
[78] K.J. Lohmann, B.E. Witherington, C.M. Lohmann, M. Salmon, Orientation, navigation, and natal beach homing in sea turtles. The biology of sea turtles, CRC Press, 1997, pp. 108–135.
[79] M. Maar, K. Bolding, J.K. Petersen, J.L. Hansen, K. Timmermann, Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark, J. Sea Res. 62 (2-3) (2009) 159–174.
[80] P.T. Madsen, M. Wahlberg, J. Tougaard, K. Lucke, P. Tyack, Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs, Mar. Ecol. Prog. Ser. 309 (2006) 279–295.
[81] L.F. Marangoni, T. Davies, T. Smyth, A. Rodríguez, M. Hamann, et al., Impacts of artificial light at night in marine ecosystems—a review, Glob. Change Biol. 28 (18) (2022) 5346–5367.
[82] B. Marmo, I. Roberts, M.P. Buckingham, S. King, C. Booth, Modelling of Noise Effects of Operational Offshore Wind Turbines including noise transmission through various foundation types, Scottish Government, Edinburgh, 2013.
[83] G.R. Martin, A.N. Banks, Marine birds: vision-based wind turbine collision mitigation, Glob. Ecol. Conserv. (2023) e02386.
[84] A. Martinez, G. Iglesias, Multi-parameter analysis and mapping of the levelised cost of energy from floating offshore wind in the Mediterranean Sea, Energy Convers. Manag. 243 (2021) 114416.
[85] E.A. Masden, D.T. Haydon, A.D. Fox, R.W. Furness, Barriers to movement: modelling energetic costs of avoiding marine wind farms amongst breeding seabirds, Mar. Pollut. Bull. 60 (7) (2010) 1085–1091.
[86] S.M. Maxwell, F. Kershaw, C.C. Locke, M.G. Conners, C. Dawson, et al., Potential impacts of floating wind turbine technology for marine species and habitats, J. Environ. Manag. 307 (2022) 114577.
[87] MedECC, 2020. Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report [Cramer, W., Guiot, J., Marini, K. (eds.)] Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632pp.
[88] M.F. Mickle, R.H. Pieniazek, D.M. Higgs, Field assessment of behavioural responses of southern stingrays (*Hypanus americanus*) to acoustic stimuli, R. Soc. Open Sci. 7 (1) (2020) 191544.
[89] W. Miles, S. Money, R. Luxmoore, R.W. Furness, Effects of artificial lights and moonlight on petrels at st Kilda, Bird. Study 57 (2) (2010) 244–251.
[90] T. Miles, S. Murphy, J. Kohut, S. Borsetti, D. Munroe, Offshore wind energy and the Mid-Atlantic Cold Pool: a review of potential interactions, Mar. Technol. Soc. J. 55 (4) (2021) 72–87.
[91] MITECO , 2023. *Ordenación del espacio marítimo* . ⟨https://www.miteco.gob.es/es/costas/temas/proteccion-medio-marino/ordenacion-del-espacio-maritimo.html⟩ (Accessed: 2023-11-27).
[92] W.A. Montevecchi, Influences of artificial light on marine birds, Ecol. Conséq. Artif. night Light. (2006) 94–113.
[93] T.A. Mooney, M.H. Andersson, J. Stanley, Acoustic impacts of offshore wind energy on fishery resources, Oceanography 33 (4) (2020) 82–95.
[94] E. Moore, S. Lyday, J. Roletto, K. Litle, J.K. Parrish, et al., Entanglements of marine mammals and seabirds in central California and the north-west coast of the united states 2001–2005, Mar. Pollut. Bull. 58 (7) (2009) 1045–1051.
[95] Nedwell, J., Brooker, A., Barham, R., 2012. Assessment of underwater noise during the installation of export power cables at the Beatrice offshore wind farm. *Subacoustech Environment Report NE318R0106*.
[96] Newton, K.C., 2017. *Cognitive and Magnetosensory Ecology of the Yellow Stingray, Urobatis jamaicensis*. Dissertation. Florida Atlantic University, USA, 118pp.
[97] K.C. Newton, A.B. Gill, S.M. Kajiura, Electroreception in marine fishes: chondrichthyans, J. Fish. Biol. 95 (1) (2019) 135–154.
[98] B. Nightingale, T. Longcore, C.A. Simenstad, Artificial night lighting and fishes, Ecol. Conséq. Artif. night Light. 11 (2006) 257–276.
[99] NYSERDA, 2020. Summary of discussions from the bird and bat specialist committee of the environmental technical working group (e-twg). Technical report, 33pp.
[100] A. Olabi, M.A. Abdelkareem, Renewable energy and climate change, Renew. Sustain. Energy Rev. 158 (2022) 112111.
[101] Orr, T., Herz, S., Oakley, D., 2013. *Evaluation of lighting schemes for offshore wind facilities and impacts to local environments*. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Herndon, VA. OCS Study BOEM 2013-0116. 429 pp.
[102] OSC, 2022. Literature review on barrier effects, ghost fishing, and electromagnetic fields for floating windfarms. Literature review No. 1, for Equinor ASA, by Ocean Science Consulting Limited, Spott Road, Dunbar, Scotland, 99pp.
[103] OSPAR, 2008. OSPAR background document on potential problems associated with power cables other than those for oil and gas activities. OSPAR commission technical report, 50pp.
[104] K.J. Parton, T.S. Galloway, B.J. Godley, Global review of shark and ray entanglement in anthropogenic marine debris, Endanger. Species Res. 39 (2019) 173–190.
[105] I.K. Petersen, A.D. Fox, Changes in bird habitat utilisation around the Horns Rev 1 offshore wind farm, with particular emphasis on Common Scoter, Department of Wildlife Ecology and Biodiversity, National Environmental Research Institute - University of Aarhus, Denmark, 2007, p. 36.
[106] Peterson, T., Pelletier, S., Giovanni, M., 2016. *Long-term bat monitoring on islands, offshore structures, and coastal sites in the Gulf of Maine, mid-Atlantic, and great lakes*. Technical report, Stantec Consulting Services Inc., Topsham, ME (United States), 171pp.
[107] H. Poot, B.J. Ens, H. de Vries, M.A. Donners, M.R. Wernand, et al., Green light for nocturnally migrating birds, Ecol. Soc. 13 (2) (2008).
[108] Pörtner, H.-O., Scholes, R.J., Agard, J., Archer, E., Arneth, A., *et al.,* 2021. *Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change*. IPBES secretariat, Bonn, Germnay, DOI:10.5281.
[109] H.-O. Pörtner, R. Scholes, A. Arneth, D. Barnes, M.T. Burrows, et al., Overcoming the coupled climate and biodiversity crises and their societal impacts, Science 380 (6642) (2023) eabl4881.
[110] S.J. Price, R.B. Figueira, Corrosion protection systems and fatigue corrosion in offshore wind structures: current status and future perspectives, Coatings 7 (2) (2017) 25.

[111] E. Quintana-Rizzo, S. Leiter, T. Cole, M. Hagbloom, A. Knowlton, et al., Residency, demographics, and movement patterns of north Atlantic right whales *Eubalaena glacialis* in an offshore wind energy development area in southern New England, USA, Endanger. Species Res. 45 (2021) 251–268.

[112] Ramasco, V., 2022. Glider study at Hywind Scotland. Technical report, Akvaplan-niva report: 2021 62861.01, 46pp.

[113] M. Rebke, V. Dierschke, C.N. Weiner, R. Aumüller, K. Hill, et al., Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions, Biol. Conserv. 233 (2019) 220–227.

[114] J.T. Reubens, S. Degraer, M. Vincx, The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research, Hydrobiologia 727 (2014) 121–136.

[115] J.T. Reubens, S. Vandendriessche, A.N. Zenner, S. Degraer, M. Vincx, Offshore wind farms as productive sites or ecological traps for gadoid fishes?–Impact on growth, condition index and diet composition, Mar. Environ. Res. 90 (2013) 66–74.

[116] Reynaud, M., Le Bourhis, E., Soulard, T., Perignon, Y., 2021. Rapport de suivi environnemental de l'éolienne flottante FLOATGEN, site d'essais SEM-REV. Tecnical report, 87pp.

[117] F. Rezaei, P. Contestabile, D. Vicinanza, A. Azzellino, Towards understanding environmental and cumulative impacts of floating wind farms: Lessons learned from the fixed-bottom offshore wind farms, Ocean Coast. Manag. 243 (2023) 106772.

[118] Risch, D., Favill, G., Marmo, B., van Geel, N., Benjamins, S., *et al.*, 2023. *Characterisation of underwater operational noise of two types of floating offshore wind turbines*. Technical report, Scottish Association for Marine Science (SAMS), 62pp.

[119] A. Rodríguez, N.D. Holmes, P.G. Ryan, K.-J. Wilson, L. Faulquier, et al., Seabird mortality induced by land-based artificial lights, Conserv. Biol. 31 (5) (2017) 986–1001.

[120] Rusu, E., Rusu, L., 2019. Evaluation of the wind power potential in the European nearshore of the Mediterranean Sea. In *E3S Web of Conferences*, volume 103, page 01003. EDPSciences.

[121] M. Salmon, Artificial night lighting and sea turtles, Biologist 50 (4) (2003) 163–168.

[122] H. Sandvik, K. Einar Erikstad, Seabird life histories and climatic fluctuations: A phylogenetic-comparative time series analysis of north Atlantic seabirds, Ecography 31 (1) (2008) 73–83.

[123] Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., *et* al., 2022. Climate change 2022: mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, NY, USA, 2042pp.

[124] P. Sigray, M. Linné, M.H. Andersson, A. Nöjd, L.K. Persson, et al., Particle motion observed during offshore wind turbine piling operation, Mar. Pollut. Bull. 180 (2022) 113734.

[125] K. Slavik, C. Lemmen, W. Zhang, O. Kerimoglu, K. Klingbeil, et al., The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea, Hydrobiologia 845 (2019) 35–53.

[126] P. Smith, L. Beaumont, C.J. Bernacchi, M. Byrne, W. Cheung, et al., Essential outcomes for cop26, Glob. Change Biol. 28 (1) (2022) 1–3, https://doi.org/10.1111/gcb.15926.

[127] M. Solan, C. Hauton, J.A. Godbold, C.L. Wood, T.G. Leighton, et al., Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties, Sci. Rep. 6 (1) (2016) 1–9.

[128] Sotta, C., Niliot, P., Lefeuvre, C., 2012. *Documentary summary of the environmental impact of renewable marine energy*. Marine Energy in Far Peripheral Island Communities (MERiFIC). Tecnical report, 124pp.

[129] T.H. Soukissian, D. Denaxa, F. Karathanasi, A. Prospathopoulos, K. Sarantakos, et al., Marine renewable energy in the Mediterranean Sea: status and perspectives, Energies 10 (10) (2017) 1512.

[130] J.A. Stanley, S.M. Van Parijs, L.T. Hatch, Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock, Sci. Rep. 7 (1) (2017) 14633.

[131] C. Stenton, E. Bolger, M. Michenot, J. Dodd, M. Wale, et al., Effects of pile driving sound playbacks and cadmium co-exposure on the early life stage development of the Norway lobster, *Nephrops norvegicus*, Mar. Pollut. Bull. 179 (2022) 113667.

[132] Svendsen, J.C., Ibanez-Erquiaga, B., Savina, E., Wilms, T., 2022. Effects of operational off-shore wind farms on fishes and fisheries. Review report. DTU Aqua. DTU Aqua-rapport No. 411-2022, 66pp.

[133] K. Takahashi, Release rate of biocides from antifouling paints, chapter 1, in: T. Arai, H. Harino, M. Ohji, W.J. Langston (Eds.), Ecotoxicology of Antifouling Biocides, Springer, 2009.

[134] B. Taormina, J. Bald, A. Want, G. Thouzeau, M. Lejart, et al., A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions, Renew. Sustain. Energy Rev. 96 (2018) 380–391.

[135] T. Tricas, A.B. Gill, Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species, U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA, 2011. OCS Study BOEMRE 2011-09.

[136] A.C. Utne-Palm, Visual feeding of fish in a turbid environment: physical and behavioural aspects, Mar. Freshw. Behav. Physiol. 35 (1-2) (2002) 111–128.

[137] S. Vaselli, I. Bertocci, E. Maggi, L. Benedetti-Cecchi, Effects of mean intensity and temporal variance of sediment scouring events on assemblages of rocky shores, Mar. Ecol. Prog. Ser. 364 (2008) 57–66.

[138] M. Wahlberg, H. Westerberg, Hearing in fish and their reactions to sounds from offshore wind farms, Mar. Ecol. Prog. Ser. 288 (2005) 295–309.

[139] D. Ward, J. Melbourne-Thomas, G.T. Pecl, K. Evans, M. Green, et al., Safeguarding marine life: conservation of biodiversity and ecosystems, Rev. Fish. Biol. Fish. 32 (1) (2022) 65–100.

[140] D. Wilhelmsson, T. Malm, R. Thompson, J. Tchou, G. Sarantakos, et al., Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy (eds.), IUCN, Gland, Switzerland, 2010, p. 102 (eds.).

[141] Wilson, B., Batty, R., Daunt, F., Carter, C., 2007. Collision risks between marine renewable energy devices and mammals, fish and diving birds. Report to the Scottish Executive. Scottish Association for Marine Science, Oban, Scotland, PA37 1QA. 110pp.

[142] B.E. Witherington, The problem of photopollution for sea turtles and other nocturnal animals, Behav. Approaches Conserv. wild (1997) 303–328.

[143] Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In Proceedings of the 18th international conference on evaluation and assessment in software engineering (pp. 1-10).

[144] L.E. Wysocki, J.P. Dittami, F. Ladich, Ship noise and cortisol secretion in European freshwater fishes, Biol. Conserv. 128 (4) (2006) 501–508.