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Making eco-sustainable floating offshore wind farms: Siting, mitigations, and compensations

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ABSTRACT

Floating Offshore Wind Farms (FOWFs) are the most promising renewable energy resource. Floating turbines are installed at progressively increasing water depths, interacting with offshore and deep-sea ecosystems. Thus, specific criteria to enable a sound and accurate Environmental Impact Assessment (EIA) are required. The still limited understanding of the impacts of FOWFs, and the concerns for the conflicts in the use of maritime space (e.g., fisheries), might lead to a more precautionary approach and constrain their development. Here we describe the characteristics of the deep habitats potentially impacted and identify a set of comprehensive and standardized criteria, response variables and approaches for a reliable EIA based on an Ecosystem-based approach. These analyses will support an appropriate design and site prioritization to respect the "Do No Significant Harm" principle. Considering the wide heterogeneity among habitats and geographic regions, we examined the potential interactions of FOWFs with i) Vulnerable Marine Ecosystems; ii) critical habitats; iii) migratory routes of large marine vertebrates; iv) habitat-forming species, benthic/pelagic organisms, v) migratory routes of birds/chiropters; vi) other human uses leading to cumulative/synergistic effects and any other potential interference. We identified mitigation and compensation measures and explored the potential of wind-farm areas as "Other Effective Conservation Measures" to support sustainable fisheries and passive restoration. Adequate siting, EIA and systematic monitoring can minimize FOWFs' environmental interactions, with final negligible, or even positive effects on marine ecosystems. Standardized criteria could significantly reduce the bottlenecks in permitting while offering a strategic vision for the sustainable use of the maritime space.

1. Introduction

The ecological transition towards decarbonization calls for a shift from fossil fuels to renewable energy resources. Recent estimates indicate that up to ~50,000 wind turbines could be installed by 2050 worldwide ([1] and references therein). Among renewable energy sources, Offshore Wind Farms (OWF) represent one of the most suitable options to generate "green energy" [2–5].

The development of OWFs will support the achievement of goals of the Paris Agreement, aimed at reducing by 55% the CO_2 emissions by 2030 and reaching "net zero CO_2 emission" by 2050. In addition, rigorous and fast development of new Floating Offshore Wind Farms (FOWFs) will contribute to the Sustainable Development Goals (SDGs) of the "2030 UN Agenda for Sustainable Development", especially the goal number 7, requiring the need to "ensure access to affordable, reliable, sustainable and modern energy for all", and number 13 that asks "to take urgent actions to combat climate changes and its impacts" as

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List of abbreviations

OWF	Offshore Wind Farms
FOWF	Floating Offshore Wind Farm
VME	Vulnerable Marine Ecosystem
IUCN	International Union for Conservation of Nature
WORM	World Register of Marine Species
EIA	Environmental Impact Assessment
MSFD	Marine Strategy Framework Directive
EMB	European Marine Board
DNSH	Do No Significant Harm
EU	European Union
UNGA	United Nations General Assembly
RFMO/As	States and Regional Fisheries Management Organizations/Arrangements
FAO	Food Agriculture Organization
CR	Critically Endangered
EN	Endangered
VU	Vulnerable
SPA/BD	The Protocol Concerning Specially Protected Areas and Biological Diversity in the Mediterranean
UNEP-MAP-RAC/SPA	United Nations Environmental Programs - Mediterranean Action Plan - Regional Activity Centre/ Special Protected Area
MNP	Marine Noise Pollution
SEL	Sound Exposure Level
$SEL_{(ss)}$	Sound Exposure Level $_{(single\ strike)}$
$SEL_{(cum)}$	Sound Exposure Level $_{(cumulative)}$
HVAC	High Voltage Alternating Current
SML	Surface Mixed Layer
VPR	Video Plankton Recorder
OECM	Other Effective Conservation Measures
FAD	Fish Aggregation Device
CPUE	Catch Per Unit Effort
NOAA	National Oceanic and Atmospheric Administration
ROV	Remotely Operated Vehicle
AUV	Autonomous Underwater Vehicle
NIS	Non-Indigenous Species
SPC	Submarine Power Cable
DC	Direct Current
AC	Alternating Current
EMF	Electromagnetic Field
MSP	Maritime Spatial Planning
CEFS	Cells of Ecosystem Functioning
FRA	Fishery Restricted Area
MPA	Marine Protected Area
EMP	Environmental Monitoring Program
BACI	Before vs After, Control vs Impact
CI	Control vs Impact
BAG	Before vs After Gradient
LCA	Life Cycle Assessment
MMO	Marine Mammal Observer

well as the goal number 14: "conserve and sustainably use the oceans, seas and marine resources for sustainable development".

OWFs have been initially conceived as fixed structures (monopiles, tripods, jackets, gravity-based foundations), in shallow waters (depth typically <50–70 m, global average distance from the shore ca. 20 km [6]), but now being replaced by offshore floating structures (e.g., semisubmersible, tensioned leg platforms, and spars anchored (dead-weights) to the deep seafloor (i.e., >200-m depth [7]). Floating offshore wind farms (FOWFs) can be installed down to 900-m depth or more [8]. Winds are stronger and more constant in offshore waters and technological improvements are increasing the energy produced per turbine while reducing the cost of installation at greater depths [9,10]. Consequently, it is reasonable to assume that FOWFs will become the most suitable option to achieve the goal of a full supply of renewable energy in the future [11,12]. According to this perspective, offshore and deep-sea ecosystems will be the primary targets of the potential impacts generated by OWFs. OWFs based on fixed turbines have posed concerns for the possible impacts on coastal marine ecosystems and on some specific components, such as: i) marine mammals and fish [13–15]; ii) benthic habitats and food webs [15]; iii) electro-magnetic sensitive species, such as elasmobranchs, teleost fish, crustaceans and sea turtles, because of the electromagnetic fields generated by the underwater power cables ([15–19]; hereafter for species nomenclature we refer to the WORM database). However, the impacts of FOWFs are far from being elucidated, as the presence of floating turbines anchored on the deep seafloor makes current knowledge on coastal OWFs inapplicable to predict the effects of this new technology [15,20]. FOWFs might cover areas of thousands of km^2 and although it has been supposed that FOWFs have a lower impact than fixed ones, their installation and decommissioning could, nonetheless, determine potentially relevant impacts [21].

Current concerns call for the need to develop robust criteria for the Environmental Impact Assessment (EIA) of these installations. Most EIAs of fixed OWFs have traditionally focused on four biological components: 1) mammals, 2) birds, 3) fish and 4) benthic organisms. Among these, only mammals and birds have received significant attention due to the higher public interest and legal protection [1]. However, these four components are far from including all ecosystem constituents that can interact with FOWFs and are thus insufficient to address the impacts on both structural and functional features of marine ecosystems. Moreover, the adoption of a much wider (holistic) approach in EIA is increasingly recommended (e.g., Marine Strategy Framework Directive, MSFD; EMB Navigating the future V [22]) but still scarcely adopted. However, a standardized approach to assess the impacts is lacking, especially for deep-sea habitats [23,24]. Future EIAs should also respect the "Do No Significant Harm" principle [25], also to identify all potential mitigation measures needed to make any environmental effect negligible. Finally, a relevant gap in future FOWF planning and best practices is the need to include the consideration of compensation for any accidental or residual (not predicted) impact of FOWFs, by identifying the restoration tools and protocols needed to intervene.

Deep-sea ecosystems remain largely unknown [26] and this could lead to a more precautionary approach by permitting authorities. The concern for the potential environmental impacts of FOWFs is leading all countries to adopt careful permission procedures. Bottlenecks in the development of FOWFs include the time taken to obtain the necessary permissions. Some governments are starting to use a more planned approach for releasing permits, identifying suitable sites *a priori*, carrying out preliminary technical and environmental surveys, and consulting with the public and other marine users. The bottlenecks might be significantly reduced also by adopting standardized criteria for assessing the environmental impact [27].

Despite the huge relevance of this renewable energy source in the future, we still lack comprehensive criteria and standardized procedures enabling their correct planning, siting and avoidance of impacts of the FOWFs. Here we develop, for the first time, the best practices needed to fill these gaps, suggesting a holistic approach to assess their environmental impact, taking into account migratory species, water column and deep-sea ecosystem, including all biodiversity components and the effects of the FOWFs on ecosystem functioning. To reach this objective we provide an overview of all ecosystems and habitat types potentially affected by the installation of FOWFs and, when appropriate, we extend the available knowledge acquired from fixed foundation turbines to FOWFs to regulate their future installation. We also identify and propose the use of mitigation measures for all potential impacts and compensation actions to face residual or accidental damage, even minor ones (ecological restoration; nature-based solutions; establishment of other effective conservation measures, OECMs) [28].

This review aims also at providing all future proponents with the criteria and approaches that can make faster the environmental impact assessment and positive authorization processes of the future FOWFs. The adoption of comprehensive criteria, standardized procedures and best practices to support appropriate siting and use of mitigation measures can make FOWFs eco-compatible, potentially supporting the scaling up of this renewable energy production.

2. Methods

2.1. Setting the stage: offshore and deep-sea habitats

Assessing the potential impacts of FOWFs means understanding the distribution of species and habitats together with the functioning of the marine ecosystems in the areas where the wind farms are planned. Most of the wind farms all over the world, being fixed, are still close to the shore (the global average distance from the shore is 18.8 km) as they are limited by the water depth for fixing the piles (on average 14.6 m, maximum depth ca 70 m). In the future, most FOWFs will be located from 12 to >30 miles (approximately 20–60 km) anchored at great depths.

FOWFs can intercept several migratory species or vulnerable habitats (Fig. 1) such as those considered and described below.

Offshore habitats of the water column - Approximately 95% of the ocean surface is represented by offshore areas, defined as those portions of the ocean that insist over depths >200 m. Pelagic and deep-sea ecosystems are refuge habitats [32]. The biodiversity in these ecosystems is poorly known, but available studies indicate that species richness remains high also at mid-slope depths.

Benthic deep-sea habitats - They include the seafloor below 200-m depth, which represent the world's largest biome, covering more than 65% of the Earth's surface and including more than 95% of the global biosphere. Deep seafloor includes complex and heterogeneous ecosystems [24]. The deep-sea systems of interest for the installation of FOWFs include: a) continental slopes, beyond the shelf break; b) submarine canyons; c) guyots, seamounts, and underwater mountains formed from volcanoes often with vent activity; d) deep-sea plains; e) carbonate mounds; f) pockmarks and mud volcanoes. Since 2006, the UN General Assembly (UNGA) adopted a series of resolutions dedicated to the protection of fragile benthic biodiversity hotspots in the deep sea, collectively called Vulnerable Marine Ecosystems (VMEs), defined for their: i) uniqueness or rareness, ii) functional significance, iii) fragility, iv) life-history of species, v) structural complexity [33–36]. Many VMEs have a wide distribution. The main anthropogenic activity threatening VMEs is bottom trawling. The Endangered Species Act identified "critical habitats" as the areas that contain features essential to the conservation of a species or habitat of conservation interest and may require targeted management and protection. This is particularly relevant for the species included in the Categories of the IUCN Red Lists (CR, Critically Endangered; EN, Endangered; VU, Vulnerable) as well as in regional protection documents (e.g., Annex II of the List of endangered or threatened species of the SPA/BD protocol of the Barcelona Convention). Threatened species and habitats (e.g., white coral, gorgonians, sponges and coralligenous) are a priority for the EIA of FOWFs (Table 1).

Fauna inhabiting the continental slopes - Soft bottoms at 200-1000-m depth are inhabited by bamboo corals, gorgonians, sea pens, large aggregations of crinoids, sea urchins, holothurians and burrowing fauna [37–44]. Continental slopes consist of mostly terrigenous sediments and include large areas of soft sediments, boulders and exposed rock faces, which offer the opportunity for a variety of animals (UNEP-MAP-RAC/SPA, 2013) and for commercial species [45–48].

Submarine canyons - Steep-walled incisions of the continental slopes with generally V-shaped cross sections can create complex networks along continental margins and include important habitats [47,49,50]. Often characterised by upwelling waters support primary production, host nurseries, and are feeding habitats for cetaceans [49–57].

Seamounts and other reliefs - These hotspots in the ocean, often host unique communities [58–60]. Together with lower-relief features such as knolls and pinnacles, they contribute enormously to increase the

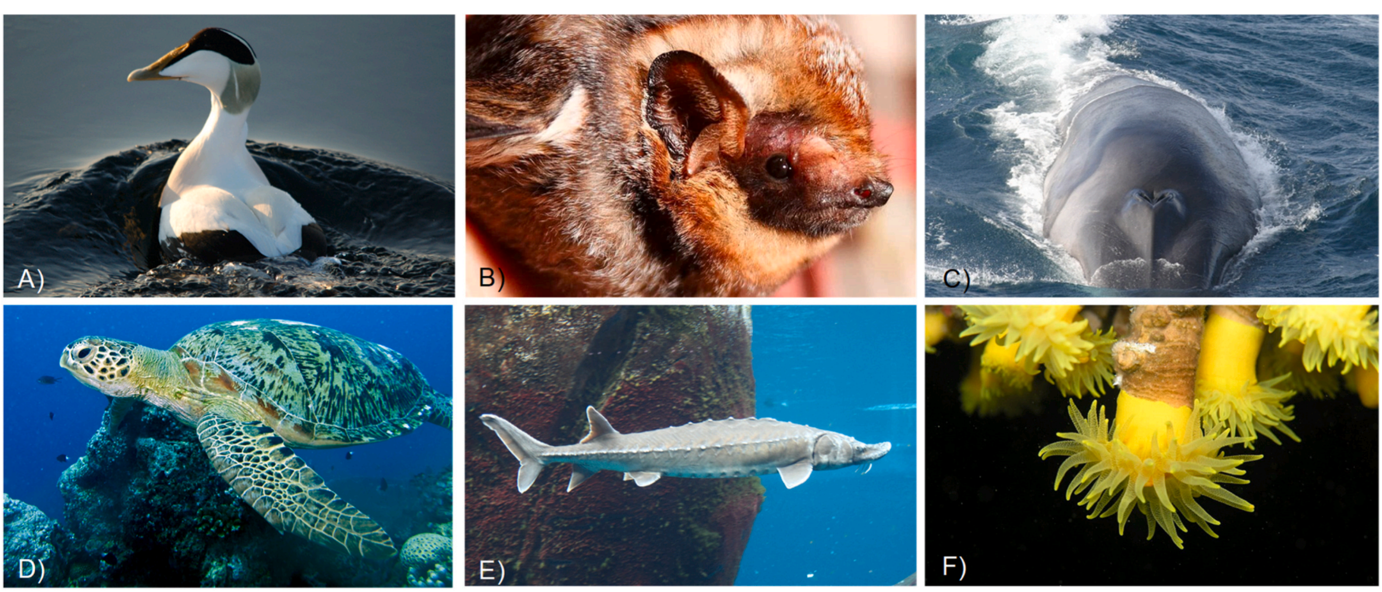

Fig. 1. Species potentially impacted by floating offshore wind farms and their infrastructures: A) *Somateria mollissima* (Near Threatened *sensu* IUCN); B) *Lasiurus cinereus semotus* (Least concern *sensu* IUCN); C) *Balaenoptera physalus* ([30]; Vulnerable species *sensu* IUCN); D) *Chelonia mydas* ([30]; Endangered *sensu* IUCN); E) *Acipenser oxyrinchus* ([30]; Vulnerable *sensu* IUCN); and F) *Dendrophyllia cornigera* ([21]; Vulnerable *sensu* IUCN [31]). (Images: Arnstein Rønning (A), Frank Bonaccorso USGS (B), Annie Douglas (C), Bernard Dupont (D), Simon Pierre Barrett €, Marco Busdraghi (F). Creative commons: CC BY-SA 2.0 (D), CC BY-SA 3.0 (A, E), CC BY-SA 4.0 (F), Public domain (B, C).

Table 1
List of the Vulnerable marine ecosystems in deep-sea areas all over the world.

Northwest Atlantic	Annex 1.E
NAFO CEM 2019	VME Indicator Species (species listed) Large-sized sponges (Porifera) 17 species (or spp.) Stoney corals (Cnidaria) 4 species Small gorgonian corals (Cnidaria) 8 species Large gorgonian corals (Cnidaria) 18 species Sea pens (Cnidaria)13 species Tube-dwelling anemones (Cnidaria) 1 species Erect bryozoans (Bryozoa) 1 species Sea lilies (Crinoids) 3 species Sea squirts (Chordata) 1 species List of Physical VME Indicator Elements Seamounts, Canyons, Knolls, Southeast shoal, Steep flanks >6.4°
Northeast Atlantic	**Annex 5**
NEAFC Rec. (am. 10:2018))	**VME Habitat type (examples listed)** 1. Cold-water coral reef a. *Lophelia pertusa* reef (*1 sp)* b. *Solenosmilia variabilis* reef (1 sp) 2. Coral garden a. Hard bottom garden i. Hard bottom gorgonian and black coral gardens (9 families) ii. Colonial scleractinians on rocky outcrops (2 species) iii. Non-reefal scleractinian aggregations (2 species) b. Soft-bottom coral gardens i. Soft-bottom gorgonian and black coral gardens (1 family) ii. Cup-coral fields (2 families) iii. Cauliflower coral fields (1 family) 3. Deep-sea sponge aggregations a. Other sponge aggregations (3 families) b. Hard-bottom sponge gardens (4 families) c. Glass sponge communities (2 families) 4. Seapen fields (8 families) 5. Tube-dwelling anemone patches (1 family) 6. Mud- and sand-emergent fauna (5 families) 7. Bryzoan patches Physical elements Isolated seamounts, Steep-slopes and peaks on mid-ocean ridges, Knolls, Canyon-like features, Steep flanks >6.4°
Southeast Atlantic	Annex 6.1
SEAFO CM 30/15	VME Indicators listed by SC - see SEAFO SC Report, 2016, 2017 Sponges (Porifera) Gorgonian corals (Gorgonacea) Hydrocorals (Anthoathecatae) Stony corals (Scleractinia) Black corals (Anthipatharia) Zoanthids (Zoantharia) Soft corals (Alcyonacea) Sea pens (Pennatulacea) Erect bryozoans (Bryozoa) Sea lilies (Crinoidea) Basket stars (Ophiuroidea) Annelida (Serpulidae) Sea squirts (Ascidiacea) Tube-dwelling Sea anemones (Ceriantharia)
North Pacific **NPFC CMM 2018–05 (Western)** **NPFC CMM 2017–06 (Eastern)**	Para. 4G (Western), Para 3 g (Eastern) cold water corals (Alcyonacea, Antipatharia, Gorgonacea, Scleractinia)
South Pacific	Annex 5
SPRFMO CMM 3–2019	Sponges (Porifera: Demospongiae and Hexactinellidae) Stony corals (Scleractinia: Solenosmilia; Goniocorella; Oculina; Enallopsammia; Madrepora; Lophelia) Black corals (Antipatharia) True soft corals (Alcyonacea: all taxa excluding Gorgonacea)

Table 1 (*continued*)

Northwest Atlantic	Annex 1.E
	Sea fans octocorals (Gorgonacea: Holaxonia; Calaxonia; Scleraxonia) Sea pens (Pennatulacea) Anemones (Actiniaria) Hydrocorals (Stylasteridae)
Southern Ocean CCAMLR CM 22–07 (2013)	Para. 2ii. As in VME Taxa Classification Guide Gorgonians (Gorgonacea: 5 families) Hydroids (Hydroidellina) Hydrocorals (Stylasterids) Stony corals (Scleractinia) Black corals (Antipatheria) Zoanthids (Zoantharia) Sponges (Hexactinellida, Demospongiae) Anemones, soft corals, Sea pens (Cnideria) Sea squirts (Ascidiacea) Lace corals (Bryozoan) Chemosynthetic organisms (various) Lamp shells (Brachiopoda) Acorn worms (Pteribranchia) Serpulid tube worms (Serpulidae) Zenophyophors (Zenophyophora) Goose and acorn barnacles (Bathylasmatidae) Antarctic scallop (*Adamussium colbecki*) Sea lilies, etc (Echinoderms: 3 orders)
Mediterranean	(a) Mediterranean VME indicators features
Appendix 3(A)/Annex 1	The following features potentially support VMEs:
VME ind. Features and taxa	Seamounts and volcanic ridges Canyon and trenches Steep slopes Submarine reliefs (slumped blocks, ridges, cobble fields, etc) Cold seeps (pock marks, mud volcanoes, methanogenic hard bottom) Hydrothermal vents (b) Mediterranean VME indicator habitats Cold water coral reefs Coral gardens: - Hard bottom coral gardens - Soft bottom coral gardens Sea pen fields Deep sea sponge aggregations: -"Ostur" sponge aggregations - Hard bottom sponge gardens - Glass sponge communities - Soft bottom sponge gardens Tube-dwelling anemone patches Crinoid fields Oyster reef and other giant bivalves Seep and vents communities Other dense emergent fauna (c) Mediterranean VME indicator taxa Cnidaria Anthozoa: Hexacorallia (Antipatharia, Scleractinia), Octocorallia, (Acyonacea, Pennatulacea); Ceriantharia Hydrozoa, Hydroidolina Porifera, (sponge) Demosponges Porifera, Hexactinellida Amphidiscophora Hexasterophora Bryozoa Gymnolaemata and Stenolaemata Echinodxermata Crinoidea Articulata Mollusca bivalvia: Gryphaeidae (*Neopycnodonte cochlear, N. zibrowii*) Heterodonta* (Lucinoida) (e.g., *Lucinoma Kazani*), Pteriomorphia* (Mytiloida) (e.g., *Idas modiolaeformis*) Annellida* Polychaeta: Sedentaria (Canalipalpata) (e.g., *Lamellibranchia anaximandri*, *Siboglinum* spp.) Arthropoda* Malacostraca, Eumalacostraca (Amphipoda)

heterogeneity of the deep seafloor [61]. Suspension feeders, particularly deep-sea corals, gorgonians, sponges and fishes, usually dominate the hard bottoms [62–64]. A complex trophic network includes top predators (cetaceans and sharks).

Deep-sea coral reefs, coral gardens and carbonate mounds - They are preferentially distributed on topographic irregularities and are important habitat formers as their bioconstructions produce locally elevated secondary hard substrates associated with strong bottom currents [62,65,66]. These habitats include hotspots of biodiversity dominated by scleractinians, colonial octocorals, black corals, sponges and giant bivalves [41,65,67–75].

Pockmarks and mud volcanoes – These habitats occurring on continental margins worldwide down to >1000 m [71], originate from the expulsion of gas from over-pressured gas pockets or continuous hydrocarbon fluid discharge, creating spatial heterogeneity [76]. Chemosymbiotic communities are associated with mud volcano fields [77]. These habitats might be also important for some marine mammals (e.g., Cuvier's beaked whales, *Ziphius cavirostris*) [78]. An example of the potentially impacted deep-sea habitats reported above is illustrated in Fig. 2.

2.2. Setting the stage: vulnerable coastal habitats

FOWFs are located in offshore and deep-sea areas, but their sealines reach the land and can cross protected or vulnerable habitats and species (e.g., those considered in the European Habitat Directive 92/43/CEE and in the IUCN red list). Within the mesophotic zone (from 40 to 200-m depth) coralligenous habitats (encrusting algae) are widespread at mid-latitudes in temperate-warm seas (such as the Mediterranean Sea [62,79]). At depths <40 m we encounter other habitats potentially highly susceptible to damage including the seagrass meadows [80], and macroalgal forests (either formed by the kelp or by other brown algae), which are in progressive regression in most areas of the world. The impact of sealines should be carefully assessed, mitigated, and eventually compensated [81–83]. At very shallow depths: "Sandbanks slightly covered by sea water", "Mudflats and sandflats not covered by seawater at low tide" and other habitats included in the European Habitat Directive 92/43/CEE contain more than 600 species and are included by IUCN in the red list. An example of the coastal habitats potentially impacted by the sea cables is reported in Fig. 3.

2.3. Literature survey

A literature survey was conducted to gather information on offshore wind-farm effects across different marine habitats and biogeographic regions at a global spatial scale (i.e., worldwide). More specifically, to achieve the objectives of the review, the overall research question that guided the analysis was: what is the current knowledge about FOWF implementation? The following sub-questions were considered: what are the known effects of FOWFs across species and habitats?; what are the examples of restoration interventions after FOWF implementation?; what are the gaps of knowledge to support the implementation of FOWFs?

The temporal extent considered was from 1970 to 2023. To get a comprehensive data set, the research was expanded including and combining Web of Science, Scopus, and Google Scholar (first 200 studies), also considering the results from the grey literature (e.g., technical reports) recovered through an in-depth search.

To include all available information in the review, we selected the following key terms: "offshore" or "windfarms" or "wind farms", and "floating", and/or "deep sea", "seabirds", "marine mammals", "fisheries", "cumulative impacts", "bats". Since the results of the literature search in the field of restoration might be biased by the lack of data on specific areas or definitions, we carried out a specific search using also "deep-sea restoration", and "corals restoration". Searches were undertaken within article titles, abstracts, keywords, and main text. We considered and carefully analyzed papers published in international journals, contributions to scientific congresses as well as project reports and deliverables of projects carried out at the international, national, or regional level and made available to public administrations for territory management purposes. When a review was found, also the references reported therein were considered. As a result, 972 documents were identified. As far as criteria inclusion/exclusion, we excluded double or repeated documents, documents not available for download, documents not pertinent (e.g., regarding other kinds of ecosystems, like river estuaries), and documents not reporting data coherent with the topic investigated. Master/PhD theses were considered when published as scientific papers/reports.

Although a large body of information is derived from fixed offshore wind farms, some of the problems and solutions reported for fixed wind farms can be applied or re-defined in the context of the open waters and deep-sea habitats on which FOWF installations insist. The main limitation of this analysis is thus related to the currently limited field information on floating offshore wind farms. However, since we did not carry out statistical analyses, modelling or quantifications, the risk of inaccuracy or error is low.

Since the technology and design of FOWFs are changing very rapidly and the size of the turbines increases, a constant recalibration of the proposed criteria is desirable, as it might potentially expand the risk of collision for migratory birds and bats. The potential of positive effects derived from the development of protection measures will require specific assessments, while the efficacy of the mitigation measures will be tested only.

3. Potential environmental impacts of floating offshore wind farms

It is now recognized that the impact generated by FOWFs, is different from that of fixed turbines: different installation depths (and thus different habitats interested), the use of anchors/deadweights instead of piles infixed in the seafloor. Differences might arise among biogeographic regions [21]. Here, using an ecosystem-based approach, we analyzed all potential impacts (either positive or negative) determined by FOWFs on the following ecological compartments reflecting the 3D development of these infrastructures: 1) air; 2) water column; and 3) seafloor.

Fig. 2. Deep-sea habitats/ecosystems possibly impacted by FOWF infrastructures: A) a rocky bottom at mesophotic depths; B) a sea pen forest; C) a deep coral field (Images: NOAA (A, C), John Turnball (B). Creative commons: CC BY-SA 2.0 (B), Public domain (A, C).

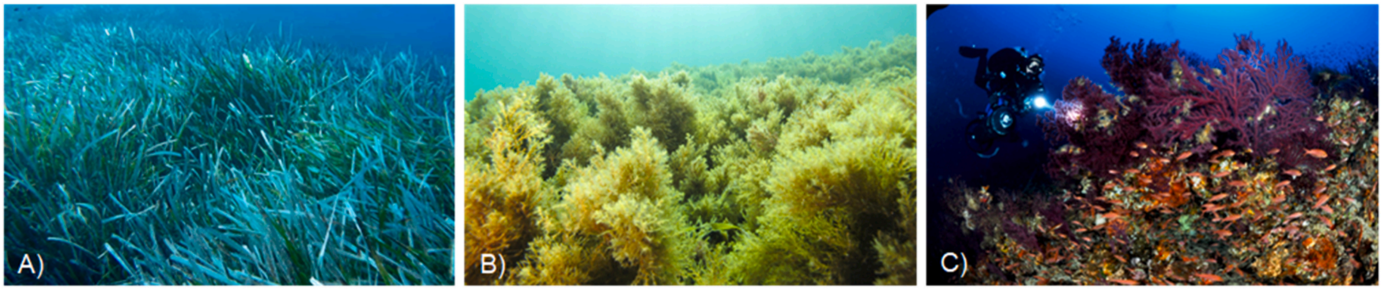

Fig. 3. Coastal habitats/ecosystems possibly impacted by FOWF infrastructures: A) *Posidonia oceanica* meadow (Natura 2000 code 1120, Posidonia beds priority habitat, *sensu* European Habitat Directive 92/43/CEE, Annex I); B) macroalgal forest dominated by *Cystoseira s.l.* Species (Natura 2000 code 1170, Reefs); C) coralligenous habitat (Natura 2000 code 1170, Reefs). Image: Frédéric Ducarme (A), Arnaud Abadie (B), Carlo Cerrano (C). Creative commons: CC BY-SA 3.0 (A, B).

3.1. Impacts on seascape, air, noise, vibrations, and collisions

Wind farms have the theoretical advantage of reducing global air pollution by replacing fossil fuels with green renewable energy, but one of the main reasons for social reluctance to accept the installation of FOWFs is their potential visual impact [84], potentially conflicting with blue tourism [85–89]. For this reason, FOWFs should be placed far away from the shore (EWEA, 2015; e.g., >40–60 km). FOWFs generally have the hub at ca 170 m above sea level and the height at the tip of the blades can be higher than 250 m at a 50-km distance from the shore they would be invisible to the human eye. Atmospheric wakes appearing in the lee of wind farms extend on scales up to 65 km, with a wind speed reduction of up to 43% inside the wakes leading to turbulence effects [90–92] altering the meteorology at the micro-scale [93,94] and an increase or decrease of temperature [93]. They can locally alter the precipitation regimen [95,96], and potentially alter the spread of air pollutants through an edge effect [97,98]. Information on the possible alteration of wind speed and direction caused by FOWFs is too limited to draw any conclusion. However, all these effects are likely to have negligible consequences in open waters.

Impacts of noise and vibration - The definition “marine noise pollution” (MNP) has been introduced (see MSFD 56/2008) to define any source of anthropogenic sound occurring in the marine environment capable of producing deleterious effects on marine life [99–101]. Sound exposure level (SEL) is the energy of the entire sound pulse and is the best descriptor for fish and cetacean hearing injury. Both the number of pile strikes and the levels influence the extent of the injury [102], for this reason, either $SEL_{(ss)}$ (the value of a single strike) and $SEL_{(cum)}$ (the cumulative value of several strikes over a given period of time) should be determined. Noise pollution can be produced during the construction phase of fixed OWFs due to the use of vibration or percussive hammers [103]. However, FOWFs do not need foundations and pile driving and this can reduce dramatically the impact of noise during construction, limiting the effects of the noise produced by working vessels and the anchoring process. Previous studies indicate that cable laying can produce underwater noise, up to 178–188.5 dB re 1 μPa (<50 kHz) at a 1-m distance from the area subjected to trenching for the cable displacement [104,105]. There is no available data about noise pollution due to FOWFs during the operation phase, but we know that the fixed OWFs show peaks up to 153 dB re 1 mPa at 1 m at 16 Hz [104]. The biological effects of noise pollution on organisms will be discussed in the next sections. The vibration of the blades and towers can influence marine life [106]. In the construction phase noise will be mainly produced by the ships used and by the cable laying. High Voltage Alternating Current (HVAC) cables are often subjected to vibration due to the Coulomb force occurring between conductors, which can emit a sound level of 100 dB re 1 μPa at 1 m distance [19].

Potential impact of collisions on (sea)birds and chiropters - Birds are strongly vulnerable to human impacts [107]. Several bird species are on the red list of IUCN (see also the Birds Directive 2009/147/EC and the Protection of Birds Act 1954). “Seabirds” include birds that spend an important part of their life at sea, predominantly feeding in marine waters and are well adapted to the marine environment [108]. They include also migratory species, which do not primarily depend on marine resources for their feeding [107]. According to the UN, about 1800 avian species (20% of the total) migrate every year, so these species are potentially vulnerable to collision with the FOWF blades. OWFs have an impact on birds through collision-induced mortality and foraging habitat loss [109] and 250,000–500,000 birds are killed annually by colliding with wind turbines on land in the USA [110]. Most migrating birds usually fly at a height from 200 to 1500 m above sea level [109]. One difference with onshore wind farms is that FOWFs are taller and show the lowest tip of the blade is at 70–100 m from the sea surface.

Seabirds’ behavioral responses to the presence of FOWFs include avoiding, indifference, or attraction [111]. The foraging behavior and diving time have been proposed as good descriptors of the environmental impact of FOWFs on (sea)birds. Birds may show two types of avoidance behavior at offshore wind farms: 1) “macro-avoidance” occurs when birds alter their flight path to keep away from the entire wind farm; 2) “micro-avoidance” happens when birds enter the wind farm but avoid individual turbines [109,112,113]. The knowledge of the seabirds present in the FOWF areas is mandatory for adopting adequate mitigation measures since the species flying most of the time will be more vulnerable than those mostly swimming [114]. There are 9 factors influencing the birds’ vulnerability to FOWFs: 1) flight maneuverability, 2) flight altitude, 3) percentage of time flying, 4) nocturnal flight disturbance by ship and helicopter traffic, 5) flexibility in habitat use, 6) biogeographical population size, 7) adult survival rate, 8) local threat and 9) conservation status. These factors can be integrated into a vulnerability index helping in predicting the impact and applying mitigation measures [114]. Species living near the coast are more susceptible than those living in the high-seas areas [107]. Only a portion of bird species migrates flying at the blade rotation height (70–300 m a.s.l.). Bar-headed geese can reach heights of 18,000 m to pass over the Himalayas so it is possible to predict that several species will fly above the height of 300 m or might deviate their flying height to pass over the turbines. The common seabirds (e.g., razorbill, guillemot, unidentified auk, black-headed gull, black-legged kittiwake, great cormorant, northern fulmar, and various gull species) show a median value of fly height <35 m [115] and therefore would be not at risk with FOWF blades. Conversely, white-tailed eagles, black-backed gulls and herring gulls, as well as other seabirds can pass up to one-fourth of their fly time at the maximum height of 150–170 m indicating a real collision risk [109]. The development of new floating offshore wind turbines is associated with an increase in their blade size and thus the spatial area covered and maximum altitude of the tip by the future windfarms, with a consequent increased risk of collision for birds and bats. In addition, when birds fly headwind, they might fly closer to the sea surface. Whereas with tailwind they fly up high to where it will whisk them along faster. For this reason, predicting the exact bird-flight height is a complex issue. Seabirds collide with FOWFs typically at night or in hours with scarce visibility when they cannot avoid the turbines [114]. The attraction of birds to wind farms is correlated with their "reef effect" and local turbulences that cause a major prey availability for the birds feeding on the sea surface [116]. It is also possible that fish can seek refuge in the wind farms. It has been also hypothesized that offshore turbines can deepen the vertical distribution of fish obligating the (sea) birds to perform deeper and longer dives to capture the prey [117]. At the same time, the floating structures being colonized by a wide array of species (fouling and mobile organisms) can facilitate bird feeding. The emerged portion of the floating foundations of the turbine can be also used by some species for a stopover during their migrations.

Bats include approximately 1100 species, some of which are migratory and protected by the "UN Convention on Migratory Species of Wild Animals". Most of them travel only for short distances, while others are known to migrate for long distances (up to 2000 km [118]). In Europe, the most susceptible migratory species are: *Nyctalus noctula*, *Nyctalus leisleri*, *Pipistrellus nathusii*, and *Vespertilio murinus* [119]. Although there is no data about the collision and mortality of bats due to floating offshore windfarms [120], data from land windfarms indicate that they might be subjected to a high mortality rate (10–12 bats are killed/turbine annually [121]). Bats changed altitude rapidly when they were near tall vertical obstacles such as ships, bridges, and wind turbines, but all migrating bats observed over the sea fly at relatively low altitudes (*N. noctula* flies <10 m above the surface although a few can reach 40 m). Since the lowest altitude of the blades is 60–70 m from the sea surface, the collision risk of bats with turbines of the FOWFs could be very limited if not negligible.

3.2. Impacts on the water column and associated assemblages

Effects on water circulation and plankton - The water column is subjected to a seasonal stratification, with a thermocline that is disrupted by decreasing solar energy and wind action with consequent water mixing and nutrient exchange. This seasonal process influences the water column productivity and food web dynamics [122,123]. FOWFs can increase the turbulence at the local scale and enhance water mixing [122,124], but these effects are expected to be extremely localized, typically only in the first 100 m downstream of the structure. Previous studies on fixed wind farms showed that a single turbine can increase by 7–10% the local water mixing, generating ~10% of the turbulent kinetic energy and can cause the reduction by 5% of the peak velocity until approximately 1 km from each turbine [125]. Since FOWFs do not have a fixed foundation, these effects might be strongly reduced. Larger scale effects of OWFs can alter the stratification, which is on average 1–2 m shallower in and around the OWF clusters and alter the current speed (±10% [91]). The influence of FOWFs on natural upwellings [126] is less plausible, nonetheless, large FOWFs can increase or decrease the net primary production with consequences on the survival of fish larvae [91]. Field investigations confirmed the increased vertical mixing leading to a doming of the thermocline and subsequent transport of nutrients into the surface mixed layer (SML). Video Plankton Recorder (VPR) revealed potential effects on meroplankton [127] and nekton species distribution [128]. The pilings of FOWF and the catenaries can be colonized by non-indigenous species (NIS) [89] so enhancing their potential spreading. However, all these processes are likely to be less relevant in offshore than in coastal waters.

Potential impacts on fish and fisheries - Wind turbines might attract marine life due to a reef effect, which depends on their location [129,130]. The impacts caused by fixed OWFs occur also during their construction with the production of noise and sediment loads due to pile driving [15]. FOWFs do not require pile driving and their effects are expected to be limited to the anchoring on the seafloor, which can cause a temporary resuspension of the bottom sediments, but do not have a significant negative impact on fish assemblages [131–134]. Thus, anchoring, when appropriately sited, can cause negligible impacts on this component. Reef effects are difficult to detect, but FOWFs can attract several fish that can find refuge areas and considerable sources of food on the structures [135–137]. The chains and the anchors of the turbines represent an additional hard substrate for organisms' colonization that can attract several fish species. In this regard, previous studies reported that turbines do not determine significant changes in pelagic fish assemblages [127,138], and no effects were observed in terms of fish diversity and abundance compared to adjacent areas [131,132]. The detection of noise by fish depends on: i) the size and number of windmills, ii) the hearing abilities of the fish, iii) background noise level, iv) blade design and wind speed, v) water depth and vi) type of sea bottom [139]. Results from the OWFs, indicate the lack of negative effects on the hearing abilities of fish, even within a few meters of distance, but noise-induced behavioral reactions can be detected within a range of 4 m from the pile, and only at wind speeds >13 m s^{-1}. As far as vibrations produced by the foundation of fixed monopile turbines are concerned, the impact of FOWFs might be negligible if the blades rotated at ca 170 m from the sea surface and in the absence of pile foundations. Furthermore, vibration and noise transmission to the high depths is expected to be negligible or absent. Previous studies pointed out that OWFs led to increased fish catches in adjacent areas [140,141], as planktonophagous species are favored by FWOFs and fisheries restriction in OWF areas can increase the size and biomass of commercial fish species [131,135,142,143], thus acting as Other Effective Conservation Measures. Such effects have been detected to 500 m from the turbines [144]. FOWF floating structures can act as fish aggregation devices (FADs) that are known to concentrate several fish species [138,145,146]. Marine windfarms often conflict with industrial fisheries (e.g., tuna and swordfish) as the longline is impossible within and around the FOWF, and trawling should be avoided for safety reasons. Windfarms can be managed to reduce overfishing [136,147,148] and to increase the Catch per Unit Effort (CPUE) for the black seabream and the Atlantic cod [132,133,149] suggesting that is feasible to conjugate fisheries and FOWFs [150]. However, this is not always possible [151], indeed neutral or positive responses by fishermen to OWFs are also reported [152].

Potential impacts on marine mammals and large migratory species - Two potential sources of impact on marine mammals and large vertebrates should be taken into account: i) noise and ii) risk of collision with the floating structures. Noise can affect the reproduction of marine mammals, the capacity to communicate, hearing prey and predatory species and feeding ability [153]. Marine mammals are sensitive to noise impact, especially during pile driving for OWFs (<120 dB only at a 100-m distance) and, to a lesser extent, during the operational phase [13]. Underwater noise of wind turbines is of low frequencies <1 kHz and intensity, considerably lower than ship noise [13,154], thus the balance between windfarm-induced noise and lack of ship noise could easily result in an overall positive effect (mitigation) of FOWFs on noise production. The noise impact on marine mammals is limited to the range frequency at which a marine mammal can detect the noise [13]. The "Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing" (V2 NOAA 2018) subdivides marine mammals into four groups. Outside the range of auditory impacts, the risk is considered highly unlikely or very low. Since all groups have a minimum level of hearing range significantly below 1 kHz, the expected impact of this frequency is expected to be low or negligible on most marine mammals, including those sensitive to low-frequencies, such as baleen whales (7 Hz–35 kHz), phocid pinnipeds (e.g., true seals; 50 Hz–86 kHz and otariid pinnipeds (e.g., sea lions and fur seals; 60 Hz-39 kHz). All other mammals and sea turtles have hearing ranges much higher and thus completely unaffected by low frequencies. The noise produced by the ship (100 dB, 63–125 Hz [155]) can impact mammals only during farm construction, but it excludes any fatal consequence. The larger the marine space occupied by wind farm area the higher the possibility of collision of large cetaceans with the floating systems, but this risk appears negligible when compared to the impact of collision with ships, one of the main causes of death of whales [156]. Again, limited ship traffic (or speed) in the FOWF area the more beneficial are the effects on the marine mammals. We conclude that the impact of FOWFs on marine mammals and migratory marine species is expected to be negligible [154,157] and that the possibility that FOWFs attract some cetaceans and pinnipeds out of curiosity [158] is not excluded, thus offering potential benefits for whale watching tourism.

3.3. Potential impacts on the seafloor and associated biodiversity

One of the main impacts of FOWFs on benthic habitats is represented by their mooring (i.e., chains and cables connecting the turbines to the anchors). Contrary to the gravity-based foundations, which might require intensive dredging activity [159] and cause physical destruction of the seafloor [159,160], FOWFs require a mooring system consisting of anchors (n = 2–4) deployed on the seafloor [161]. The use of dynamic anchors is based on the release of the anchors that penetrate the soft seabed; therefore, it does not need an external energy source or additional mechanical interaction with the seafloor [162]. The deployment of these anchors/deadweights can determine, along with the chain of connection to the turbine, impacts on deep-sea habitats. An intense, although localized, impact is expected during installation, especially when ships need anchoring for the works and can cause sediment resuspension as well as mechanical disturbance due to the displaced sediments. In addition, the anchors (e.g., the torpedo) might require the deposition of a trait of chain on the seafloor before the release of the anchor and its penetration in soft sediments. This could cause direct physical disturbance or contaminants' re-suspension into the water column and have the potential to clog the feeding apparatus of suspension-feeding organisms, such as bivalves, sponges, and sea squirts [163]. Considering that each turbine might require 2–4 anchors and that up to four turbines are deployed in an area of 1 km^2, the impact of anchoring on the seafloor is likely to be one of the most relevant direct physical impacts of FOWFs (e.g., the torpedo anchor is composed of an anchor head, an anchor rod, and anchor wings, with a length of 12–15 m, a diameter of 0.8–1.1 m, and a weight of 240–950 kN). Since anchors represent an additional hard substrate introduced on the bottom, they can be rapidly colonized by benthic fauna, including alien species. While this phenomenon was already studied for fixed OWFs [164], an investigation conducted on 41 structures, as well as the turbine substructures, mooring lines, suction anchors and infield cables reported 121 taxa of macrofauna and macroalgae are present on the submerged parts of FOWFs with anemones and polychaetes colonizing the mid-sections (80–20-m depth) of the turbines, while macroalgae and mussels dominate the upper portion [165]. Such zonation pattern was consistent among different structures and the hard substrates increased the colonization and reproduction of several taxa [166]. An additional effect of the floating systems is that biofouling colonizing the structure can cause trophic enrichment, potentially altering the structures [167,168]. Overall, the presence of the submerged part of the turbines and anchors in the open sea, especially for SPAR platforms, can increase the local relevance of hard bottom fauna [169] and potentially favor the spread of NIS [170]. This in turn can influence the local food webs and attract species preying upon these taxa. The biodeposition from the structures is expected to increase benthic biomass and biodiversity, and the anchors can facilitate the recruitment of deep-water corals and other vulnerable species.

3.4. Potential impacts of submarine power cables

Submarine power cables (SPCs) show a widespread distribution on the world's seafloor. Their total length is in the order of 10^6 km, but their impact on marine life and ecosystems is still largely underestimated [19]. We can identify three main effects of SPCs on marine ecosystems: 1) the physical damage on the seafloor; 2) the creation of a novel (hard) substrate available for colonization; 3) the generation of electromagnetic fields. Although SPCs connected to FOWFs can be partly suspended in the water column, they lay down on the seafloor. SPCs are often covered by sediment through a cutting wheel in rocky sediments and ploughing or water jetting in soft sediments. In other cases, rock-mattress covering, cable anchoring, ducting, cast-iron shells, concrete slabs, steel plates or dumped rocks can be used. Their impact on the seafloor can be exacerbated by the large ships used for their deployment, which use a considerable number of anchoring stabilizers and produce a plume of resuspended sediments (several dozen mg L^{-1} [19]). These plumes might affect pelagic fish eggs [171] and decrease megafaunal abundance along the sealine track [172], with negligible to long-lasting effects [172,173]. It is thus reasonable to assume that without dredging and sealine displacements no significant impacts can be detected. The use of mattresses or other materials, for sea-cable stabilization can cause physical damage and affect benthic life [174]. When a cable is deployed on a soft bottom, its displacement can cause a disturbance, and sediment resuspension that increases turbidity. Sealines create new hard substrates that are rapidly colonized by a variety of organisms. Although this can be seen as an alteration of habitat features, the ultimate effects are potentially positive for the local assemblages, contributing to enhancing the biomass and possibly creating refugia for some species. Previous studies explored the potential impact of the electromagnetic field (EMF) generated by the current flow passing through the sealine during the operational phase, which is composed of two components: electric and magnetic fields. SPCs can carry direct current (DC) or alternating current (AC) whose E-fields usually are confined within the armored cable [175]. However, AC cables showed a limitation due to power loss causing a reduction of the maximum transmission distance to less than 100 km [19]. Therefore, most of the SPCs used are DC [19]. EMFs are not always perceptible by marine species, for instance, eel's migration was not affected by EMFs due to SBP, while salmon smolt may be influenced [176] and some effects are apparent on the larval stages [177], with reduced swimming speed [16] and avoiding [178] are reported. Electric fields increase in strength as voltage increases and may reach 1000 μV m^{-1} [19], while the magnetic field can reach 5000 μT at the surface of the cable [179]. Elasmobranchs, for instance, can be attracted by electric fields generated by DC between 0.005 and 1 μV cm^{-1} and avoid electric fields >10 μV cm^{-1} [180,181]. Therefore, cable deployment can have an impact on this component, altering the shark's behavior and reducing their hunting or reproductive area [17]. Marine mammals also show magneto sensitivity, but, so far, there are no studies supporting the hypothesis of the effects of sealines on their migrations [17]. Many invertebrate taxa, such as mollusks and crustaceans, include magneto-sensitive species, but available studies reported no effects associated with sealines [179]. When electric energy is transported, a certain amount is lost as heat by the Joule effect, causing an increase in temperature at the cable surface. While cable warming can be mitigated by water and current on the SPC surface, in the case of the buried cable, the heat can propagate even at several tens of centimeters distance especially in the presence of cohesive sediment [19]. This can cause changes in the physical-chemical properties of the seafloor with consequences for the biological community, which can potentially show an increase in thermophilic species. However, these effects appear to be spatially limited and no direct evidence of impacts on the biological communities has been reported so far.

4. Criteria for a proper environmental impact assessment (EIA) of FOWFs

The construction of FOWFs, if not adequately planned in space, monitored and mitigated, could have non-negligible impacts on marine ecosystems and local economies. In many cases, the EIA is based on simple literature analysis, without fine-scale habitat mapping and that is insufficient to ascertain the potential impacts. The increasing availability of digital twin simulations could allow the definition of the scenarios of risk of FOWF operating in extreme conditions. In this regard, the climate and meteorology of the area should be preliminarily investigated and described, as well as the possibility of anomalous waves and their increase in frequency and intensity due to climate change.

To respect the *Do no Significant Harm* approach [25] a crucial step is represented by careful EIAs. This requires the development of an ecosystem-based approach in project planning, identification of appropriate sites and selection of the best available technologies. The main issues needed to make the FOWFs eco-compatible are: i) appropriate siting and identification of the most eco-compatible project design; ii) potential impacts *in fieri* (during construction), *post operam* (after the installation) and during the decommissioning phase; iii) cumulative impacts; iv) environmental monitoring plan; v) mitigation measures; vi) compensation measures (ecological restoration).

4.1. Appropriate siting and identification of the most eco-compatible project designs

The siting of offshore wind farms is based on three crucial steps: 1) the identification of profitable areas where wind energy is available; 2) the identification of sites where impacts should be excluded as protected areas and vulnerable habitats; 3) the identification of possible conflicts with other human uses of the sea space such as fishing areas and navigation corridors [89]. The development of alternative scenarios in the design of the FOWFs should provide a comparative analysis of the potential environmental impacts including anchoring, turbine technologies, modalities of construction, management during the operational phase and decommissioning. Alternative scenarios to be discussed with stakeholders should also compare different sealines tracks and the international regulation in terms of maritime law, as well as an appropriate distance from the shore to minimize or avoid any visual impact (whenever possible 40–50 km from the shore).

FOWF planning should examine the potential interactions with Areas protected by National and/or International Regulations, Critical habitats, Reserves and Natural Marine Parks, and other ecosystems of high ecological value/interest with a 3D approach and consider the potential effects in a large area of approximately 5 miles from the borders of the windfarm. The first environmental criterion for FOWF siting is certainly represented by their potential impacts on vulnerable habitats/ecosystems. Since FOWFs are expected to occupy large areas (even >1000 km^2), it is likely that large areas will include ecologically important habitats. For this reason, the highest priorities in the EIA study should be given to: i) habitat mapping, ii) routes of migratory species, iii) links with other marine ecosystems through connectivity (i.,e., Cells of Ecosystem Functioning CEFS) [27,89].

To avoid or minimize impacts, the first priority is habitat mapping requiring geo-referred ROV/AUV videos and accurate habitat description of the entire area, enabling the planning of the exact position for the deployment of the anchors to avoid the impact on bottom habitats. The ecological impact of anchor penetrating the sediments is expected to be negligible on soft bottoms without vulnerable megafaunal assemblages, but it can be relevant on soft bottoms hosting megafaunal assemblages or on hard bottoms. Therefore, the presence of vulnerable habitats must be assessed and carefully mapped at a high resolution (e.g., 1:1000). Fine-scale habitat mapping of deep-sea habitats will allow defining the exact location of the anchors and cables to avoid, whenever possible, any potential impact on valuable marine habitats. The second priority is the identification of the migratory routes of birds to assess the risks of collisions with the FOWF. The third priority is the assessment of the connectivity amongst deep-sea ecosystems, which according to the ecosystem approach should be considered also in the Maritime Spatial Planning (MSP). This would enable ecosystem mapping, considering the marine environment in four dimensions (the surface of the seafloor, the volume of water above it, and the timing of important ecological processes [22]) and would allow the understanding of the ecosystems of the FOWF area in a much wider maritime space. In this respect, specific software (e.g., MARXAN), largely used in the framework of spatial prioritization for conservation and maritime spatial planning, allows the combination of spatial information from different sources (from the wind chart to the information about connectivity) and the development of scenarios for the prioritization of FOWF areas co-optimized with other uses, accounting for ecological, social and economic objectives.

A new FOWF project needs to be coherent also with the national and international legislations and the regional environmental plans. The anchoring/mooring systems must be placed in safety zones forbidden to navigation, or where a minimum safety distance is defined. The presence of areas and sites of potential archaeological interest does not represent a problem *per se*, since once appropriately identified using magnetometric and other adequate analyses, it is possible to avoid anchoring in the areas of archaeological interest. In addition, the ban on trawling, which is certainly the main source of physical impact and the theft of archaeological artefacts, in the FOWF area would represent an added value.

The environmental phases of the project implementation should be detailed, identifying a study phase, a construction phase, an operational and a decommissioning phase. The anchoring and mooring methodologies should be defined *ex-ante* to guarantee the best environmental performance while ensuring the lowest ecological impact. Similarly, the sealines as well as the ballasts/mattresses eventually used to avoid their displacement must be installed on bottoms lacking vulnerable habitats, such as bioconstructions, seagrass meadows [62], and animal forests [155]. An additional value for making eco-compatible FOWFs is the identification of advanced technological solutions to avoid impacts on navigation safety and maritime transportation and consider the potential interference with boating activities.

4.2. Impacts on seabed stability and hydrodynamic conditions

Submarine landslides and seabed instability represent additional sources of uncertainty in a FOWF project. This requires appropriate measurements to exclude the possibility that the anchoring might trigger landslides or that the FOWF is vulnerable to episodic extreme events. Multibeam Echosounder and Sub-bottom Profiler can be used to create bathymetric maps, to characterize the seafloor morphology and the seismic hazard, as well as, additional factors, such as gas infiltrations. Accurate hydrodynamic studies are needed to detect the possible effect on water currents, including upwelling or downwelling phenomena. The hydro-morpho-dynamic and modelling assessments should be based on the most up-to-date, three-dimensional and validated modelling.

4.3. Presence of contaminants

Another component to investigate is the presence of any form of contamination of the seabed, including the presence of shipwrecks and/or munitions, since anchor deployment on contaminated sediments might cause their dispersal and transfer to the biota, their bioaccumulation and biomagnification.

4.4. Impacts on migratory and sedentary species

To address this aspect, *in-situ* data should be acquired for all migratory species: i) cetaceans and other large vertebrates (e.g., marine turtles), ii) birds and chiropters. The assessments should be conducted with *ad hoc* surveys of appropriate duration and frequency. Data on flight height are needed to assess the probability of collision [191]. The presence of species foraging in the areas must be carefully considered to avoid the stress of dislocation.

4.5. Impacts on biodiversity and ecosystem services

Monitoring of NIS in floating structures and deep seafloor is needed to prevent/monitor the spread of such species. The presence of endangered/protected species can be monitored using georeferenced HD video/imaging (ROVs/AUVs). Non-destructive approaches are always preferred to avoid habitat damage, but the collection of macrofaunal samples (box-corers/multi-corers) is needed on soft bottoms to monitor benthic biodiversity. Fish biomass including species of commercial interest is a key requisite for the monitoring along with recruitment dynamics of pelagic species (along with physical-oceanography data), to design a connectivity landscape.

4.6. Cumulative impact assessment and conflicting activities

The spatial expansion of offshore renewables is causing a widespread debate regarding local and cumulative environmental and socio-economic effects on other human activities [182], which can lead to substantial delays during the permitting process [20]. For this reason, a detailed analysis of the outcomes of cumulative impacts is a priority in the permission procedures. The analysis of cumulative impacts of FOWFs must include all possible interactions, namely: i) fishing activities (either bottom-contact and pelagic fisheries); ii) presence of oil and gas (or other resource exploitation) platforms and position of existing sealines; iii) proximity to the shore for tourism and boating; iv) proximity to other OWFs; v) combination of FOWFs with floating photovoltaic panels; vi) association of FOWFs with aquaculture activities; vii) interactions with maritime transportation, navigation and traffic; vii) interaction with touristic activities; ix) presence of cables/sealines (e.g., telecommunications). The analysis of cumulative impacts derived from the spatial overlap of multiple human uses and including the vulnerability of habitats should be conducted in a wide area of 10 km distance from the boundary of the FOWF area and along the corridor of the sealine connecting the wind farm to the shore, possibly comprised within a Cell of Ecosystem Functioning. The most common interaction between FOWFs and the use of maritime space is related to ship traffic, which in the presence of FOWFs should be reduced, except in potential corridors, but could concentrate in adjacent areas. The co-location of FOWFs and oil and gas platforms in the same area requires a careful assessment of the potential cumulative effects and interferences. One of the most concerning cumulative impacts is with the fishing sector, which if not prohibited in the FOWF area can cumulate the impacts of fisheries and generate overfishing in the area showing an increase in biomass [136,182–184]. To reduce the conflicts created by the interactions between FOWFs and fisheries, in some cases it has been proposed, within the framework of MSP, the segregation of OWFs and fishing areas [182,185], which however, might increase the costs of fishing displacement to other areas. Some wind farm areas could produce effects similar to those of the military areas [186]. Yet, offshore aquaculture in FOWF areas is possible [187] for seaweeds and bivalves, which produce negligible impacts [188,189], while intensive aquaculture could cause more significant impacts [190].

The installation of FOWFs in close proximity to navigation corridors is a potential source of conflict which deserves careful spatial planning. It is evident that international routes must remain free for navigation, and it is strictly necessary for an international collaboration among states to manage maritime traffic. FOWF siting should thus not only exclude international navigation corridors but also consider the proximity of the FOWFs to such areas. In fact, here, vessel traffic will be increased by the boats used for FOWF maintenance operations and this could increase the collision risk with other ships. This is of particular importance in the light of increase in the ship size, which will increase the risk of collision with OWFs and with the maintenance boats. The navigation in the area covered by FOWFs must be done following the IMO (i.e., International Maritime Organization) guidelines contained in "*Ships' Routing*", which recommends "*improve the safety of navigation in converging areas and in areas where the density of traffic is great or where freedom of movement of shipping is inhibited by restricted space, the existence of obstructions to navigation, limited depths or unfavorable meteorological conditions*". These guidelines include traffic separation schemes, traffic lanes, separation zones or lines, recommended routes, precautionary areas and areas to be avoided.

5. Environmental monitoring plan (EMP)

The EMP should include all ecosystem components illustrated in the previous paragraphs and should cover the entire wind farm area and the sealine. The plan should incorporate the comprehensive ecological descriptors of the Marine Strategy Framework Directive [26], which include: i) biodiversity and the presence/spread of NIS, ii) the presence and of marine mammals and large vertebrates, iii) the stocks of species of commercial interest and the local food webs, iii) changes in primary production, iv) seafloor/benthic habitat integrity, v) changes in hydrographic conditions; vi) contaminants (either sediments and biota); vii) marine litter; vii) noise. The EMP should also include: 1) migration/foraging of birds and chiropters; 2) turbine-induced mortality of migratory species; 3) presence of sedentary sea birds.

The monitoring activities should start at least 12 months before wind farm construction and be carried out throughout its entire lifespan, with intensification during the construction phase. The need to shift from sporadic monitoring to an observation strategy is widely recognized [211] as observation systems allow non-invasive, cost-effective and high-frequency long-term monitoring. A BACI sampling design (i.e., Before *vs* After, Control *vs* Impact) or ACI (i.e., After Control *vs* Impact) design are the most used sampling designs for environmental impact assessment but are based on some assumptions: i) suitable multiple controls should be found (i.e., same ecological and physical characteristics, but far enough to be unaffected by the FOWF); ii) the area within the wind farm is homogeneous [212]. A BAG design (i.e., Before *vs* After Gradient) can solve these constraints allowing the identification of the spatial scales of windfarm effects and improving the statistical power of the analysis by incorporating "distance" as an independent variable in analytical models [212,213].

The consistency of methodology used in all phases and consistent with the available literature for a larger area. The monitoring-observation of the impacts should be based on samplings carried out on a seasonal basis (4 times on a yearly basis) and, if any impact is detected, it has to be intensified to identify the most suitable compensation actions. An overview of the key components of interest in the definition of the EIA is reported in Fig. 4.

6. Life cycle assessment (LCA) and decommissioning of the wind farms

While the impact of the energy produced by wind farms is close to zero (no direct emission of CO_2 or other pollutants), the impact of raw material acquisition and the construction of the turbines, floating structures and sealines might not be negligible. The most required materials are steel and concrete, which can determine environmental impacts during the production phase. Moreover, relying on floating structures at a relevant distance from the shore increases the material demand, the potential impacts of the installation phase, and requires more complex infrastructures for the transmission of the generated electricity. The Life Cycle Assessment (LCA) is a technique to evaluate the potential environmental impacts (air, water, and soil emissions), material and energy consumption of products, processes, and activities (ISO 14040-44 standards [192,193]). LCA is the most comprehensive methodology since it includes all stages of energy production (with the so-called *cradle-to-grave* approach) and several impact categories encompassing the most relevant environmental impacts. LCA studies performed on both onshore and offshore wind farms have been mainly focused on the evaluation of Global Warming Potential (GWP [194,196,197]), comparing different construction materials [198] or end-of-life treatment options [199]. GWP values show great variability depending on site characteristics, capacity factor and wind conditions [200]. In

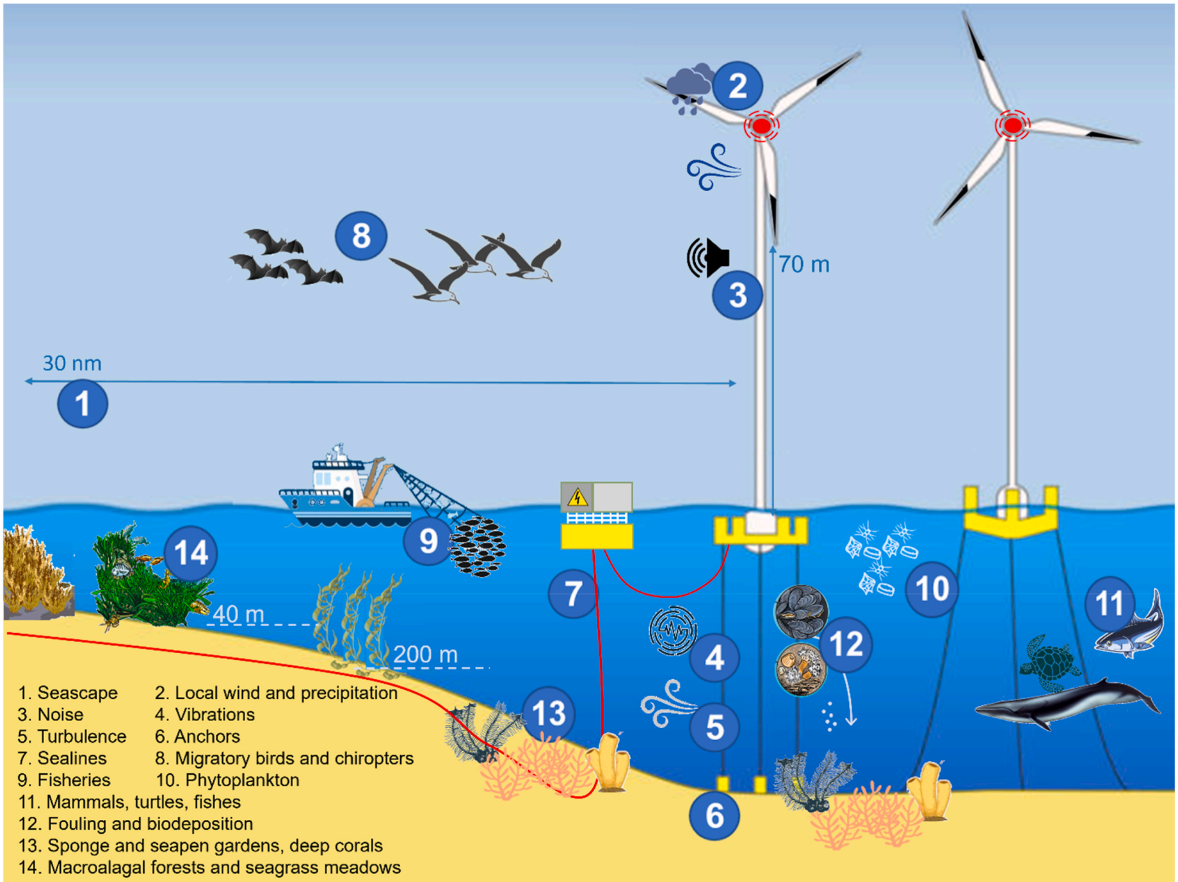

Fig. 4. Illustration of the interactions of floating offshore wind farms and cables connecting to the shore with all environmental components to be considered for a rigorous Environmental Impact Assessment.

addition, the impact assessment of the installation activities should include the vessel operations and the wind farm maintenance during the operational life, both in terms of spare parts and transport operations [201,202]. Comprehensive LCA studies on FOWF are still limited [201, 203–206], but a recent case study (FOWF of 3 GW in the Mediterranean Sea), using 15 MW turbines indicated that the acquisition of raw materials, either floaters and turbine structures determined the largest potential impacts for all categories (apart from the abiotic depletion category in which the materials for the power cables, such as copper, covered more than half of the overall potential impacts [207]). A clear reduction of the environmental burdens was observed when comparing with the current energy mix for all impact categories but one, i.e., the abiotic depletion, and this is related to the huge amounts of materials required for the construction of components. The design stage allows for reducing the impacts and selecting the less-impacting alternatives. However, since the LCA studies strongly depend on several key assumptions, such as system boundaries, cut-off rules, modelling approach, allocation rules, and impact categories, there is a need to define a common framework and specific rules to avoid discrepancies in LCA limiting their efficacy in decision support [208].

An LCA is needed also for planning FOWF decommissioning. The floating structures, as well as the chains connecting the floating structures to the mooring system, can be removed and recycled on land, while the anchors can be designed to operate, and modules which have been eventually colonized by vulnerable species, and supporting the biodiversity recovery, can be eventually left *in situ*, after authorization, at the end of the wind farm life (see below for mitigation and compensation measures). Such structures are deterrents for trawling and fishing, with long-term positive ecological effects as indicated by fish abundance detected by acoustic telemetry in comparison with control areas where OWFs are not present [136,147]. Decommissioning is one of the most impacting activities within the FOWF lifespan and must be adequately planned, mitigated and compensated [209,210]. The decommissioning plan should include: 1) the methodology selected for the removal of the structures, also considering the possible presence of habitats created at the base of the structures themselves; 2) ecosystem restoration interventions for all marine areas/habitats damaged by the anchoring or during the decommissioning; 3) cost-benefit analyses for all different available options; 4) the schedule and resource allocation.

7. Mitigation measures

The operational hierarchy routinely utilized in EIA consists of avoiding, minimizing, and mitigating. Whilst there are a variety of technical measures used to address specific environmental impacts, avoiding impacts is the most effective option and needs to be thoroughly programmed in strategic planning processes. Potentially adverse, even minimal, impacts may occur during the project lifetime but can be negligible if appropriate mitigation measures are adopted for the different project phases (materials and manufacturing; transport and assembly; installation; operation and maintenance; and decommissioning and disposal). Mitigation interventions must be defined during the preliminary phase of the project but can be implemented if needed during the project lifespan.

Mitigation measures for the impact of anchoring - Mitigation measures for the ballast and anchor impact, with specific attention to both their deployment in deep environments and sealine track, should be included. The impact of anchoring can be mitigated by: 1) selecting soft bottoms lacking vulnerable biota for the location/penetration of the anchors; 2) avoiding or minimizing the deposition of the connecting chain during the deployment of the anchor; 3) using tense or semi-tense chains in such a way as to limit occupation and damage to benthic habitats only to ballast alone.

Mitigation measures for the sealines - The most important mitigation measure for sealines is avoiding the crossing of any vulnerable habitat both in the deep sea and in shallower areas. Cable burial could mitigate the impact of electromagnetic fields associated with the pipelines. If possible, cable burying should be done at depths greater than 1 m. Burial can also limit the shifts of the cable which can move for dozens of meters under some conditions, thus damaging the adjacent benthic habitats, but the impact of sediment resuspension for its burial should be even more relevant, albeit temporary, so that this measure should be carefully evaluated in terms of costs and benefits. Generally, the use of matrasses to stabilize or protect the cables should be preferred to minimize these effects. In the project planning, the cables connecting all turbines should be connected to a single cable (or to the minimum number of cables) before getting in contact with the seafloor, so that the potential impact on the benthic habitats is minimized. If more sealines are needed, these should be in the closest possible proximity to the installation. Avoidance/mitigation measures are particularly relevant in the deployment phase, during which the vessel is stabilized using several anchors that might cause an important physical disturbance to benthic habitats. In this case, the most appropriate mitigation measures consist in the identification, through a high-definition habitat mapping, of the exact location of the areas where the anchors can be placed. These areas must be identified during the project phase, since the ships that will perform the decommissioning should be placed near the installation. The sealine track should, as far as possible, avoid crossing over rocky bottoms and seagrass meadows. If this is not possible, the passage across vegetated habitats can be mitigated using a tailored trenching which is subsequently covered by the seagrass meadow leaving the cable under the seagrass [214]. Another useful mitigation is avoiding the deployment of sealines during the migration period of marine mammals or the nesting of sea turtles [19].

Mitigation measures for migratory birds and bats - Currently utilized mitigation strategies include permanent and operational measures. Among the permanent mitigations, the increase of hub height and a larger inter-distance among wind turbines can avoid bird collisions (most species fly at height <70 m [110]). The use of flashing lights marking their location is also suggested instead of steady red lights to allow the detection of the aerogenerators by birds even at night. Permanent deterrents include also painting with ultraviolet reflecting colors, which can also be applied to the tower and blades [215] as it is already done for inshore windfarms. The black painting of one of the rotor blades is very effective in reducing the visual effect of motion smear [216]. Another mitigation measure for bats could be the installation of acoustic deterrent devices (ADD), which have been successfully utilized in terrestrial windfarms, with a reduction of bat fatalities >50% in the ADD-equipped turbines [217]. The use of these devices in offshore windfarms is still limited [218], but there is a large potential to exploit in offshore windfarms the positive results obtained from the terrestrial experience [29,219]. A mitigation measure for seasonal birds is avoiding the construction in sensitive periods. Mitigation measures for reducing bird collision risks during the operational phase include: i) stopping the rotors during bird migration; ii) temporary shutdown in reproductive season or some hours of the day [215]; iii) temporary shutdown of the rotors once a radar (or a thermo-scanner) system detects the approach of the flock; iv) use of deterrents (visual or audible) activated by a bird-detection radar system. Any further technological innovation aimed at reducing the impacts on fauna is encouraged. Technologies enabling the detection of birds, or their deterrence will be implemented in the future. It is also possible to equip the turbines with drone-carrying acoustic devices which can move emitting changing signals thus decreasing the probability of habituation [220]. In any case, FOWF impact on bats is expected to be negligible, due to their height of flight (<40 m, while the lowest height of the blades is ca. 70 m).

Mitigation measures for fisheries and socio-economic activities - Fishing activities are typically forbidden in FOWF areas. This can have important benefits in terms of recovery of the commercial species, and the “fishery restricted windfarm areas” can protect several fish species (including elasmobranchs) as well as macro- and megafauna, whose species sensitive to trawling activities showed a recovery [221]. The recovery effects might require a long time (i.e., decades) to be appreciable, and appropriate reference areas are needed to be quantified. Therefore, the use of a BACI or a BAG (Before–After-Gradient) design in the monitoring programs is highly recommended [221]. Despite this, the effects on species diversity, and abundance are not always relevant [222, 223]. The fishery restriction can benefit fishing activities in neighboring areas (through spillover effects) but can concentrate trawling and other fishing practices in the surrounding wind farms. The development of offshore aquaculture activities associated with the farm can mitigate the reduced fishery areas and the socio-economic impact of the FOWFs [187]. FOWF areas can include corridors for the navigation of fishing vessels allowing them to target dislocated working areas.

The development of FOWFs might locally affect fishing activities with potential economic loss linked to an increase of the operational costs driven by the need to find other suitable fishing areas or a temporary decrease in fishing catches leading, ultimately, to a reduction of job opportunities in this sector. However, the re-employment of the fisherman into the new jobs created by FOWF installation, maintenance and routine operation should be highly considered [202]. The Global Wind Energy Council in 2021 estimated that 3.3 million jobs worldwide could be created by the offshore wind farm sector by 2026 (data from the International Renewable Energy Agency) and in the US it is projected to support approximately 201,000 to 265,000 jobs by 2030 and 526,000 to 670,000 jobs by 2050 [202]. In addition, future FOWFs might be associated with the development of offshore integrated aquaculture, which is expected to be far more sustainable in open waters and that can profit from the sharing of infrastructures and vessels’ supply from the FOWFs. Since aquaculture is a largely expanding field with important employment opportunities, this could be a potentially relevant activity for the conversion of the classical fishery into a more sustainable productive sector. Another economic sector that could benefit from the FOWF development is tourism, with an increasing tourism flow and especially a growing interest in eco-sustainable tourism activities [2]. All these activities might offer alternative employment to the fisherman. Wind power technology needs continued improvement and implementation, which can be highly beneficial for the development of the technology industry, with a consequent increased opportunity for investments and employment. Overall, the development of wind energy industries can determine not only environmental benefits but it has also the potential to increase the local economy.

Mitigation measures for marine mammals - The reduction of navigation speed in the proximity of the FOWFs is the most relevant mitigation measure for marine mammals [224], as at <10 knots accidents become negligible [225]. Another measure during the construction phase is the surveillance of marine mammals by Marine Mammal Observers (MMOs). The surveillance can be enforced with passive acoustic monitoring (hydrophones), which detect the vocalizing mammals [226]. Another measure is the “soft start”, which is the progressive adaptation of the system to the operational phase to allow mammals to adapt to the wind farm [227]. Reducing noise during construction activities is important, especially during sensitive seasons (breeding, feeding), which can be obtained using electric vessels or suspending construction activities. The most critical step is likely the construction phase, whose impact is temporarily limited, and 1 h after the completion of the pile driving, a reduction of 100% of the noise (detected by a passive acoustic monitoring device) is reported at a 2 km distance [228]. The impact of noise and vibrations in the operational phase is negligible and does not require mitigation measures. The risk of mammals’ collision with the floating structures is unknown, but a possible mitigation is avoiding the presence of sharp structures. The use of sonar deterrents should be carefully evaluated [229]. Also, the presence of corridors could reduce the risk of collision. A summary of the mitigation measures for the different components of interest is reported in Table 2.

8. Compensation measures and ecological restoration

When the mitigation actions are insufficient and the DNSH principle cannot be respected, or in case of unexpected accidents or in case of residual unexpected impacts, a compensation plan should be planned. This does not mean financial compensation but, rather, the definition of restoration actions able to recover ecological integrity and the biodiversity of the impacted area. Compensation measures should be planned in all projects, including those expected to avoid any significant impact and tailored for the deep-sea or mesophotic habitats of interest in the windfarm area.

Cold-water corals and other sessile organisms (gorgonians, sea pens, sponge fields) are the most vulnerable deep-sea components that can be damaged by FOWFs (particularly by anchoring). The restoration of cold-water corals and other sessile species can be carried out either by transplant of deep-coral fragments from donor colonies or through the deployment of 3D artificial structures that can facilitate their recruitment [28].

The ecological restoration must be carried out according to the criteria and methods of Restoration Ecology (Society for Ecological Restoration) [28]. Restoration activities can be needed also for the impact of sealines (e.g., seagrass restoration by replanting or transplanting or the reintroduction of damaged macroalgal forests [82]). The compensation intervention can be carried out even outside the FOWF area and can include the reintroduction/restocking of endangered species, the creation of nurseries and/or restoration of impacted habitats in nearby areas, when feasible. When the compensation for a loss of a specific component is actually impossible, compensation actions can be performed on different species from those impacted, but still of high ecological interest. Additional compensation actions consist of the removal of abandoned infrastructures, marine litter etc. The restoration conducted after decommissioning can exploit the biodiversity colonizing the FOWF structures [230], including deep-water corals, gorgonians etc. [231], which can be eventually transplanted or relocated thought the use of artificial substrates [232]. Other possible socio-economic compensations are using the FOWF for eco-tourism boating or diving around artificial reefs and turbine foundations to attract tourists [233] or developing aquaculture plants, floating photovoltaic power plants, associated with the FOWFs. A summary of the compensation measures for the different components of interest is reported in Table 3.

8.1. Coupling renewable energy production with environmental protection

The Agenda 2030 of the UN sets a target of protecting 30% of marine areas by 2030. Offshore wind farms, if properly managed with an ecosystem-based approach, may contribute to this target. Protecting FOWF areas from any external impact can lead to Other Effective Area-based Conservation Measures (OECM) where conservation is achieved mainly as a by-product of management. Given the FOWF size (1000 km^2 or more) they can contribute significantly to expanding marine protected areas (MPAs). MPAs are designed to protect biodiversity following the principles of ecological coherence (IUCN 2019 [234]), while OECM are designated in FOWF areas thus largely excluding ecologically relevant habitats [21], yet they might contain some vulnerable habitats thus contributing to their protection. Moreover, FOWFs in degraded areas can have beneficial effects as passive restoration tools. FOWF can contribute to expanding protection targets in 3D, which is rarely the case for most MPAs, yet the efficacy of FOWFs is OECM should be determined case by case with a holistic and integrated approach [235,236].

Table 2
Summary of the mitigation measures for the different components of interest.

Typology of mitigation measures	Description
Mitigation measures for the impact of anchoring	Selecting soft bottoms lacking vulnerable biota for the location/penetration of the anchors
	Avoiding or minimizing the deposition of the connecting chain during the deployment of the anchor
	Using tense or semi-tense chains in such a way as to limit occupation and damage to benthic habitats only to ballast alone
Mitigation measures for the sealines	Avoiding the crossing of any vulnerable habitat both in the deep sea and in shallower areas
	Cables burying at depths greater than 1 m
	Use of matrasses to stabilize or protect the cables
	The cable passage across vegetated habitats can be mitigated using a tailored trenching which is subsequently covered by the seagrass meadow leaving the cable under the seagrass
	Avoiding the deployment of the sealines, during the migration period of marine mammals or the nesting of sea turtles
Mitigation measures for migratory birds and bats	Use of flashing lights
	Painting parts of the towers and of the blades with ultraviolet reflecting colors
	Black Paint for at least one of the rotor blades
	Installation of acoustic deterrent devices
	Radar system to stop the rotors during bird migration
	Temporary shutdown in reproductive season or some hours of the days
	Temporary shutdown of the rotors once a radar system detects the approach of flock
	Use of deterrents (visual or audible) activated by a bird-detection radar system
Mitigation measures for fisheries and socio-economic activities	Planning the development of aquaculture activities associated with the farm and sharing facilities created by the farms for the fishermen so reducing the costs of offshore aquaculture management
	Create corridor for fishing vessels to reach target working area
Mitigation activities for marine mammals and species sensitive to noise and vibrations	Install FOWF outside their feeding (e.g., including active canyons with deep-water upwellings) or reproduction grounds
	Reduction of the speed of the vessels in proximity of the FOWFs
	Surveillance of the presence of marine mammals by Marine Mammal Observers (MMOs), trained to detect the presence of individuals and stopping temporarily the activities till the complete transition to a safe area
	The application of the “soft start”, which consists in the progressive adaptation of the system to the operational phase to allow resident mammals to adapt to the new conditions
	Suspension of noise generating construction activities during biologically sensitive seasons such as breeding or feeding periods of relevant species. Such restrictions can be adopted also for maintenance works and can include the use of vessels with effective noise reduction strategies
	Use of bubble curtains to reduce the levels of noise emitted during construction
	Covering the floating system with soft material, avoiding the presence of sharp structures that could injury the mammals during their transit
	Open corridors among the turbines able to minimize the possibility of collision

Table 3
Summary of the compensation measures for the different components of interest.

Typology of compensation measures	Description
Passive restoration	Protect the marine ecosystems within the wind farm areas to enhance natural recovery
Active restoration	Increasing of the rugosity of mined substrata to promote larval settlement
	Rearing and transplant of nubbins of deep corals
	Electrified artificial reefs to enhance survival/growth/recruitment rate of Cold-Water Corals
	Recruitment of larvae in shallow depths and translocation in deeper areas
	Transplanting fragments from donor colonies
	Deployment of hard artificial substrata
	Addition of artificial sponges to enhance recruitment of associated fauna
	3D structures for the recruitment and/or transplant of colonial organisms
	Replanting or transplanting seagrasses or other ecologically in the area interested by the sea cables reaching the shore
	Re-introduction of algal forests
	Collection of the precious and ecologically relevant organisms colonizing the anchors or other infrastructures *in situ* and transplanting these organisms in suitable habitats for re-populating regions damaged by human activities
Restocking of target species of commercial interest	Restocking of endangered species
	Creation of nurseries and/or restoration of impacted habitats in nearby areas
	Creation of aquaculture systems able to reproduce or maintain the target species of restoration
Environmental Cleaning	Removal of abandoned infrastructures
	Removal of marine litter and ghost nets
Green-House Gases (GHG) compensation	Offsetting of unavoidable GHGs by local initiatives in climate protection measures and Voluntary Emission Reduction projects, developed according to international standards and favouring investment in local climate contributions
Socio-economic compensations	Use the FOWFs for recreational activities such as observational boating or diving attracting a new type of tourists
	Use of FOWFs for the development of integrated aquaculture plants
	Associating FOWFs with photovoltaic power plants
	Using vessels for FOWFs commuting to support personnel involved in intensive or extensive offshore aquaculture in proximity of the wind farm.
	Economic compensation for the decrease in fishery yield if observed based on the historical data for the same area

9. Conclusions

FOWFs represent a game changer in the production of renewable energy worldwide and are expected to increase significantly in the future, covering wider portions of the oceans. All FOWFs in the future should be subjected to an EIA procedure and, standardized criteria to assess and reduce their potential impact on the marine environment are desired.

The available information summarized here shows that the impact of FOWFs can be minimized or avoided depending on their design, siting and available knowledge. Floating offshore farms are anchored on the deep seafloor and detailed deep-sea habitat mappings (e.g., spatial distribution of VMEs, critical habitats and IUCN endangered species) would allow an acceleration of the permitting process. FOWF implementation will be also an opportunity to improve our knowledge of offshore and deep-sea habitats. The mitigation measures already available, if carefully planned and implemented, can make the impacts of FOWFs negligible on migratory species, while at the same time providing potentially positive effects on fisheries and biodiversity. FOWFs, if adequately managed as OECM, can also contribute to the achievement of conservation targets.

The "Energy transition" is certainly one of the most urgent challenges at a global scale. At the same time, the provisioning of food is becoming of crucial importance in the coming years. From this perspective, the combination of FOWFs with aquaculture farms seems to be a promising approach that can bring economic advantage to both sectors. In addition, anchors can act as substrates for cold-water corals and other protected or vulnerable species, and future studies could explore the potential use of these newly recruited corals for the restoration of degraded habitats. Nonetheless, this review highlights the presence of important knowledge gaps and limitations that require dedicated research in the future. One of the most relevant either in terms of the costs associated and the time needed to cope with the gap is the limited knowledge we have about deep-sea ecosystems, particularly in terms of habitat mapping (over large areas often in the order of 1000 km^2) needed to locate the vulnerable habitats to be avoided by FOWF anchoring. This, together with the time needed for the construction and deployment of the turbines is the most time-consuming phase, which might slow down the permitting process. FOWFs association with offshore aquaculture plants seems to be a promising approach but their potential interference should be carefully assessed. The analysis of the effectiveness of the OECM in protecting marine biodiversity while, at the same time restocking fisheries is another crucial topic to explore, either for the actual achievement of the protection targets of the UN Agenda 2030 (protecting 30% of the ocean) and for the expected positive effects on the fish restocking.

Future research needs include the development of new sensors and technologies that will expand our ability to avoid any collision with migratory species, to recycle all FOWF components, and restore deep-sea ecosystems accidently impacted or during FOWF installation or decommissioning.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Roberto Danovaro reports financial support was provided by National Biodiversity Future Centre.

Data availability

No data was used for the research described in the article.

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References

[1] Wilding TA, Gill AB, Boon A, Sheehan E, Dauvin JC, Pezy JP, et al. Turning off the DRIP ('Data-rich, information-poor')– rationalising monitoring with a focus on marine renewable energy developments and the benthos. Renew Sustain Energy Rev 2017;74:848–59. https://doi.org/10.1016/j.rser.2017.03.013.
[2] Soares-Ramos EP, de Oliveira-Assis L, Sarrias-Mena R, Fernández-Ramírez LM. Current status and future trends of offshore wind power in Europe. Energy 2020; 202:117787. https://doi.org/10.1016/j.energy.2020.117787.

[3] Telsnig T. Wind energy - technology development report 2020, EUR 30503 EN. ISBN 978-92-76-27273-1 (online),978-92-76-27272-4 (print). Luxembourg: Publications Office of the European Union; 2020. https://doi.org/10.2760/742137 (online),10.2760/425873 (print), JRC123138.
[4] Nielsen FG. Perspectives and challenges related offshore wind turbines in deep water. Energies 2022;15(8):2844. https://doi.org/10.3390/en15082844.
[5] Glasson J, Durning B, Welch K, Olorundami T. The local socio-economic impacts of offshore wind farms. Environ Impact Assess Rev 2022;95:106783. https://doi.org/10.1016/j.eiar.2022.106783.
[6] Díaz H, Soares CG. Review of the current status, technology and future trends of offshore wind farms. Ocean Eng 2020;209:107381. https://doi.org/10.1016/j.oceaneng.2020.107381.
[7] Castro-Santos L, Bento AR, Silva D, Salvação N, Guedes Soares C. Economic feasibility of floating offshore wind farms in the north of Spain. J Mar Sci Eng 2020;8(1):58. https://doi.org/10.3390/jmse8010058.
[8] Sclavounos P, Tracy C, Lee S. Floating offshore wind turbines: responses in a seastate pareto optimal designs and economic assessment. In: International Conference on offshore Mechanics and Arctic engineering; 2008. p. 31–41. 48234.
[9] Musial W, Butterfield S. *Future for offshore wind energy in the United States* (No. NREL/CP-500-36313). Golden, CO (US): National Renewable Energy Lab.; 2004.
[10] Philipp B, Musial W, Duffy P, Cooperman A, Shields M, Heimiller D, Optis M. The cost of floating offshore wind energy in California between 2019 and 2032. Golden, CO: National Renewable Energy Laboratory; 2020. NREL/TP-5000-77384, https://www.nrel.gov/docs/fy21osti/77384.pdf.
[11] Cermelli C. Windfloat: a floating foundation for offshore wind turbines. Part II: hydrodynamics analysis. ASME 28th international conference on ocean, offshore and arctic engineering (OMAE2009) 2009;1:1–9.
[12] Myhr A, Bjerkseter C, Ågotnes A, Nygaard TA. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. Ren energy 2014;66: 714–28. https://doi.org/10.1016/j.renene.2014.01.017.
[13] Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack AP. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. Mar Ecol Prog Ser 2006;309:279–95. https://doi.org/10.3354/meps309279.
[14] Thomsen F, Lüdemann K, Kafemann R, Piper W. Effects of offshore wind farm noise on marine mammals and fish, vol. 62. Biola, Hamburg, Germany on behalf of COWRIE Ltd; 2006.
[15] Bailey H, Brookes KL, Thompson PM. Assessing environmental impacts of offshore wind farms: lessons learned and recommendations for the future. Aquat Biosyst 2014;10(1):1–13. https://doi.org/10.1186/2046-9063-10-8.
[16] Westerberg H, Lagenfelt I. Sub-sea power cables and the migration behavior of the European eel. Fish Manag Ecol 2008;15(5-6):369–75. https://doi.org/10.1111/j.1365-2400.2008.00630.x.
[17] Tricas T, Gill AB. Effects of EMFs from undersea power cables on elasmobranchs and other marine species. U.S. Dept. Of the interior, bureau of ocean energy management, regulation, and enforcement, pacific OCS region. Camarillo, CA: OCS Study BOEMRE 2011-09; 2011.
[18] Gill AB, Gloyne-Philips I, Kimber J, Sigray P. Marine renewable energy, electromagnetic (EM) fields and EM-sensitive animals. In: Marine renewable energy technology and environmental interactions. Dordrecht: Springer; 2014. p. 61–79.
[19] Taormina B, Bald J, Want A, Thouzeau G, Lejart M, Desroy N, Carlier A. A review of potential impacts of submarine power cables on the marine environment: knowledge gaps, recommendations and future directions. Renew Sustain Energy Rev 2018;96:380–91. https://doi.org/10.1016/j.rser.2018.07.026.
[20] Galparsoro I, Menchaca I, Garmendia JM, Borja Á, Maldonado AD, Iglesias G, Bald J. Reviewing the ecological impacts of offshore wind farms. Sustain Ocean 2022;1(1):1. https://doi.org/10.1038/s44183-022-00003-5.
[21] Lloret J, Turiel A, Solé J, Berdalet E, Sabatés A, Olivares A, Gili JM, Vila-Subirós J, Sardá R. Unravelling the ecological impacts of large-scale offshore wind farms in the Mediterranean Sea. Sci Total Environ 2022;824:153803. https://doi.org/10.1016/j.scitotenv.2022.153803.
[22] Boero F, Cummins V, Gault J, Huse G, Philippart C, Schneider R, et al. Navigating the future V: marine science for a sustainable future. Position paper of the European Marine Board, Ostend, Belgium 2019;(24):1–89. https://doi.org/10.5281/zenodo.2809392. ISBN: 9789492043.
[23] Ramirez-Llodra E, Brandt A, Danovaro R, De Mol B, Escobar E, German CR, et al. Deep, diverse and definitely different: unique attributes of the world's largest ecosystem. Biogeosciences 2010;7(9):2851–99. https://doi.org/10.5194/bg-7-2851-2010.
[24] Danovaro R, Snelgrove PV, Tyler P. Challenging the paradigms of deep-sea ecology. Trends Ecol Evol 2014;29(8):465–75. https://doi.org/10.1016/j.tree.2014.06.002.
[25] Dusík J, Bond A. Environmental assessments and sustainable finance frameworks: will the EU Taxonomy change the mindset over the contribution of EIA to sustainable development? Impact Assess Proj Apprais 2022;40(2):90–8. https://doi.org/10.1080/14615517.2022.2027609.
[26] Danovaro R, Aguzzi J, Fanelli E, Billett D, Gjerde K, Jamieson A, et al. An ecosystem-based deep-ocean strategy. Science 2017;355(6324):452–4. https://doi.org/10.1126/science.aah7178.
[27] deCastro M, Salvador S, Gómez-Gesteira M, Costoya X, Carvalho D, Sanz-Larruga FJ, Gimeno L. Europe, China and the United States: three different approaches to the development of offshore wind energy. Renew Sustain Energy Rev 2019;109:55–70. https://doi.org/10.1016/j.rser.2019.04.025.
[28] Da Ros Z, Dell'Anno A, Morato T, Sweetman AK, Carreiro-Silva M, Smith CJ, et al. The deep sea: the new frontier for ecological restoration. Mar Pol 2019;108: 103642. https://doi.org/10.1016/j.marpol.2019.103642.
[29] Solick DI, Newman CM. Oceanic records of North American bats and implications for offshore wind energy development in the United States. Ecol Evol 2021;11 (21):14433–47. https://doi.org/10.1002/ece3.8175.
[30] Macrander AM, Brzuzy L, Raghukumar K, Preziosi D, Jones C. Convergence of emerging technologies: development of a risk-based paradigm for marine mammal monitoring for offshore wind energy operations. Integrated Environ Assess Manag 2021;18(4):939–49. https://doi.org/10.1002/ieam.4532.
[31] Gori A, Reynaud S, Orejas C, Gili JM, Ferrier-Pagès C. Physiological performance of the cold-water coral *Dendrophyllia cornigera* reveals its preference for temperate environments. Coral Reefs 2014;33:665–74. https://doi.org/10.1007/s00338-014-1167-9.
[32] Fossheim M, Primicerio R. Habitat choice by marine zooplankton in a high-latitude ecosystem. Mar Ecol: Prog Ser 2008;364:47–56. https://doi.org/10.3354/meps07483.
[33] FAO. Report of the technical consultation on international guidelines for the management of deep-sea fisheries in the high seas, Rome. 4–8 February and 25–29 August 2008. Food Agric. Organ. U.N. Fish. Aquac. Rep. 2009;881:86.
[34] Kenchington E, Murillo FJ, Lirette C, Sacau M, Koen-Alonso M, Kenny A, et al. Kernel density surface modelling as a means to identify significant concentrations of vulnerable marine ecosystem indicators. PLoS One 2014;9(10):e109365. https://doi.org/10.1371/journal.pone.0109365.
[35] Lockhart SJ, Hocevar J. Combined abundance of all vulnerable marine ecosystem indicator taxa inadequate as sole determiner of vulnerability, antarctic peninsula. Front Mar Sci 2021;8:577761. https://doi.org/10.3389/fmars.2021.577761.
[36] Ashford OS, Kenny AJ, Barrio Froján CR, Downie AL, Horton T, Rogers AD. On the influence of vulnerable marine ecosystem habitats on peracarid crustacean assemblages in the Northwest Atlantic Fisheries Organisation Regulatory Area. Front Mar Sci 2019;6:401. https://doi.org/10.3389/fmars.2019.00401.
[37] Cartes JE, LoIacono C, Mamouridis V, López-Pérez C, Rodríguez P. Geomorphological, trophic and human influences on the bamboo coral *Isidella elongata* assemblages in the deep Mediterranean: to what extent does Isidella form habitat for fish and invertebrates? Deep-Sea Res Part I Oceanogr Res Pap 2013;76: 52–65. https://doi.org/10.1016/j.dsr.2013.01.006.
[38] Bo M, Bavestrello G, Angiolillo M, Calcagnile L, Canese S, Cannas R, et al. Persistence of pristine deep-sea coral gardens in the Mediterranean Sea (SW Sardinia). PLoS One 2015;10(3):e0119393. https://doi.org/10.1371/journal.pone.0119393.
[39] Mechó A, Aguzzi J, Company JB, Canals M, Lastras G, Turon X. First in situ observations of the deep-sea carnivorous ascidian Dicopia antirrhinum Monniot C., 1972 in the Western Mediterranean Sea. Deep-Sea Res Part I Oceanogr Res Pap 2014;83:51–6. https://doi.org/10.1016/j.dsr.2013.09.007.
[40] Longo C, Mastrototaro F, Corriero G. Sponge fauna associated with a Mediterranean deep-sea coral bank. J Mar Biolog Assoc 2005;85(6):1341–52. https://doi.org/10.1017/S0025315405012518.
[41] Mastrototaro F, d'Onghia G, Corriero G, Matarrese A, Maiorano P, Panetta P, et al. Biodiversity of the white coral bank off cape santa maria di Leuca (Mediterranean Sea): an update. Deep Sea Res Part II Top Stud Oceanogr 2010;57 (5–6):412–30. https://doi.org/10.1016/j.dsr2.2009.08.02.
[42] Angeletti L, Taviani M, Canese S, Foglini F, Mastrototaro F, Argnani A, et al. New deep-water cnidarian sites in the southern Adriatic Sea. Mediterr Mar Sci 2014;15 (2):263–73. https://doi.org/10.12681/mms.558.
[43] Maldonado M, Aguilar R, Blanco J, Garcia S, Serrano A, Punzon A. Aggregated clumps of lithistid sponges: a singular, reef-like bathyal habitat with relevant paleontological connections. PLoS One 2015;10(5):e0125378. https://doi.org/10.1371/journal.pone.0125378.
[44] Buhl-Mortensen P, Dolan M, Buhl-Mortensen L. Prediction of benthic biotopes on a Norwegian offshore bank using a combination of multivariate analysis and GIS classification. ICES J Mar Sci 2009;66(9):2026–32. https://doi.org/10.1093/icesjms/fsp200.
[45] Colloca F, Carpentieri P, Balestri E, Ardizzone GD. A critical habitat for Mediterranean fish resources: shelf-break areas with *Leptometra phalangium* (Echinodermata: crinoidea). Mar Biol 2004;145:1129–42. https://doi.org/10.1007/s00227-004-1405-8.
[46] Aguzzi J, Sardà F. A history of recent advancements on *Nephrops norvegicus* behavioral and physiological rhythms. Rev Fish Biol Fish 2008;18:235–48. https://doi.org/10.1007/s11160-007-9071-9.
[47] D'onghia G, Capezzuto F, Cardone F, Carlucci R, Carluccio A, Chimienti G, et al. Macro-and megafauna recorded in the submarine Bari Canyon (southern Adriatic, Mediterranean Sea) using different tools. Mediterr Mar Sci 2015:180–96. https://doi.org/10.12681/mms.1082.
[48] Sarda F, Aguzzi J. A review of burrow counting as an alternative to other typical methods of assessment of Norway lobster populations. Rev Fish Biol Fish 2012; 22:409–22. https://doi.org/10.1007/s11160-011-9242-6.
[49] Company JB, Puig P, Sarda F, Palanques A, Latasa M, Scharek R. Climate influence on deep sea populations. PLoS One 2008;3(1):e1431. https://doi.org/10.1371/journal.pone.0001431.
[50] Fabri MC, Pedel L, Beuck L, Galgani F, Hebbeln D, Freiwald A. Megafauna of vulnerable marine ecosystems in French mediterranean submarine canyons: spatial distribution and anthropogenic impacts. Deep Sea Res Part II Top Stud Oceanogr 2014;104. https://doi.org/10.1016/j.dsr2.2013.06.016. 184-07.
[51] Lastras G, Canals M, Ballesteros E, Gili JM, Sanchez-Vidal A. Cold-water corals and anthropogenic impacts in La Fonera submarine canyon head, northwestern

Mediterranean Sea. PLoS One 2016;11(5):e0155729. https://doi.org/10.1371/journal.pone.0155729.
[52] Lo Iacono C, Agate M, Sulli A, Cartigny M, Robert K, Gori A, Russo T. Development, human impact and habitat distribution in submarine canyons of the Central and Western Mediterranean. In: CIESM workshop monograph. CIESM; 2015. vol. 47.
[53] Della Tommasa L, Belmonte G, Palanques A, Puig P, Boero F. Resting stages in a submarine canyon: a component of shallow-deep-sea coupling? Hydrobiologia 2000;440:249–60. https://doi.org/10.1023/A:1004139715482.
[54] Puig P, Company JB, Sardà F, Palanques A. Responses of deep-water shrimp populations to intermediate nepheloid layer detachments on the Northwestern Mediterranean continental margin. Deep-Sea Res Part I Oceanogr Res Pap 2001; 48(10). https://doi.org/10.1016/S0967-0637(01)00016-4. 2195-07.
[55] Fernandez-Arcaya U, Rotllant G, Ramirez-Llodra E, Recasens L, Aguzzi J, Flexas MDM, et al. Reproductive biology and recruitment of the deep-sea fish community from the NW Mediterranean continental margin. Prog Oceanogr 2013;118:222–34. https://doi.org/10.1016/j.pocean.2013.07.019.
[56] Fernandez-Arcaya U, Ramirez-Llodra E, Aguzzi J, Allcock AL, Davies JS, Dissanayake A, et al. Ecological role of submarine canyons and need for canyon conservation: a review. Front Mar Sci 2017;4:5. https://doi.org/10.3389/fmars.2017.00005.
[57] Sardà F, Canals M, Tselepides A, Calafat A, Flexas MDM, Espino M, Tursi A. An introduction to Mediterranean deep-sea biology. Sci 2004;68:7–38. https://doi.org/10.3989/scimar.2004.68s37. Mar.
[58] Samadi S, Bottan L, Macpherson E, De Forges BR, Boisselier MC. Seamount endemism questioned by the geographic distribution and population genetic structure of marine invertebrates. Mar Biol 2006;149:1463–75. https://doi.org/10.1007/s00227-006-0306-4.
[59] Pitcher TJ, Morato T, Hart PJB, Clark MR, Haggan N, Santos RS. The depths of ignorance an ecosystem evaluation framework for seamount ecology, fisheries, and conservation. In: Pitcher TJ, Morato T, Hart PJB, Clark MR, Haggan N, Santos RS, editors. Seamounts: ecology, fisheries, and conservation. Oxford: Blackwell Fisheries and Aquatic Resources Series 12. Blackwell Publishing; 2007. p. 476–88.
[60] Morato T, Hoyle SD, Allain V, Nicol SJ. Seamounts are hotspots of pelagic biodiversity in the open ocean. Proc Natl Acad Sci USA 2010;107(21):9707–11. https://doi.org/10.1073/pnas.0910290107.
[61] Würtz M, Rovere M. Atlas of the Mediterranean seamounts and seamount-like structures. Gland, Switzerland: IUCN; 2015. p. 276.
[62] Ingrosso G, Abbiati M, Badalamenti F, Bavestrello G, Belmonte G, Cannas R, et al. Mediterranean bioconstructions along the Italian coast. Adv Mar Biol 2018;79: 61–136. https://doi.org/10.1016/bs.amb.2018.05.001.
[63] Pusceddu A, Gambi C, Zeppilli D, Bianchelli S, Danovaro R. Organic matter composition, metazoan meiofauna and nematode biodiversity in Mediterranean deep-sea sediments. Deep Sea Res Part II Top Stud Oceanogr 2009;56(11–12): 755–62. https://doi.org/10.1016/j.dsr2.2008.10.012.
[64] Aguilar R, Correa ML, Calcinai B, Pastor X, De la Torriente A, Garcia S. First records of asbestopluma hypogea vacelet and boury-esnault, 1996 (Porifera, Demospongiae cladorhizidae) on seamounts and in bathyal settings of the Mediterranean Sea. Zootaxa 2011;2925(1):33–40. https://doi.org/10.11646/zootaxa.2925.1.3.
[65] Freiwald A, Beuck L, Rüggeberg A, Taviani M, Hebbeln D. R/V Meteor Cruise M70-1 Participants. The white coral community in the central Mediterranean Sea revealed by ROV surveys. Oceanography 2009;22(1):58–74. www.jstor.org/stable/24860923.
[66] Taviani M, Freiwald A, Zibrowius H. Deep coral growth in the Mediterranean Sea: an overview. In: Freiwald A, Roberts JM, editors. Cold-water corals and ecosystems. Erlangen Earth conference series. Berlin, Heidelberg: Springer; 2005. p. 137–56. https://doi.org/10.1007/3-540-27673-4_7.
[67] Taviani M, Angeletti L, Ceregato A. Chemosynthetic bivalves of the family solemyidae (Bivalvia, protobranchia) in the neogene of the mediterranean basin. J Paleontol 2011;85(6):1067–76. https://doi.org/10.1666/10-119.1.
[68] Beuck L, Aguilar R, Fabri MC, Freiwald A, Gofas S, Hebbeln D, et al. Biotope characterisation and compiled geographical distribution of the deep-water oyster Neopycnodonte zibrowii in the Atlantic Ocean and Mediterranean Sea. Rapports de la Commission Internationale pour l'Exploration Scientifique de la Mer Mediterranee. 2016;41:462.
[69] Taviani M, Angeletti L, Beuck L, Campiani E, Canese S, Foglini F, Freiwald A, Montagna P, Trincardi F. Reprint of'On and off the beaten track: megafaunal sessile life and Adriatic cascading processes'. Mar Geol 2016;375:146–60. https://doi.org/10.1016/j.margeo.2015.10.003.
[70] Taviani M, Friewald A, Beuck L, Angeletti L, Remia A, Vertino A, Mark D, Schembri PJ. The deepest known occurrence of the precious red coral Corallium Rubrum (L. 1758) in the Mediterranean Sea. International Workshop on Red Coral Science, Management, and Trade: Lessons from the Mediterranean 2010: 87–93. Naples.
[71] Taviani M, Angeletti L, Ceregato A, Foglini F, Froglia C, Trincardi F. The Gela Basin pockmark field in the strait of Sicily (Mediterranean Sea): chemosymbiotic faunal and carbonate signatures of postglacial to modern cold seepage. Biogeosciences 2013;10(7):4653–71. https://doi.org/10.5194/bg-10-4653-2013.
[72] Costantini F, Taviani M, Remia A, Pintus E, Schembri PJ, Abbiati M. Deep-water *Corallium rubrum* (L., 1758) from the Mediterranean Sea: preliminary genetic characterisation. Mar Ecol 2010;31(2):261–9. https://doi.org/10.1111/j.1439-0485.2009.00333.x.
[73] Rosso A, Vertino A, Di Geronimo I, Sanfilippo R, Sciuto F, Di Geronimo R, Violanti D, Corselli C, Taviani M, Mastrototaro F, Tursi A. Hard-and soft-bottom thanatofacies from the Santa Maria di Leuca deep-water coral province, Mediterranean. Deep Sea Res Part II Top Stud Oceanogr 2010;57(5–6):360–79. https://doi.org/10.1016/j.dsr2.2009.08.024.
[74] Sanfilippo R, Vertino A, Rosso A, Beuck L, Freiwald A, Taviani M. Serpula aggregates and their role in deep-sea coral communities in the southern Adriatic Sea. Facies 2013;59:663–77. https://doi.org/10.1007/s10347-012-0356-7.
[75] Calcinai B, Moratti V, Martinelli M, Bavestrello G, Taviani M. Uncommon sponges associated with deep coral bank and maerl habitats in the Strait of Sicily (Mediterranean Sea). Ital J Zool 2013;80(3):412–23. https://doi.org/10.1080/11250003.2013.786763.
[76] Zeppilli D, Mea M, Corinaldesi C, Danovaro R. Mud volcanoes in the Mediterranean Sea are hot spots of exclusive meiobenthic species. Prog Oceanogr 2011;91(3):260–72. https://doi.org/10.1016/j.pocean.2011.01.001.
[77] Olu-Le Roy K, Sibuet M, Fiala-Médioni A, Gofas S, Salas C, Mariotti A, Foucher JP, Woodside J. Cold seep communities in the deep eastern Mediterranean Sea: composition, symbiosis and spatial distribution on mud volcanoes. Deep-Sea Res Part I Oceanogr Res Pap 2004;51(12):1915–36. https://doi.org/10.1016/j.dsr.2004.07.004.
[78] Woodside JM, David L, Frantzis A, Hooker SK. Gouge marks on deep-sea mud volcanoes in the eastern Mediterranean: caused by Cuvier's beaked whales? Deep-Sea Res Part I Oceanogr Res Pap 2006;53(11):1762–71. https://doi.org/10.1016/j.dsr.2006.08.011.
[79] Bevilacqua S, Airoldi L, Ballesteros E, Benedetti-Cecchi L, Boero F, Bulleri F, et al. Mediterranean rocky reefs in the Anthropocene: present status and future concerns. Adv Mar Biol 2021;89:1–51. https://doi.org/10.1016/bs.amb.2021.08.001.
[80] Austin S, Wyllie-Echeverria S, Groom MJ. A comparative analysis of submarine cable installation methods in northern puget sound, Washington. J Mar Environ Eng 2004;7(3):173–83.
[81] Danovaro R, Nepote E, Martire ML, Carugati L, Da Ros Z, Torsani F, et al. Multiple declines and recoveries of Adriatic seagrass meadows over forty years of investigation. Mar Pollut Bull 2020;161:111804. https://doi.org/10.1016/j.marpolbul.2020.111804.
[82] Bianchelli S, Danovaro R. Impairment of microbial and meiofaunal ecosystem functions linked to algal forest loss. Sci Rep 2020;10(1):19970. https://doi.org/10.1038/s41598-020-76817-5.
[83] Tamburello L, Chiarore A, Fabbrizzi E, Colletti A, Franzitta G, Grech D, et al. Can we preserve and restore overlooked macroalgal forests? Sci Total Environ 2020; 806:150855. https://doi.org/10.1016/j.scitotenv.2021.150855.
[84] Maslov N, Claramunt C, Wang T, Tang T. Method to estimate the visual impact of an offshore wind farm. Appl Energy 2017;204:1422–30. https://doi.org/10.1016/j.apenergy.2017.05.053.
[85] Ladenburg J, Dubgaard A. Willingness to pay for reduced visual disamenities from offshore wind farms in Denmark. Energy Pol 2007;35(8):4059–71. https://doi.org/10.1016/j.enpol.2007.01.023.
[86] Voltaire L, Loureiro ML, Knudsen C, Nunes PA. The impact of offshore wind farms on beach recreation demand: policy intake from an economic study on the Catalan coast. Mar Pol 2017;81:116–23. https://doi.org/10.1016/j.marpol.2017.03.019.
[87] Lilley MB, Firestone J, Kempton W. The effect of wind power installations on coastal tourism. Energies 2010;3(1):1–22. https://doi.org/10.3390/en3010001.
[88] Westerberg V, Jacobsen JB, Lifran R. The case for offshore wind farms, artificial reefs and sustainable tourism in the French mediterranean. Tourism Manag 2013; 34:172–83. https://doi.org/10.1016/j.tourman.2012.04.008.
[89] Boero F, Foglini F, Fraschetti S, Goriup P, Machpherson E, Planes S, Soukissian T, CoCoNet Consortium. CoCoNet: towards coast to coast networks of Marine Protected Areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential. SCI-RES.IT 2016;6(supplement):1–95. https://doi.org/10.2423/i22394303v6SpI.
[90] Broström G. On the influence of large wind farms on the upper ocean circulation. J Mar Syst 2008;74(1–2):585–91. https://doi.org/10.1016/j.jmarsys.2008.05.001.
[91] Daewel U, Akhtar N, Christiansen N, Schrum C. Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. Commun. Earth Environ 2022;3(1):292. https://doi.org/10.1038/s43247-022-00625-0.
[92] Christiansen N, Daewel U, Djath B, Schrum C. Emergence of large-scale hydrodynamic structures due to atmospheric offshore wind farm wakes. Front Mar Sci 2022;9:818501. https://doi.org/10.3389/fmars.2022.818501.
[93] Siedersleben SK, Lundquist JK, Platis A, Bange J, Bärfuss K, Lampert A, et al. Micrometeorological impacts of offshore wind farms as seen in observations and simulations. Environ Res Lett 2018;13(12):124012. https://doi.org/10.1088/1748-9326/aaea0b.
[94] Platis A, Siedersleben SK, Bange J, Lampert A, Bärfuss K, Hankers R, et al. First in situ evidence of wakes in the far field behind offshore wind farms. Sci Rep 2018;8 (1):2163. https://doi.org/10.1038/s41598-018-20389-y.
[95] Pan Y, Yan C, Archer CL. Precipitation reduction during Hurricane Harvey with simulated offshore wind farms. Environ Res Lett 2018;13(8):084007. https://doi.org/10.1088/1748-9326/aad245.
[96] Al Fahel N, Archer CL. Observed onshore precipitation changes after the installation of offshore wind farms. Bull Atmos Sci Technol 2020;1. https://doi.org/10.1007/s42865-020-00012-7. 179-03.
[97] Ruan Z, Lu X, Wang S, Xing J, Wang W, Chen D, et al. Impacts of large-scale deployment of mountainous wind farms on wintertime regional air quality in the Beijing-Tian-Hebei area. Atmos Environ 2022;278:119074. https://doi.org/10.1016/j.atmosenv.2022.119074.

[98] Mo J, Huang T, Zhang X, Zhao Y, Liu X, Li J, et al. Spatiotemporal distribution of nitrogen dioxide within and around a large-scale wind farm – a numerical case study. Atmos Chem Phys 2017;7:14239–52. https://doi.org/10.5194/acp-17-14239-2017.
[99] Di Franco E, Pierson P, Di Iorio L, Calò A, Cottalorda JM, Derijard B, et al. Effects of marine noise pollution on Mediterranean fishes and invertebrates: a review. Mar Pollut Bull 2020;159:111450. https://doi.org/10.1016/j.marpolbul.2020.111450.
[100] Parsons ECM, Dolman SJ, Wright AJ, Rose NA, Burns WCG. Navy sonar and cetaceans: just how much does the gun need to smoke before we act? Mar Pollut Bull 2008;56(7):1248–57. https://doi.org/10.1016/j.marpolbul.2008.04.025.
[101] Bailey H, Senior B, Simmons D, Rusin J, Picken G, Thompson PM. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. Mar Pollut Bull 2010;60(6):888–97. https://doi.org/10.1016/j.marpolbul.2010.01.003.
[102] Andersson MH, Andersson BL, Pihl J, Persson LK, Sigray P, Andersson S, et al. A framework for regulating underwater noise during pile driving. Stockholm, Sweden: Swedish Environmental Protection Agency; 2017. Report No. 6775.
[103] Mooney TA, Andersson MH, Stanley J. Acoustic impacts of offshore wind energy on fishery resources. Oceanography 2020;33(4):82–95. https://www.jstor.org/stable/26965752.
[104] Nedwell J, Howell D. A review of offshore windfarm related underwater noise sources. Cowrie Rep 2004;544:1–57.
[105] Bald J, Hernández C, Galparsoro I, Rodríguez JM, Muxika I, Enciso YT, Marina D. Environmental impacts over the seabed and benthic communities of submarine cable installation in the Biscay Marine Energy Platform (bimep). Bilbao Marine Energy Week 2015. https://doi.org/10.13140/RG.2.2.31050.08649.
[106] Velia H. Electrify the north sea: offshore wind experts warn that the scale of Europe's green energy ambition requires the development of a novel, internationally linked North Sea grid to transport power more effectively from deep offshore to demand onshore. But with such infrastructure never having been built before, and the climate clock ticking, can it be done? Eng Technol 2021;16(9):1–4. https://doi.org/10.1049/et.2021.0909.
[107] Stienen EWM, Waeyenberge V, Kuijken E, Seys J. Trapped within the corridor of the Southern North Sea: the potential impact of offshore wind farms on seabirds. In: de Lucas M, Janss GFE, Ferrer M, editors. Birds and wind farms. Risk assessment and mitigation. first ed. Madrid: Quercus; 2007. p. 71–80.
[108] Furness RW, Monaghan P. Seabird feeding ecology. In: Seabird Ecology. Tertiary level biology. Boston, MA: Springer; 1987. p. 23–4. https://doi.org/10.1007/978-1-4613-2093-7_3.
[109] Furness RW, Wade HM, Masden EA. Assessing vulnerability of marine bird populations to offshore wind farms. J Environ Manag 2013;119:56–66. https://doi.org/10.1016/j.jenvman.2013.01.025.
[110] Johnson DH, Loss SR, Smallwood KS, Erickson WP. Avian fatalities at wind energy facilities in North America: a comparison of recent approaches. Hum-Wildl Interact 2016;10(1):3.
[111] Dierschke V, Furness RW, Garthe S. Seabirds and offshore wind farms in European waters: avoidance and attraction. Biol Conserv 2016;202:59–68. https://doi.org/10.1016/j.biocon.2016.08.016.
[112] Mendel B, Schwemmer P, Peschko V, Müller S, Schwemmer H, Mercker M, Garthe S. Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (Gavia spp.). J Environ Manag 2019;231:429–38. https://doi.org/10.1016/j.jenvman.2018.10.053.
[113] Peschko V, Mendel B, Müller S, Markones N, Mercker M, Garthe S. Effects of offshore windfarms on seabird abundance: strong effects in spring and in the breeding season. Mar Environ Res 2020;162:105157. https://doi.org/10.1016/j.marenvres.2020.105157.
[114] Garthe S, Hüppop O. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. J Appl Ecol 2004;41(4):724–34. https://doi.org/10.1111/j.0021-8901.2004.00918.x.
[115] Borkenhagen K, Corman AM, Garthe S. Estimating flight heights of seabirds using optical rangefinders and GPS data loggers: a methodological comparison. Mar Biol 2018;165(1):17. https://doi.org/10.1007/s00227-017-3273-z.
[116] Vanermen N, Courtens W, Van de walle M, Verstraete H, Stienen EWM. Seabird monitoring at offshore wind farms in the Belgian part of the North Sea. Updated results for the Bligh Bank & first results for the Thorntonbank. In: Degraer S, Brabant R, Rumes B, Vigin L, editors. Environmental impacts of offshore wind farms in the Belgian part of the north sea: environmental impact monitoring reloaded. Royal Belgian institute of natural sciences, OD natural environment, marine ecology and management section; 2016. p. 287–2016.
[117] Scott B, Langton R, Philpott E, Waggitt J. Seabirds and marine renewables: are we asking the right questions?. In: Shields M, Payne A, editors. Marine renewable energy technology and environmental interactions. Humanity and the sea Dordrecht: Springer; 2014. https://doi.org/10.1007/978-94-017-8002-5_7. 81–92.
[118] Brabant R, Laurent Y, Vigin L, Lafontaine RM, Degraer S. Bats in the Belgian Part of the North Sea and possible impacts of offshore wind farms. In: Degraer S, Brabant R, Rumes B, Vigin L, editors. Environmental impacts of offshore wind farms in the Belgian part of the North Sea: environmental impact monitoring reloaded. Royal Belgian Institute of Natural Sciences, OD natural environments. Section: Marine Ecology and Management; 2016. p. 235–46.
[119] Rydell J, Bach L, Dubourg-Savage MJ, Green M, Rodrigues L, Hedenström A. Bat mortality at wind turbines in northwestern Europe. Acta Chiropt 2010;12(2):261–74. https://doi.org/10.3161/150811010X537846.
[120] Gaultier SP, Blomberg AS, Ijäs A, Vasko V, Vesterinen EJ, Brommer JE, Lilley TM. Bats and wind farms: the role and importance of the Baltic Sea countries in the European context of power transition and biodiversity conservation. Environ Sci Technol 2020;54(17):10385–98. https://doi.org/10.1021/acs.est.0c00070.
[121] Voigt CC, Lehnert LS, Petersons G, Adorf F, Bach L. Wildlife and renewable energy: German politics cross migratory bats. Eur J Wildl Res 2015;61:213–9. https://doi.org/10.1007/s10344-015-0903-y.
[122] Carpenter JR, Merckelbach L, Callies U, Clark S, Gaslikova L, Baschek B. Potential impacts of offshore wind farms on North Sea stratification. PLoS One 2016;11:1–28. https://doi.org/10.1371/journal.pone.0160830.
[123] Dannheim J, Bergström L, Birchenough SN, Brzana R, Boon AR, Coolen JW, et al. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES J Mar Sci 2020;77(3):1092–108. https://doi.org/10.1093/icesjms/fsz018.
[124] Cazenave PW, Torres R, Allen JI. Unstructured grid modelling of offshore wind farm impacts on seasonally stratified shelf seas. Prog Oceanogr 2016;145:25–41. https://doi.org/10.1016/j.pocean.2016.04.004.
[125] Schultze LKP, Merckelbach LM, Horstmann J, Raasch S, Carpenter JR. Increased mixing and turbulence in the wake of offshore wind farm foundations. J Geophys Res Oceans 2020;125(8):e2019JC015858. https://doi.org/10.1029/2019JC015858.
[126] Raghukumar K, Chartrand C, Chang G, Cheung L, Roberts J. Effect of floating offshore wind turbines on atmospheric circulation in California. Front Energy Res 2022;10:863995. https://doi.org/10.3389/fenrg.2022.863995.
[127] Floeter J, van Beusekom JE, Auch D, Callies U, Carpenter J, Dudeck T, et al. Pelagic effects of offshore wind farm foundations in the stratified North Sea. Prog Oceanogr 2017;156:154–73. https://doi.org/10.1016/j.pocean.2017.07.003.
[128] Stanley JA, Radford CA, Jeffs AG. Effects of underwater noise on larval settlement. In: The effects of noise on aquatic life. New York: Springer; 2012. p. 371–4. https://doi.org/10.1007/978-1-4419-7311-5_84.
[129] Langhamer O. Artificial reef effect in relation to offshore renewable energy conversion: state of the art. Sci World J 2012;2012. https://doi.org/10.1100/2012/386713.
[130] Wilson AB. Offshore wind energy in europe, briefing. November. European Parliamentary Research Service; 2020. Online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/659313/EPRS_BRI(2020)659313_EN.pdf.
[131] Lindeboom HJ, Kouwenhoven HJ, Bergman MJN, Bouma S, Brasseur SMJM, Daan R, et al. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. Environ Res Lett 2011;6(3):035101. https://doi.org/10.1088/1748-9326/6/3/035101.
[132] Bergström L, Sundqvist F, Bergström U. Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community. Mar Ecol Prog Ser 2013;485. https://doi.org/10.3354/meps10344. 199-10.
[133] Van Hal R, Griffioen AB, Van Keeken OA. Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm. Mar Environ Res 2017;126:26–36. https://doi.org/10.1016/j.marenvres.2017.01.009.
[134] Wilber DH, Carey DA, Griffin M. Flatfish habitat use near North America's first offshore wind farm. J Sea Res 2018;139:24–32. https://doi.org/10.1016/j.seares.2018.06.004.
[135] Reubens JT, Degraer S, Vincx M. Aggregation and feeding behaviour of pouting (Trisopterus luscus) at wind turbines in the Belgian part of the North Sea. Fish Res 2011;108(1):223–7. https://doi.org/10.1016/j.fishres.2010.11.025.
[136] Reubens JT, Pasotti F, Degraer S, Vincx M. Residency, site fidelity and habitat use of Atlantic cod (*Gadus morhua*) at an offshore wind farm using acoustic telemetry. Mar Environ Res 2013;90:128–35. https://doi.org/10.1016/j.marenvres.2013.07.001.
[137] Stenberg C, Støttrup JG, van Deurs M, Berg CW, Dinesen GE, Mosegaard H, et al. Long-term effects of an offshore wind farm in the North Sea on fish communities. Mar Ecol Prog Ser 2015;528:257–65. https://doi.org/10.3354/meps1126.
[138] Wilhelmsson D, Malm T, Öhman MC. The influence of offshore windpower on demersal fish. ICES J Mar Sci 2006;63(5):775–84. https://doi.org/10.1016/j.icesjms.2006.02.001.
[139] Wahlberg M, Westerberg H. Hearing in fish and their reactions to sounds from offshore wind farms. Mar Ecol Prog Ser 2005;288. https://doi.org/10.3354/meps288295. 295-09.
[140] Shimada H, Asano K, Nagai Y, Ozawa A. Assessing the impact of offshore wind power deployment on fishery: a synthetic control approach. Environ Resour Econ 2022;83(3). https://doi.org/10.1007/s10640-022-00710-0. 791-29.
[141] Halouani G, Villanueva CM, Raoux A, Dauvin JC, Lasram FBR, Foucher E. A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm. J Mar Syst 2020;212:103434. https://doi.org/10.1016/j.jmarsys.2020.103434.
[142] Ashley MC, Mangi SC, Rodwell LD. The potential of offshore windfarms to act as marine protected areas–A systematic review of current evidence. Mar Pol 2014;45:301–9. https://doi.org/10.1016/j.marpol.2013.09.002.
[143] Degraer S, Brabant R, Rumes B, Vigin L, editors. Environmental impacts of offshore wind farms in the Belgian part of the north sea: marking a decade of monitoring, research and innovation. Brussels: royal Belgian institute of natural sciences, OD natural environment. Marine Ecology and Management; 2019. p. 134.
[144] Hvidt CB, Leonhard SB, Klaustrup M, Pedersen J. Hydroacoustic monitoring of fish communities in offshore windfarms. Horns Rev Offshore Wind Farm Annu Rep 2006;54.
[145] Castro JJ, Santiago JA, Hernández-García V. Fish associated with fish aggregation devices off the canary islands (Central-East atlantic). Sci Mar 1999;63(3–4):191–8. https://doi.org/10.3989/scimar.1999.63n3-4191.

[146] Fayram AH, De Risi A. The potential compatibility of offshore wind power and fisheries: an example using bluefin tuna in the Adriatic Sea. Ocean Coast Manag 2007;50(8). https://doi.org/10.1016/j.ocecoaman.2007.05.004. 597-05.
[147] Brickhill MJ, Lee SY, Connolly RM. Fishes associated with artificial reefs: attributing changes to attraction or production using novel approaches. J Fish Biol 2005;67:53–71. https://doi.org/10.1111/j.0022-1112.2005.00915.x.
[148] Reubens JT, Vandendriessche S, Zenner AN, Degraer S, Vincx M. Offshore wind farms as productive sites or ecological traps for gadoid fishes?–Impact on growth, condition index and diet composition. Mar Environ Res 2013;90:66–74. https://doi.org/10.1016/j.marenvres.2013.05.013.
[149] Schwartzbach A, Behrens JW, Svendsen JC. Atlantic cod *Gadus morhua* save energy on stone reefs: implications for the attraction versus production debate in relation to reefs. Mar Ecol Prog Ser 2020;635:81–7. https://doi.org/10.3354/meps13192.
[150] Hooper T, Ashley M, Austen M. Perceptions of Fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Mar Pol 2015;61:16–22. https://doi.org/10.1016/j.marpol.2015.06.031.
[151] Schupp MF, Kafas A, Buck BH, Krause G, Onyango V, Stelzenmüller V, et al. Fishing within offshore wind farms in the North Sea: stakeholder perspectives for multi-use from Scotland and Germany. J Environ Manag 2021;279:111762. https://doi.org/10.1016/j.jenvman.2020.111762.
[152] Alexander KA, Wilding TA, Heymans JJ. Attitudes of Scottish Fishers towards marine renewable energy. Mar Pol 2013;37:239–44. https://doi.org/10.1016/j.marpol.2012.05.005.
[153] Nabi G, McLaughlin RW, Hao Y, Wang K, Zeng X, Khan S, Wang D. The possible effects of anthropogenic acoustic pollution on marine mammals' reproduction: an emerging threat to animal extinction. Environ Sci Pollut Res 2018;25(20):19338–45. https://doi.org/10.1007/s11356-018-2208-7.
[154] Tougaard J, Henriksen OD, Miller LA. Underwater noise from three types of offshore wind turbines: estimation of impact zones for harbor porpoises and harbor seals. J Acoust Soc Am 2009;125(6):3766–73. https://doi.org/10.1121/1.3117444.
[155] Rossi S, Bramanti L. Perspectives on the marine animal forests of the world. Nature Switzerland: Springer; 2020. p. 530. https://doi.org/10.1007/978-3-030-57054-5.
[156] Castro BT, Prieto González R, O'Callaghan SA, Dominguez Rein-Loring P, Degollada Bastos E. Ship strike risk for fin whales (*Balaenoptera physalus*) off the garraf coast, NW Mediterranean Sea. Front Mar Sci 2022;9:492. https://doi.org/10.3389/fmars.2022.867287. 9.
[157] Russell DJ, Hastie GD, Thompson D, Janik VM, Hammond PS, Scott-Hayward LA, et al. Avoidance of wind farms by harbour seals is limited to pile driving activities. J Appl Ecol 2016;53(6):1642–52. https://doi.org/10.1111/1365-2664.12678.
[158] Scheidat M, Tougaard J, Brasseur S, Carstensen J, van Polanen Petel T, Teilmann J, Reijnders P. Harbour porpoises (Phocoena phocoena) and wind farms: a case study in the Dutch North Sea. Environ Res Lett 2011;6(2):025102. https://doi.org/10.1088/1748-9326/6/2/025102.
[159] Hiscock K, Tyler-Walters H, Jones H. High level environmental screening study for offshore wind farm developments–marine habitats and species project. Report from the Marine Biological Association to the Department of Trade and Industry New & Renewable Energy Programme; 2002.
[160] Coates DA, Van Hoey G, Colson L, Vincx M, Vanaverbeke J. Rapid macrobenthic recovery after dredging activities in an offshore wind farm in the Belgian part of the North Sea. Hydrobiologia 2015;756(1):3–18. https://doi.org/10.1007/s10750-014-2103-2.
[161] Leimeister M, Kolios A, Collu M. Critical review of floating support structures for offshore wind farm deployment. J Phys: Conf Ser 2018;1104:012007. https://doi.org/10.1088/1742-6596/1104/1/012007.
[162] Richardson MD. Dynamically installed anchors for floating offshore structures (Doctoral dissertation. University of Western Australia; 2008.
[163] Davis AR, Broad A, Gullett W, Reveley J, Steele C, Schofield C. Anchors away? The impacts of anchor scour by ocean-going vessels and potential response options. Mar Pol 2016;73:1–7. https://doi.org/10.1016/j.marpol.2016.07.021.
[164] Nall CR, Schläppy ML, Guerin AJ. Characterization of the biofouling community on a floating wave energy device. Biofouling 2017;33(5):379–96. https://doi.org/10.1080/08927014.2017.1317755.
[165] Karlsson R, Tivefälth M, Duranović I, Martinsson S, Kjølhamar A, Murvoll KM. Artificial hard-substrate colonisation in the offshore hywind scotland pilot park. Wind Energy Sci 2022;7(2):801–14. https://doi.org/10.5194/wes-7-801-2022.
[166] De Mesel I, Kerckhof F, Norro A, Rumes B, Degraer S. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia 2015;756(1):37–50. https://doi.org/10.1007/s10750-014-2157-1.
[167] Coates DA, Deschutter Y, Vincx M, Vanaverbeke J. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. Mar Environ Res 2014;95:1–12. https://doi.org/10.1016/j.marenvres.2013.12.008.
[168] Decurey B, Schoefs F, Barillé AL, Soulard T. Model of bio-colonisation on mooring lines: updating strategy based on a static qualifying sea state for floating wind turbines. J Mar Sci Eng 2020;8(2):108. https://doi.org/10.3390/jmse8020108.
[169] Kerckhof F, Degraer S, Norro a, Rumes B. Offshore intertidal hard substrata: a new habitat promoting non-indigenous species in the Southern North Sea: an exploratory study. R Belg Inst Nat Sci 2011;32:27–37.
[170] Sheehy DJ, Vik SF. The role of constructed reefs in non-indigenous species introductions and range expansions. Ecol Eng 2010;36(1):1–11. https://doi.org/10.1016/j.ecoleng.2009.09.012.
[171] Hammar L, Wikström A, Molander S. Assessing ecological risks of offshore wind power on Kattegat cod. Renew Energy 2014;66:414–24. https://doi.org/10.1016/j.renene.2013.12.024.
[172] Dunham A, Pegg JR, Carolsfeld W, Davies S, Murfitt I, Boutillier J. Effects of submarine power transmission cables on a glass sponge reef and associated megafaunal community. Mar Environ Res 2015;107:50–60. https://doi.org/10.1016/j.marenvres.2015.04.003.
[173] Andrulewicz E, Napierska D, Otremba Z. The environmental effects of the installation and functioning of the submarine SwePol Link HVDC transmission line: a case study of the Polish Marine Area of the Baltic Sea. J Sea Res 2003;49(4):337–45. https://doi.org/10.1016/S1385-1101(03)00020-0.
[174] Maxwell SM, Kershaw F, Locke CC, Conners MG, Dawson C, Aylesworth S, et al. Potential impacts of floating wind turbine technology for marine species and habitats. J Environ Manag 2022;307:114577. https://doi.org/10.1016/j.jenvman.2022.114577.
[175] CMACS. A baseline assessment of electromagnetic fields generated by offshore windfarm cables. 2003. COWRIE Report EMF - 01-2002 66.
[176] Wyman MT, Klimley AP, Battleson RD, Agosta TV, Chapman ED, Haverkamp PJ, et al. Behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable. Mar Biol 2018;165(8):1–15. https://doi.org/10.1007/s00227-018-3385-0.
[177] Nyqvist D, Durif C, Johnsen MG, De Jong K, Forland TN, Sivle LD. Electric and magnetic senses in marine animals, and potential behavioral effects of electromagnetic surveys. Mar Environ Res 2020;155:104888. https://doi.org/10.1016/j.marenvres.2020.104888.
[178] Hutchison Z, Sigray P, He H, Gill AB, King J, Gibson C. Electromagnetic Field (EMF) impacts on elasmobranch (shark, rays, and skates) and American lobster movement and migration from direct current cables. Sterling (VA): US Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2018;3:2018.
[179] Albert L, Deschamps F, Jolivet A, Olivier F, Chauvaud L, Chauvaud S. A current synthesis on the effects of electric and magnetic fields emitted by submarine power cables on invertebrates. Mar Environ Res 2020;159:104958. https://doi.org/10.1016/j.marenvres.2020.104958.
[180] Gill AB, Gloyne-Phillips I, Neal KJ, Kimber JA. The potential effects of electromagnetic fields generated by sub-sea power cables associated with offshore wind farm developments on electrically and magnetically sensitive marine organisms – a review. 2005 [Final report].
[181] Gill AB, Huang Y, Gloyne-Philips I, Metcalfe J, Quayle V, Spencer J, Wearmouth V. COWRIE 2.0 Electromagnetic Fields (EMF) Phase 2: EMF-sensitive fish response to EM emissions from sub-sea electricity cables of the type used by the offshore renewable energy industry. Commissioned by COWRIE Ltd (project reference COWRIE-EMF-1-06); 2009. p. 68.
[182] Stelzenmüller V, Gimpel A, Haslob H, Letschert J, Berkenhagen J, Brüning S. Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs. Sci Total Environ 2021;776:145918. https://doi.org/10.1016/j.scitotenv.2021.14591.
[183] Krone R, Gutow L, Brey T, Dannheim J, Schröder A. Mobile demersal megafauna at artificial structures in the German Bight–Likely effects of offshore wind farm development. Estuar Coast Shelf Sci 2013;125:1–9. https://doi.org/10.1016/j.ecss.2013.03.012.
[184] Methratta ET. Distance-based sampling methods for assessing the ecological effects of offshore wind farms: synthesis and application to fisheries resource studies. Front Mar Sci 2021;8:674594. https://doi.org/10.3389/fmars.2021.674594.
[185] Stelzenmüller V, Diekmann R, Bastardie F, Schulze T, Berkenhagen J, Kloppmann M, et al. Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: a first socio-economic scoping. J Environ Manag 2016;183. https://doi.org/10.1016/j.jenvman.2016.08.027. 794-05.
[186] Berkenhagen J, Döring R, Fock HO, Kloppmann MH, Pedersen SA, Schulze T. Decision bias in marine spatial planning of offshore wind farms: problems of singular versus cumulative assessments of economic impacts on fisheries. Mar Pol 2010;34(3):733–6. https://doi.org/10.1016/j.marpol.2009.12.004.
[187] Buck BH, Krause G, Michler-Cieluch T, Brenner M, Buchholz CM, Busch JA, et al. Meeting the quest for spatial efficiency: progress and prospects of extensive aquaculture within offshore wind farms. Helgol Mar Res 2008;62(3):269–81. https://doi.org/10.1007/s10152-008-0115-x.
[188] Van den Burg SW, Kamermans P, Blanch M, Pletsas D, Poelman M, Soma K, Dalton G. Business case for mussel aquaculture in offshore wind farms in the North Sea. Mar Pol 2017;85:1–7. https://doi.org/10.1016/j.marpol.2017.08.007.
[189] Van den Burg SW, Röckmann C, Banach JL, Van Hoof L. Governing risks of multi-use: seaweed aquaculture at offshore wind farms. Front Mar Sci 2020;7:60. https://doi.org/10.3389/fmars.2020.00060.
[190] Mirto S, Danovaro R, Mazzola A. Microbial and meiofaunal response to intensive mussel-farm biodeposition in coastal sediments of the western Mediterranean. Mar Pollut Bull 2000;40(3):244–52. https://doi.org/10.1016/S0025-326X(99)00209-X.
[191] Kleyheeg-Hartman JC, Krijgsveld KL, Collier MP, Poot MJM, Boon AR, Troost TA, Dirksen S. Predicting bird collisions with wind turbines: comparison of the new empirical Flux Collision Model with the SOSS Band model. Ecol Model 2018;387:144–53. https://doi.org/10.1016/j.ecolmodel.2018.06.025.
[192] ISO. UNI EN ISO 14040:2021 Environmental management—life cycle assessment—principles and framework. 2021.
[193] ISO. UNI EN ISO 14044:2021 Environmental management—life cycle assessment—requirements and guidelines. 2021.

[194] Kouloumpis V, Azapagic A. A model for estimating life cycle environmental impacts of offshore wind electricity considering specific characteristics of wind farms. Sustain Prod Consum 2022;29. https://doi.org/10.1016/j.spc.2021.10.024. 495-06.
[196] Wang S, Wang S, Liu J. Life-cycle green-house gas emissions of onshore and offshore wind turbine. J Clean Prod 2019;210:804–10. https://doi.org/10.1016/j.jclepro.2018.11.031.
[197] Raadal HL, Vold BI, Myhr A, Nygaard TA. GHG emissions and energy performance of offshore wind power. Renew Energy 2014;66:314–24. https://doi.org/10.1016/j.renene.2013.11.075.
[198] Kasner R. The environmental efficiency of materials used in the lifecycle of a wind farm. Sustain Mater Technol 2022;34:e00512. https://doi.org/10.1016/j.susmat.2022.e00512.
[199] Gennitsaris S, Sagani A, Sofianopoulou S, Dedoussis V. Integrated LCA and DEA approach for circular economy-driven performance evaluation of wind turbine end-of-life treatment options. Appl Energy 2023;339:120951. https://doi.org/10.1016/j.apenergy.2023.120951.
[200] Bhandari R, Kumar B, Mayer F. Life cycle greenhouse gas emission from wind farms in reference to turbine sizes and capacity factors. J Clean Prod 2020;277:123385. https://doi.org/10.1016/j.jclepro.2020.123385.
[201] Garcia-Teruel A, Rinaldi G, Thies PR, Johanning L, Jeffrey H. Life cycle assessment of floating offshore wind farms: an evaluation of operation and maintenance. Appl Energy 2022;307:118067. https://doi.org/10.1016/j.apenergy.2021.118067.
[202] Msigwa G, Ighalo JO, Yap PS. Considerations on environmental, economic, and energy impacts of wind energy generation: projections towards sustainability initiatives. Sci Total Environ 2022:157755. https://doi.org/10.1016/j.scitotenv.2022.157755.
[203] Yuan W, Feng JC, Zhang S, Sun L, Cai Y, Yang Z, Sheng S. Floating wind power in Deep-Sea area: life cycle assessment of environmental impacts. Adv Appl Energy 2023:100122. https://doi.org/10.1016/j.adapen.2023.100122.
[204] Yang J, Chang Y, Zhang L, Hao Y, Yan Q, Wang C. The life-cycle energy and environmental emissions of a typical offshore wind farm in China. J Clean Prod 2018;180:316–24. https://doi.org/10.1016/j.jclepro.2018.01.082.
[205] May R, Jackson CR, Middel H, Stokke BG, Verones F. Life-cycle impacts of wind energy development on bird diversity in Norway. Environ Impact Assess Rev 2021;90:106635. https://doi.org/10.1016/j.eiar.2021.106635.
[206] Vrasdonk E, Palme U, Lennartsson T. Reference situations for biodiversity in life cycle assessments: conceptual bridging between LCA and conservation biology. Int J Life Cycle Assess 2019;24:1631–42. https://doi.org/10.1007/s11367-019-01594-x.
[207] Brussa G, Grosso M, Rigamonti L. Life cycle assessment of a floating offshore wind farm in Italy. Sustain Prod Consum 2023;39:134–44. https://doi.org/10.1016/j.spc.2023.05.006.
[208] Del Borghi A, Moreschi L, Gallo M. Communication through ecolabels: how discrepancies between the EU PEF and EPD schemes could affect outcome consistency. Int J Life Cycle Assess 2020;25. https://doi.org/10.1007/s11367-019-01609-7. 905 –01.
[209] Spielmann V, Brey T, Dannheim J, Vajhøj J, Ebojie M, Klein J, Eckardt S. Integration of sustainability, stakeholder and process approaches for sustainable offshore wind farm decommissioning. Renew Sustain Energy Rev 2021;147:111222. https://doi.org/10.1016/j.rser.2021.111222.
[210] Hall R, Topham E, João E. Environmental Impact Assessment for the decommissioning of offshore wind farms. Renew Sustain Energy Rev 2022;165:112580. https://doi.org/10.1016/j.rser.2022.112580.
[211] She J, Muniz Pinella A, Benedetti-Cecchi L, Boheme L, Boero F, et al. An integrated approach to coastal and biological observations. Front Mar Sci 2019;314. https://doi.org/10.3389/fmars.2019.00314.
[212] Methratta ET. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. ICES J Mar Sci 2020;77(3). https://doi.org/10.1093/icesjms/fsaa026. 890-00.
[213] Vandendriessche S, Derweduwen J, Hostens K. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. Hydrobiologia 2015;756(1):19–35. https://doi.org/10.1007/s10750-014-1997-z.
[214] Alagna A, D'Anna G, Musco L, Fernandez TV, Gresta M, Pierozzi N, Badalamenti F. Taking advantage of seagrass recovery potential to develop novel and effective meadow rehabilitation methods. Mar Pollut Bull 2019;149:110578. https://doi.org/10.1016/j.marpolbul.2019.110578.
[215] Marques AT, Batalha H, Rodrigues S, Costa H, Pereira MJR, Fonseca C, et al. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. Biol Conserv 2014;179:40–52. https://doi.org/10.1016/j.biocon.2014.08.017.
[216] May R, Nygård T, Falkdalen U, Åström J, Hamre Ø, Stokke BG. Paint it black: efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. Ecol Evol 2020;10(16):8927–35. https://doi.org/10.1002/ece3.6592.
[217] Arnett EB, Hein CD, Schirmacher MR, Huso MM, Szewczak JM. Evaluating the effectiveness of an ultrasonic acoustic deterrent for reducing bat fatalities at wind turbines. PLoS One 2013;8(6):e65794. https://doi.org/10.1371/journal.pone.0065794.
[218] Edrén SMC, Andersen SM, Teilmann J, Carstensen J, Harders PB, Dietz R, Miller LA. The effect of a large Danish offshore wind farm on harbor and gray seal haul-out behavior. Mar Mamm Sci 2010;26(3):614–34. https://doi.org/10.1111/j.1748-7692.2009.00364.x.
[219] Weaver SP, Hein CD, Simpson TR, Evans JW, Castro-Arellano I. Ultrasonic acoustic deterrents significantly reduce bat fatalities at wind turbines. Glob Ecol Conserv 2020;24:e01099. https://doi.org/10.1016/j.gecco.2020.e01099.
[220] Werber Y, Hareli G, Yinon O, Sapir N, Yovel Y. Drone-mounted audio-visual deterrence of bats: implications for reducing aerial wildlife mortality by wind turbines. Remote Sens Ecol Conserv 2022. https://doi.org/10.1002/rse2.316.
[221] Coates DA, Kapasakali DA, Vincx M, Vanaverbeke J. Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea. Fish Res 2016;79:131–8. https://doi.org/10.1016/j.fishres.2016.02.019.
[222] Duineveld GC, Bergman MJ, Lavaleye MS. Effects of an area closed to fisheries on the composition of the benthic fauna in the southern North Sea. ICES J Mar Sci 2007;64(5). https://doi.org/10.1093/icesjms/fsm029. 899-08.
[223] Bergman MJ, Ubels SM, Duineveld GC, Meesters EW. Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone. ICES J Mar Sci 2015;72(3):962–72. https://doi.org/10.1093/icesjms/fsu193.
[224] Burger C, Schubert A, Heinänen S, Dorsch M, Kleinschmidt B, Žydelis R, et al. A novel approach for assessing effects of ship traffic on distributions and movements of seabirds. J Environ Manag 2019;251:109511. https://doi.org/10.1016/j.jenvman.2019.109511.
[225] Kelley DE, Vlasic JP, Brillant SV. Assessing the lethality of ship strikes on whales using simple biophysical models. Mar Mamm Sci 2021;37:251–67. https://doi.org/10.1111/mms.12745.
[226] Verfuss UK, Sparling CE, Arnot C, Judd A, Coyle M. Review of offshore wind farm impact monitoring and mitigation with regard to marine mammals. In: Popper A, Hawkins A, editors. The effects of noise on aquatic life II. Advances in experimental medicine and biology, vol. 875. New York, NY: Springer; 2016. p. 1175–82. https://doi.org/10.1007/978-1-4939-2981-8_147.
[227] Lüdeke J. Exploitation of offshore wind energy. In: Salomon M, Markus T, editors. Handbook on marine environment protection. Cham: Springer; 2018. p. 165–88. https://doi.org/10.1007/978-3-319-60156-4_9.
[228] Brandt MJ, Diederichs A, Betke K, Nehls G. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Mar Ecol Prog Ser 2011;421:205–16. https://doi.org/10.3354/meps08888.
[229] Greenhill L, Leakey C, Diz D. Workshop report: driving the transition to a resilient and inclusive future: the role of the ocean and policy coherence. 2021.
[230] Smyth K, Christie N, Burdon D, Atkins JP, Barnes R, Elliott M. Renewables-to-reefs?–Decommissioning options for the offshore wind power industry. Mar Pollut Bull 2015;90(1–2):247–58. https://doi.org/10.1016/j.marpolbul.2014.10.045.
[231] Margheritini L, Colaleo G, Contestabile P, Bjørgård TL, Simonsen ME, Lanfredi C, et al. Development of an eco-sustainable solution for the second life of decommissioned oil and gas platforms: the mineral accretion technology. Sustainability 2020;12(9):3742. https://doi.org/10.3390/su12093742.
[232] Boch CA, DeVogelaere A, Burton E, King C, Lord J, Lovera C, et al. Coral translocation as a method to restore impacted deep-sea coral communities. Front Mar Sci 2019;6:540. https://doi.org/10.3389/fmars.2019.00540.
[233] Westerberg V, Jacobsen JB, Lifran R. Offshore wind farms in the Mediteranean seascape: a tourist appeal or a tourist repellent. In: 18. Annual conference EAERE; 2011. p. 23. June.
[234] Borg J, Burgess S, Milo-Dale L. Protecting our Ocean: europe's challenges to meet the 2020 deadlines. WWF; 2019. https://wwfeu.awsassets.panda.org/downloads/protecting_our_ocean.pdf.
[235] Boero F, De Leo F, Fraschetti S, Ingrosso G. The Cells of Ecosystem Functioning: towards a holistic vision of marine space. Adv Mar Biol 2019;82:129–53. https://doi.org/10.1016/bs.amb.2019.03.001.
[236] Thiede J, Aksnes D, Bathmann U, Betti M, Boero F, Boxshall G, et al. Marine Sustainability in an age of changing oceans and seas. Luxembourg: Publications Office of the European Union; 2016. p. 52. EASAC Policy Report 28, http://www.interacademies.net/File.aspx?id=29455.