Knowledge synthesis

The impacts of offshore wind power on biodiversity and recommendations for assessing the risks

REFERENCE

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AUTHORS AND COORDINATORS

Hélène Soubelet, Claire Salomon et Jean-François Silvain

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INTRODUCTION

The impacts of offshore wind power have effects that, by their intensity, duration and/or severity, cause significant changes to biodiversity (Willsteed *et al.*, 2018).

Ever since the first deployment of offshore wind turbines, there has been controversy over the cost and alleged economic and environmental benefit of offshore wind power. Numerous research studies have tried to assess the impacts, whether positive or negative, of these installations on biodiversity and marine ecosystems, generating a high volume of publications. These impacts are very variable and differ depending on the wind turbine's life stage, location, type, its foundation and anchoring technology, the associated infrastructure, and the species that interact with these installations. Turbines are generally grouped together in offshore wind farms (OWFs), over more or less large areas, and at a variable distance from the coast. Coastlines are themselves highly biodiverse and culturally important areas, where sharing the use of the land, the sea, and their resources is a real issue. It is important to be aware here that the utilization of marine renewable energies leads to globally expanding human activities in marine habitats (Vilela *et al.*, 2021).

In 2019, a rapid review of the scientific literature on the impacts of renewable energy infrastructures on biodiversity, based on nearly 400 articles published between 1974 and 2020 on onshore and offshore wind power, highlighted the following negative impacts, affecting mainly birds and bats (French Foundation for Biodiversity Research (*Fondation pour la recherche sur la biodiversité*, FRB), 2019):

- mortality from collision or barotrauma due to blade movement;
- mortality from habitat loss or habitat modification;
- the barrier effect of wind farms inducing avoidance behaviours and the displacement of certain populations;
- disturbance caused by noise and electromagnetic fields generated during construction or operation (particularly on sea mammals);
- disturbance linked to light pollution (warning lights on turbines), affecting the flight of nocturnal species.

As well as positive effects:

- a "reef" effect, leading to the colonization of the base of the structure by communities of marine species;
- a "reserve" effect due to the exclusion of fishing from OWF areas, creating *de facto* protected areas.

Other risks or impacts are less well documented but nonetheless real, such as an increased risk of the spread of non-indigenous species and the homogenization of habitats, as well as the loss of environmental, socio-cultural, and touristic value. More globally, the mid- to long term effects of the installation of numerous OWFs on marine ecosystems remain to be established.

Offshore wind installations can thus have negative or positive impacts on biodiversity and fisheries resources, but it is difficult to say whether their impacts are globally and unequivocally "positive", "negative", or "neutral". Such conclusions depend on the biological community or species in question, and combine both quantitative (the number of bird collisions, for example) and qualitative (fatalities will not have the same impact on long-lived low reproductive species compared to short-lived high reproductive species) components. Even though there are still important technical obstacles that prevent the precise quantification of the direct and indirect impacts of OWFs (*e.g.* counting bird carcasses at sea is nearly impossible), and many uncertainties and knowledge gaps (see Appendix 1), in particular in terms of quantifying the impacts of the cumulative pressures arising from the planned multiplication of OWFs in

France and across Europe, the publication rate on this topic has grown, especially over the past eight years, and is still growing, reflecting the development of offshore wind power worldwide (Appendix 1).

This paper is an exploratory review of the latest results from scientific papers on offshore wind power (Chapter 1) and associated recommendations (Chapter 2).

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Chapter 1. Update of the current state of knowledge on the impacts of offshore wind installations on biodiversity

The chapter is based on a recent literature review by Galparsoro *et al.* (2022) on the impacts of OWFs, and an article by Baulaz *et al.* (2022) that surveyed the pressures exerted by these installations and their effects on ecosystem services. These articles were complemented with information, references, and conclusions from the report by the National Council for Nature Protection (*Conseil national de la protection de la nature*, CNPN) on the development of offshore wind power in France and its impacts on biodiversity, natural heritage and landscapes. Finally, additional information was provided by the analysis of recent scientific publications on this topic.

1.1. Synthesis of the literature review by Galparsoro *et al.* (2022)

In their recent literature review, Galparsoro *et al.* (2022) analyzed a total of 867 scientific findings extracted from 158 publications on the pressures from OWFs on biodiversity/ecosystems. The type of study and the characteristics of the installations are presented in Figure 1 and Figure 2, respectively.

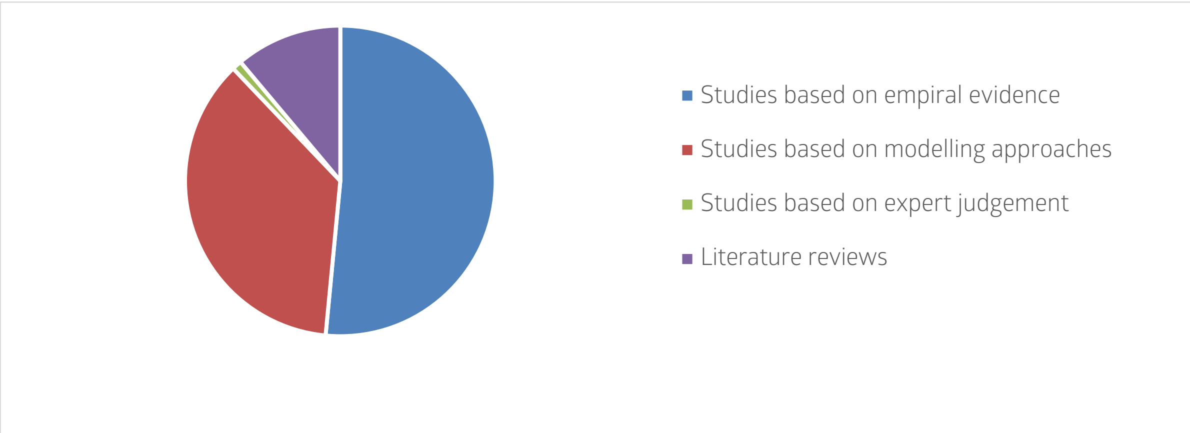

Figure 1: Percentage of studies (out of 158 selected publications).

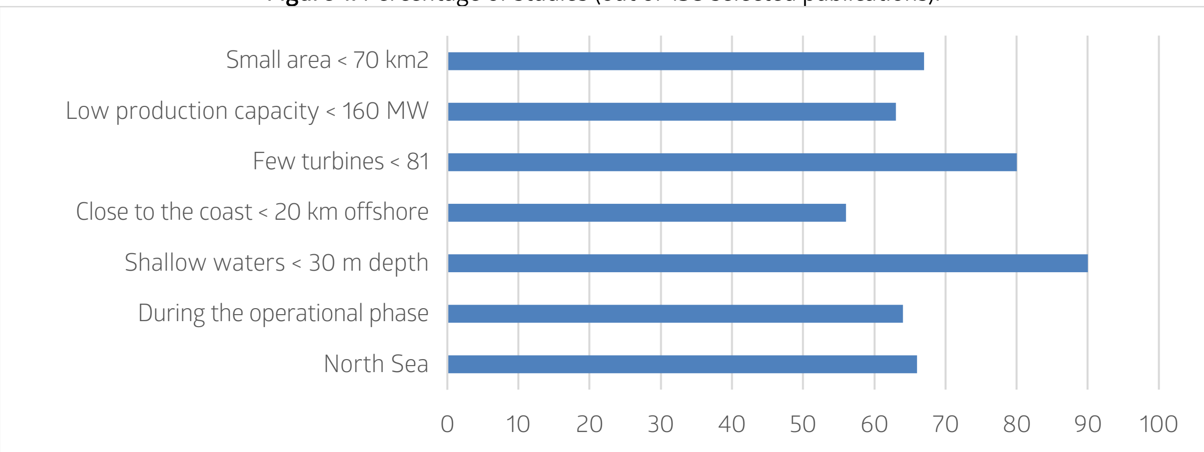

Figure 2: Percentage of studies (out of 158 selected publications).

Among the 867 findings, 72 % reported negative impacts, while 13 % were positive. 54 % of impacts were reported to be high or moderate, while low or negligible impacts accounted for 32 %.

Figure 3 shows the proportion of scientific studies that demonstrate an impact on one or more of the three dimensions of ecosystem integrity, namely its composition (including the impact on different taxonomic groups such as fish, birds, etc.), structure (the impact on habitats, biotic homogenization, etc.), and function (*e.g.* the impact on species interactions, or their ability to adapt).

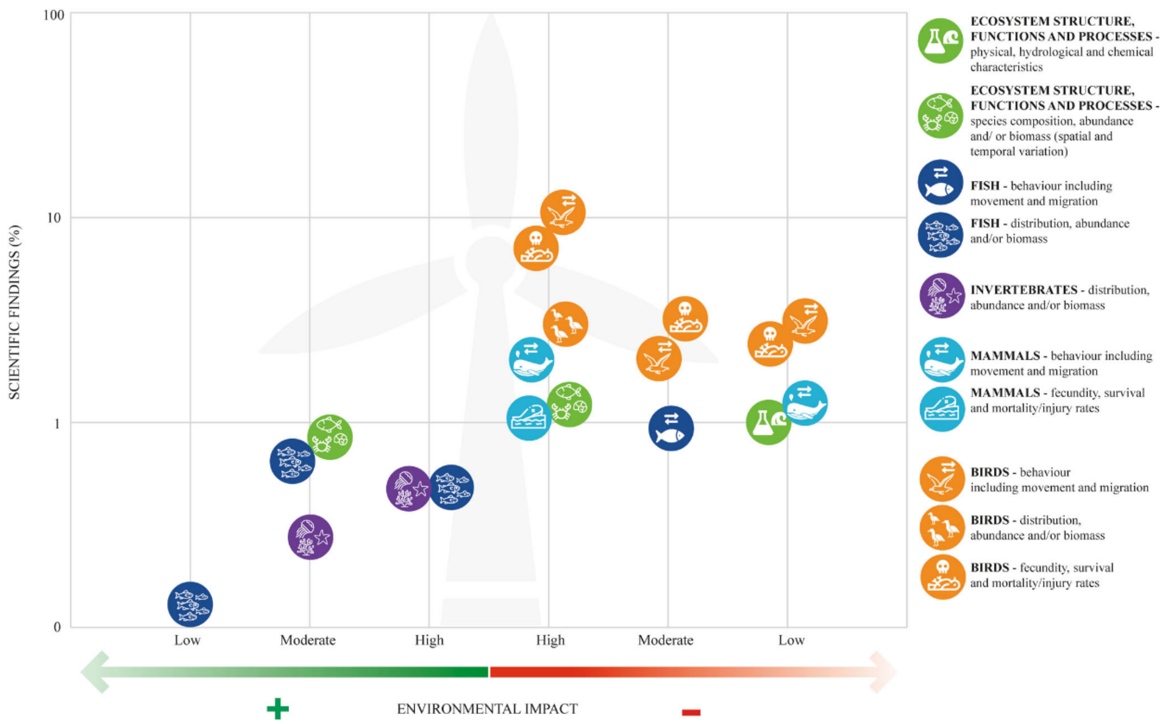

Figure 3: The number of studies reporting a positive or negative impact on indicators of ecosystem integrity (composition, structure and function, from Galparsoro *et al.*, 2022).

The synthesis of the results from these scientific studies shows that offshore wind energy production can have both positive and negative effects on marine ecosystems.

We can see that negative impacts are reported more frequently and are better documented (high level of scientific consensus), especially in relation to birds, marine mammals, and ecosystem structure. Positive impacts, usually in relation to fish and invertebrates, are less documented (greater uncertainty). The impacts on ecosystem function can be both positive or negative, but are generally still poorly documented.

An additional difficulty for assessing the impact of offshore wind energy is that the ecological risks associated with offshore wind installations can vary depending on local environmental characteristics, the vulnerability of affected species (for instance, the presence of migratory bird species that are particularly sensitive to wind turbines), and the initial state and resilience of the area, which can change substantially for some ecosystem elements.

Moreover, the number of publications plays an important role in the interpretation of the robustness of an impact (for instance, if only one article describes an impact or the magnitude of a pressure on an element of the ecosystem, a cautious interpretation is warranted).

From the 867 findings, 10 pressures were analyzed, the most frequent of which being biological disturbance and sound (62 % and 18 % of the findings, respectively). The lack of studies on certain pressures or certain elements of ecosystem function represents a gap in the analysis of the impacts of offshore wind energy devices (see Appendix 1).

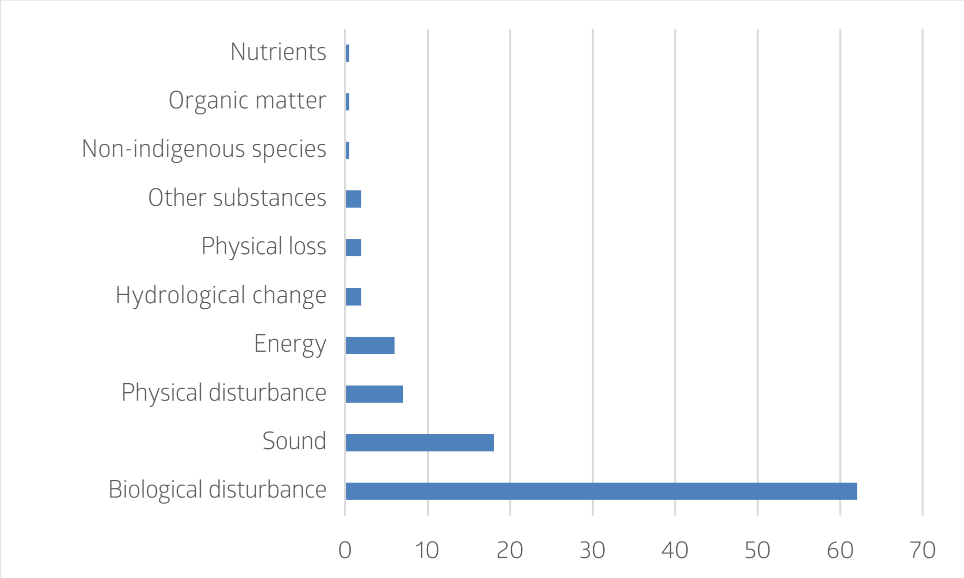

Figure 4: Types of pressure exerted on marine ecosystems (% of studies, out of 158 selected publications).

Physical disturbance
Biological disturbance
Sound (including noise)
Energy (including electromagnetic fields)
Hydrological change
Non-indigenous species
Nutrient input
Organic matter input
Input of other substances (organic and non-organic)

Table 1. Types of pressure that need to be considered.

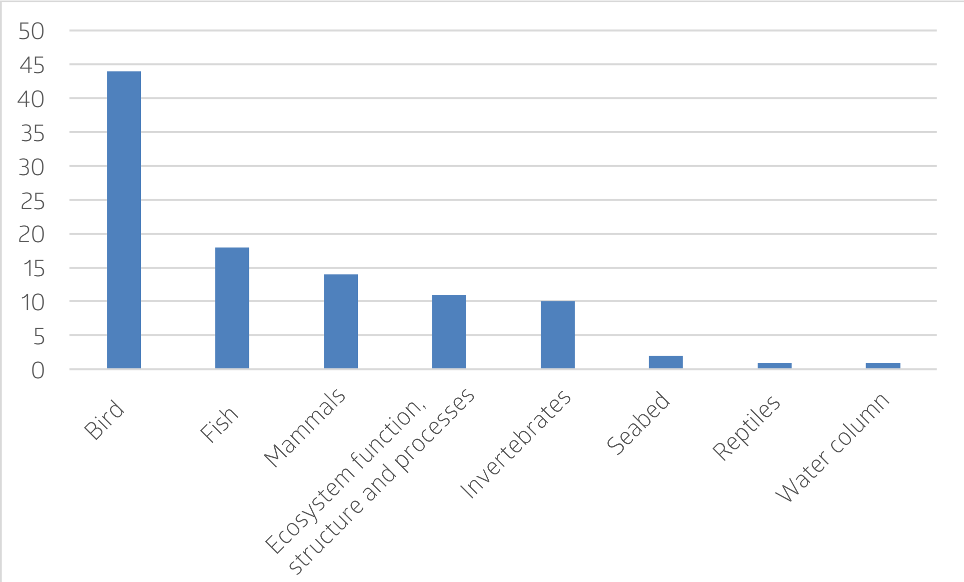

Figure 5: What is impacted? (% of studies, out of 158 selected publications).

87 % of publications focused on species (especially birds, and to a lesser extent fish), 11 % on ecosystem structure, functions and processes, and 3 % on habitats (seabed and water column).

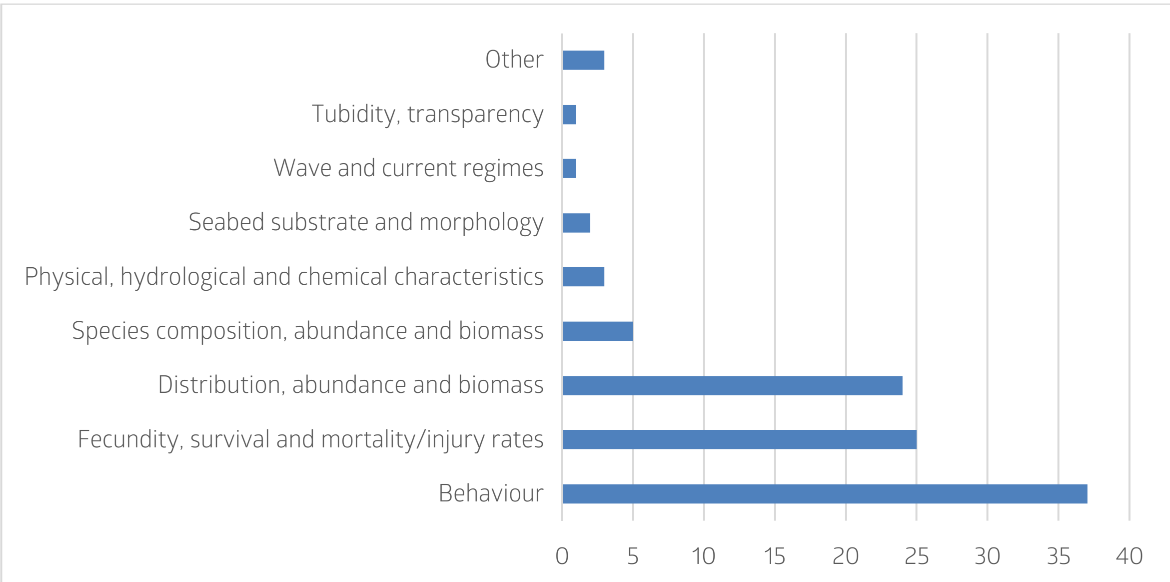

Figure 6: Types of impact (% of studies, out of 158 selected publications).

The most studied indicators in the literature were behaviour (37 %), fecundity, survival and mortality /injury rates (25 %) and distribution, abundance and/or biomass (24%).

A description of the impacts by taxonomic group is possible by crossing pressure (Table 1), type of impact (positive or negative) and its magnitude (see Figures 5 and 6 showing the percentage of studies reporting an impact linked to biological disturbance and noise).

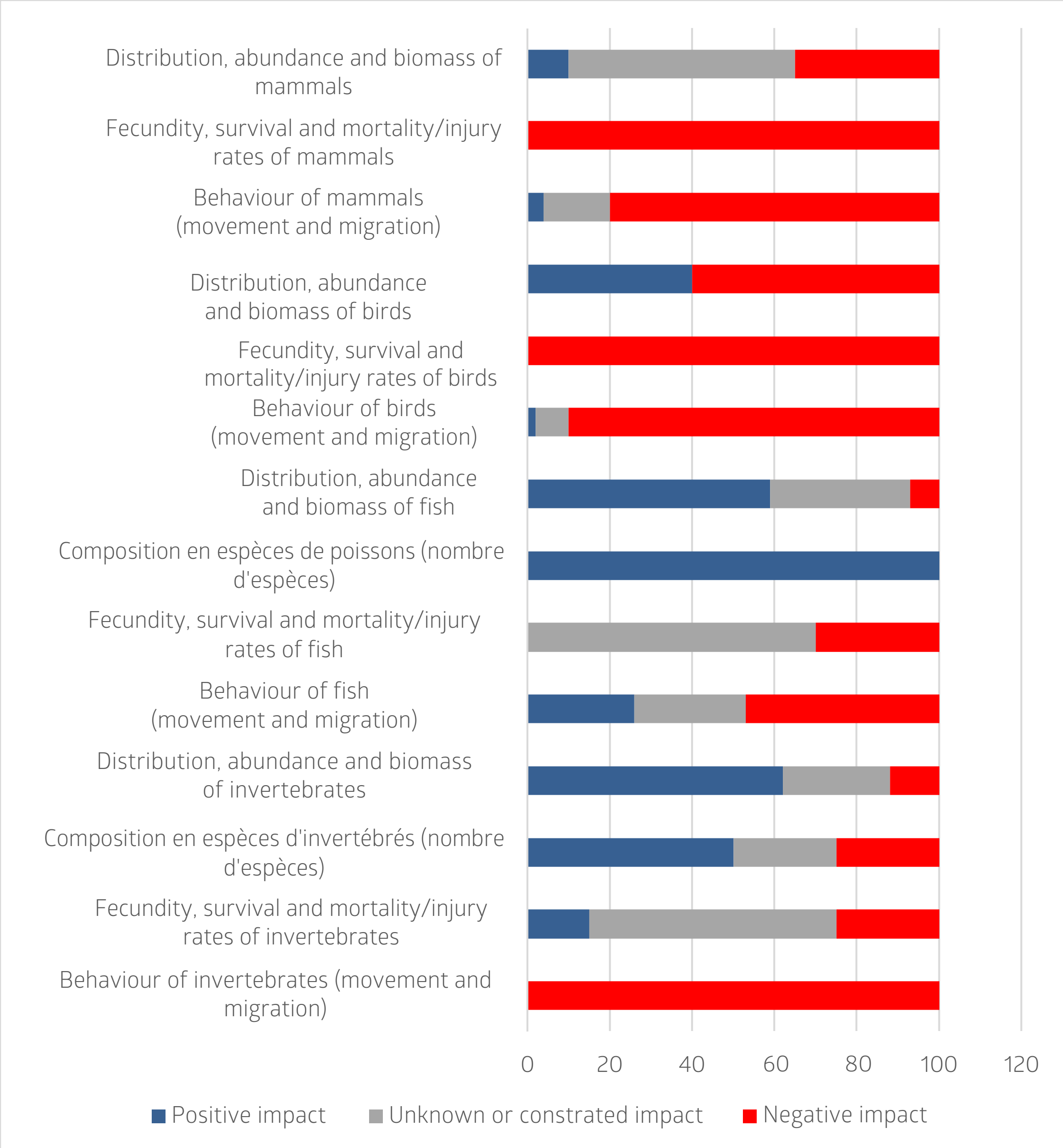

Figure 7: Direction and nature of the impact (biological disturbance) of operating offshore wind turbines on different taxonomic groups (% of studies reporting an impact).

Figure 7 shows the percentage of studies reporting an impact affecting different indicators of biological disturbance in mammals, birds, fish and invertebrates (from Galparsoro *et al.*, 2022, supplementary material). Overall, the most frequently reported impacts were negative impacts on fecundity, survival and mortality rates, and the behaviour of mammals, birds and invertebrates, and broadly positive impacts on fish species composition and the distribution and abundance of fish and invertebrates.

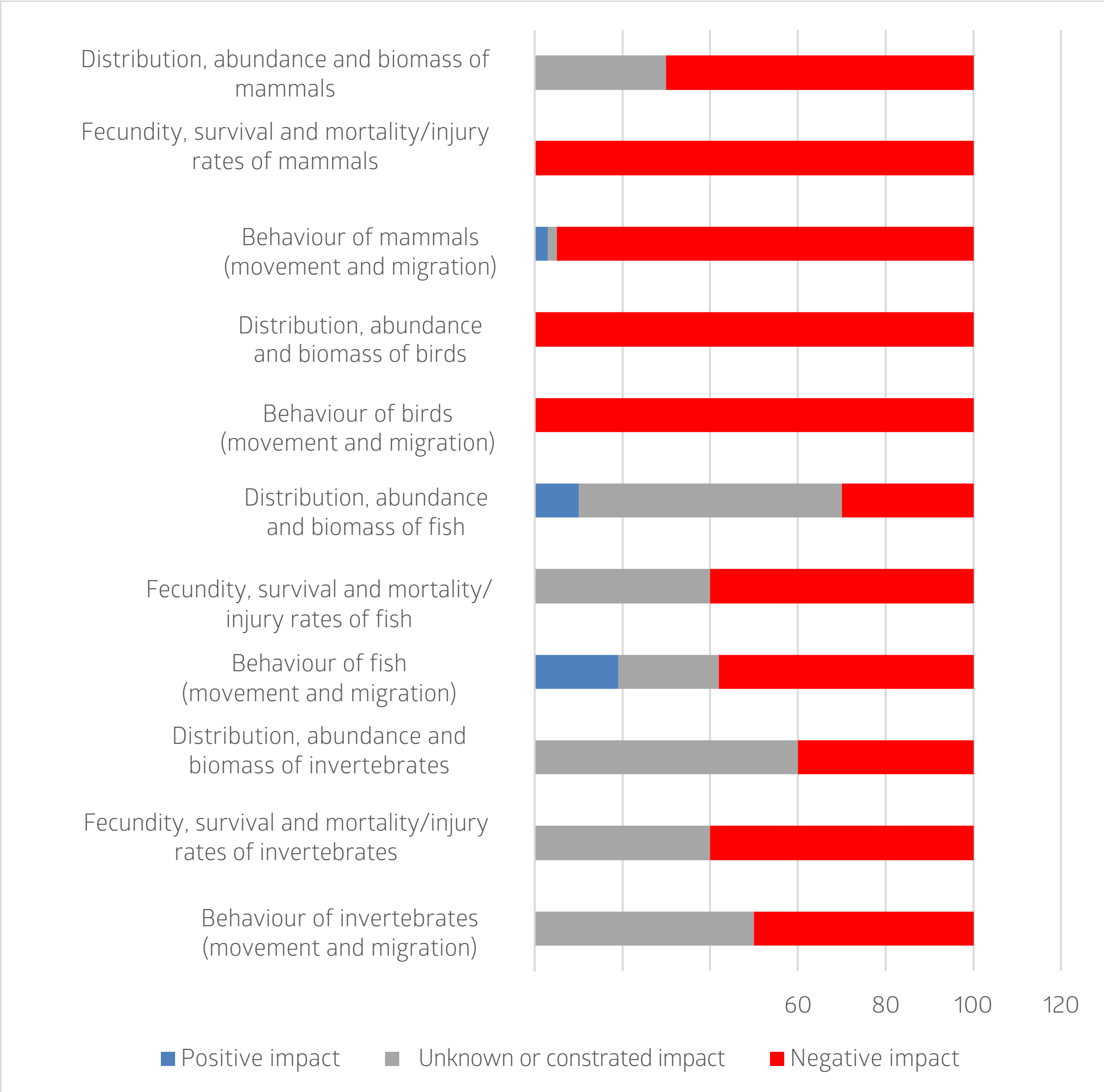

Figure 8: Direction and nature of the impact of noise from operating offshore wind turbines on different taxonomic groups (% of studies reporting an impact).

Figure 8 shows the percentage of studies reporting an impact of noise produced by operating offshore wind turbines on indicators in mammals, birds, fish and invertebrates (from Galparsoro *et al.*, 2022, supplementary material).

1.2. Impacts on species

1.2.1. Impacts on birds

For all ecosystem components, negative effects, ranging from moderate to high, represented 45 % of the scientific findings, of which 32 % were effects on birds (changes in abundance due to mortality by collision or displacement, changes in distribution, and behavioural changes to avoid installations). Species are variably sensitive to pressures from wind turbines, and show different responses depending on their ecology (*e.g.* flight altitude, distribution, migration period, sex).

We will frequently refer to the report by the CNPN on the subject of the impacts of offshore wind energy on biodiversity (CNPN, 2021).

Mortality from collision

Flight altitude, for example, is a potential mortality factor: the most emblematic birds that fly at rotor height are northern gannets, black-legged kittiwakes, little gulls, terns, skuas, brants and loons, which are all potentially at risk (CNPN, 2021). Most collisions involve gulls, because they are present in high numbers all year round in coastal maritime areas. These collisions are problematic, notably for lesser black-backed gulls (*Larus fuscus*) and great black-backed gulls (*Larus marinus*), which are less common; however, the prevalence of gull collisions should not give the impression that other species are less at risk (CNPN, 2021).

The clearest and best documented negative impacts affect species such as the common guillemot (*Uria aalge*) and the northern gannet (*Morus bassanus*), which display an avoidance behaviour near operating wind energy devices. During the breeding season, the abundance of common guillemots (*Uria aalge*) in the OWF area decreased by 75% (Peschko *et al.*, 2020). In the German North Sea, loon (Gaviidae) density was found to decrease by 94 % within a 1 km radius of the OWF, and by 52 % within a 10 km radius (Garthe *et al.*, 2023). Avoidance behaviour and habitat loss have energetic costs that can only increase with the multiplication of the number of OWFs (Schwemmer *et al.*, 2023). A study in the Netherlands assessing the impact of wind farm development in the North Sea predicts that common guillemots and razorbills (*Alca torda*) will have the highest mortality due to habitat loss, followed by northern fulmars (*Fulmarus glacialis*) (Soudijn *et al.*, 2022). By contrast, other marine birds such as large gulls (*e.g.* the European herring gull (*Larus argentatus*)), seem attracted to these installations due to enhanced feeding opportunities in the intertidal reaches of the turbines (Vanermen *et al.*, 2017). Only 1 % of results showed high to moderate positive effects on birds, for instance, by attracting gulls or cormorants that perch on these structures (CNPN, 2021), even though this behaviour increases the risk of collision (Vanermen *et al.*, 2020).

This type of impact contributes significantly to the controversies surrounding offshore wind power, and poses a number of questions regarding the anthropogenization of the planet and the space left for non-humans. For instance, it is important to clearly differentiate between what is related to direct mortality and what is related to behavioural reactions that will lead to habitat loss (loss of feeding habitats for seabirds, and changes in migration paths), which may cause indirect mortality. It is also important to distinguish seabirds, which are often long-lived (meaning that adult mortality is low) with (very) low reproductive rates, from landbirds with short life cycles and high reproductive rates. As highlighted in the CNPN report (2021), procellarids (shearwaters and fulmars), alcids (puffins, guillemots, and razorbills), and northern gannets only lay one egg each year, are slow to reach sexual maturity, and have a lifespan of more than 30 years (up to 50 years for procellarids). By contrast, tits lay around twenty eggs a year, and have an adult lifespan of only two years. Terns and larids (gulls) have an intermediate strategy, laying three or four eggs a year and having a lifespan of around 20 years. Both seabirds and landbirds migrate over water and have the same collision risk, but the impact of these collisions on their population dynamics will differ: a 5 % increase in mortality was considered incompatible with the survival of seabird species (Dierchke *et al.*, 2003), and this can be as low as 1 % for vulnerable or declining species (Everaert, 2013) (in CNPN, 2021). Observations made on onshore wind power, whose impact on birds must be assessed not only quantitatively but also qualitatively (their major impact on certain rare species of raptors), are also applicable to offshore wind power. However, the differences between seabirds and landbirds must not lead us to neglect the risk of massive mortality in landbirds during their nocturnal migration under certain weather conditions in the Channel and the North Sea, but also in the Mediterranean where hundreds of millions of birds leave the coast at dusk from September 1 to October 31, knowing that 25 % of this nocturnal migration takes place at an altitude of less than 200 m (CNPN, 2021).

Long term studies are needed, especially on seabirds, to assess the incidence of direct mortality, the effects of breeding or feeding habitat loss, and the effects of changes in migration paths on species demographics, while bearing in mind the constraints, such as the near impossibility of finding bird carcasses at sea. It is also essential to take into account the cumulative effects associated with the multiplication of OWFs, often in close proximity.

Reflections on the impacts on birds and the current state of knowledge on this matter should lead to new ideas for reducing these impacts.

1.2.2. Impacts on mammals

Up to 7 % of results showed that OWFs had a negative impact on marine mammals (all of which have protected status in France), depending on the development phase of the OWF. During construction, pile driving operations can have a significant impact on the health, abundance and distribution of mammals, as seen for example from the avoidance behaviour displayed by harbour porpoises (*Phocoena phocoena*), which temporarily leave the construction area (Brandt *et al.*, 2018). Spatial avoidance has also been observed in common bottlenose dolphins (CNPN, 2021). The extent of dolphin habitat loss due to prolonged construction works was assessed and measured with relative certainty using prior knowledge of this species' hearing and sensitivity to high sound levels (Bailey *et al.*, 2014). Observations of animals in captivity suggest that the common bottlenose dolphin and the harbour seal are sensitive to these auditory pressures (CNPN, 2021).

Species	**Acute auditory risk**	**Extent of habitat loss**	**Consequence on populations**
Minke whale	Threshold **unknown**	**Unknown**	Effect **unknown**
Harbour porpoise	Threshold known	Known	Effect certain
Common dolphin	Threshold **unknown**	**unknown**	Effect **unknown**
Common bottlenose dolphin	Threshold known	Studied	Effect assessed
Grey seal	Threshold **unknown**	**unknown**	Effect **unknown**
Harbour seal	Threshold known	Studied	Effect assessed

Table 2: Summary of the current knowledge of the effects of sound levels on the marine mammals occurring in French waters (Alexandre Gannier for the CNPN).

After the construction phase, the abundance of harbour porpoises in the North Sea seems to increase, these animals using the installations more frequently that the control areas (but see Nachtsheim *et al.* (2021), who note a decline in this species' density). This may be due to an increase in food availability as a result of less fishing, artificial reef effects, and the absence of boats (positive effects) or, conversely, to a reduction in the primary biomass available for the pelagic ecosystem as a result of an increase in common mussel biomass (negative effect) (CNPN, 2021). Russell *et al.* (2014) showed that individual harbour seals (*Phoca vitulina*) undertake feeding trips to offshore wind structures in Scotland. As stated in the CNPN (2021) report, there is no doubt that certain species will adapt to changes to this environment, all the more so with the increase in the number of offshore wind installations, which will have an impact on the entire marine ecosystem. Thus, it may be that the installation of offshore wind turbines on a massive scale will result in a significant long term increase in common bottlenose dolphin populations, attracted by changes to the fish assemblage composition (increase in prey such as cod and *Trisopterus*) on the continental shelf of the Gulf of Gascony, as well as promote the establishment of grey seal colonies; it is therefore possible that harbour porpoise populations will suffer unfavourable consequences from the increase in abundance of these two species. And naturally, an increase in these two species would also have an impact on another predator of fish: the fisherman.

This illustrates how a change in the ecosystem can have unforeseen consequences. The CNPN (2021) stresses that there are likely to be ecosystemic effects but these cannot be assessed by modelling. In particular, the effects on North Sea harbour porpoises cannot be extrapolated to other species of marine mammals on the French coast, bearing in mind that the growing effects of climate change also need to be taken into account.

The impacts of offshore wind energy on bats are poorly known (lack of carcasses) but potentially high. We now know that many bat species (like seabirds, they are long-lived species with low reproductive rates) migrate over water. Consequently, we need to be able to estimate to what extent the development of OWFs will contribute to the mortality of these animals, and find ways to mitigate this impact.

Indeed, as mentioned in the CNPN's report (2021), the ability of bats to travel long distances over water during migration is now well established from observations made from offshore oil and gas platforms in the North Sea and the Baltic Sea (Stansfield, 1966; Boshaller and Bekker, 2008; Ahlén *et al.*, 2009; Rydell *et al.*, 2014; Rodrigues *et al.*, 2014). The first proven case of a migration between England and the continent only dates back to 2013, where a Nathusius' pipistrelle (one of the species most impacted by onshore wind turbines) travelled 600 km between the north of Somerset (western England) and the Netherlands (Bat Conservation Trust, 2014). A number of Scandinavian species travel more than 400 km across the Baltic Sea between Sweden and Germany, and 170 to 225 km between Sweden and Poland during 9 hour-long overnight flights, although some individuals may also rest on boats (Ahlén *et al.*, 2009). The study of Ahlén *et al.* (2009) also showed that many species (11 – 14 of the 18 Scandinavian species), whether resident or migratory, forage at sea (as far as 14 – 19 km from the coast) between Sweden and Denmark, in search of flying insects or crustaceans. In Belgium, Brabant *et al.* (2017) found 4 species at sea, including the Nathusius' pipistrelle, as far as 25 km from the coast; the latter is also the most frequently found at sea in the Netherlands (Lagerveld *et al.*, 2014) (in CNPN, 2021).

Like in birds, flight altitude influences mortality in bats (direct collision and barotrauma), and Alhén *et al.* (2009) noted that both migratory and resident bats at sea, which often fly near the water surface, change their flight altitude in the presence of vertical structures such as lighthouses, boats and wind turbines, and find themselves at rotor height (CNPN, 2021). Moreover, one cannot ignore the impact, like on land, of the loss of feeding habitats for species that use marine environments for food.

There are important gaps in our knowledge of bat ecology and long term studies are needed to better assess the present and future impacts of offshore wind energy on this taxonomic group, some species of which are in decline in Europe. There is therefore a need to develop practices that can effectively reduce mortality; a better understanding of the phenology and climate conditions associated with bat migrations would probably help in this regard (Brabant *et al.*, 2021).

1.2.3. Impacts on fish

Three non-mutually exclusive phenomena can occur near artificial reefs:

- an increase in global fish abundance with positive effects on survival and growth (for instance, less energy needed for foraging);
- attraction without any net increase in local populations;
- a decline in the state of the population from an ecological trap effect, where individuals are attracted to sub-optimal habitats (Reubens *et al.*, 2014).

Moreover, the prohibition of bottom trawling near wind energy installations for safety reasons eliminates the pressure from fishing, which is the most important pressure on marine biodiversity (Ipbes, 2019).

Little research on the impact, either positive or negative, on fish has been carried out. The review by Galparsoro *et al.* (2022) documents 2 % of moderate negative impacts and 2 % of moderate positive impacts. These impacts are species dependent. The most vulnerable species appear to be elasmobranchs (rays, sharks), large migratory fish (such as tuna, *Thunnus* sp.) and Clupeidae, which can be disturbed, depending on the complexity of their auditory system, by the sounds emitted during construction or when turbines are operating. Elasmobranchs seem to be particularly sensitive to electromagnetic fields from underwater cables (CNPN, 2021). Nonetheless, the literature also documents positive effects, notably from ecological changes linked to the reef effect, *i.e.* the installation of hard substrates on originally sandy substrates, such as the diversification and complexification of habitats, and an increase in fish concentration and thus an increase in the local availability of prey (Tickell *et al.*, 2019) that attract predators and scavengers. Spillover effects (*i.e.* an increase in the number of individuals of a species that cross over into neighbouring habitats) have been documented for small fish living near the seabed (demersal fish) and rockfish. Multiple studies have found that species numbers also increased, sometimes above the number of species in natural reefs (Zettler *et al.*, 2006 ; Wilhelmsson *et al.*, 2008), and in all cases, above the number of species occurring in adjacent soft sediment environments. The reef effect can also induce the proliferation and expansion of invasive species (CNPN, 2021), and the disappearance of indigenous species (Degraer *et al.*, 2013). Moreover, potential chemical pollutants associated with the use of metallic structures and anodes used to prevent their corrosion, which may release aluminium, must not be ignored (CNPN, 2021; table from Baulaz *et al.*, 2023, see below).

The cumulation of changes at the scale of each installation, and in particular the reef effect on a small scale, can have effects on ecosystem services, such as an increase in abundance of overfished species. There is also a connectivity effect (connection between different reefs) within OWFs that affects different life stages (larvae, adults), depending on the species and its biology, including seasonal or opportunistic species (Reubens *et al.*, 2014; Russel *et al.*, 2014).

Species that benefit from the installations	Nature and source of the positive impact	Reference(s)
Atlantic cod (*Gadus morhua*), pouting (*Trisopterus luscus*), Arctic sculpin (*Myoxocephalus scorpioides*)	Predators of communities of organisms that colonize parts of the turbines	Mavraki *et al.,* 2020
Atlantic horse mackarel (*Trachurus trachurus*)	Occasional predator of organisms that colonize parts of the turbines	Mavraki *et al.,* 2020
Atlantic mackarel (*Scomber scombrus*)	Not for feeding, but to find shelter or other individuals of the same species, which can lead to the formation of bigger shoals and thus increase their safety and the chance of finding food and mates	Mavraki *et al.,* 2020
Atlantic cod (*Gadus morhua*), pouting (*Trisopterus luscus*), black sea bass (*Centropristis striata*), golsinny wrasse (*Ctenolabrus rupestris*)	Spend at least part of their life cycle close to offshore wind structures	Bergström *et al.*, 2013; Reubens *et al.*, 2014; Wilber *et al.*, 2020
Pouting (*Trisopterus luscus*)	Populations fare better inside the OWF than outside in the summer and autumn during the juvenile phases, before migrating to their spawning grounds outside Belgian waters	Reubens *et al.*, 2014
Six species of flat fish	Benefical effect of OWFs on larval fluxes to nursery grounds on the southern coast of the North Sea	Barbut *et al.*, 2020

Table 3: Example of species that benefit from offshore wind installations (from Galporsoro *et al.*, 2022).

1.2.4. Impacts on benthic communities

According to the review by Galparsoro *et al.* (2022), studies on benthic communities (*i.e.* organisms that reside on the sediments of aquatic environments) are still scarce, but most report positive effects.

Two perspectives need to be considered here. First, the direct positive impacts from reef and reserve effects: these effects are mainly due to the process of ecological succession following changes in the environment. Species that colonize this new environment modify the local functioning of the ecosystem and allow even more species to colonize the area. Second, offshore wind installations seem to have fewer negative impacts than other types of renewable energy installations: in particular, their higher yield allows for a lower use of natural space, the landscape is less impacted, there is less noise, and production and delivery costs are lower.

Ecological successions on and near offshore wind installations

OWFs and the concentration of marine organisms they attract affect ecosystem structure and functioning, at least on a local scale (Degraer *et al.*, 2020).

During the pioneer stage (0 -2 years), there is a structural ecological response to the disturbance represented by habitat loss (usually the loss of soft sediments) caused by the installation of offshore wind turbines. This new habitat is colonized by flora and fauna, with an increase in diversity and biomass compared to the surrounding soft sediments. Colonizing species may include non-indigenous species that are extending their spatial distribution and/or reinforcing their population, locally rare species (*e.g.* hard substrate-associated fish), and habitat-forming species that further increase habitat complexity.

ROLE OF HABITAT-FORMING SPECIES

Some species create habitats and induce a "stepping-stone" effect. Over time, these species can create secondary biogenic reefs that are home to many – often rare – species and offer great value with regards to ecosystem functioning. It is important to understand the role of these artificial habitats in maintaining local populations of these rare species, as they are likely to have important implications for the future decommissioning of OWFs (Fowler *et al.*, 2020).

The most dominant colonizing species of offshore wind installations is the blue mussel (*Mytilus edulis*), which has profound bio-engineering and reef construction effects on surrounding sediments. Mussels shells form secondary hard substrates at the base of the turbines, or further away by passive transport, providing a habitat for other species. In addition, mussels aggregate with macrofaunal communities on sediments. This was seen on mobile sediments near turbines (< 50 m) in Belgian and American waters (Lefaible *et al.*, 2019). The range and longevity of these aggregates is poorly known, as is their contribution to the restoration of bivalve reef function, which historically was provided by oyster beds (*Ostrea edulis*) in the North Sea (Bennema *et al.*, 2020).

During the intermediate stage (3 – 5 years), there is a biological and functional diversification with the appearance of suspension feeding organisms that transform the living pelagic organic matter pool (phytoplankton, zooplankton, and detritus) into partially dissolved and bioavailable nutrients, and produce (pseudo)faeces that are partly deposited on the seafloor (see Table 4). Over 95 % of the biomass on artificial structures can be composed of various species of suspension feeders (Coolen *et al.*, 2020), several of which are highly resource flexible, switching between suspended food sources, possibly due to interspecific competition or benefiting from food sources available in abundance (Mavraki *et al.*, 2020). By filtering the water, the organisms remove particles that would have otherwise passed by, resulting in lower turbidity and increased light penetration. This "biofilter" effect has been demonstrated at the local scale and in the laboratory, however, in-depth understanding of this effect under real conditions, in particular in OWFs, is currently lacking (Dannheim *et al.*, 2020). There can also be local depletion of organic matter from the water column and an increase in organic matter on the seafloor from faecal deposits that alter the surrounding seafloor communities by locally increasing food availability. Higher trophic levels (fish, birds, marine mammals) also profit from locally increased food availability and/or shelter.

Species	Mode of action	Comment
Blue mussel *Mytilus edulis*	Actively filters water and ingests particles from it.	One of the most abundant species
Amphipod *Jassa herdmani*	Grabs particles from the passing water to eat and to build its tube.	
Plumose anemone *Metridium senile*	Passively extends its tentacles in the water, waits for particles to stick to them, then takes the particles in.	Very abundant

Table 4: Examples of suspension feeders and their mode of action.

The climax stage (6 + years) is co-dominated by plumose anemones (*Metridium senile*) and blue mussels (*Mytilus edulis*) (Kerckhof *et al.*, 2019) in the older and deeper section (~15 – 50 m) (Coolen *et al.*, 2020. In the long term, the vertical section of offshore foundations forms a uniform habitat dominated by a few competitive species. In addition, OWFs attract very mobile predatory species.

1.2.5. Impacts on rare species

Habitat change and in particular the addition of hard substrates in an environment consisting mostly of mobile sediments may help the establishment and reproduction of locally rare, even endangered, species. This phenomenon should increase with the multiplication of OWFs, and contribute to the size, distribution and connectivity of populations of rare species (examples given in Table 5).

Geographic area	Rare species (reference)	Comment
North Sea	Barnacle (*Balanus perforatus*) (De Mesel *et al.*, 2015)	Hard substrate species
OWF in operation for 5 years	Grey triggerfish (*Balistes carolinensis*) and goldsinny wrasse (*Ctenolabrus rupestris*) (Van Hal *et al.*, 2017)	Three times more fish around hard structures that on soft sediments
Block Island Wind Farm (USA) and the North Sea	Colonization by coral (*Astrangia poculata*), stony coral (*Desmophyllum pertusum*), and the European flat oyster (*Ostrea edulis*) (Kerckhof *et al.*, 2019).	

Table 5: Examples of rare species found at OWFs.

1.2.6. Impacts on non-indigenous species

The installation of offshore wind turbines creates new habitats in open waters and provides an opportunity for non-indigenous species to occupy an empty ecological niche and extend their distribution or increase their population size. No report has yet been published on the expansion and proliferation of non-indigenous infralittoral species in relation to the installation of wind turbines. Although there are concerns that OWFs could threaten indigenous communities (Glasby *et al.*, 2007; Adams *et al.*, 2014), this has not yet been demonstrated.

A number of species have been documented (examples given in Table 6).

Geographic area	**Non-indigenous species (reference)**	**Comment**
Southern North Sea	Pacific oyster (*Crassostrea gigas*) and marine splash midge (*Telmatogeton japonicus*) (De Mesel *et al.*, 2015)	Historical OWF site in shallow coastal waters
Subtidal samples, Belgium	Common slipper limpet (*Crepidula fornicata*)	
Subtidal samples, the Netherlands	Six out of 11 non-indigenous species were found (Coolen *et al.*, 2020a)	
Bock Island Wind Farm (USA)	Invasive non-indigenous tunicate (*Didemnum vexillum*)	Observed on foundations and as an epibiont of mussels

Table 6: Examples of non-indigenous species found at OWFs in Europe and the USA.

1.3. Typology of the potential pressures of OWFs on ecosystems during construction and operation

The study by Baulaz *et al.* (2023) suggests that all trophic levels are affected, to varying degrees, by OWFs.

1.3.1. Construction phase

Pressures	**Spatial extent** *Local: < 100 m from the turbine; buffer zone: 500 m to 4 km from the wind farm; regional: up to 20 km from the wind farm*	**Impacts**	**References**
Modification of the ecosystem: - rearrangement of the benthos,	Local	- possible benthic anoxia, - lowered light levels for primary producers, - physical damage to filter and suspension feeders,	Dannheim *et al.*, 2020; Lange *et al.*, 2010

- increased turbidity, - alteration of organic matter and detritus fluxes.		- egg smothering for secondary and tertiary consumers.	
Modification of the ecosystem: - digging and crushing of the substrate during the installation of foundations and connecting cables.	Regional	- mortality of infauna and sessile species and loss of essential habitats, - stress and avoidance behaviours are to be noted for species able to move away from the construction site, - over 27 % loss of primary producers and groups of primary consumers.	Degraer *et al.*, 2019
Sound and vibrations: from pile driving (installation of foundations in the seduments).	Buffer zone	- physical damage and stress - avoidance of the construction area and changes in the distribution of the most sensitive groups of species (top predators, particularly marine mammals, and to a lesser extent some species of fish and crustaceans).	Dannheim *et al.*, 2020; Degraer *et al.*, 2019; Lindeboom *et al.*, 2011; Petersen and Malm, 2006

Table 7: Nature, spatial extent, and impact of pressures during the construction phase (from Baulaz *et al.*, 2023).

1.3.2. Operational phase

Pressures	**Spatial extent** *Local: < 100 m from the turbine; buffer zone: 500 m to 4 km from the wind farm; regional: up to 20 km from the wind farm*	**Impacts**	**References**
Collisions with masts and blades	Local	Bird and bat fatalities	Garthe and Hüppop, 2004
Barrier effect: avoidance, exclusion	Regional	Behavioural: - changes in migration routes, reduction in feeding areas, loss of resting sites,	Reviewed in CNPN, 2021; Peschko *et al.*, 2020; Vilela *et al.*, 2021; Soudijn *et al.*,

		- increased energy expenditure and risk of indirect mortality, - increased energy expenditure of migratory species of fish, birds and marine mammals as they seek to avoid farms by a long distance (up to 3 km).	2022; Garthe *et al.*, 2023; Schwemmer *et al.*, 2023
Reef effect: new colonization substrates and new habitats for hard substrate species	Local	Affects the entire trophic network: - changes in community structure, evolution towards a more complex ecosystem with an increase in the diversity and biomass of filter-feeding bivalves and pelagic fish, the aggregation of top predators and increased predation. - a stepping stone effect for non-native hard substrate species can also be observed.	Lange *et al.,* 2010; Dannheim *et al.,*2020; Degraer *et al.,* 2019; Petersen and Malm, 2006; Lindeboom *et al.,*2011; Raoux *et al.,* 2017; Glarou *et al.,* 2020; Mavraki, 2020; Burkhard and Gee, 2012; Mangi, 2013
Reserve effect due to fishing restrictions	Buffer zone	Species targeted by fisheries will benefit, with, in the long term, an ecological spillover effect and increased fish biomass around the farm.	Busch *et al.,* 2011, Glarou*et al.,* 2020, Lange *et al.,* 2010, Lindeboom*et al.,* 2011, Mangi, 2013, Petersen and Malm, 2006
Changes in functional habitats	Local and buffer zone	Some soft substrate species (infauna and certain primary producers) and some diving and surface birds are impacted.	Burkhard and Gee, 2012; Degraer *et al.,* 2019; Lindeboom *et al.,* 2011
Sounds and vibrations from the rotation of wind turbine blades	Local and regional	Disturb some species of macroinvertebrates (crustaceans), fish, marine mammals, and birds.	Dannheim *et al.,* 2020; Lindeboom *et al.,* 2011; Petersen and Malm, 2006
Lights and flickering shadows	Local and regional	Can affect certain species of fish, birds and bats.	Garthe and Hüppop, 2004
Electromagnetic fields	Local and regional	Can cause changes in behaviour and stress, disrupt migration, and decrease predation efficiency.	Dannheim *et al.,* 2020; Öhman *et al.,* 2007; Petersen and Malm, 2006
Hydrodynamic changes: erosion, “sediment sorting” leading to a modification of the substrate particle size, changes in currents, temperature and the resuspension of sediments and nutrients around wind farms	Regional	Primary producers and consumers can be affected insignificantly.	Busch *et al.,* 2010; Dannheim *et al.,* 2020; Degraer *et al.,* 2019; Lindeboom *et al.,* 2011

Trace metal emissions, mainly aluminium from anticorrosion devices	Regional	Would remain below the threshold values of toxicity for species and human health.	Golding *et al.,* 2015; Kirchgeorg *et al.,* 2018
Enrichment in organic matter and detritus as an indirect consequence of the increase in bivalve abundance. The decomposition process may release small quantities of hydrogen sulphide (H_2S).	Local	Unspecified	Dannheim *et al.,* 2020

Table 8: Nature, spatial extent, and impact of pressures during the operational phase (from Baulaz *et al*., 2023).

1.4. Impacts on ecosystem services

Ecosystem services are the benefits that humans derive from ecosystems. They have been classified into four main categories:

- provisioning services (wood, food, fibers),
- cultural services (landscapes, identity, well-being),
- regulating services (regulation of air quality, water quality, climate change, extreme events, pathogens),
- supporting services (creation of functional habitats, soil formation and fertility, pollination, chemical cycling, etc.).

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services(IPBES) lists 18 ecosystem services (see Table 9) and shows that in general, human activity improves provisioning and cultural services but strongly degrades regulating and supporting services.

Service category	Service
Provisioning services	Energy
	Food and feed
	Materials (wood, cotton)
	Medicinal, biochemical and genetic resources
Cultural services	Learning and inspiration
	Physical and psychological experiences
	Supporting identities
Regulating services	Regulation of air quality

	Regulation of climate
	Regulation of ocean acidification
	Regulation of freshwater and coastal water quality
	Regulation of freshwater quantity, location and timing
	Regulation of hazards and extreme events
	Regulation of detrimental organisms and biological processes
Supporting services	Habitat creation and maintenance
	Formation, protection and decontamination of soils and sediments
	Pollination and dispersal of seeds and other propagules
	Maintenance of options

Table 9: Ecosystem services (IPBES, 2019).

The impact of OWFs on ecosystem services can be positive (habitat creation, protected areas, nursery effect, and the provision of resources for fisheries in adjacent areas) or negative, especially for cultural services (altering the landscape). Note that impacts that seem positive may not be recognized as such by stakeholders (*e.g.* the nursery effect), and conversely negative impacts that do have any real scientific backing may be used as an argument against OWFs (*e.g.* the fact that no-fishing zones have a large impact on fishing activity).

The experts consulted estimated that all ecosystem services would be affected by offshore wind farms. These modifications result in major changes in the ecosystem production function (except primary production), showing strong damage to trophic interactions. For example, a change in secondary production or in specific species or genetic diversity can lead to a gain or loss of biomass, triggering beneficiaries like fishermen to adapt their practices.

Within the OWF context, this regime shift is mainly caused by the reef effect, which will develop in the long term a richer and more complex ecosystem that the soft substrate ecosystem existing prior to construction. It is known that ecosystem service supply is linked to high biodiversity. As a result, the reef effect will be of benefit to the ecosystem service supply in different ways:

- the increase in abundance of some fish species and top predators will benefit the supply of provisioning and cultural ecosystem services;
- regulating ecosystem services will be promoted by an improvement in system functionality;
- changes in biotic compartments result in numerous indirect "top-down" and "bottom-up" cumulative effects linked to trophic cascades. The result of these processes is the development of a food web dominated by filter-feeding bivalves (Mavraki *et al.*, 2020), which are keystone organisms playing a major role in the provision of many ecosystem services, *e.g.* by filtering large volumes of water, by decreasing turbidity, and by accumulating nutrients (Armoškaitė *et al.,* 2020).

However, the deployment of OWFs also contributes to a large-scale ecosystem homogenization and to a decrease in the diversity of functional traits in the marine environment (Degraer *et al.*, 2019), with contrasted effects:

- ⇨ an increase in the provision of most ecosystem services at the local scale, but at the same time a decline in specialist and often rare species, which is a global issue;
- ⇨ changes in the access to provisioning and cultural ecosystem services and the ability of the various beneficiaries to adapt their practices. These modifications of practices may result in three types of indirect impact on marine/coastal territories:
  - an over-exploitation of the services (*e.g.* over-fishing or over-use of the coastline) in response to the relocation of the beneficiaries around the OWFs;
  - conflicts of use resulting from the exploitation of one service at the detriment of another;

- pressure on the ecosystems adjacent to the OWFs, which can modify their capacity to provide services at a large scale.

In particular, the researchers have shown that fishing, a provisioning ecosystem service, and the maintenance of habitats and thus of cultural ecosystem services are most impacted due to changes in the tropic network and ecosystem functions. These changes are mainly caused by changes in the functional habitat, and reef and reserve effects during the construction and operational phases.

Determining how changes in biodiversity impact ecosystem processes and functions is crucial to determine the effect of OWFs on the provision of associated ecosystem services.

1.4.1. Provision of fisheries and pharmaceutical resources

Fishing provides animal proteins and is an important food provisioning service in France. Fishing restrictions at OWFs create important tensions with fishermen. A French research team (Halouani *et al.*, 2020) quantified the effect of spillover, which could mitigate the impact of loss of access on fishing activities, by simulating a fishing closure scenario at an OWF. The model predicted an increase in catches of up to 7 % near the wind farm and a slight increase in the proportion of high trophic level species. However, the influence of spillover effects is limited in space and the expected increase in biomass and catches are highly localized in areas around the OWF installation. At the scale of the Bay of Seine, further analysis of spillover effects revealed a spatial pattern and suggested that the implementation of an exclusion zone inside the OWF could concentrate highly mobile predators.

It is with the fishing industry that the strongest disagreements arise, and in particular regarding the existence of a net migration effect from protected areas to adjacent areas, also known as the spillover effect (Di Lorenzo *et al.*, 2020; Halouani *et al.*, 2020). This effect is well documented for protected areas, but remains to quantified for the smaller areas around wind turbines where human activity persists and, through the disturbance it causes to wildlife, could see this effect being cancelled out.

Another characteristic of the study by Baulaz *et al.* (2023) is to have considered ecosystem service access (*i.e.* the process that allows humans to benefit from ecosystem services) as one of the possible impacts (positive or negative), and to suggest an approach to **identify the causal chains** identifying the main potential impacts of OWFs on changes in the supply and demand of ecosystem services.

They identified the main impacts of the two phases of the life of OWFs, namely construction and operation:

- **During construction**, these changes result mainly from the digging and crushing of the substrate that will lead to a loss accounting for more than 27% of the primary producers and primary consumers groups;
- **During production**, the reef effect, the reserve effect, and change of functional habitat are the most affecting pressures on the ecosystem., resulting in (1) a global increase in the abundance and diversity of pelagic fish within the farm and nearby, despite increased predation by top predators, which increases services to fisheries, aquaculture, and the pharmaceutical industry, and (2) a decrease the abundance and diversity of flatfish due to the loss of soft substrate habitats.

The intensity of the impacts on the biomass production service depends on three parameters:

1. the species fished locally;
2. the regulation of activity within the OWF;
3. the intensity of the ecological spillover effect.

1.4.2. Regulating services

The expected main effects are modifications **in water filtration, nutrient production, and recycling**. These processes will be reduced during the construction phase, due to the rearrangement of benthos (leading to a resuspension of materials and pollutants and an increased turbidity), and the increased mortality rate of filtering organisms. However, the filtration production and recycling of nutrients will improve afterwards during the operational phase, with an increase in abundance of filtering bivalves, the most affected group. Moreover, this service would be affected by two threats, the introduction of invasive and/or toxic species, facilitated by the reef effect, and the potential transfer into the food web of metal emissions, even though this pressure leads to only 4 % of the modification of the system.

1.4.3. Supporting services and creation of functional habitats

There are **negative impacts linked to the loss of benthic and pelagic functional habitats** for species in mobile substrates (during construction, mainly from digging, crushing of the substrate and rearrangement of the benthos), and **positive impacts linked to creation of new functional habitats** (during the operation phase). The installation of different hard substrates (pylons, cables, etc.) that have reef effects (providing habitats for nurseries, spawning, feeding and refuge). These new habitats can indirectly promote the establishment of non-native species. The migratory routes of some top predators can also be strongly affected (13 % and 31 % of the impacts are related to top predators during construction and production phase respectively). Avifauna is particularly sensitive to these changes: some species show avoidance behaviours in the North Sea (*e.g.* the common eider *Somateria mollissima,* the northern fulmar *Fulmarus glacialis*), while others are attracted towards the OWF area (*e.g.* the great cormorant *Phalacrocorax carbo*). The latter are consequently more exposed to collisions.

1.4.4. Cultural services

More than 21 % of the impacts relate to cultural ecosystem service supply, because they are associated with almost all ecosystem functions. During construction, marine megafauna and avifauna, which are « charismatic species », are expected to avoid the OWF area, which will negatively impact ornithology and observation activities. By contrast, during the operation phase, the greater secondary production and specific species and genetic diversity would promote the aggregation of top predators of heritage interest, and fisheries resources of recreational interest. Also, the increased water filtration (changes in biogeochemical cycles and nutrient production and recycling functions) contributes to a clearer and more attractive seascape. The coupling of these different effects on species will increase the variety of sea spaces with potential recreational uses, even if the landscape functions are among the less impacted functions.

1.4.5. Access to ecosystem services and trade-offs

Trade-offs between ecosystem services are partly determined by the access to these services, but also by the quality of regulating services that support ecosystem resilience to pressures. In particular, changes in regulating services will affect the supply of both provisioning and cultural services. In the same way, changes in social values and associated shifts profoundly reconfigure the functioning of marine-coastal territories, potentially leading to conflicts between maritime human activities, economic considerations, and regulatory and socio-cultural changes. These social, economic, and cultural impacts are often neglected in scientific sphere, but they determine the local acceptability and are therefore essential to consider as part of maritime spatial planning.

There are four types of changes in ecosystem service access that will lead to either a gain or a loss of benefit (financial or not) for beneficiaries: changes in practices, usage, biomass, and socio-cultural values (see Figure 10).

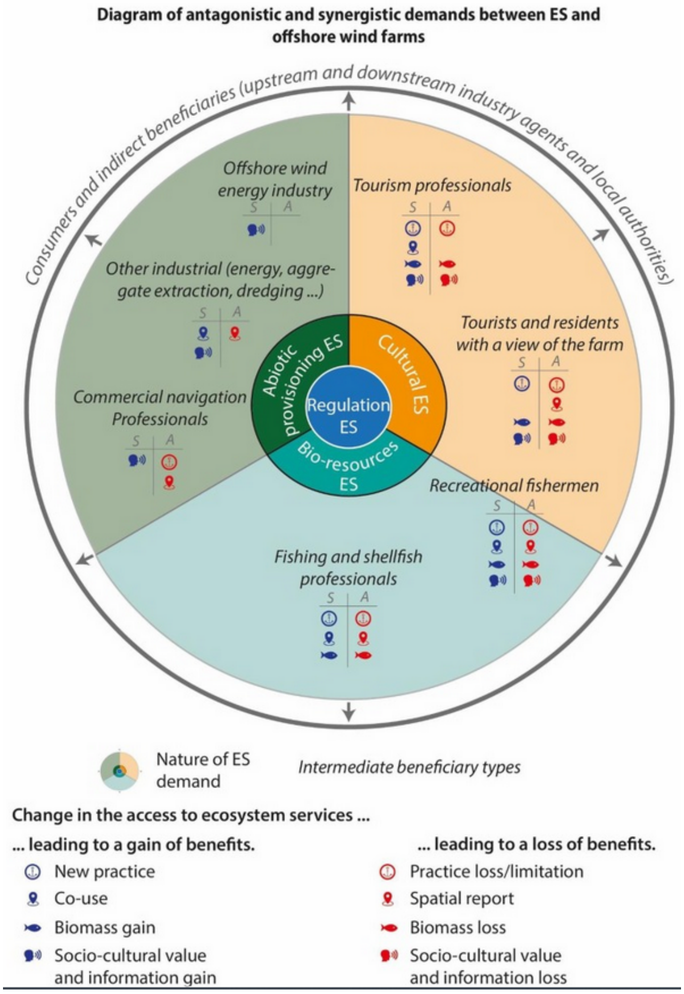

Figure 10: Target diagram of synergistic and antagonistic ecosystem service demands between beneficiaries and OWFs (from Baulaz *et al.*, 2023).

Ecosystem service access mobilizes practices, tools, facilities, and mobility that define the material access, but also legislation, economy, labour force, knowledge, commitment, or cultural investment, for the socio-cultural access to ecosystem services. Access to ecosystem services conditions the nature and intensity of the potential exploitation of these services by beneficiaries and thus most of the pressures on ecosystems and potential conflicts of uses.

Changes to ecosystem services occur *via*:

- **the appearance of new practices** (*e.g.* marine and coastal leisure tourism, educational, or museum exhibitions) or conversely, **a loss or a limitation of practices** for safety reasons (*e.g.* navigation restrictions, limitations on boat size, type of fishing gear, restricted access to wrecks and heritage features);
- **spatial shifts in new or established activities**, linked to new uses (*e.g.* tourism) or restriction of established uses (*e.g.* no-fishing areas), or delayed uses;
- **changes in biomass** and the ability to access this biomass;
- **changes in the social values of the marine environment**, for example the loss of some essential qualities of the sea (*e.g.*, the feeling of wilderness, open spaces, or freedom from anthropic

structures) or conversely, the development of an image of a territory developing renewable energy;
- **losses or gains of knowledge or skills** (*e.g.* fishing).

Consequently, when considering all the effects of OWFs on coastal territories, one needs to consider the indirect impacts, relative to the adaptations of beneficiaries. These indirect impacts are social aspects of sustainability that are often under-considered (Frederiksen *et al.*, 2021).

CHAPTER 2: RECOMMENDATIONS FOR MANAGEMENT AND DECISION-MAKING

The progressive expansion of OWFs to meet energy production objectives, including floating devices in deeper areas and farther offshore, faces relevant technical, economic, social and ecological concerns worldwide. Among other challenges, it will:

1/ add to and be affected by the increasing demand for ocean space, which needs to be considered in order to avoid, or at least minimize, spatial conflicts;

2/ require the development of tools for ecological risk assessment that need to be further integrated into decision-support tools to identify future deployment areas (not in high biodiversity areas), and inform the consent process (through the implementation of machine learning and modelling approaches such as Bayesian networks).

Indirect impacts, which tend not to be fully investigated, must also be considered. Increases in prey species (*e.g.* pressure tolerant) at OWFs will increase food availability at higher trophic levels (*e.g.* bird and mammal species), thereby increasing populations. Other species from the same taxonomic groups may be adversely affected, for instance by collisions.

Two research groups (Dannheim *et al.*, 2020; Degraer *et al.*, 2019) recommend that four different spatial scales be considered when assessing the impacts of OWFs: the individual turbine, the OWF, the buffer zone, and the regional level. Moreover, impacts should also be assessed along the depth of the water column.

The intensity and nature of the impacts of OWFs vary depending on:
- the proximity of other OWFs and protected areas, nearby human activities, and local spatial planning strategies;
- the perception of natural maritime environments by users and regulators;
- the adaptability of ecosystem service beneficiaries to OWF impacts;
- the technical and design characteristics of OWFs (foundation, number of turbines, size, and distance from the coast);
- the state of biodiversity and the potential synergistic effects of OWFs and other pressures (Baulaz *et al.*, 2023).

All these elements must be considered jointly.

Impacts may spread far from the OWF area, when affected populations migrate: a decline in migratory populations may have consequences on their destination. It is therefore fundamental to consider the spatial and temporal distribution of the most sensitive species when determining the risks associated with a given project. However, this approach requires better access to year round species distribution and abundance data, and knowledge of the migration routes of birds, fish, and marine mammals.

Moreover, as well as checking that offshore wind power projects do not cause significant environmental harm, new projects must be assessed for their compliance with the targets of the Global Biodiversity Framework adopted in December 2022 in Montreal.

TARGET 1. Ensure that all areas are under participatory, integrated, and biodiversity inclusive spatial planning and/or effective management processes addressing land and sea use change, to bring the loss of areas of high biodiversity importance, including ecosystems of high ecological integrity, close to zero by 2030, while respecting the rights of indigenous peoples and local communities.

Maritime spatial planning – an indispensable process - needs to integrate the two underlying objectives of target 1 of the Global Biodiversity Framework: it must 1) be the result of an inclusive and participatory process involving all users of the sea and the coast, and 2) be accompanied by an assessment of the presence and state of high biodiversity areas, in order to stop their degradation.

The concertation process needs to include all users: industry, fisheries, tourists, local communities, scientists, and political decision-makers. Ways to integrate future generations and biodiversity in the planning process need to be put in place. The process must result in a shared and transparent assessment of the planned uses and their impacts on biodiversity, ecosystem services, access to natural resources and to services, and other activities. It must integrate fair and equitable objectives for sharing the sea, biotic and abiotic resources, and ecosystem services. The social and environmental impacts must also be shared so that one group is not more impacted than another. It must be clearly recognized that some users or wildlife can suffer from use restrictions, the loss of biodiversity or ecosystem services, and therefore compensation mechanisms must be put in place.

The identification of areas of high environmental interest should inform where OWFs should or should not be deployed. Note that avoiding impacts, the first tier of the avoid-reduce-compensate sequence, is a legal requirement, even though this sequence is seldom applied in an effective and transparent manner.

TARGET 2. Ensure that by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity.

The objective of the proliferation of man-made structures (oil and gas platforms, cage aquaculture, coastal defense structures, OWFs) is not to protect or increase biodiversity. There is a risk that this target will be missed if it is not clearly identified from the start, or that there will be unforeseen consequences.

Even so, offshore wind turbines, although they were not designed to be artificial reefs, have similar impacts (both positive and negative) (Degraer *et al.*, 2020).

One question here is knowing how these installations can contribute to biodiversity restoration. As previously mentioned, the net positive effect of offshore wind turbines on biodiversity is relatively clear, although their social benefits are debated. For instance, does the increase in fish biomass compensate for the loss of fishing areas?

To reinforce the benefits, a good understanding of the mechanisms underlying the impacts of OWFs is needed in order to design installations that benefit biodiversity. This approach is mandatory for the development of new installations in the Netherlands (Ministerie van Economische Zaken, 2019).

It is therefore possible to:

- decide that biodiversity restoration is one of the main objectives of the project, and design the installation in a way that provides a net benefit for biodiversity:

  Examples:
  - place fish hotels or other structures near wind turbines (Hermans *et al.*, 2020).
  - avoid placing hard structures (deliberately or not) away from wind turbines to avoid contributing to the homogenization of the oceans (Firth *et al.*, 2020).
  - consider the size of the OWF, so as to minimize the transformation of the area.

- prefer eco-engineering and nature-based solutions:

  Example:
  - use scour protection to improve fish habitats, or restore oyster banks (Glarou *et al.*, 2020).

TARGET 3. Ensure and enable that by 2030 at least 30 per cent of terrestrial, inland water, and of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem functions and services, are effectively conserved and managed through ecologically representative, well-connected and equitably governed systems of protected areas and other effective area-based conservation measures, recognizing indigenous and traditional territories where applicable, and integrated into wider landscapes, seascapes and the ocean, while ensuring that any sustainable use, where appropriate in such areas, is fully consistent with conservation outcomes, recognizing and respecting the rights of indigenous peoples and local communities, including over their traditional territories.

As with Target 2, the question here is to design OWFs so that they play a role as an "other effective area-based conservation measure". The exclusion of fishing from OWFs is an opportunity to reduce the main pressure on marine biodiversity (IPBES, 2019). The benefit of having an exclusion zone is the "reserve effect", *i.e.* a refuge for wildlife reproduction and survival, seen in highly protected areas. However, studies are lacking to fully assess the reserve effect and that for two reasons: these areas can be too small (lack of data on the minimal size needed to induce more positive than negative effects), and other human activities, especially those associated with offshore wind energy production, persist. Moreover, because of tensions associated with spatial planning (Target 1), it may be better for biodiversity to build in areas with multiple activities (fishing, aquaculture, energy production), in order to conserve highly protected areas where the most impactful activities are prohibited (Claudet *et al.*, 2021). Two avenues are possible here, and must be discussed during the concertation process (aim of Target 1).

It is possible to:
- either consider that the reserve effect is one the main objectives of the project, and design the installation in a way as to provide a net benefit for biodiversity, and in this case, reduce anthropogenic pressures such as pollution (noise, light, or electromagnetic pollution) that can decrease, or even cancel out the reserve effect for certain species.
- or share the area with other activities in order to conserve highly protected areas elsewhere, where restoration measures can be put in place if needed.
- and fund studies and research projects to better quantify the reserve effect (see Target 21).

TARGET 4. Ensure urgent management actions to halt human induced extinction of known threatened species and for the recovery and conservation of species, in particular threatened species, to significantly reduce extinction risk, as well as to maintain and restore the genetic diversity within and between populations of native, wild and domesticated species to maintain their adaptive potential, including through in situ and ex situ conservation and sustainable management practices, and effectively manage human-wildlife interactions to minimize human-wildlife conflict for coexistence.

Since OWFs can harbour rare, more or less threatened species, it is possible to:
- reduce the anthropogenic pressures that strongly impact these rare or threatened species;
- contribute to knowledge acquisition on the rare and threatened species that are likely to be found in or around OWFs (species monitoring, research projects, studies) and fund studies to better understand their biology.
- take part in monitoring studies of rare or threatened species.

TARGET 5. Ensure that the use, harvesting and trade of wild species is sustainable, safe and legal, preventing overexploitation, minimizing impacts on non-target species and ecosystems, and reducing the risk of pathogen spill-over, applying the ecosystem approach, while respecting and protecting customary sustainable use by indigenous peoples and local communities.

Not applicable.

TARGET 6. Eliminate, minimize, reduce and or mitigate the impacts of invasive alien species on biodiversity and ecosystem services by identifying and managing pathways of the introduction of alien species, preventing the introduction and establishment of priority invasive alien species, reducing the rates of introduction and establishment of other known or potential invasive alien species by at least 50 per cent, by 2030, eradicating or controlling invasive alien species especially in priority sites, such as islands.

Since OWFs can favour certain invasive alien species, it is possible to:

- reduce attractive habitats for these species, when known;
- put measures in place to enhance biodiversity as much as possible: indeed, invasive alien species can thrive in low diversity degraded environments, or be more tolerant to certain pressures;
- restore habitats and reduce anthropogenic pressures in order to harbour the highest possible number of species, including potential predators;
- contribute to or fund the monitoring of invasive alien species in and around OWFs.

TARGET 7. Reduce pollution risks and the negative impact of pollution from all sources, by 2030, to levels that are not harmful to biodiversity and ecosystem functions and services, considering cumulative effects, including: reducing excess nutrients lost to the environment by at least half including through more efficient nutrient cycling and use; reducing the overall risk from pesticides and highly hazardous chemicals by at least half including through integrated pest management, based on science, taking into account food security and livelihoods; and also preventing, reducing, and working towards eliminating plastic pollution.

Pollution risks from OWFs that impact biodiversity are mainly from noise, lights and electromagnetic fields. There is also the emission of pollutants such as heavy metals, and the resuspension of pollutants in sediments during construction. For all these pressures, operators must:

- carry out an assessment at each installation, as pressures will vary depending on the type, size and surface area;
- propose measures to reduce these pressures and their associated risks, once they have been identified and assessed, in compliance with Target 7 of the Global Biodiversity Framework.

TARGET 8. Minimize the impact of climate change and ocean acidification on biodiversity and increase its resilience through mitigation, adaptation, and disaster risk reduction actions, including through nature-based solution and/or ecosystem-based approaches, while minimizing negative and fostering positive impacts of climate action on biodiversity.

Renewable energy is by nature favourable to climate change mitigation. However, before any project is undertaken, it is important to precisely define what the project contributes in terms of energy substitution. If the aim is just to generate more energy for new uses, or to maintain unsustainable uses, it may be collectively better to review the project to avoid its externalities.

TARGET 9. Ensure that the management and use of wild species are sustainable, thereby providing social, economic and environmental benefits for people, especially those in vulnerable situations and those most dependent on biodiversity, including through sustainable biodiversity-based activities, products and services that enhance biodiversity, and protecting and encouraging customary sustainable use by indigenous peoples and local communities.

Not applicable.

TARGET 10. Ensure that areas under agriculture, aquaculture, fisheries and forestry are managed sustainably, in particular through the sustainable use of biodiversity, including through a substantial increase of the application of biodiversity friendly practices, such as sustainable intensification, agroecological and other innovative approaches contributing to the resilience and long-term efficiency and productivity of these production systems and to food security, conserving and restoring biodiversity and maintaining nature's contributions to people, including ecosystem functions and services.

Not applicable.

TARGET 11. Restore, maintain and enhance nature's contributions to people, including ecosystem functions and services, such as regulation of air, water, and climate, soil health, pollination and reduction of disease risk, as well as protection from natural hazards and disasters, through nature-based solutions and/or ecosystem-based approaches for the benefit of all people and nature.

The assessment of the state of marine and coastal ecosystems must evolve from providing a static (number of species before and after the installation) to a dynamic picture that takes into account the ecosystem and societal components of coastal areas.

The ecosystem service approach effectively provides a more global view of the impacts of offshore renewable energy on biodiversity. It allows us to understand the causal links between human activity, pressures, and the consequences on ecosystem functions and services (Boehert and Gill, 2010; Shadman *et al.*, 2021). The IPBES framework (18 ecosystem services, see Table 8/9) allows to take into account all major services and assess their state pre- and post-installation.

Project developers and operators must:

- identify the environmental and socio-economic parameters that allow the monitoring of the global impacts of OWFs in order to anticipate potential conflicts between different human activities.
- identify the cumulative environmental impacts and trade-offs between different ecosystem services, and the variables that change their dynamics.
- put measures in place to reduce the impact on ecosystem services, and thus facilitate the integration of new uses of the sea alongside existing ones.

TARGET 12. Significantly increase the area and quality and connectivity of, access to, and benefits from green and blue spaces in urban and densely populated areas sustainably, by mainstreaming the conservation and sustainable use of biodiversity, and ensure biodiversity-inclusive urban planning, enhancing native biodiversity, ecological connectivity and integrity, and improving human health and well-being and connection to nature and contributing to inclusive and sustainable urbanization and the provision of ecosystem functions and services.

Not applicable.

TARGET 13. Take effective legal, policy, administrative and capacity-building measures at all levels, as appropriate, to ensure the fair and equitable sharing of benefits that arise from the utilization of genetic resources and from digital sequence information on genetic resources, as well as traditional knowledge associated with genetic resources, and facilitating appropriate access to genetic resources, and by 2030 facilitating a significant increase of the benefits shared, in accordance with applicable international access and benefit-sharing instruments.

Not applicable.

TARGET 14. Ensure the full integration of biodiversity and its multiple values into policies, regulations, planning and development processes, poverty eradication strategies, strategic environmental assessments, environmental impact assessments and, as appropriate, national accounting, within and across all levels of government and across all sectors, in particular those with significant impacts on biodiversity, progressively aligning all relevant public and private activities, fiscal and financial flows with the goals and targets of this framework.

To improve environmental impact assessments in relation to offshore wind energy, different aspects need to be reinforced:

- follow the avoid – reduce – compensate sequence, prioritizing "avoid" and "reduce";
- integrate current scientific knowledge during project design and in impact assessments; especially knowledge of lesser studied species, such as fish or invertebrates, and knowledge of ecosystem dynamics;
- develop mitigation measures based on scientific knowledge to reduce the impact on biodiversity.

A research group in France (Brignon *et al.*, 2022) proposed a method to assess all possible impacts. Their method combined expert judgement, consensus building, and a scoring system to prioritize the pairs of pressures and receptors of the marine environment to work on. The scoring system was based on the ecological importance of receptors, the degree of knowledge of the effect of a pressure on a receptor and the sensitivity of each receptor to pressures.

Another point to consider is the selection of species for monitoring these impacts and their reduction. Indeed, it is not possible to follow every single migratory species that could be impacted. Making a choice, or establishing a hierarchy, is necessary. Marc Desholm, a Danish researcher, devised an indicator to identify the migratory species most at risk of collision across large areas with many OWFs (such as the North Sea, and the eastern or western coasts of North America), or to investigate other factors (*e.g.* high mortality due to hunting, collisions with turbines, flares on oil platforms, or collisions with other elevated structures). However, this indicator does not take into account the other impacts wind turbines may have on birds (for instance, displacement and habitat modification).

This approach was applied to a dataset comprising 38 migratory bird species at the Nysted offshore wind farm, located in one of the main bottlenecks for bird migration in the Baltic Sea. Two indicators were selected to characterize the sensitivity of each individual species: relative abundance and demographic sensitivity (survival and reproductive rates). These two indicators seem effective and functional, as they take into account known characteristics of population dynamics and relative abundance for different species at the migration site. The two indicators can be adapted to the level of information available (*e.g.* only a list of species, or the number of individuals of an annual migratory species and their avoidance or attraction behaviour). Finally, having only two independent indicators makes this approach simple. However, none of these two indicators has up to now been linked to estimated mortality rates, and even less to impacts at the population level.

TARGET 15. Take legal, administrative or policy measures to encourage and enable business, and in particular to ensure that large and transnational companies and financial institutions: (a) Regularly monitor, assess, and transparently disclose their risks, dependencies and impacts on biodiversity, including with requirements for all large as well as transnational companies and financial institutions along their operations, supply and value chains and portfolios; (b) Provide information needed to consumers to promote sustainable consumption patterns; (c) Report on compliance with access and benefit-sharing regulations and measures, as applicable; in order to progressively reduce negative impacts on biodiversity, increase positive impacts, reduce biodiversity-related risks to business and financial institutions, and promote actions to ensure sustainable patterns of production.

Assess the impacts over the entire value chain. Use a systemic approach :

- Ensure that the impacts on all the components of biodiversity (species, habitats: composition, ecosystem structure and function) are avoided or reduced and that they do not compromise the robustness, resilience and capacity of biodiversity to provide goods and services.
- Make decisions based on the best evidence available to anticipate the environmental and social impacts and choose projects, processes and solutions that preserve the potential for greenhouse gas mitigation, other human activities, and marine ecosystems.
- Use integrative approaches to gather relevant information that provide a global view of the positive and negative impacts, and the trade-offs between different different management options.

Contrôler les impacts des installations :

- Contribute to scientific knowledge by monitoring biodiversity and making the data open access for research purposes.
- Follow the avoid – reduce – compensate sequence, prioritizing “avoid” and “reduce”.
- Monitor sites on a regular basis to understand the impacts on biodiversity.
- Update processes as new evidence on the impacts and risks becomes available.

Communicate regularly on the risks associated with the chosen management options. Be transparent about the trade-offs between different management options, the choices made within the framework of the project (size of the OWF, materials used, waste management, management of the impacts on biodiversity, ecosystem services, and other human activities, and potential compensation).

TARGET 16. Ensure that people are encouraged and enabled to make sustainable consumption choices including by establishing supportive policy, legislative or regulatory frameworks, improving education and access to relevant and accurate information and alternatives, and by 2030, reduce the global footprint of consumption in an equitable manner, including through halving global food waste, significantly reducing overconsumption and substantially reducing waste generation, in order for all people to live well in harmony with Mother Earth.

It is possible to:
- be transparent on the contribution of the project to France’s environmental footprint;
- play a role in campaigns to help reduce energy overconsumption;
- fund research to better characterize the way in which people depend on biodiversity, and the risks associated with the loss of ecosystem services.
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TARGET 17. Establish, strengthen capacity for, and implement in all countries biosafety measures as set out in Article 8(g) of the Convention on Biological Diversity and measures for the handling of biotechnology and distribution of its benefits as set out in Article 19 of the Convention.

Not applicable.

TARGET 18. Identify by 2025, and eliminate, phase out or reform incentives, including subsidies, harmful for biodiversity, in a proportionate, just, fair, effective and equitable way, while substantially and progressively reducing them by at least 500 billion United States dollars per year by 2030, starting with the most harmful incentives, and scale up positive incentives for the conservation and sustainable use of biodiversity.

Not applicable.

TARGET 19. Substantially and progressively increase the level of financial resources from all sources, in an effective, timely and easily accessible manner, including domestic, international, public and private resources, in accordance with Article 20 of the Convention, to implement national biodiversity strategies and action plans, by 2030 mobilizing at least 200 billion United States dollars per year, including by: (a) Increasing total biodiversity related international financial resources from developed countries, including official development assistance, and from countries that voluntarily assume obligations of developed country Parties, to developing countries, in particular the least developed countries and small island developing States, as well as countries with economies in transition, to at least US$ 20 billion per year by 2025, and to at least US$ 30 billion per year by 2030; (b) Significantly increasing domestic resource mobilization, facilitated by the preparation and implementation of national biodiversity finance plans or similar instruments according to national needs, priorities and circumstances; (c) Leveraging private finance, promoting blended finance, implementing strategies for raising new and additional resources, and encouraging the private sector to invest in biodiversity, including through impact funds and other instruments; (d) Stimulating innovative schemes such as payment for ecosystem services, green bonds, biodiversity offsets and credits, benefit-sharing mechanisms, with environmental and social safeguards; (e) Optimizing co-benefits and synergies of finance targeting the biodiversity and climate crises; (f) Enhancing the role of collective actions, including by indigenous peoples and local communities, Mother Earth centric actions and non-market-based approaches including community based natural resource management and civil society cooperation and solidarity aimed at the conservation of biodiversity; (g) Enhancing the effectiveness, efficiency and transparency of resource provision and use.

Not applicable.

TARGET 20. Strengthen capacity-building and development, access to and transfer of technology, and promote development of and access to innovation and technical and scientific cooperation, including through South-South, North-South and triangular cooperation, to meet the needs for effective implementation, particularly in developing countries, fostering joint technology development and joint scientific research programs for the conservation and sustainable use of biodiversity and strengthening scientific research and monitoring capacities, commensurate with the ambition of the goals and targets of the framework.

Not applicable.

TARGET 21. Ensure that the best available data, information and knowledge, are accessible to decision makers, practitioners and the public to guide effective and equitable governance, integrated and participatory management of biodiversity, and to strengthen communication, awareness-raising, education, monitoring, research and knowledge management and, also in this context, traditional knowledge, innovations, practices and technologies of indigenous peoples and local communities should only be accessed with their free, prior and informed consent, in accordance with national legislation.

Scientific research can improve:

- knowledge of the impacts of offshore wind energy on biodiversity;
- environmental impact assessments;
- knowledge of biodiversity:
    - Is there a net emigration effect from protected to adjacent areas (environmental spillover)?
    - What potential for a nursery effect and an increase in biomass for commercial species?
    - What proportion represents the movement of opportunistic species (without an increase in the number of individuals) and the increase in populations favoured by these new habitats and the absence of fishing?
    - What could prevent conflicts of use, in particular with the fishing industry?

TARGET 22. Ensure the full, equitable, inclusive, effective and gender-responsive representation and participation in decision-making, and access to justice and information related to biodiversity by indigenous peoples and local communities, respecting their cultures and their rights over lands, territories, resources, and traditional knowledge, as well as by women and girls, children and youth, and persons with disabilities and ensure the full protection of environmental human rights defenders.

TARGET 23. Ensure gender equality in the implementation of the framework through a gender-responsive approach where all women and girls have equal opportunity and capacity to contribute to the three objectives of the Convention, including by recognizing their equal rights and access to land and natural resources and their full, equitable, meaningful and informed participation and leadership at all levels of action, engagement, policy and decision-making related to biodiversity.

Concertation with all social groups is important for the acceptability of offshore wind projects. Decision-makers and developers must take into account the impacts of OWFs, including in terms of loss of ecosystem services, that weigh on society and other human activities, when deciding on the location and size of an OWF (Hastik *et al.*, 2015).

As much as possible, it is important to ensure that these installations are not detrimental to future generations or to biodiversity in their access to marine areas and biological resources.

APPENDIX 1: KNOWLEDGE GAPS ON THE IMPACTS OF OFFSHORE WIND INSTALLATIONS

Electricity production from wind power has grown exponentially worldwide over the last decade, spurred on by the geopolitical context (climate change, the desire for resilience and less dependency, and the increase in energy prices), technological advances, lower production costs, and high subsidies from the State and private investors. Moreover, the average actual cost of energy (a near 55 % decrease is expected between 2018 and 2030), and a decrease in production costs by 2050 (from 37 % to 49 %) make the offshore wind energy sector increasingly competitive compared to fossil fuels.

OWFs already represented 10 % of all new wind power installations in the world in 2019 (nearly 80 % in Europe), and should contribute to more than 20 % of the electricity production capacity by 2025. To achieve this, global capacity must be increased by a factor of 10 by 2030 (to 228 GW) and continue to grow to reach 1000 GW by 2050.

To meet these objectives, experts predict that by 2035, 11 to 25 % of all new offshore projects in the world will have floating foundations.

Objectives in Europe are even more ambitious. Indeed, the objective of the European Offshore Renewable Energy Strategy (part of the Green Deal) is to make the European Union a world leader in these technologies, so that these will make up at least 50 % of the energy mix by 2050 and cover 30 % of the future energy demands in Europe.

To contribute to the European Union's goal of climate neutrality (between 240 and 450 GW of offshore wind power production), increases in capacity are still needed by 2050.

However, this development is taking place even though there are **substantial knowledge gaps on the environmental impacts of wind power**. We lack precise and quantified information on most of the impacts of OWFs: avoidance by local marine fauna, impact of light pollution, impact of electromagnetic fields, impact of the release of trace metals, impact on the economy, employment, landscapes, and the socio-cultural values associated with the sea. There is also much uncertainty regarding these impacts, which are strongly context-dependent, as a whole.

Moreover, scientists disagree regarding the extent of the impacts of OWFs. In addition, most publications contain studies that were carried out on a small localized scale (*e.g.* in shallow waters, near the coast, with a small number of turbines, low production capacity, over a small surface area). The acquisition of new data monitoring the development of these installations would help fill these gaps and be of great value for decision-makers, operators and industry. The monitoring process must focus on the pressures and impacts on specific elements of the ecosystem (including protected and vulnerable habitats and species), for which there is less certainty.

Impacts on tropical species and habitats

Despite the relatively high number of species studied, there is a historical bias towards species with a northern distribution such as the harbour porpoise (*Phocoena phocoena*), the harbour seal (*Phoca vitulina*), the common guillemot (*Uria aalge*), and the Atlantic cod (*Gadus morhua*) (Galparsoro *et al.*, 2020), and fewer studies of invertebrates and tropical species. Even though this is beginning to change (Lemos *et al.*, 2023), more research on the latter, and their habitats, is needed, especially in the context of the massive deployment of OWFs worldwide, including in tropical areas.

There is a relatively high level of agreement in the scientific literature on the type of impact (positive, negative) that offshore wind power has on biodiversity. However, there are significant knowledge gaps regarding the quantitative (*e.g.* mortality) and qualitative extent of these impacts and the interactions between OWF pressures and biodiversity, including species, habitats and ecosystem structure, functions and processes. This quantification is crucial to assess all the environmental risks associated with OWFs.

Impacts of large-scale OWFs and extended networks of OWFs

Copping *et al.* (2020) claim that several stressors of the marine environment caused by marine renewable energy are sufficiently well-informed and have a low impact, especially in the context of isolated devices or small networks. These include (1) effects of underwater noise from marine renewable energy devices on marine mammals and fish; (2) electromagnetic fields emitted by export power cables on certain marine species; (3) changes in benthic and pelagic habitats; and (4) changes in the movement of water and sediments.

They recommend focusing research efforts on understanding and preventing impacts for which there is still a high level of uncertainty or lack of knowledge, in particular the risk to marine animals from collisions with moving parts of the devices, and on installations that present the highest risk, *i.e.* large-scale OWFs and networks of OWFs.

Impacts of cumulative pressures

Human activities generate multiple co-occurring pressures that can have a cumulative (synergistic or antagonistic) impact on the ecosystem. The multiple interactions between human activities and ecosystem elements must be studied urgently, given that future wind power developments will add to the cumulative impacts of existing human activities and climate change. Moreover, because of increasing demand for maritime space, multiple uses of the sea are likely to occur in the same area as wind energy production, and an increase in local cumulative pressures is likely by exacerbating the environmental impacts in an increasingly anthropogenized maritime environment (Vilela *et al.*, 2021).

Impacts of wind variation on biodiversity

A research team in Germany (Akhtar *et al.*, 2021) estimated that energy production from OWFs in the North Sea can be reduced by 20 % or more due to downwind reductions in wind speed caused by the wind farm itself, affecting the farm's performance as well as that of neighbouring downwind farms, and increasing energy production costs and economic losses. More generally, the impact on biodiversity of local wind variation, especially on seabirds (migratory or not) is not known. According to Akhtar *et al.* (2021), the annual mean wind speed deficit within a wind farm can reach 2 – 2.5 ms^{-1} depending on the wind farm geometry. The mean deficit, which decreases with distance, can extend 35 – 40 km downwind during prevailing southwesterly winds. Wind speed deficits are highest during spring (mainly March – April) and lowest during November – December.

Impacts on ecosystem services

There are only a limited number of studies on the impacts on ecosystem services. More in-depth analyses on the effects of OWFs on the provision of ecosystem services could potentially highlight their impact (positive or negative) on other maritime sectors operating in the area.

A research team in France (Baulaz *et al.*, 2023) have shown that impacts are not well documented for certain trophic levels, such as zooplankton and primary consumers (other than filter-feeders), and that certain results are contradictory (*e.g.* some studies describe both an avoidance and an attraction behaviour for certain bird species within OWFs (Blew *et al.*, 2008; Skov *et al.*, 2018)).

Impacts on nutrient cycling

While studies on the effects of blue mussel (*Mytilus edulis*) aquaculture have provided data on water clarification (Cranford, 2019) and its effect on benthic and pelagic nutrient cycling (Petersen *et al.*, 2019), similar data for other species in OWFs are lacking. However, such data would allow the estimation of the local biogeochemical footprint of an OWF. Moreover, integrating these data into oceanographic models would allow the assessment of the changes associated with these installations on a larger scale.

Knowledge on the way artificial reefs affect the carbon flow in locally modified trophic networks is also lacking. Observations and modelling suggest an increased abundance of fish (Reubens *et al.*, 2014) and large crustaceans (Kroner *et al.*, 2017) as well as an increased importance of detritus-based trophic systems. However, the quantification of the carbon flow through OWF-specific trophic network is lacking.

Impacts of climate change

Finally, artificial reefs, like natural reefs, are subjected to a warmer and more acidic marine environment. The combination of acidification and temperature rise produces substantial, non-additive, and complex changes in community dynamics (Queiró *et al.*, 2015), affects pelagic and benthic nutrient cycling (Braeckman *et al.*, 2014), and changes predator/prey interactions (Draper and Weissburg, 2019).

Finally, the gap between risk perception and reality, arising from uncertainty or lack of data on the real environmental impacts of marine renewable energy, should not be underestimated.

Data on the implications and consequences of offshore wind energy for other maritime sectors (*e.g.* fishing, tourism) are also lacking.

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