Science of the Total Environment 824 (2022) 153803

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short communication

Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea

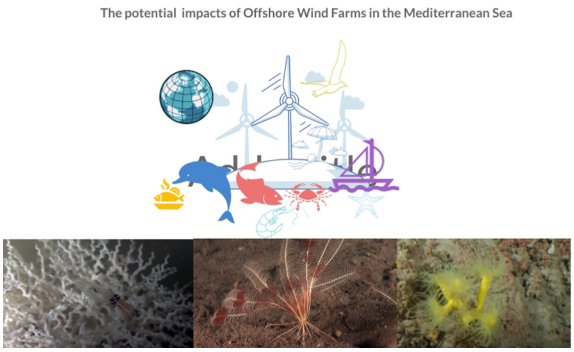
Josep Lloret [a,*], Antonio Turiel [b], Jordi Solé [c], Elisa Berdalet [b], Ana Sabatés [b], Alberto Olivares [d], Josep-Maria Gili [b], Josep Vila-Subirós [e], Rafael Sardá [d]

[a] *Institute of Aquatic Ecology, University of Girona, C/ Maria Aurèlia Capmany 69, 17003 Girona, Catalonia, Spain*
[b] *Institut de Ciències del Mar (CSIC), Passeig Marítim de la Barceloneta 37-49, 08003 Barcelona, Catalonia, Spain*
[c] *Department of Earth and Ocean Dynamics, University of Barcelona, C/Martí i Franqués s/n, 08028 Barcelona, Catalonia, Spain*
[d] *Centre d'Estudis Avançats de Blanes (CSIC), Ctra. d'accés a la Cala St. Francesc, 14, 17300 Blanes, Girona, Catalonia, Spain*
[e] *Department of Geography, University of Girona, Plaça Ferrater Mora 1, 17004 Girona, Catalonia, Spain*

HIGHLIGHTS

- Offshore wind farms (OWF) pose serious environmental risks to the Mediterranean Sea.
- OWF models cannot be simply imported from the northern European seas to other seas.
- OWF should be excluded from areas of high biodiversity and/or high valuable seascape.
- OWF development should be forbidden in or in the vicinity of Marine Protected Areas (MPAs).
- Biodiversity loss and climate change are interconnected and must be tackled simultaneously.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 December 2021
Received in revised form 2 February 2022
Accepted 7 February 2022
Available online 9 February 2022

Editor: Pavlos Kassomenos

Keywords:
Offshore energy
Marine protected areas, environmental impacts, biodiversity
Maritime spatial planning, seascape
Renewable energy
Mediterranean Sea

ABSTRACT

The need for alternative energy systems like offshore wind power to move towards the Green Deal objectives is undeniable. However, it is also increasingly clear that biodiversity loss and climate change are interconnected issues that must be tackled in unison. In this paper we highlight that offshore wind farms (OWF) in the Mediterranean Sea (MS) pose serious environmental risks to the seabed and the biodiversity of many areas due to the particular ecological and socioeconomic characteristics and vulnerability of this semi-enclosed sea. The MS hosts a high diversity of species and habitats, many of which are threatened. Furthermore, valuable species, habitats, and seascapes for citizens' health and well-being coexist with compounding effects of other economic activities (cruises, maritime transport, tourism activities, fisheries and aquaculture) in a busy space on a narrower continental shelf than in other European seas. We argue that simply importing the OWF models from the northern European seas, which are mostly based on large scale projects, to other seas like the Mediterranean is not straightforward. The risks of implementing these wind farms in the MS have not yet been well evaluated and, considering the Precautionary Principle incorporated into the Marine Strategy Framework Directive and the Maritime Spatial Planning Directive, they should not be ignored. We propose that OWF development in the MS should be excluded from high biodiversity areas containing sensitive and threatened species and habitats, particularly those situated inside or in the vicinity of Marine Protected Areas or

---

Abbreviations: OWF, Offshore Wind Farm(s); CCWF, Cap de Creus Wind Farm; MS, Mediterranean Sea; MPA, Marine Protected Area(s); EU, European Union; MSFD, Marine Strategy Framework Directive; GES, Good Environmental Status.

[*] Corresponding author.
E-mail address: josep.lloret@udg.edu (J. Lloret).

http://dx.doi.org/10.1016/j.scitotenv.2022.153803

areas with valuable seascapes. In the absence of a clearer and comprehensive EU planning of wind farms in the MS, the trade-off between the benefits (climate goals) and risks (environmental and socioeconomic impacts) of OWF could be unbalanced in favor of the risks.

1. The context

The offshore wind energy sector has been expanding since the 1990s when the first offshore wind farms (OWF) were built. Interest in OWF and other sources of renewable energy is growing in many parts of the world as a crucial component of the global fight to mitigate climate change (EEA, 2009; Dannheim et al., 2020; Bennun et al., 2021; ICES, 2021). OWF constitute a key sector in the European Union's so-called “Blue Economy” (European Commission, 2021), receiving priority financial interest from the member states (particularly since the COVID-19 pandemic, with the EU's Next Generation Funds). The ‘Blue Economy’ is a contested but increasingly influential concept that is gaining considerable traction in the ocean-based sustainable development narrative (Voyer and van Leeuwen, 2019). A particular area of contestation is which ocean-based industries, sectors, or projects can be ‘Blue’ in the sense of producing socioeconomic benefits from a sustainable exploitation or use of the marine ecosystems. OWF are experiencing a significant boom in the North Sea, the North Atlantic and the Baltic Sea, accounting for more than 85% of all offshore wind capacity in European waters (European Parliament, 2019). With the goal of Europe becoming climate neutral by 2050, the EU estimates that offshore wind must provide 30% of Member States' electricity demand by 2050, increasing from the current 12 GW capacity to a target of more than 300 GW, which means multiplying by 15 the marine space allocated to wind energy (European Parliament, 2019).

While in terms of reducing greenhouse gas emissions the benefits of OWF and other renewable sources such as solar and biomass are undeniable (EEA, 2009), the risks posed to the marine ecosystems are diverse and must not be neglected (Gill, 2005; Perrow, 2019; ICES, 2021). The biodiversity crisis has led to calls for the adoption of a succinct Global Goal for Nature, which should be combined with development and climate goals to create an integrated and overarching direction for global agreements aimed at an Equitable, Nature-Positive, Carbon-Neutral world (Locke et al., 2021). In this context, the European Commission (2020a) highlights that designated sea spaces for offshore energy exploitation should be compatible with biodiversity protection, considering socioeconomic consequences for sectors relying on the good health of marine ecosystems and integrating other uses of the sea as much as possible. In addition, the European Commission recently adopted the Biodiversity Strategy for 2030 (European Commission, 2020b) with the overall goal of putting biodiversity on the path to recovery by 2030, and of protecting 30% of marine and terrestrial land, of which 10% must be strictly protected.

The development of offshore wind energy in the MS is currently in its infancy, with no OWF in operation to date in the region, apart from pilot projects (e.g., just three floating turbines in the French part of the Gulf of Lion; https://info-efgl.fr./ and www.provencegrandlarge.fr). This situation of small-scale testing is about to change with abrupt plans for around 30 OWF projects in the Mediterranean countries (Soukissian et al., 2017; WWF, 2019), raising concerns about their potential effects on marine wildlife and ecosystems already affected by a wide range of economic activities (fisheries, recreational boats, cruises, cargo ships and aquaculture, among others) in the area. Several Mediterranean countries, including Spain, France, Italy and Greece are currently effecting legal changes regarding OWF and establishing new legal tools to facilitate their development. The narrow continental shelf and steep bathymetry in many parts of the MS largely constrain offshore wind energy potential compared to the Baltic and the North Sea (EEA, 2009). This containment means that wind farms can easily be projected close to the coast where most Mediterranean Marine Protected Areas (MPAs), which host high biodiversity, are located (IUCN, 2008). This fact makes it more difficult to balance wind potential needs in the MS with the biodiversity conservation goals on a spatial basis. Furthermore and notably, offshore wind energy potential is much lower in the MS than in the northern European Seas. The overall estimated potential for offshore wind energy in Mediterranean countries such as Croatia, Cyprus, France, Greece, Italy, Malta, Slovenia and Spain for the period 2030–2050 is approximately three times lower than the estimated values of northern European countries such as the United Kingdom, Norway, Sweden, Netherlands, and Denmark (EEA, 2009; European Commission, 2020c).

In this paper, we present arguments to demonstrate that simply importing the OWF models, or the massive deployment of large wind farms from the northern European Seas to other seas like the MS, is not straightforward. To illustrate these environmental and policy aspects, we will use the example of a large OWF designed to be built in the Costa Brava region of the northern Catalan Sea (Spain, NW Mediterranean) in the waters of Cape Creus/Gulf of Roses (MITECO, 2021). This large OWF (referenced here as CCWF) is surrounded by eight MPAs (mainly Natura 2000 areas) and is used here as a case study of the first large OWF proposed in the MS (Fig. 1).

This paper is structured as follows. Based on a literature review, in the second section we assess the historical pressures of OWF on different components of the marine environment and their corresponding impacts in terms of the Good Environmental Status concept, emphasizing the particularities of the MS. In the third section, we describe the incompatibility of OWF with MPAs and other areas of high ecological value in the MS. In the subsequent sections, we explore different conflicts between OWF and various maritime activities. Last, we present key recommendations to assess OWF pressures on the marine environment to be considered by policy makers before operational licensing.

2. The environmental pressures of OWF on the marine environment of the MS

While there are no robust empirical studies of environmental changes caused by operational OWF in the MS to date due to a lack of these facilities in operation, the potential environmental effects in the MS during the construction, operation, and decommissioning phases of future OWF in the MS can be identified using the scientific literature on analog cases in other oceans and seas such as the North Sea, the Baltic Sea and the North Atlantic (Bray et al., 2016). Nonetheless, the knowledge gained from northern European seas can only be partially applied to OWF development in the MS since the region has its own set of unique environmental and socioeconomic characteristics, which are detailed in the next sections and paragraphs. Also important is that compared to other seas and oceans there is less knowledge about the conservation status of Mediterranean deep-sea marine habitats (IUCN, 2019a), which is a handicap for proposing suitable marine areas for the construction of OWF. In general, there are still substantial knowledge gaps on the quantification of the environmental pressures of OWF in the MS. Table 1 summarizes the potential environmental effects of OWF in the MS translated into the 11 Good Environmental Status descriptors of the European Marine Strategy Framework Directive (MSFD).

2.1. Species and habitats

Most of the European research carried out in the North Sea, the Baltic Sea and the North Atlantic has shown that offshore wind development has potential negative impacts on the marine environment (Table 1). Nevertheless, some studies have found evidence of OWF benefits during the operative phase for benthic habitats and animals (including benthic fish, marine mammals, and sessile invertebrates) when wind farms are built in areas with relatively homogenous seabeds (ICES, 2008; Vaissière

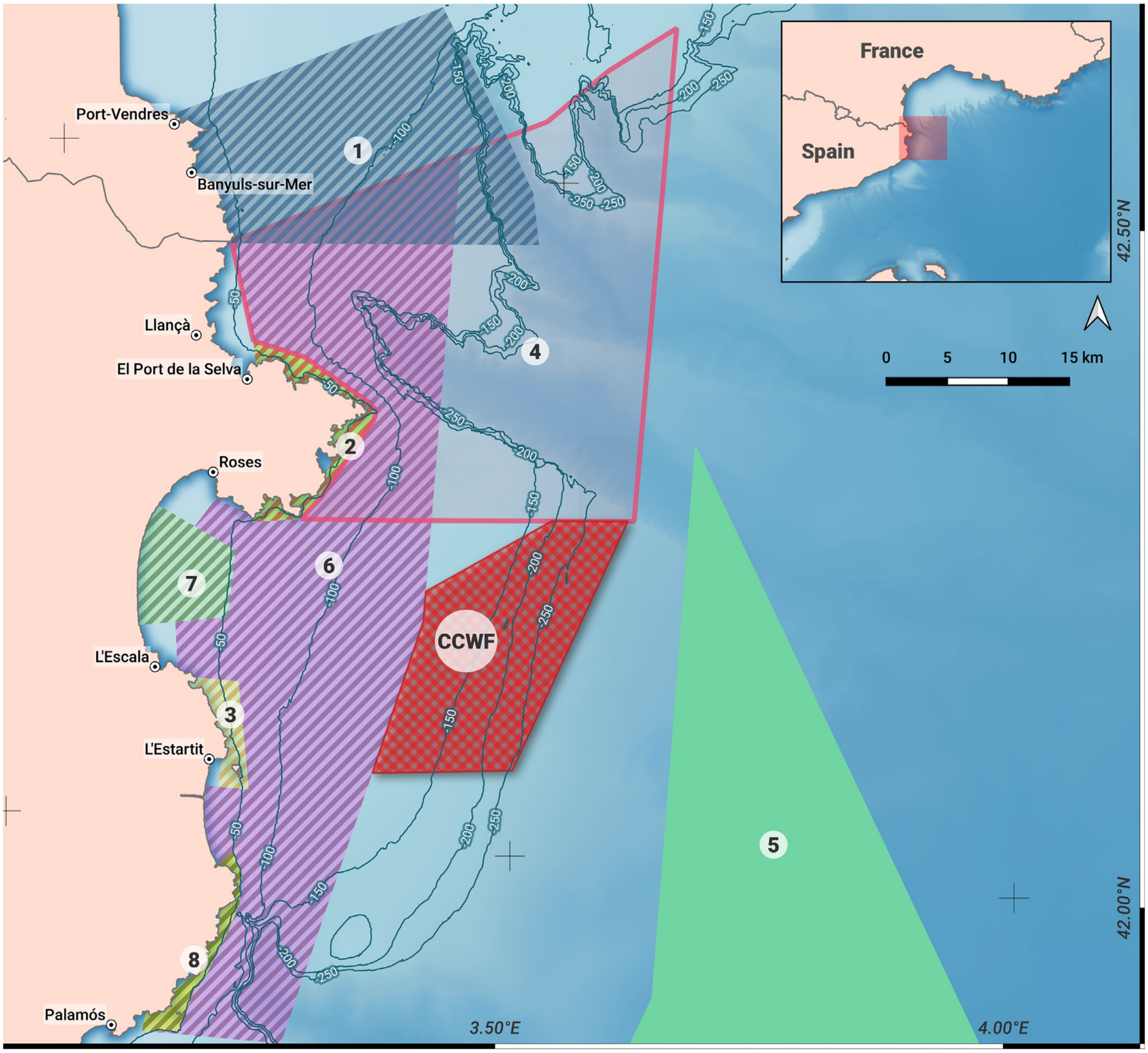


Fig. 1. Map of the region showing all the MPAs in the area where the Cap de Creus/Gulf of Roses offshore wind farm (CCWF) is proposed: (1) SPA of Cap Bear-Cap Cerbère, (2) SPAMI, SCI, SAC, and SPA of Cap de Creus, (3) SPAMI, SCI, SAC, and SPA of Montgrí-Medes-Baix Ter, (4) SCI "Western Submarine Canyon System of the Gulf of Lions", (5) "Mediterranean Cetacean Migration Corridor", (6) SPA of the "Espacio Marino del Empordà", (7) maritime part of the SCI, SAC and SPA of the Aiguamolls de l'Empordà; and (8) SCI, SPA and SAC "Litoral del Baix Empordà". SAC: Natura 2000 Special Areas of Conservation; SCI: Natura 2000 Sites of Community Importance; SPA: Natura 2000 Special Protection Areas; SPAMI: Specially Protected Areas of Mediterranean Importance. Note: All boundary lines are approximate and for illustration purposes only.

et al., 2014; Hammar et al., 2016; Mavraki et al., 2021). Under these circumstances, the installation of foundations and piles can create an artificial reef that may provide space for the settlement, shelter and foraging for some species. However, these broad continental shelves with muddy sediments are rare in the MS, where the continental shelf has an enormous morphological and sedimentary heterogeneity, with rocky outcrops alternating with soft sediments (Gili et al., 2014). Therefore, any ecological benefits related to an increase of habitat heterogeneity linked to OWF, as described for northern European Seas, would be nil or absent in the MS, given its already high habitat heterogeneity.

In addition to the sandy and muddy habitats, there are many important and fragile benthic habitats in the MS, including seagrass meadows and sublittoral rocks in shallow areas, coralligenous reefs, maerl beds, seamounts, deep-sea coral reefs, and submarine canyons along the continental shelf and slope (European Commission, 2016). The MS has the highest proportion of threatened habitats (32%), well ahead of the North-East Atlantic (23%), the Black Sea (13%), and the Baltic Sea (8%) (European Commission, 2016). The particular complexity and fragility of Mediterranean habitats is an important aspect to take into consideration in the planning of OWF in the EU maritime regions analyzed. By way of example, the CCWF is projected to be built in an area encompassing eight MPAs (Fig. 1) with high substratum heterogeneity, comprising fragile habitats such as seagrass (*Posidonia oceanica, Cymodocea nodosa* and *Zostera* sp.) meadows, gravel fields, rocky bottoms, crinoid beds, coralligenous assemblages, maërl beds, and communities of deep-sea corals (*Madrepora oculata, Lophelia pertusa* and *Dendrophyllia cornigera*) in nearby submarine canyons, many of which act as natural reefs (Sardá et al., 2012; Gili et al., 2014; Domínguez-Carrió et al., 2014; García de Vinuesa, 2021). These habitats are likely to be disturbed by the foundations of the turbines.

A further point to consider is that the creation of new and artificial substrates favors the colonization by opportunistic species and the arrival of non-indigenous species that can alter the local biodiversity balance (Airoldi and Bulleri, 2011; De Mesel et al., 2015). This is particularly worrying in the case of the MS, which hosts the highest number of marine, coastal and estuarine non-indigenous species among all European Seas. Indeed, a total of 69% of all non-indigenous species in European Seas have been recorded in the MS, compared to 21% in the North-East Atlantic Ocean and 5% in the Baltic Sea (Wise Marine, 2021). The MS is one of

Table 1
Summary of potential environmental effects of Offshore Wind Farms (construction, operation, and decommissioning stages combined) in the Mediterranean Sea translated into the 11 Good Environmental Status (GES) descriptors of the Marine Strategy Framework Directive.

GES descriptor	Effects of the offshore wind farms	References
#1 Biodiversity: The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions	Loss of fragile benthic marine and coastal habitats important for biodiversity, particularly in protected areas	Gill, 2005; Perrow, 2019; ICES, 2021
	Disturbance to sensitive and threatened species (birds, mammals, sea turtles and fish) due to piles, anchors and cables (including the effects of electromagnetic fields and artificial lights, and entanglement risks). The OWF may cause species injury or death, changes in their behavioural response (attraction to and avoidance of the turbines) and/or changes in habitat.	Zettler and Pollehne, 2006; Vermeij et al., 2010; Benjamins et al., 2014; Bergström et al., 2014; Leopold et al., 2015; Goodale and Milman, 2016; WWF, 2014, 2019; Stanley et al., 2020; Hutchison et al., 2020; Taormina et al., 2020; De Jong et al., 2020; Jones et al., 2021; Anderson et al., 2021, Farr et al., 2021
	As floating wind farms expand in size and increase in distance from the shore, longer and higher capacity subsea cables are required to interconnect facility components to each other, to the seafloor, and to the shore. This may increase the extent of electromagnetic fields in the water column and potentially interact with a great diversity of marine organisms.	Benjamins et al., 2014; Farr et al., 2021.
	For floating wind farms, midwater mooring lines and floating substructures may similarly act as fish aggregation devices and settlement surfaces for invertebrates and algae, thus altering species composition in pelagic communities. Additional concerns are the potential for marine mammal collision and entanglement with these mooring lines and subsea cables	Benjamins et al., 2014; Farr et al., 2021.
	Risk of accidents (associated with natural hazards, such as storms and extreme events, and wind turbine accidents, including fire, the aerogenerator itself falling into the sea and ship collisions)	Biehl and Lehmann, 2006; Asian et al., 2017
	Artificial reef effect: when wind farms are built in areas with homogenous seabeds, the installation of foundations and piles may provide space for settlement, shelter and foraging for some species (positive effect)	ICES, 2008; Vaissière et al., 2014; Hammar et al., 2016; Degraer et al., 2020; Mavraki et al., 2021
	Habitat destruction on nearshore and inland fragile areas (estuaries, coastal lagoons, large shallow inlets and bays, etc.) due to the building of new terrestrial/ coastal infrastructure	This study
#2 Non-indigenous species: Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems	New, artificial substrates favor the colonization of non-indigenous species	Glasby et al., 2007; Duarte et al., 2013; De Mesel et al., 2015
#3 Commercial fish and shellfish: Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock	Effects on exploited species due to sound, vibrations and electromagnetic fields from cables	Zettler and Pollehne, 2006; Bergström et al., 2014; Leopold et al., 2015; Hutchison et al., 2020
	In the absence of fishing (usually forbidden within wind farms), biodiversity and the abundance of benthopelagic and benthic species using OWF for shelter and as feeding grounds may increase, with potential spillover effects (positive effect)	Halouani et al., 2020; Degraer et al., 2020; Gill et al., 2020; Mavraki et al., 2021.
	OWF will alter the dynamics (periodicity, access to areas occupied by wind farms) of scientific fishery resource surveys, thus affecting the stock assessment and management of fishery resources	Methratta et al., 2020.
#4 Food webs: All elements of the marine food webs, as far as they are known, occur at normal abundance and diversity and at levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity	Colonization by new (atypical) communities (sessile benthic species) that may modify food webs and biogeochemical cycling	Wilhelmsson and Langhamer, 2014; Coolen et al., 2020; Dannheim et al., 2020
	Increase of suspension feeders leading to changes in local primary production	Slavik et al., 2019; Mavraki et al., 2020
#5 Eutrophication: Human-induced eutrophication is minimised, and especially its adverse effects, such as biodiversity losses, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters	Unknown	
#6 Sea-floor integrity: Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems in particular are not adversely affected	Habitat alterations due to the installation and dismantling of pile foundations, cables, and anchors, the scour of the seabed, and the strumming of the cables	Gill, 2005; Wilhelmsson and Langhamer, 2014; Slavik et al., 2019; Perrow, 2019; Degraer et al., 2020; Coolen et al., 2020; ICES, 2021
	Floating OWF require mooring and anchoring systems consisting of heavy chains to keep their substructures stationary, and in some cases, the use of suction anchors that may require scour protection through rock dumping, affecting sea-floor integrity.	Statoil, 2015; Defingou et al., 2019; Farr et al., 2021
#7 Hydrographical conditions: Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems	Changes in atmospheric and oceanic dynamics leading to alterations in local primary productivity and carbon flow to the benthos, and changes in larval transport pathways.	Christensen et al., 2013; Clark et al., 2014; Ludewig, 2015; Carpenter et al., 2016; Grashorn and Stanev, 2016; Floeter et al., 2017; van Berkel et al., 2020, Lampert et al., 2020; Dannheim et al., 2020; Gill et al., 2020; Akhtar et al., 2021
	Oceanographic processes that could be affected by offshore wind farms include downstream turbulence, surface wave energy, local scour, inflowing currents and surface upwelling.	
	Turbulent mixing generated by turbine structures and wind reduction that can modify ocean vertical mixing and, in turn, stratification patterns	Ludewig, 2015; van Berkel et al., 2020; Miles et al., 2020

Table 1 (*continued*)

GES descriptor	Effects of the offshore wind farms	References
	While the floating OWF may initially have a smaller impact on the underwater hydrodynamics than a fixed OWF, the higher emerged structure (up to 250 m) could significantly modify the wind field	This study
#8 Contaminants in the marine environment: Contaminants are at a level not giving rise to pollution effects	Contamination from chemical emissions, including organic compounds such as bisphenol A and metals such as aluminum, zinc, and indium from corrosion and biofouling protection measures and sacrificial anodes	Kirchgeorga et al., 2018; De Witte and Hostens, 2019; Farr et al., 2021
	Pollution from the industrialization of the coastline, including the associated hydrogen plants	GIZ, 2020; WindEurope, 2021, Khan et al., 2021
	Pollution from accidents	Biehl and Lehmann, 2006; Asian et al., 2017
	Floating OWF may hold internal tanks that may contain both solid ballast and ballast water typically dosed with sodium hydroxide, a chemical compound that is toxic for aquatic organisms	European Commission, 2007; Statoil, 2015
#9 Contaminants in seafood: Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards	Unknown	
#10 Marine litter: Properties and quantities of marine litter do not cause harm to the coastal and marine environment	Unknown	
#11 Energy, including Underwater Noise: Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment	Changes to water quality: increase in local water turbidity arising from suspended solids	Gill, 2005; Perrow, 2019; ICES, 2021
	Significant marine noise and vibration from turbines and mounting structures (including floating OWF, which require mooring and anchoring systems consisting of heavy chains to keep their substructures stationary)	Gill, 2005 Statoil, 2015; Perrow, 2019; Defingou et al., 2019; Stanley et al., 2020; ICES, 2021; Jones et al., 2021; Farr et al., 2021
	Emission of electromagnetic fields can affect electrosensitive species, such as marine mammals and bottom dwelling species (e.g., elasmobranchs and decapods)	Zettler and Pollehne, 2006; Bergström et al., 2014; Leopold et al., 2015; Hutchison et al., 2020

the places most affected by the presence of opportunistic and invasive species due to several factors such as climate change (Galil, 2007) and the construction of artificial substrates (Glasby et al., 2007). Furthermore, artificial structures have been described as playing a very important role in jellyfish proliferations because they are ideal substrates for the establishment of their sessile polyp phase (Duarte et al., 2013).

While both fixed and floating OWF are being planned in the MS, the geomorphology of the sea suggests that floating foundations may be the most appropriate installations in many areas (WWF, 2019). Although floating wind farms supposedly have a lower impact than fixed (traditional) wind farms during the non-operational stages of their life history, the effects of installations of this type on the marine environment can still be important during the operational and decommissioning stages (Table 1). Few studies have analyzed the environmental impact of the specific features of floating OWF such as the deployment of mooring and anchoring systems, consisting of heaving chains to keep their substructures stationary; the potential use of suction anchors that may require scour protection through rock dumping; the deployment of additional, longer, and higher capacity subsea cables to interconnect facility components to each other, to the seafloor, and to the shore; the use of inter-array cables suspended within the water column, rather than solely along the seafloor as is often the case with fixed-bottom OWF; and the use of internal tanks that contain both solid ballast and ballast water typically dosed with sodium hydroxide (Statoil, 2015, Farr et al., 2021; Garcia-Teruel et al., 2022). All these specific technical characteristics pose their own environmental risks, which are detailed in Table 1. Furthermore, the environmental footprint of floating offshore turbines measured by the Global Warming Potential (GWP)[1] could be greater than that of bottom-fixed turbines (Mendecka and Lombardi, 2019), particularly because, unlike bottom-fixed turbines, it may not always be possible to perform major repairs on floating turbines offshore (i.e., they may need to be towed to the shore for major repairs, thus increasing the GWP; Garcia-Teruel et al., 2022).

All the adverse effects described in the northern European seas could be magnified in a semi-closed sea like the Mediterranean, one of the world's hot spots for marine biodiversity (Bray et al., 2016). Although it covers just 0.82% of the global oceanic surface and accounts for 0.32% in terms of volume, the MS hosts 4%–18% of all known marine species with a high proportion (about 30%) of endemism (Bianchi and Morri, 2000). Globally, more than 600 fish and 22 marine mammal species (Notarbartolo di Sciara, 2016; EEA, 2020) have been recorded in the MS compared to 230 fish and 19 mammal species in the North Sea (EEA, 2020). The MS is also an important habitat for seabirds: many marine birds species (33) breed in the MS and migrate to the Atlantic Ocean after the breeding season (EEA, 2020). Nevertheless, this rich biodiversity is particularly threatened in the MS (EEA, 2020). The map of the integrated classification of biodiversity conditions in European seas (EEA, 2021a) shows a higher coverage of "problem areas" (i.e., areas with poor, moderate and bad biodiversity status) in the MS than in the North Sea and the North Atlantic. Seven of the 12 marine mammals occurring regularly in the Mediterranean region are listed as "threatened" on the IUCN's Red List (Notarbartolo di Sciara, 2016). Furthermore, as of 2018 five species of seabirds appear on the list of endangered or threatened species established under the Protocol Concerning Specially Protected Areas and Biological Diversity in the Mediterranean (UNEP, 2021). In addition, over half of the 519 native marine fish species assessed in the MS are threatened by fishing, with 40% of the 76 species of cartilaginous fish species present in the MS listed in threatened categories on the IUCN's Red List (IUCN, 2011). The need to protect ecologically valuable Mediterranean species and habitats from OWF development may also be a challenge for other ecologically valuable habitats, such as the deep-sea coral habitats found in some North Atlantic areas (e.g., Fosså et al., 2002; Buhl-Mortensen et al., 2017; NOAA, 2021).

It is increasingly clear that biodiversity loss and climate change are interconnected issues that must be tackled in unison. Marine habitats are recognized as important carbon sinks with great carbon storage potential

---

[1] The GWP associated to an energy generating technology represents the equivalent weight of CO_2 that will generate the greenhouse gas emissions occurring throughout the life of the project.

(Mitra and Zaman, 2015), constituting the so called 'blue carbon'. While climate change is a major driver of biodiversity loss, preserving biodiversity and ecosystems are vital to combatting climate change. Biodiversity may mitigate climate change impacts on (i) biodiversity itself, as more diverse systems could be more resilient to climate change impacts, and (ii) ecosystem functioning through the positive relationship between this and diversity (Roberts et al., 2017; Hisano et al., 2018*)*. Therefore, any loss of the rich marine biodiversity of the MS due to OWF implementation may be counterproductive for mitigating the effects of climate change.

2.2. Threats of OWF to MPAs

Mediterranean MPAs often occupy sites exposed to rough weather conditions (e.g., strong winds), dispelling human pressures (to a certain point) and thus allowing their pristine environmental conditions to be maintained over time. Because strong winds are a pre-requisite for site selection for the implementation of OWF, the plans for OWF and MPAs in the MS can easily overlap, rendering the installation of large OWF projects a challenge.

Let's take the area where the CCWF is projected as an example. Suitable conditions and requirements in terms of wind and bathymetric constraints for the wind farm have been found in an area where eight different MPAs coexist, including Special Areas of Conservation (SAC) and Sites of Community Importance (SCI) designated under the European Commission Habitats Directive (92/43/EEC); Special Protection Areas (SPA) designated under the European Commission Birds Directive (2009/147/EC); Specially Protected Areas of Mediterranean Importance (SPAMI) designated under the Barcelona Convention of 1976 for Protection against Pollution in the Mediterranean and a Mediterranean Cetacean Migration Corridor, established by the Government of Spain (Fig. 1). This is a good example of how, based on technical criteria only (wind potential, depth, etc.), energy companies would choose to build OWF in ecologically valuable and sensitive areas where they could easily run counter to the conservation of MPAs. Hence, policy makers are faced with the challenge of balancing OWF deployment and environmental protection.

It is important to highlight the role of MPAs in mitigating the effects of climate change in the oceans and alleviating some of its expected hardships (e.g., reduced food security, sea-level rise) by promoting intact and complex ecosystems with high diversity and abundance of species (Roberts et al., 2017). MPAs can particularly maintain carbon sequestration and storage and act as an insurance policy against climate change (Roberts et al., 2017). Any impact of OWF on the Mediterranean MPAs could therefore compromise this role.

Although the role of MPAs is becoming increasingly important due to global community aims to protect 30% of the world's oceans by 2030 (HAC, 2021), there is still little guidance on the identification of OWF locations compatible with MPAs in the MS. The Maritime Spatial Planning Directive strongly encourages the declaration of MPAs, which are also included in the member states' program of coastal measures contained in the MSFD. As key tools for protecting marine biodiversity and ecosystems in the MS, it is essential that the relation of MPAs to activities such as OWF is well defined. In Germany, designated protected areas (e.g., the Wadden Sea German National Park) and shipping routes close to the German coastline constitute massive obstacles for the installation of wind turbines. Offshore wind areas are therefore limited because approximately one-third of the German Economic Exclusive Zone is protected (marine reserve and Nature 2000 areas), meaning that wind farm projects must keep a significant distance from the shore (usually at least 40 km) and be installed in relatively deep waters (Schomerus and Maly, 2017).

Although OWF could incidentally help to increase local biodiversity around the underwater structures by excluding fishing and becoming a so-called 'other effective area-based conservation measure' (OECM), which may have preservation benefits outside MPAs (IUCN, 2019b), it is very unlikely that farms such as CCWF, projected in areas of high ecological value, could fit into this category. A beneficially placed OWF is one in a degraded area where the underwater structures could help restore the damaged ecosystem and increase biodiversity. It could then operate as an OECM, as do military waters that are managed for the purpose of defense (IUCN, 2019b).

2.3. Atmospheric and oceanic dynamics

OWF can modify the atmospheric and oceanic dynamics through the influence of both emerged and underwater structures (Table 1). For example, a marked reduction in wind speed in the immediate and downstream OWF of up to 70–90% has been estimated in the North Sea (Christensen et al., 2013; Ludewig, 2015; Akhtar et al., 2021). Wind speed reduction will affect both the atmospheric boundary layer and, consequently, the surface mixed layer, which in turn will impact the photic zone and thus marine primary production. Indeed, wind is one of the main factors modulating ecosystem productivity in many regions of the MS, including the northern Catalan Sea (Estrada, 1996). Strong north-westerly winds in the Gulf of Lions constitute a main fertilizing driver by favoring nutrient rich water upwelling along the Catalano-Levantine coast of Spain. However, compared with other semi-enclosed seas adjacent to the European continent, such as the Baltic Sea and the North Sea (e.g., Hoepffner, 2006), the MS chlorophyll levels in summer are an order of magnitude lower (Powley et al., 2017). Considering the oligotrophic character of the MS, the effects of turbine structures on the local atmospheric and oceanic dynamics and primary productivity could have a much larger impact in the MS than in other northern European Seas.

The effects of OWF on atmospheric and oceanic dynamics may be particularly pronounced at a local level through modification of the wind fields and oceanographic parameters including turbulence, mixing, and vertical stratification (Ludewig, 2015; Grashorn and Stanev, 2016; van Berkel et al., 2020; Miles et al., 2020). Specific local effects that end up impinging on local ecosystem functioning include alteration of the seawater's vertical density stratification generated by the wind turbines' underwater foundations and reduced wind speeds locally inside the installation's footprint and regionally as a downwind wake (van Berkel et al., 2020). In the MS, the installation of floating OWF with emerged structures up to 250 m high can alter wind speeds and the associated vertical water mixing, potentially resulting in a negative effect on the local primary production essential for the health of the ecosystem and upper levels of the food webs.

2.4. Cumulative pressures

While the effects of one wind farm on a particular wildlife population may be negligible, the aggregate effects of multiple wind farms through space and time will amplify the effects caused by other sectors (Gușatu et al., 2021). Cumulative pressures can be particularly important in the MS because of the increased deployment of OWF combined with pressures from other marine activities and sea users in this area. The MS has historically and remains threatened by intense pressure from multiple uses and stressors, causing major shifts in the marine ecosystem and widespread conflict among marine users (Micheli et al., 2013). OWF will add pressures to those generated by other maritime sectors such as cruises, maritime transport, fisheries, and tourism activities. For example, some of the world's busiest marine traffic routes are in the Mediterranean, introducing a high level of background noise. The extra noise generated by OWF and their associated vessel traffic may lead to cumulative noise impacts on marine mammals in these areas, affecting their behavior (WWF, 2019; Tougaard et al., 2020). Another threat is pollution. The MS is considered one of the most polluted European Seas, with a huge 93% of its coastal areas classified as 'problem areas' (i.e., areas that are impaired as a result of contaminants such as synthetic chemicals and heavy metals mobilized by human activities) compared to 79% in the North-East Atlantic Ocean (EEA, 2018). The extra pollution potentially generated by floating OWF (e.g., from internal water ballast tanks typically containing sodium hydroxide, a chemical compound that is toxic for aquatic organisms; Table 1) may lead to cumulative impacts on the Mediterranean marine ecosystem. Because the cumulative adverse effects of OWF on wildlife vary by taxonomic group and the offshore wind energy development phase, it is important to address these cumulative pressures in more detail. However, apart from a small number of studies (see e.g., National Academies, 2017; Goodale et al., 2019; BOEM, 2020), the cumulative adverse effects of OWF on wildlife remains relatively unexplored and poorly understood (Goodale and Milman, 2016).

2.5. Other environmental pressures related to OWF in the MS

Other environmental pressures related to OWF in northern European Seas may be magnified in the MS because of its particular features. First, the risk of accidents. While the global production of wind energy is on the increase, there is a significant gap in the academic and practice literature on the analysis of wind turbine accidents (Asian et al., 2017). The risks associated with natural hazards such as storms and other extreme events exacerbated by climate change, such as hurricane Gloria in 2020 in the Western Mediterranean (Amores et al., 2020; De Alfonso et al., 2021), can be added to those of wind turbine accidents, including fire, the aerogenerator itself falling into the sea and ship collisions (Asian et al., 2017; Biehl and Lehmann, 2006). The latter constitutes a considerable threat to the environment due to damage to the ships' structure potentially causing the leakage of operating supplies or cargo (e.g., oil or chemicals) and structural damage to the OWF itself (Biehl and Lehmann, 2006). Because the MS is among the world's busiest waterways in terms of maritime transport (Randone et al., 2019), cruising (Lloret et al., 2021a) and recreational boating (Carreño and Lloret, 2021), there may be a substantial risk of collision between commercial and passenger ships in the traffic lanes in the Mediterranean and OWF.

Second, there are the environmental concerns related to the industrialization of coastal areas. Ports are crucial to OWF because all the required turbines and equipment are transported through them and they are the base from where they are operated and maintained (WindEurope, 2021). Furthermore, it has been acknowledged that over the next decade ports will play a key role in upscaling renewable hydrogen infrastructures associated with large wind farms (WindEurope, 2021). The development of harbors and other infrastructure related to OWF in Mediterranean coastal areas will put additional pressure on a region already considered a hotspot of urban development on a global scale (Wolff et al., 2020). Urbanization and industrialization of the coastline is one of the major problems in the Mediterranean region, often leading to loss of biodiversity due to habitat destruction and landscape fragmentation (MedECC, 2020). Despite the potential socioeconomic benefits of port development, the enlargement and industrialization of some small ports in Mediterranean coastal towns (e.g., for lodging wind farm service vessels) could result in the loss of the maritime cultural heritage linked to fishing and tourism activities that sustains the economy of many Mediterranean coastal areas (WWF, 2017). The impact would be exacerbated in coastal areas with MPAs, which are usually low populated and industrialized.

Last, the nearshore and inland environmental impacts of associated OWF infrastructures (access roads, sub-stations, transmission lines and temporary structures) built prior to, during, and after construction should be considered. Power lines must drive the OWF generated energy to the global distribution grid on land. In highly urbanized Mediterranean coastal areas, including the proposed area for the CCWF, these power lines may be forced to cross non-urbanized zones that can be fragile ecosystems (estuaries, coastal lagoons, large shallow inlets, bays, etc.), causing negative impacts on these ecosystems. Furthermore, the different components of the hydrogen infrastructures associated with large wind farms may place specific pressures on the environment linked to water and land use, brine release, hydrogen leaks and hazards (GIZ, 2020; Khan et al., 2021).

3. Interactions between OWF and other maritime activities

In the MS, the spatial conflicts in marine areas that are already overcrowded with other multiple uses may be more intense than in their northern sea counterparts. The expansion of the OWF sector increases competition for space with other economic sectors in an already busy MS. The narrow continental shelf in many places means that where depths are adequate to install offshore wind farms, human activities (fisheries, aquaculture, and tourism activities) are concentrated in a reduced space and projects quickly face opposition from local stakeholders and end users.

3.1. Fisheries

In northern European seas where OWF have been developed, the scientific and policy debate has mainly centered on the impact on fisheries, particularly in the North Sea where there is the greatest spatial overlap between fisheries and OWF (European Parliament, 2019, Van Hoey et al., 2021). Excluding fisheries from OWF (particularly fishing fleets deploying bottom contacting gears, which are affected the most by the OWF) has a range of negative direct and indirect economic, social and environmental effects on individual fishers, the fishing industry, fishery-dependent coastal communities and wider society (Schupp et al., 2021; Stelzenmüller et al., 2022). The impact of OWF on Mediterranean fisheries would be exacerbated if we consider the special importance of small-scale fisheries in this region (more than 80% of the total fishing fleet is composed of small-scale vessels that mostly use bottom contacting gears), which have been playing a dominant role in the livelihoods of coastal communities for centuries (Gómez et al., 2006; FAO, 2020), and the poorer status of Mediterranean stocks compared to those in northern European Seas. While in the North-East Atlantic Ocean and the Baltic Sea 24–47% of all stocks meet at least one of two criteria defining the Good Environmental Status in the regions, in the MS only 9% of the stocks meet at least one criterion (EEA, 2021b). In addition, offshore wind energy developments in the MS could also affect scientific fishery resource surveys, which have been gathering data used in stock assessments for more than 20 years. This impact has also been highlighted in the Northeast United States, where a number of scientific surveys overlap with wind development areas (Methratta et al., 2020).

In the North Atlantic, it has been reported that OWF can provide foraging opportunities and shelter for benthic fish in locations previously exposed to fisheries, and particularly bottom trawling. OWF exclude any fishing operations during their construction and, in some countries such as Germany, the operational phase effectively acts as a fishing area closure (Kafas et al., 2018; Schupp et al., 2021). In the absence of fishing, biodiversity and the abundance of benthic species using OWF for shelter and as feeding grounds may increase (Hammar et al., 2016; Gill et al., 2020; Mavraki et al., 2021). In any case, these potential positive effects on fisheries would not be directly applicable to all OWF because any eventual increase in fish productivity has to be balanced against the loss of fishing grounds to wind farms. In addition, some OWF in the MS such as the CCWF are planned to be built in areas already closed to trawl fisheries, where there are already many benefits arising from the prohibition of trawling compared to an analogous open one nearby (Balcells et al., 2016; Sala-Coromina et al., 2021; Tuset et al., 2021).

3.2. Tourism

As stated in the previous sections, and unlike areas like the North Sea, most of the MS has a relatively narrow continental shelf, meaning that OWF are often projected close to the coast. In the MS, the debate regarding the potential impacts of OWF on seascape and coastal tourism is particularly intense. Compared to the North Sea and the North Atlantic, tourism is a major economic driver in the MS, where maritime and coastal leisure activities (sailing, scuba diving, swimming and bird and whale watching) take place that are very important for the local economy as ecotourism activities (Europarc, 2019). The OWF may have negative ecological consequences on many vulnerable and threatened species and habitats (see Section 2.1) that are important for leisure activities like scuba diving and bird and whale watching. The seascapes of Mediterranean MPAs such as Cape Creus Natural Park provide scenic and subsequently amenity/socioeconomic value for the local and tourist communities who enjoy their views (Torres and Hanley, 2016), or whose appreciation together with other leisure and sport activities undertaken in the marine park is enhanced by the surrounding scenery (Lloret et al., 2021b). A similar situation occurs in other popular areas for maritime activities such as Jurien Bay Marine Park in Australia (McCartney, 2006). Therefore, the economic and social loss of seascapes as part of the marine goods and services that can be affected by OWF could be significant. This is especially pertinent in areas of high biodiversity and with valuable landscapes / seascapes, or in other words, those that are considered iconic and whose historical interaction of natural and cultural elements, factors and processes have shaped them as high quality visually aesthetic sites (Kalivoda et al., 2014; Feleki et al., 2018).

In the MS, fear that the recreational value of the coastal use can be jeopardized by the visual impacts of OWF is intense. For example, the impact of OWF projects on beach recreation demand during the summer season in the Mediterranean region of Catalonia (Spain), precisely where the CCWF is projected, has been estimated as a significant welfare loss of up to €203 million per season (Voltaire et al., 2017). The installation of wind farms will cause a shift to visits to beaches without them, implying that the estimated negative economic impacts will occur mostly in areas where wind farms are located (Voltaire et al., 2017; Voltaire and Koutchade, 2020). The notion that the visual impacts of wind farms on the ocean horizon will deter visitors to coastal destinations has also been a primary concern for local communities and policy makers in northern Europe and the US. The general public and coastal recreational users such as recreational fishers, leisure boaters and beachgoers are often concerned about potential negative impacts of OWF on the landscape (Gee, 2010; Rudolph, 2014; Firestone et al., 2009; Ladenburg, 2009; Ladenburg and Dubgaard, 2009; Landry et al., 2012; Sullivan et al., 2013; Parsons et al., 2020).

Large OWF projects in the MS such as the CCWF have been strongly rejected by local communities (see for example https://stopmacroparceolicmari.org/), local governmental agencies, local tourism businesses and environmental NGOs, among others. The CCWF is proposed to be built between 8 and 30 km from the shore, whereas in 2019 OWF were installed in European Seas at an average distance of 59 km, with the greatest distance from shore of up to 100 km in German waters (WindEurope, 2020). This farm (CCWF) is an example of how ocean industries in the MS belonging to the Blue Economy are struggling to harmonize local values and opinions about the use of this space with their own (Voyer and van Leeuwen, 2019). The intangible qualities of the seascape are a cause of difference of opinion among the local population and planners and decision-makers, who can disregard the symbolic significance of the sea and the role it plays in the both the meaning and quality of the place and the well-being of the local population and visitors (Gee, 2010). Furthermore, OWF can be perceived by residents as an imposition of a large-scale industrial business with the capacity to transform the seascape through a process of industrialization of the sea (Burkhard and Gee, 2012; Gee, 2013). Nonetheless, attitudes towards wind farms depend on their specific characteristics and the context, with the height and number of the turbines, their size, and the landscape where they are installed particularly significant determinants (Wolsink, 2010; Devine-Wright, 2005; Westerberg, 2012).

3.3. Other activities

Another crucial topic is the interaction between OWF, shipping (NorthSEE, 2017; Twigg et al., 2020) and aquaculture (Soukissian et al., 2017; Van Hoey et al., 2021). This multi-dimensional interaction is often viewed as a marine spatial conflict, with different stakeholders vying for adequate space. The MS is one of the busiest seas in the world in terms of shipping, with 21 of its ports among the busiest 100 in the world (Bray et al., 2016; Soukissian et al., 2017). OWF may restrict the navigable space available to ships, leading to increased traffic density and risk of collision (NorthSEE, 2017). During the past decades, Mediterranean aquaculture has expanded dramatically (Bolognini et al., 2019) and, as has occurred in northern European Seas (Van Hoey et al., 2021), the expansion of OWF will lead to competition for space between OWF and aquaculture sites in certain places.

4. Recommendations for the future development of OWF projects in the MS

In this last section, we make some basic recommendations for governments and policymakers to help shape the post-pandemic rush of OWF proposals in the MS by energy companies. Although lessons learned from countries where OWF have been developed much earlier, such as Germany (Lüdeke, 2017; Schomerus and Maly, 2017) and the UK (Singh Ghaleigh, 2017), can be considered for the implementation of OWF in the MS, the particularities of the MS in relation to impact assessments, spatial planning and mitigation measures (Defingou et al., 2019) make careful consideration of the particular environmental, social and economic impacts of OWF necessary. These recommendations could be useful for the planning of OWF not only in the MS but also in all areas of the world with fragile species and habitats, MPAs and/or valuable seascapes, such as the Australian and New Zealand coasts and the Canadian and US Atlantic.

Policy makers in the MS must apply the Precautionary Principle to ensure that the collective pressure of all activities is kept within levels compatible with the preservation of marine ecosystems and the correct ecosystem functioning of the entire network of MPAs. This Principle, detailed in Article 191 of the Treaty on the Functioning of the European Union and in Principle 15 of the 1992 Rio Declaration on Environment and Development, and incorporated in the MSFD (2008/56/EC) and the Maritime Spatial Planning Directive (2014/89/EU), aims at ensuring a higher level of environmental protection through preventive decision-taking in the case of risk. In this regard, independent diagnoses (impacts assessment) must examine the potential environmental, social and economic consequences of constructing OWF facilities (including seascape and cultural impacts) during all the phases: the pre-construction phase (including site assessment and the required geotechnical and geophysical surveys that may interact with the marine environment), the construction phase, the operational phase and the decommissioning phase. This analysis should be conducted with the broad participation of the scientific community (including marine and fisheries biologists, social scientists, economists, experts in renewable energy, etc.) and should follow an ecosystem-based approach (CBD, 2021). Standardized monitoring programs to assess the diversity of impacts in the MS, and especially those concerning the cumulative impacts of OWF and other maritime activities over a long period (Lüdeke, 2017; Defingou et al., 2019; Gușatu et al., 2021), must be established and should cover timeframes before, during and after construction. German experiences suggest that around eight years of data comprising the pre-construction phase (three years), the construction phase (two years), and the operational phase (three years) are needed to build a strong database to show the effects of OWF (BSH, 2013). Monitoring programs should use different techniques to detect changes in the different components of the marine ecosystem potentially affected by OWF in the MS (Table 2). In particular, threatened, sensitive or endangered species and their critical or essential habitats should be considered. The monitoring should also include the surveillance of other maritime activities such as maritime traffic and fishing activities. A diversity of non-invasive and environmentally friendly tools such as the macrofauna Automatic Identification System should be used. It is also important to develop detailed guidelines for the assessment of cumulative adverse effects, addressing the different taxonomic groups and OWF phases (Goodale and Milman, 2016). Furthermore, a detailed analysis of the implications for the wind field and hydrography on a regional scale and the effects on ecosystem functioning should be undertaken.

More detailed and integrated assessments at regional, national and local scales, such as the Cumulative Effect Assessment methodology (Gușatu et al., 2021) and the Distance-Based Sampling Method (Methratta, 2021), are needed to make decisions about developing OWF in the MS, accompanied by energy-saving policies and the consideration of alternatives to large OWF (such as self / local generation and consumption in coastal communities). The need to develop more integrated, holistic, coordinated approaches to evaluate the cumulative impacts of OWF over a long period is particularly relevant in the MS. Each Mediterranean country is presently

Table 2
Summary of monitoring approaches to evaluate the impact of OWF in the MS (modified from WWF, 2019).

Element	Tools and methods
Abiotic environment	Monitoring certain abiotic parameters (e.g., sediment grain size distribution, water temperature and oxygen levels) Developing monitoring strategies for OWF released chemical compounds Monitoring of heavy metals and other chemical pollutants in the water column and in the sediments
Habitats / Benthic communities	Characterization of the sediment and habitat structure and their dynamics Video survey of benthic fauna, macrophytes and habitat structure Sampling (with grabs, beam trawls, dredges, etc.,) of infauna and epifauna Investigation of growth and demersal megafauna on the underwater construction structure, of benthos and habitat structures for installation of cable routes
Fish	Trawl surveys Use of existing sampling and survey data Non-invasive methods (e.g., hydroacoustic methods, scuba diving surveys in shallow waters)
Birds	Ship-based and (digital) aircraft-based surveys (video/photo) along transects Use of radars for long-term monitoring data on seabird behavior around OWFs and to monitor migration intensity, flight direction and flight altitude
Marine mammals	Passive acoustic monitoring from temporary and permanent monitoring-stations (Digital) aircraft-based surveys
Sea turtles	Monitoring through ship surveys or (digital) aircraft-based surveys Satellite or acoustic tracking of tagged animals

planning their own OWF without an overall transnational planning effort. Environmental impacts of OWF, particularly those caused by floating turbines, should include not only direct impacts on the marine species and habitats by the structure itself but also those caused by the activities related to the manufacture, operation, disposal and recycling stages of the OWF. To this effect, different impact categories to be analyzed include Acidification Potential, Eutrophication Potential, Global Warming Potential and Cumulative Energy Demand (Garcia-Teruel et al., 2022).

International guideline documents such as the technical recommendations for avoiding or mitigating the environmental impacts of OWF in the MS (WWF, 2019), the Guidance Document on Wind Energy Developments and EU Nature Legislation (European Commission, 2020d), the guidelines for project developers to mitigate biodiversity impacts associated with wind energy development of the IUCN (Bennun et al., 2021), the recommendations of EASME/EMFF of the European Commission to avoid impacts of OWF on fisheries and aquaculture (Van Hoey et al., 2021), and the IMR recommendations for OWF development (De Jong et al., 2020) should be thoroughly considered and applied by policy makers and businesses. The recommendations stemming from the Pharos4MPAs project (WWF, 2019) should be particularly considered because they cover the different roles and objectives of decision makers, MPA managers and the OWF sector in the MS. One of them, for example, is that specifications for pilot OWF (2–3 turbines) should always be considered in sensitive areas before proposing larger OWF.

The EU mandates in relation to the Blue Economy must be fully met before any decision is made: the initiative must be environmentally sustainable, offer long-term social and economic benefits (especially for the territories where it is established), and at the same time protect and restore the biodiversity, productivity, and resilience of marine ecosystems, while based on participatory and effective governance that is inclusive, accountable and transparent. It must also promote the sustainable use of the sea through spatial planning that optimizes the location of OWF (Yates and Bradshaw, 2018) and implements an ecosystem-based approach that considers not only the diversity of species and habitats but also ecological functions (nurseries, feeding grounds, spawning areas, migration corridor, etc.) and associated ecosystem goods and services. The development of offshore renewable energy in the MS must comply with EU environmental legislation and the integrated maritime policy, which includes the protection of vulnerable marine ecosystems, and with the obligations to reach Good Environmental Status (European MSFD). Policy makers should also consider indirect environmental impacts outside the territories where the OWF are implemented. For example, the deep-sea mining of rare earth elements used for the construction of parts of the turbines, which are obtained from the tailings of other metallic ores, involve environmentally aggressive techniques that produce tailing ponds often containing heavy metals or radioactive elements, thus raising the issue of the disposal of radioactive waste (Nansai et al., 2015; Alves Dias et al., 2020).

Marine Spatial Planning must play a key role at an international and not only national or regional levels, placing greater emphasis on the preservation of the many existing MPA in the MS and always prioritizing the conservation of sensitive species and vulnerable habitats. It must also consider the interface between terrestrial and marine environments. Based on the Precautionary Principle, OWF should be excluded from hotspots of sensitive species (e.g., fish, marine mammals, birds and sea turtles) and fragile habitats (e.g., deep-sea corals, maerl beds and crinoid assemblages), particularly in MPAs, as well as from important fish spawning areas and migration routes. The advice against constructing OWF in sensitive or valuable areas and in areas that are of special importance for certain species was also recently advocated in Norwegian waters (de Jong et al., 2020).

The creation of buffer zones between OWF and MPAs and the establishment of corridors (i.e., areas free of OWF) between adjacent MPAs to ensure that sensitive species (birds, fish, sea turtles, marine mammals, etc.) can safely switch between MPAs should be another priority. Furthermore, a minimum distance of the OWF from the Mediterranean shore (as naturally occurs in Germany; Schomerus and Maly, 2017) should be established in certain places with valuable seascapes to avoid any important loss of seascape value. However, the implications for the marine biodiversity of moving OWF away from coastal waters to deeper waters should be well analyzed in each zone to avoid any damage to Mediterranean fragile deep-water habitats such as submarine canyons, which are key for the ecosystem functioning of the MS (Würtz, 2012).

Moreover, OWF licensing studies on the socioeconomic implications of OWF for fisheries and tourism should previously be carried out (ICES, 2021). The preservation of seascape in the MS should also be a priority, considering the links between seascape, tourism and local identity. The seascape constitutes a resource favorable to economic activity, the protection, management and planning of which can contribute to job creation. The importance of landscape/seascape is recognized by the European Landscape Convention (Council of Europe, 2000), the first international treaty committed to the protection, management and planning of all landscapes in Europe. This Convention, ratified by 40 Council of Europe member states, acknowledges that landscape is an important part of citizens' quality of life and a basic component of the European natural and cultural heritage, contributing to human well-being and consolidation of the European identity.

Last, governments should avoid any impact of OWF in existing Mediterranean MPAs or fragile sites to not compromise the 30% target set by the High Ambition Coalition for People and Nature, a United Nations initiative that aims for aspirational action to address the global climate crisis (HAC, 2021).

5. Conclusion

While there are plans to develop and expand the offshore wind energy industry in the MS, the many environmental drawbacks associated with this sector are not well considered and analyzed. The different stages of OWF implementation (from manufacture and geotechnical/geophysical surveys to operational, maintenance and decommissioning) in the MS have potential ecological impacts that strongly compromise the objectives of achieving and maintaining a Good Environmental Status of the marine environment, the goals of the European Strategy for Biodiversity 2030, and the Sustainable Development Goals of the United Nations (particularly Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development). These considerations are particularly relevant when OWF are projected near marine biodiversity hotspots including marine priority conservation areas, MPAs, and wildlife corridors.

In particular, the incompatibility between OWF and MPAs and other areas of high ecological value is evident in terms of the enormous ecological and socioeconomic risks posed by OWF on vulnerable species and habitats. We propose that OWF development in the MS should be excluded from high biodiversity areas containing sensitive and threatened species and habitats, particularly those situated in or in the vicinity of MPAs and/or areas with valuable seascapes. In these cases, we believe the risks far outweigh the benefits. However, other areas may be able to support a sustainable offshore wind sector without causing irremediable harm to vital ecosystems if avoidance, mitigation and preventive measures are well implemented and are accompanied by rigorous monitoring.

Credit authorship contribution statement

Josep Lloret: Conceptualization, methodology, supervision, writing – original draft and revised version. **Elisa Berdalet, Ana Sabatés, Josep-Maria Gili, Antonio Turiel, Josep Vila-Subirós, Alberto Olivares, Jordi Solé, Rafael Sardá**: Conceptualization, formal analysis, writing edition and revision.

Declaration of competing interest

No potential competing interest was reported by the authors, Open Access funding provided thanks to the CRUE-CSIC agreement with Elsevier.

Acknowledgements

The authors thank all the reviewers who have helped us greatly to improve the manuscript with their valuable comments and suggestions. We would also like to thank the Geographical Information Systems and Remote Sensing Service of the University of Girona, for drawing the map. This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

References

Academies, National, 2017. National Academies of Sciences, Engineering, and Medicine. Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals. The National Academies Press, Washington, DC.

Airoldi, L., Bulleri, F., 2011. Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. PLoS ONE 6 (8), e22985. https://doi.org/10.1371/journal.pone.0022985.

Akhtar, N., Geyer, B., Rockel, B., Sommer, P.S., Schrum, C., 2021. Accelerating deployment offshore wind energy alter wind climate and reduce future power generation potentials. Sci. Rep. 11, 11826. https://doi.org/10.1038/s41598-021-91283-3.

Alves Dias, P., Bobba, S., Carrara, S., Plazzotta, B., 2020. The role of rare earth elements in wind energy and electric mobility. EUR 30488 EN. Publication Office of the European Union, Luxembourg https://doi.org/10.2760/303258.

Amores, A., Marcos, M., Carrió, D.S., Gómez-Pujol, L., 2020. Coastal impacts of storm Gloria (January 2020) over the North-Western Mediterranean. Nat. Haz. Earth Syst. Sci. 20, 1955–1968. https://doi.org/10.5194/nhess-20-1955-2020.

Anderson, E.R., Butler, J., Butler, M.J., 2021. Response of fish and invertebrate larvae to backreef sounds at varying distances: implications for habitat restoration. Front. Mar. Sci. 8, 663887. https://doi.org/10.3389/fmars.2021.663887.

Asian, S., Ertek, G., Haksoz, C., Pakter, S., Ulun, S., 2017. Wind turbine accidents: a data mining study. IEEE Syst. J. 11 (3), 1567–1578. https://doi.org/10.1109/JSYST.2016.2565818.

Balcells, M., Lombarte, A., Ramon, M., Abelló, P., Mecho, A., Company, J.B., Recasens, L., 2016. Effect of a small-scale fishing closure area on the demersal community in the NW Mediterranean sea, 2016. Rapp. Comm. Int. Mer Médit. 41, p. 517

Benjamins, S., Hamois, V., Smith, H.C.M., Johanning, L., Greenhill, L., Carter, C., Wilson, B., 2014. Understanding the potential for marine megafauna entanglement risk from marine renewable energy developments. Scottish Natural Heritage Commissioned Report No, p. 791.

Bennun, L., van Bochove, J., Ng, C., Fletcher, C., Wilson, D., Phair, N., Carbone, G., 2021. Mitigating biodiversity impacts associated with solar and wind energy development. Guidelines for Project Developers. The Biodiversity Consultancy, Gland, Switzerland: IUCN and Cambridge, UK.

Bergström, L., Kautsky, L., Malm, T., Rosenberg, R., Wahlberg, M., Capetillo, N.Å., Wilhelmsson, D., 2014. Effects of offshore wind farms on marine wildlife—a generalized impact assessment. Environ. Res. Lett. 9, 034012.

van Berkel, J., Burchard, A.H., Christensen, L.O., Mortensen, O., Petersen, S., Thomsen, F., 2020. The effects of offshore wind farms on hydrodynamics and implications for fishes. Oceanography 33 (4), 108–117. https://doi.org/10.5670/oceanog.2020.410.

Bianchi, C.N., Morri, C., 2000. Marine biodiversity of the Mediterranean sea: situation, problems and prospects for future research. Mar. Pollut. Bull. 40, 367–376.

Biehl, F., Lehmann, E., 2006. Collisions of ships with offshore wind turbines: calculation and risk evaluation. In: Köller, J., Köppel, J., Peters, W. (Eds.), Offshore Wind Energy. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-34677-7_17.

BOEM (Bureau of Ocean Energy Management), 2020. National Environmental Policy Act Documentation for Impact-Producing Factors in the Offshore Wind Cumulative Impacts Scenario on the South Atlantic Continental Shelf. OCS Study 2021-043. US Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling, VA.

Bolognini, L., Grati, F., Marino, G., Punzo, E., Scanu, M., Torres, C., Hardy, P.Y., Piante, C., 2019. Safeguarding marine protected areas in the growing Mediterranean blue economy. Recommendations for Aquaculture. PHAROS4MPAs Project 52 pages.

Bray, L., Reizopoulou, S., Voukouvalas, E., Soukissian, T., Alomar, C., Vázquez-Luis, M., Deudero, et al., 2016. Expected effects of offshore wind farms on Mediterranean marine Life. J. Mar. Sci. Eng. 4 (1), 18. https://doi.org/10.3390/jmse4010018.

BSH, 2013. Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment (StUK4). Bundesamt für Seeschifffahrt und Hydrographie. 87pp.

Buhl-Mortensen, P., Gordon Jr., Don D.C., Buhl-Mortensena Jr., L., Kulka Jr., D.W., 2017. First description of a Lophelia pertusa reef complex in Atlantic Canada. Deep Sea Res. Part I: Ocean. Res. Papers. 126, pp. 21–30.

Burkhard, B., Gee, K., 2012. Establishing the resilience of a coastal-marine social-ecological system to the installation of offshore wind farms. Ecol. Soc. 17 (4), 32.

Carpenter, J.R., Merckelbach, L., Callies, U., Clark, S., Gaslikova, L., Baschek, B., 2016. Potential impacts of offshore wind farms on North Sea stratification. PLoS ONE 11, e0160830. https://doi.org/10.1371/journal.pone.0160830.

Carreño, A., Lloret, J., 2021. Environmental impacts of increasing leisure boating activity in Mediterranean coastal waters. Ocean Coast. Manag. 209, 105693.

CBD, 2021. Convention on Biological Diversity. https://www.cbd.int/ecosystem/.

Christensen, E.D., Johnson, M., Sørensen, O.R., Hasager, C.B., Badger, M., Larsen, S.E., 2013. Transmission of wave energy through an offshore wind turbine farm. Coast. Eng. 82, 25–46.

Clark, S., Schroeder, F., Baschek, B., 2014. The Influence of Large Offshore Wind Farms on the North Sea and Baltic Sea - A Comprehensive Literature Review (Report No. HZG Report 2014-6).

Coolen, J.W.P., van der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W.N.M., Faasse, M.A., Bos, O.G., et al., 2020. Benthic biodiversity on old platforms, young wind farms, and rocky reefs. ICES J. Mar. Sci. 77 (3), 1250–1265.

Council of Europe, 2000. European Landscape Convention. http://conventions.coe.int/Treaty/en/Treaties/Html/176.htm. (Accessed 31 August 2021).

Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., et al., 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES J. Mar. Sci. 77 (3), 1092–1108.

De Alfonso, M., Lin-Ye, J., García-Valdecasas, J.M., Pérez-Rubio, S., Luna, Y., Santos-Muñoz, D., et al., 2021. Storm Gloria: sea state evolution based on in situ measurements and modeled data and its impact on extreme values. Front. Mar. Sci. 30. https://doi.org/10.3389/fmars.2021.646873.

De Jong, K., Steen, H., Forland, T.N., Wehde, H., de Jong, K., Steen, H., Forland, T.N., Nyqvist, D., et al., 2020. Potensielle effekter av havvindanlegg på havmiljøet - Potential effects of offshore wind farms on the marine environment. Rapport Fra Havforskningen 2020-42 42 pp.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., Degraer, S., 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 756, 37–50.

De Witte, B., Hostens, K., 2019. Preliminary zinc analysis at offshore wind farms. In: Degraer, S., Brabant, R., Rumes, B., Vigin, L. (Eds.), Environmental Impacts Offshore Wind Farms Belgian Part North Sea. Marking a Decade of Monitoring, Research and Innovation. Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management, Brussels, pp. 27–30.

Defingou, M., Bils, F., Horchler, B., Liesenjohann, T., Nehls, G., 2019. PHAROS4MPAs- a review of solutions to avoid and mitigate environmental impacts of offshore windfarms. BioConsult. Technical report 52.

Degraer, S., Carey, D.A., Coolen, J.W., Hutchison, Z.L., Kerckhof, F., Rumes, B., Vanaverbeke, J., 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography 33, 48–57.

Devine-Wright, P., 2005. Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy. Wind Energy 8 (2), 125–139.

Domínguez-Carrió, C., Requena, S., Gili, J.M., 2014. Sistema de Cañones Submarinos Occidentales del Golfo de León. Proyecto LIFE + INDEMARES. 100 ppFundación Biodiversidad. Ministerio de Agricultura, Alimentación y Medio Ambiente. https://www.indemares.es/sites/default/files/sistema_de_canones_submarinos_occidentales_del_golfo_de_leon.pdf.

Duarte, C.M., Pitt, K., Lucas, C., Purcell, J., Uye, S., Robinson, K., Brotz, L., Decker, M.B., Sutherland, K.L., Malej, A., Madin, L., Mianzan, H., Gili, J.M., Fuentes, V., Atienza, D., Pagés, F., Breitburg, D., Malek, J., Graham, W.M., Condon, R.H., 2013. Is global ocean sprawl a cause of jellyfish blooms? Front. Ecol. Environ. 11, 91–97.

EEA, 2009. Europe's onshore and offshore wind energy potential: An assessment of environmental and economic constraints. EEA Technical Report No 6/2009 90 pp.

EEA, 2018. Contaminants in Europe's seas. Moving towards a clean, non-toxic marine environment. EEA Report No 25/2018 . https://www.eea.europa.eu/publications/contaminants-in-europes-seas/.

EEA, 2020. Europe's marine biodiversity remains under pressure. Briefing nr. 31/2020. European Environment Agency. https://www.eea.europa.eu/publications/europes-marine-biodiversity-remains-under-pressure.

EEA, 2021a. Integrated Classification of Biodiversity Condition in Europe's Seas. https://www.eea.europa.eu/data-and-maps/figures/integrated-classification-of-biodiversity-condition.

EEA, 2021b. Status of Marine Fish and Shellfish Stocks in European Seas. https://www.eea.europa.eu/data-and-maps/indicators/status-of-marine-fish-stocks-5/assessment.

Estrada, M., 1996. Primary production in the northwestern Mediterranean. Sci. Mar. 60 (supl. 2), 55–64.

EUROPARC, 2019. Sustaining ecotourism in Mediterranean Protected Areas. 24 pp. https://www.europarc.org/wp-content/uploads/2019/05/WWF-MEET-Destimed_W2_CNM2019.pdf.

European Commission, 2007. European Union Risk Assessment Report. SODIUM HYDROXIDE. CAS No: 1310-73-2 EINECS No: 215-185-5 TARGETED RISK ASSESSMENT. https://echa.europa.eu/documents/10162/0ded9c53-4082-405b-b09a-e16e57e158af.

European Commission, 2016. European Red List of Habitats. Part I: Marine Habitats. https://ec.europa.eu/environment/nature/knowledge/pdf/Marine_EU_red_list_report.pdf.

European Commission, 2020a. COM/2020/741 Final. An EU Strategy to Harness the Potential of Offshore Renewable Energy for a Climate Neutral Future. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:741:FIN.

European Commission, 2020b. COM(2020) 380 final. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU Biodiversity Strategy for 2030.

European Commission, 2020c. Study on the Offshore Grid Potential in the Mediterranean Region: Final Report. Directorate-General for Energy, Publications Office. https://data.europa.eu/doi/10.2833/742284.

European Commission, 2020d. Commission Notice Guidance Document on Wind Energy Developments and EU Nature Legislation Brussels, 18.11.2020 C(2020) 7730 Final.

European Commission, 2021. The EU Blue Economy Report. 2021. Directorate-General for Maritime Affairs and Fisheries, Brussels 165 pp.

European Parliament, 2019. Draft Report on the Impact on the Fishing Sector of Offshore Windfarms and Other Renewable Energy Systems (2019/2158(INI)) Committee on Fisheries. Rapporteur: Peter van Dalen. EU.

FAO, 2020. The State of Mediterranean and Black Sea Fisheries 2020. General Fisheries Commission for the Mediterranean, Rome.

Farr, H.K., Ruttenberg, B., Walter, R., Wang, Y.H., White, C., 2021. Potential environmental effects of deep-water floating offshore wind energy facilities. Ocean & Coastal Management 207, 105611.

Feleki, E., Achillas, C., Vlachokostas, C., Michailidou, A.V., Ortega, L., Moussiopoulos, N., 2018. Preservation of the Mediterranean identity: an intra-city analysis towards a macro-regional approach for the characterisation of urban sustainability. Sustainability 10, 3551.

Firestone, J., Kempton, W., Krueger, A., 2009. Public acceptance of offshore wind power projects in the USA. Wind En. 12 (2), 183–202.

Floeter, J., van Beusekom, J.E.E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Eberle, S., et al., 2017. Pelagic effects of offshore wind farm foundations in the stratified North Sea. Prog. Ocean. 156, 154–173.

Fosså, J., Mortensen, P., Furevik, D., 2002. The deep-water coral Lophelia Pertusa in norwegian waters: distribution and fishery impacts. Hydrobiologia 471, 1–12. https://doi.org/10.1023/A:1016504430684.

Galil, B.S., 2007. Loss or gain? Invasive aliens and biodiversity in the Mediterranean Sea. Mar. Pollut. Bull. 55 (7–9), 314–322.

García de Vinuesa, A., 2021. Evaluación de la vulnerabilidad y del estado de conservación de ecosistemas marinos bentónicos especialmente productivos del Mediterráneo frente al impacto de la pesca de arrastre, para impulsar su correcta gestión. 75 ppCSIC-University of Barcelona. https://digital.csic.es/handle/10261/233508.

Garcia-Teruel, A., Rinaldi, G., Thies, P.R., Johanning, L., Jeffrey, H., 2022. Life cycle assessment of floating offshore wind farms: an evaluation of operation and maintenance. Appl. Energy 307, 118067.

Gee, K., 2010. Offshore wind power development as affected by seascape values on the german North Sea coast. Land Use Policy 27, 185–194.

Gee, K., 2013. Trade-offs between seascape and offshore wind farming values: An analysis of local opinions based on a cognitive belief framework Dissertation zur Er-langung des mathematisch-naturwissenschaftlichen Doktorgrades "Doctor rerum natu-ralium" der Georg-August-Universität Göttingen im Promotionsprogramm Geowissen-schaften. Geographie der Georg-August University.

Gili, J.M., Sardá, R., Madurell, T., Rossi, S., 2014. Zoobenthos. In: Goffredo, S., Dubinsky, Z. (Eds.), The Mediterranean Sea: Its History and Present Challenges. Springer Science+Business Media, Dordrecht, p. 213 https://doi.org/10.1007/978-94-007-6704-1_12.

Gill, A., 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J. Appl. Ecol. 42, 605–615.

Gill, A.B., Degraer, S., Lipsky, A., Mavraki, N., Methratta, E., Brabant, R., 2020. Setting the context for offshore wind development effects on fish and fisheries. Oceanography 33 (4), 118–127.

GIZ, 2020. Summary of environmental impacts from green hydrogen projects. 100 ppDeutsche Gesellschaft für Internationale Zusammenarbeit (GIZ.

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

Gómez, S., Lloret, J., Demestre, M., Riera, V., 2006. The decline of the artisanal fisheries in Mediterranean coastal areas: the case of cap de Creus (Cape Creus). Coast. Manag. 34, 217–232.

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

Goodale, M.W., Milman, A., Griffin, C.R., 2019. Assessing the cumulative adverse effects of offshore wind energy development on seabird foraging guilds along the East Coast of the United States. Environ. Res. Lett. 14, 074018.

Grashorn, S., Stanev, E.V., 2016. Kármán vortex and turbulent wake generation by wind park piles. Ocean Dyn. 66, 1543–1557. https://doi.org/10.1007/s10236-016-0995-2.

Gușatu, L.F., Menegon, S., Depellegrin, D., Zuidema, C., Faaij, A., Yamu, C., 2021. Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin. Sci. Rep. 11, 10125. https://doi.org/10.1038/s41598-021-89537-1.

HAC, 2021. High Ambition Coalition for Nature and People. https://www.hacfornatureandpeople.org/home.

Halouani, G., Villanueva, C.-M., Raoux, A., Dauvin, J., Lasram, F., Foucher, E., Loc'h, F., Safi, et al., 2020. A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm. J. Mar. Syst. 212, 103434. https://doi.org/10.1016/j.jmarsys.2020.103434.

Hammar, L., Perry, D., Gullström, M., 2016. Offshore wind power for marine conservation. Open J. Mar. Sci. 6, 66–78. https://doi.org/10.4236/ojms.2016.61007.

Hisano, M., Searle, E.B., Chen, H.Y.H., 2018. Biodiversity as a solution to mitigate climate change impacts on the functioning of forest ecosystems. Biol. Rev. 93, 439–456. https://doi.org/10.1111/brv.12351.

Hoepffner, N., 2006. Chlorophyll-A Concentrations, Temporal Variations and Regional Differences from Satellite Remote Sensing. HELCOM Baltic Sea Environment Fact Sheets. https://helcom.fi/baltic-sea-trends/environment-fact-sheets/.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., King, J.W., 2020. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. Sci. Rep. 10, 4219. https://doi.org/10.1038/s41598-020-60793-x.

ICES, 2008. North Sea Ecosystem Overview. 24 pp. https://www.ices.dk/sites/pub/Publication%20Reports/Advice/2008/2008/6.1-6.2%20North%20Sea%20Ecosystem%20overview.pdf.

ICES, 2021. Workshop on socio-economic implications of offshore wind on fishing communities (WKSEIOWFC). ICES Sci. Rep. 3 (44) 33 pp.

IUCN, 2008. Status of Marine Protected Areas in the Mediterranean Sea. IUCN, Gland, Switzerland and Malaga, Spain and WWF Worldwide Fund for Nature, France 154 pp.

IUCN, 2011. In: Abdul Malak, D. (Ed.), Overview of the Conservation Status of the Marine Fishes of the Mediterranean Sea. vii + 61pp. IUCN, Gland, Switzerland and Malaga, Spain.

IUCN, 2019a. Thematic Report – Conservation Overview of Mediterranean Deep-Sea Biodiversity: A Strategic Assessment. IUCN, Gland, Switzerland and Malaga, Spain 122 pages.

IUCN, 2019b. Recognising and reporting other effective area-based conservation measures. IUCN-WCPA Task Force on OECMs. IUCN, Gland, Switzerland 36 pp.

Jones, I.T., Peyla, J.F., Clark, H., Song, Z., Stanley, J.A., Mooney, T.A., 2021. Changes in feeding behavior of longfin squid (Doryteuthis pealeii) during laboratory exposure to pile driving noise. Mar. Environ. Res. 165, 105250.

Kafas, A., Donohue, P., Davies, I., Scott, B.E., 2018. Displacement of existing activities. In: Yates, K.L., Bradshaw, C.J.A. (Eds.), Offshore Energy and Marine Spatial Planning, Earthscan Oceans. Routlidge, pp. 88–112 36 pp.

Kalivoda, O., Vojar, J., Zuzana Skřivanová, Z., Zahradník, D., 2014. Consensus in landscape preference judgments: the effects of landscape visual aesthetic quality and respondents' characteristics. J. Environ. Manag. 137, 36–44.

Khan, M.A., Al-Attas, T., Roy, S., Rahman, M.M., Ghaffour, N., Thangadurai, V.Nor, Eddine, G., 2021. Seawater electrolysis for hydrogen production: a solution looking for a problem? Energy Environ. Sci. 14, 4831–4839.

Kirchgeorga, T., Weinberg, I., Hornig, M., Baier, R., Schmid, M.J., Brockmeyer, B., 2018. Emissions from corrosion protection systems of offshore wind farms: evaluation of the potential impact on the marine environment. Mar. Pollut. Bull. 136, 257–268.

Ladenburg, J., 2009. Attitudes towards offshore wind farms-the role of beach visits on attitude and demographic and attitude relations. Energy Policy 38 (3), 1297–1304.

Ladenburg, J., Dubgaard, A., 2009. Preferences of coastal zone user groups regarding the siting of offshore wind farms. Ocean Coast. Manag. 52, 233–242.

Lampert, A., Bärfuss, K., Platis, A., Siedersleben, S., Djath, B., Cañadillas, B., Hunger, R., R., et al., 2020. In situ airborne measurements of atmospheric and sea surface parameters related to offshore wind parks in the German bight. Earth Syst. Sci. Data 12 (2), 935–946. https://doi.org/10.5194/essd-12-935-2020.

Landry, C.E., Allen, T., Cherry, T., Whitehead, J.C., 2012. Wind turbines and coastal recreation demand. Resour. Energy Econ. 34 (1), 93–111.

Leopold, M.F., Boonman, M., Collier, M.P., Davaasuren, N., Fijn, R.C., Gyimesi, A., De Jong, B., et al., 2015. A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea, IMARES, C166/44. Den Helder.

Lloret, J., Carreño, A., Caric, H., San, J., Fleming, L.E., 2021a. Environmental and human health impacts of cruise tourism: A review. Mar. Pollut. Bull. 173 (Part A), 112979.

Lloret, J., Gómez, S., Rocher, M., Carreño, A., San, J., Inglés, E., 2021b. The potential benefits of water sports for health and well-being in marine protected areas: a case study in the Mediterranean. Ann. Leis. Res. https://doi.org/10.1080/11745398.2021.2015412.

Locke, H., Rockström, J., Bakker, P., Bapna, M., Gough, M., Hilty, J., Lambertini, M., Morris, J., et al., 2021. A Nature-positive World: The Global Goal for Nature. https://www.nature.org/content/dam/tnc/nature/en/documents/NaturePositive_GlobalGoalCEO.pdf.

Lüdeke, J., 2017. Offshore wind energy: good practice in impact assessment, mitigation and compensation. J. Environ. Assess. Policy Manag. 19/01, S: 1750005.

Ludewig, E., 2015. On the effect of offshore wind farms on the atmosphere and ocean dynamics. Hamburg Studies on Maritime Affairs. 31. Springer International Publishing, Switzerland 52 pages.

Marine, Wise, 2021. Non Indigenous Species. https://water.europa.eu/marine-and-freshwater-water/state-of-europe-seas/pressures-impacts/non_indigenous_species.

Mavraki, N., Degraer, S., Vanaverbeke, J., Braeckman, U., 2020. Organic matter assimilation by hard substrate fauna in an offshore wind farm area: a pulse-chase study. ICES J. Mar. Sci. 77 (7–8), 2681–2693. https://doi.org/10.1093/icesjms/fsaa133.

Mavraki, N., Degraer, S., Vanaverbeke, J., 2021. Offshore wind farms and the attraction–production hypothesis: insights from a combination of stomach content and stable isotope analyses. Hydrobiologia 848, 1639–1657.

McCartney, A., 2006. The social value of seascapes in the Jurien Bay Marine Park: an assessment of positive and negative preferences for change. J. Agric. Econ. 57, 577–594. https://doi.org/10.1111/j.1477-9552.2006.00074.x.

MedECC, 2020. In: Cramer, W., Guiot, J., Marini, K. (Eds.), Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France https://doi.org/10.5281/zenodo.4768833 632pp.

Mendecka, B., Lombardi, L., 2019. Life cycle environmental impacts of wind energy technologies: a review of simplified models and harmonization of the results. Renew. Sustain. Energ. Rev. 111, 462–480.

Methratta, E.T., 2021. Distance-based sampling methods for assessing the ecological effects of offshore wind farms: synthesis and application to fisheries resource studies. Front. Mar. Sci. 8, 674594. https://doi.org/10.3389/fmars.2021.674594.

Methratta, E.T., Hawkins, A., Hooker, B.R., Lipsky, A., Hare, J.A., 2020. Offshore wind development in the northeast US shelf large marine ecosystem: ecological, human, and fishery management dimensions. Oceanography 33, 16–27. https://doi.org/10.5670/oceanog.2020.402.

Micheli, F., Halpern, B.S., Walbridge, S., Ciriaco, S., Ferretti, F., Fraschetti, S., et al., 2013. Cumulative human impacts on Mediterranean and Black Sea marine ecosystems: assessing current pressures and opportunities. PLoS ONE 8 (12), e79889. https://doi.org/10.1371/journal.pone.0079889.

Miles, T., Murphy, S., Kohut, J., Borsetti, S., Munroe, D., 2020. Could Federal Wind Farms Influence Continental Shelf Oceanography and Alter Associated Ecological Processes? A Literature Review. 24 ppRutgers /Scemfis. https://scemfis.org/wp-content/uploads/2021/01/ColdPoolReview.pdf.

MITECO, 2021. Parque eólico marino flotante Tramuntana, Cataluña (Girona). código del expediente: 20210050 https://sede.miteco.gob.es/portal/site/seMITECO/navServicioContenido.

Mitra, A., Zaman, S., 2015. Blue Carbon Reservoir of the Blue Planet. Springer Nature, Switzerland, p. 299.

Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Shigetomi, Y., Shu, S., 2015. Global mining risk footprint of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum in Japan. Environ. Sci. Technol. 49 (4), 2022–2031.

NOAA, 2021. Exploring Deep Sea Corals. https://noaa.maps.arcgis.com/apps/MapJournal/index.html?appid=16d0260cc8984a8b80c71e8289e3a748.

NorthSEE, 2017. Improving the co-existence of Offshore Energy Installations & Shipping. Report on Work-package 4.4 of the NorthSEE Project. Interreg NorthSea Region.

Notarbartolo di Sciara, G., 2016. Marine Mammals in the Mediterranean Sea: An Overview. Adv. Mar. Biol. 75, 1–36.

Parsons, G., Firestone, J., Yan, L., Toussaint, J., 2020. The effect of offshore wind projects on recreational beach use on the east coast of the United States: Evidence from contingent-behavior data. Energy Policy 144, 111659. https://doi.org/10.1016/j.enpol.2020.111659.

Perrow, M.R., 2019. A synthesis of effects and impacts. Wildlife and Wind Farms, Conflicts and Solutions, Volume 3 Offshore: Potential Effects, Chapter 10. Pelagic Publishing.

Powley, H.R., Van Cappellen, P., Krom, M.D., 2017. Nutrient Cycling in the Mediterranean Sea: The Key to Understanding How the Unique Marine Ecosystem Functions and Responds to Anthropogenic Pressures. Intech Open Book Series. https://www.intechopen.com/chapters/57227.

Randone, M., Bocci, M., Castellani, C., Laurent, C., 2019. Safeguarding Marine Protected Areas in the growing Mediterranean Blue Economy. Recommendations for Maritime Transport. PHAROS4MPAs project 36 pp.

Roberts, C.M., O'Leary, B.C., McCauley, D.J., Cury, P.M., Duarte, C.M., Lubchenco, J., Pauly, D., et al., 2017. Marine Reserves Can Mitigate and Promote Adaptation to Climate Change. Proc. Natl. Acad. Sci. 114 (24), 6167–6175.

Rudolph, D., 2014. The Resurgent conflict between offshore wind farms and tourism: Underlying storylines. Scott. Geogr. J. 130 (3), 168–187.

Sala-Coromina, J., García, J.A., Martín, P., Fernandez-Arcaya, U., Recasens, L., 2021. European hake (Merluccius merluccius, Linnaeus 1758) spillover analysis using VMS and landings data in a no-take zone in the northern Catalan coast (NW Mediterranean). Fish. Res. 237, 105870.

Sardá, R., Rossi, S., Martí, X., Gili, J.M., 2012. Marine benthic cartography of the Cap de Creus (NE Catalan Coast, Mediterranean Sea). Sci. Mar. 76 (1), 159–171.

Schomerus, T., Maly, C., 2017. Legal framework to develop offshore wind power in Germany. In: Ming-Zhi, A., Fan, C.T. (Eds.), The development of a Comprehensive Legal Framework for the Promotion of Offshore Wind Power. Wolters Kluwer, Alphen aa del Rijn, pp. 30–67.

Schupp, M.F., Kafas, A., Buck, B.H., Krause, G., Onyango, V., Stelzenmüller, V., Davies, I., Scott, B.E., 2021. Fishing within offshore wind farms in the North Sea: Stakeholder perspectives for multi-use from Scotland and Germany. J. Environ. Manag. 279, 111762.

Singh Ghaleigh, M., 2017. Legal framework to develop offshore wind power in UK. In: Ming-Zhi, A., Fan, C.T. (Eds.), The development of a Comprehensive Legal Framework for the Promotion of Offshore Wind Power. Wolters Kluwer, Alphen aa del Rijn, pp. 33–57.

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

Soukissian, T.H., Denaxa, D., Karathanasi, F., Prospathopoulos, A., Sarantakos, K., Iona, A., Georgantas, K., Mavrakos, S., 2017. Marine renewable energy in the mediterranean sea: status and perspectives. Energies 10, 1512. https://doi.org/10.3390/en10101512.

Stanley, J.A., Caiger, P.E., Phelan, B., Shelledy, K., Mooney, T.A., Van Parijs, S.M., 2020. Ontogenetic variation in the hearing sensitivity of black sea bass (Centropristis striata) and the implications of anthropogenic sound on behavior and communication. J. Exper. Biol. 223, jeb219683. https://doi.org/10.1242/jeb.219683.

Statoil, 2015. Hywind Scotland Pilot Park Project. - Enviromental Statement. http://marine.gov.scot/datafiles/lot/hywind/Environmental_Statement/Environmental_Statement.pdf. (Accessed February 2022).

Stelzenmüller, V., Letschert, J., Gimpel, A., Kraan, C., Probst, W.N., Degraer, S., Döring, R., 2022. From plate to plug: the impact of offshore renewables on European fisheries and the role of marine spatial planning. Renew. Sustain. Energ. Rev. 158, 112108.

Sullivan, R.G., Kirchler, L.B., Cothren, J., Winters, S.L., 2013. Offshore wind turbine visibility and visual impact threshold distances. Environ. Pract. 15, 33–49.

Taormina, B., Di Poi, C., Agnalt, A.L., Carlier, A., Desroy, N., Escobar-Lux, R.H., D'eu, J.F., et al., 2020. Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (Homarus gammarus). Aquat. Toxicol. 220, 105401. https://doi.org/10.1016/j.aquatox.2019.105401.

Torres, C., Hanley, N., 2016. Economic valuation of coastal and marine ecosystem services in the 21st century: an overview from a management perspective. DEA WP no. 75 Working Paper Series.

Tougaard, J., Hermannsen, L., Madsen, P.T., 2020. How loud is the underwater noise from operating offshore wind turbines? J. Acoust. Soc. Am. 148 (5), 2885. https://doi.org/10.1121/10.0002453.

Tuset, V.M., Farré, M., Fernández-Arcaya, U., Balcells, M., Lombarte, A., Recasens, L., 2021. Effects of a fishing closure area on the structure and diversity of a continental shelf fish assemblage in the NW Mediterranean Sea. Reg. Stud. Mar. Sci. 43, 101700. https://doi.org/10.1016/j.rsma.2021.101700.

Twigg, E., Roberts, S., Hofmann, E., 2020. Introduction to the special issue on understanding the effects of offshore wind development on fisheries. Oceanography 33 (4), 13–15.

UNEP, 2021. Ten Seabirds Added to the Mediterranean List of Endangered or Threatened Species. https://www.unep.org/unepmap/news/news/ten-seabirds-added-mediterranean-list-endangered-or-threatened-species.

Vaissière, A.C., Levrel, H., Pioch, S., Carlier, A., 2014. Biodiversity offsets for offshore wind farm projects: the current situation in Europe. Mar. Policy 48, 172–183.

Van Hoey, G., Bastardie, F., Birchenough, S., De Backer, A., Gill, A., de Koning, S., Hodgson, S., et al., 2021. Overview of the Effects of Offshore Wind Farms on Fisheries and Aquaculture. Publications Office of the European Union, Luxembourg.

Vermeij, M.J.A., Marhaver, K.L., Huijbers, C.M., Nagelkerken, I., Simpson, S.D., 2010. Coral larvae move toward reef sounds. PLoS ONE 5 (5), e10660. https://doi.org/10.1371/journal.pone.0010660.

Voltaire, L., Koutchade, O.P., 2020. Public acceptance of and heterogeneity in behavioral beachtrip responses to offshore wind farm development inCatalonia (Spain). Resour. Energy Econ. 60, 101152. https://doi.org/10.1016/j.reseneeco.2020.101152.

Voltaire, L., Louriero, M., Knudsen, C., Nunes, P., 2017. The impact of offshore wind farms on beach recreation demand: Policy intake from an economic study on the Catalan coast. Mar. Pol. 81, 116–123.

Voyer, M., van Leeuwen, J., 2019. Social license to operate' in the Blue Economy. Resour. Policy 62, 102–113.

Westerberg, V., 2012. Evaluation économique des changements des paysages littoraux : le cas du développement des parcs éoliennes dans le mer Méditerranée. Humanities and Social Sciences. Université Montpellier, p. 1.

Wilhelmsson, D., Langhamer, O., 2014. The influence of fisheries exclusion and addition of hard substrata on fish and crustaceans. In: Shields, M.A., Payne, A.I.L. (Eds.), Humanity and the Seas: Marine Renewable Energy and Environmental Interactions. Springer, Dordrecht, Heidelberg, New York, London, pp. 49–60.

WindEurope, 2020. Key trends and statistics 2019. Offshore Wind in Europe.

WindEurope, 2021. A 2030 Vision for European Offshore Wind Ports 44 pp. Available online at WindEurope-2030-Vision-for-European-Offshore-Wind-Ports.pdf.

Wolff, C., Nikoletopoulos, T., Hinkel, J., Vafeidis, A.T., 2020. Future urban development exacerbates coastal exposure in the Mediterranean. Nat. Sci. Rep. 10, 14420. https://doi.org/10.1038/s41598-020-70928-9.

Wolsink, M., 2010. Near-shore wind power - Protected seascapes, environmentalists' attitudes, and the technocratic planning perspective. Land Use Policy 27, 195–203.

Würtz, M., 2012. Mediterranean Submarine Canyons: Ecology and Governance. IUCN, Gland, Switzerland and Málaga, Spain, p. 216.

WWF, 2014. Power Production in the North Sea. A Literature Overview 25pp.

WWF, 2017. Reviving the economy of the Mediterranean Sea. Actions for a Sustainable Future 33 pp.

WWF, 2019. Safeguarding marine protected areas in the growing Mediterranean blue economy. Recommendations for the Offshore Wind Energy Sector. PHAROS4MPAs Project 68 pp.

Yates, K.L., Bradshaw, C.J.A., 2018. Offshore Energy and Marine Spatial Planning. London, Routledge 52 pages.

Zettler, M.L., Pollehne, F., 2006. The impact of wind engine constructions on benthic growth patterns in the western Baltic. Offshore Wind Energy. Springer, pp. 201–222.