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Impact of offshore wind farms on the fauna of the Baltic Sea

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ABSTRACT

This paper addresses the issues arising from the correlation between upcoming investments in the development of offshore wind energy and the fauna of the Baltic Sea. It presents the challenges related to the construction of offshore wind turbines and the requirements set by the European Union. Information regarding the fauna of the Baltic Sea and the threats to the body of water resulting from human activities is provided. Conclusions are drawn regarding aspects of offshore wind farms (OWFs) that may be harmful to the fauna of the Baltic Sea, as well as those that have a positive impact on animals. Finally, solutions are proposed to mitigate the negative effects of OWFs on the marine environment and enhance their positive impact.

Keywords: offshore wind farm, biodiversity, fauna, impact, renewable energy sources.

INTRODUCTION

Due to the ongoing environmental degradation, the inevitable depletion of fossil fuels over the next 30–50 years, and the current geopolitical situation in the east, it is essential to implement economic changes to meet human needs with minimal environmental impact. In light of the changes that have occurred since 2022, Baltic Sea countries, except Russia, are tightening cooperation regarding energy security and accelerating the production of renewable energy. Wind energy, particularly offshore, stands out as one of the most promising renewable sources. It offers adaptable solutions for different regions and, unlike many other renewables, can be deployed on an industrial scale to produce substantial energy output. The potential of offshore wind energy in the Baltic Sea is estimated at about 85 GW of capacity. Alongside the emergence of multi-billion investments in offshore wind energy, public campaigns promoting this solution and scientific research aimed at improving environmental conditions are also developing. An offshore wind farm (OWF), or wind power plant, is a facility composed of multiple interconnected wind turbines that collectively generate electricity. Due to the lack of natural barriers on large bodies of water, it is optimal to construct such facilities in the sea or ocean. Although this presents greater technical challenges, it remains a profitable venture. Offshore locations make it possible to harness more wind energy than on land, leading to construction plans featuring significantly larger wind turbines than those used onshore. The development of wind energy, like other energy sources, is driven by forecasts of depleting fossil fuel resources and excessive greenhouse gas emissions resulting from human activities. The most important characteristics of wind energy, both at sea and on land, are its general availability, inexhaustibility, and the absence of by-products in energy production, such as heavy metals. The first offshore wind farm was commissioned in Denmark in 1991 and operated for 26 years before ceasing operations.

The European Union has set more ambitious energy independence goals for member states, which are to be updated again at the end of 2024. These decisions stemmed from the Russian invasion of Ukraine on 24 February 2022.

Within the framework of the Integrated Maritime Policy, an approach to the management of seas and oceans has been defined, where maritime spatial planning is recognised as a key tool for ensuring sustainable development of marine areas and coastal regions. The EU Biodiversity Strategy for 2030 includes several commitments and actions aimed at restoring biodiversity in Europe.

In Poland, nine projects related to wind energy are currently being implemented. These are being conducted by both Polish and foreign companies, among which the following projects stand out:

- Baltic Power – a joint project of the Orlen Group and Northland Power.
- BC-Wind – an investment by Ocean Winds, a joint venture of EDPR and ENGIE.
- FEW Baltic II – a project by RWE Offshore Wind GmbH.
- Baltica 1, 2, and 3 OWFs – investment projects conducted by PGE Polska Grupa Energetyczna S.A. in cooperation with Ørsted.
- Bałtyk I, II and III OWF – offshore wind farm projects led by Equinor and Polenergia.

The key technical criteria for identifying suitable locations for OWFs include wind resource availability and seabed depth. Additionally, rational site selection requires considering other technical criteria, such as distance from shore, seabed morphology, sediment type, and existing power grid infrastructure.

The construction plan includes transporting components on ships equipped specifically for offshore installations. The sites designated by the authorities, which were won in tenders, are characterised by depths of 20–40 meters. The construction of wind turbines will have a direct impact on the seabed. There are two kinds of foundations: fixed and floating. The following types of foundations can be distinguished:

- monopiles – the most commonly used,
- gravity base structures (GBS),
- tripod,
- quatropod,
- jacket,
- spar floater,
- floating jacket.

The purpose of the submarine cables is to transmit energy generated by offshore wind turbines to the substations located within the wind farm. The standard voltage for submarine cables is 33/66 kV, with 66 kV increasingly being used due to developments toward greater capacities. The main components of a substation include transformers, which adjust voltage levels, and auxiliary transformers that supply power to the substation's equipment. Offshore wind farms are also equipped with backup generators that supply power to essential components during outages, grounding transformers that create a neutral point in resistor-grounded or compensated networks, and high- and medium-voltage switchgear alongside other protective equipment.

Each investment must obtain an environmental decision from the General Directorate for Environmental Protection. The parameters influencing the scale of the investment's impact on the marine environment primarily include:

- number of foundations,
- type and diameter of foundations,
- time required for the installation of each foundation,
- amount of equipment used for driving the foundations,
- depth and method of laying transmission cables,
- length of transmission cables,
- width of protective layers,
- number and density of structures within the designated investment area,
- height of wind turbines,
- rotor diameter,
- constant noise and vibrations,
- number and type of vessels and emissions of pollutants from vessels,
- type of bonding material used for sealing and protecting wind turbine masts against corrosion and biofouling.

During the proceedings to obtain the environmental decision, investors conduct the following studies on abiotic components:

- geophysical,
- geochemical,
- meteorological,
- hydrological,
- acoustic,

and on biotic components:

- phytobenthos,
- macrozoobenthos,
- ichthyofauna,
- marine mammals,
- migratory birds,
- seabirds,
- bats.

CHARACTERISTICS OF THE BALTIC SEA

The Baltic Sea is a glacial shelf sea that formed about 12.000 years ago during the retreat of the ice sheet to the north. Due to the terrain configuration, the Baltic Sea is divided into seven regions: Kattegat, the Sound and the Belt Sea, the Baltic Proper, the Gulf of Riga, the Gulf of Finland, the Bothnian Sea, and the Gulf of Bothnia. The largest area of the Baltic Sea is the Baltic Proper, which encompasses the entire Polish coastline. The Skagerrak region has the highest salinity, while the Gulf of Bothnia has the lowest. Consequently, these two regions differ significantly in terms of the occurrence of plant and animal species. The average depth of the Baltic Sea is about 50 metres; however, it is made up of shallow marine areas where depths range from 14 to 20 metres, which constitutes a significant majority of the water body, as well as deeper areas, the largest of which is the Landsort Deep at 459 metres below sea level, located near Gotland. The flora present in the area exhibits adaptive capabilities that allow them to survive under significant salinity fluctuations; these are referred to as euryhaline organisms. Some species live at depths of up to 200 metres where sunlight reaches, while the benthic zone is very poor in living organisms. Nonetheless, several species of crustaceans, such as the Baltic prawn, and many microorganisms can be identified. The seabed of the Baltic Sea, however, is sparse in living organisms, which is attributed not only to the lack of light at the assessed depths but also to anthropogenic pollution.

Fish and crustacean populations are supported by marine habitats that provide shelter from predators, feeding, spawning, and nursery grounds. Consequently, the loss of habitats and disturbances caused by the construction and operation of offshore wind farms will impact both benthic and pelagic species, as benthic ecosystems serve as a food source for economically significant species that feed near the seabed or on the seabed itself. The juvenile stages of many species also spend time among plankton, playing a significant role in pelagic food chains. During the construction phase, there is a risk of habitat loss for crustaceans and fish, which, in turn, may be restored during operation due to natural colonisation of the foundations of the wind turbines.

Currently, Baltic cod and Baltic salmon are threatened with extinction, and other fish populations, except for sprat, herring, and flounder, are heavily depleted, and their catch is restricted. In this case, offshore wind farms to be constructed in the open sea will have little impact. The primary reason for the loss of biodiversity is overfishing and water pollution. At present, it is difficult to improve the state of Baltic fish populations, and the only initiatives include catch restrictions and increased consumer awareness. There is a lack of information regarding attempts to conserve endangered species.

ENVIRONMENTAL THREATS TO THE BALTIC SEA

The Baltic Sea is currently a heavily exploited marine area, and any human activity affecting this environment has consequences for the organisms that inhabit it. Due to its shallow waters, the Baltic Sea is particularly susceptible to human-induced pollution and disturbances. A hypoxic (oxygen-depleted) zone, which covers around 20% of its surface, has formed as a result of eutrophication. All plots designated for wind turbine construction are located within Poland's economic zone and are not part of this hypoxic area, which lies farther offshore and continues to expand annually. Eutrophication occurs when excess nutrients (primarily nitrogen and phosphorus compounds) enrich the water. According to the study 'The Wastewater Disposal System Modernisation during Processing of Amber Deposit as a Way to Reduce the Anthropogenic Load on the Baltic Sea Ecosystem', industrial wastewater frequently fails to meet national environmental standards. Annually, an average of 640.000 tons of nitrogen and 30.000 tons of phosphorus are discharged into the Baltic. As a result, phytoplankton – particularly cyanobacteria – begins to bloom. These organisms are autotrophic, meaning they perform photosynthesis and assimilate simple compounds from their environment to synthesize more complex organic substances. The period of abundant food is limited to the growing season. In July, a toxic species of cyanobacteria blooms, posing risks to both humans and animals. At the end of the growing season, the algae die off and sink to the seafloor. The decomposition of this dead organic matter by bacteria consumes the oxygen present in the deep waters, producing hydrogen sulphide, which leads to the die-off of benthic fauna.

The most common species in the Baltic is the moon jellyfish (*Aurelia aurita*), classified as zooplankton despite its relatively large size. In some areas, it is the only species present. Some animal species exhibit submergence, residing near the seabed to avoid the colder surface waters, even if their natural habitats are typically shallow coastal areas.

Low biodiversity in the Baltic also results from its significant pollution levels, not only from modern human activities but also from toxic waste, munitions, unexploded ordnance (UXO), shipwrecks, and military waste left behind from the Second World War. The largest marine conservation area in the Baltic is the Słupsk Bank, with current prevention efforts focused on reducing human activity to combat eutrophication. Wind farms could potentially impact this part of the sea.

No studies have been conducted on the environmental impact of OWFs at the decommissioning stage, as there has been little or no research directly focused on this phase. The first offshore wind farm was put into operation in Denmark in 1991, and the first to be decommissioned was Sweden's Yttre Stengrund, a 2 MW farm established in 2001 and dismantled in 2015 due to the uneconomical costs of upgrading turbines and gearboxes. Similarly, Denmark's Vindeby wind farm was dismantled in 2017.

In both cases, companies have claimed that decommissioning was carried out with environmental care. Vattenfall restored the Yttre Stengrund site and removed undersea cables by summer 2016. During Vindeby's decommissioning, most metal and concrete components were repurposed, including turbine blades. A total of 33 blades, each weighing 1.2 tons, were distributed to various organisations. Some blades were repurchased by their manufacturer, LM Wind Power, some were displayed as museum pieces, and others were used as acoustic barrier material. However, 1.1 tonnes of fibreglass from the blades were cut and transported to a landfill in Rærup near Aalborg. Offshore wind farm decommissioning is assumed to have a similar environmental impact as their construction.

OWFs are relatively insignificant in this context. The most critical environmental protection actions involve reducing pollution run-off and eliminating sources of pollution, for instance, by constructing wastewater treatment facilities or decreasing agricultural and hospitality activities along the coast. Notably, the Polish coastline was one of the most forested regions until recently. However, according to 'Changes in Forest Area of Coastal Communes of Baltic Sea as a Result of the Impact of Tourist and Recreational Loads', forestation rate along coastal municipalities is diminishing as tourism expands. The study's findings reveal that forestation rate in western coastal areas is significantly lower than in the east, with 'tourism areas showing a decrease in population but an increase in accommodations', further contributing to Baltic Sea eutrophication despite sustainable development measures.

It is widely believed that clearing the Baltic Sea seabed of post-war chemicals and bombs without compromising their integrity and causing spills is now impossible. The main deterrents to remediation efforts are costs and securing funding, which has left this problem unresolved. Nonetheless, recent years have seen more decisive steps toward resolving this issue. In 2021, the European Parliament issued its first resolution proposing the removal of submerged chemical weapons from the Baltic Sea, although this document is not legally binding. Neither international nor national law has yet regulated this issue. It is accepted that offshore sector activities must consider the potential presence of chemical weapons and UXO while ensuring the preservation of the natural environment.

The European Union has initiated a new programme, the MUNIMAP (Munitions in the Baltic Sea Mapping Project), aimed at developing methods for UXO detection, risk assessment, and safe disposal of submerged munitions. All Baltic Sea countries except Russia participate in this project. Before offshore wind farm construction, it is essential to conduct the aforementioned studies on UXO presence, with detonation if any are detected. Investors must ensure the safety of personnel and wildlife, using sonar to monitor fish shoals and delay UXO detonation until fish have left the area. For marine mammals, monitoring is employed, although poor weather conditions may hamper observations. Additionally, seal deterrents are used, emitting sounds designed to displace animals from the active work area.

IMPACT OF OWF ON ZOOBENTHOS

Biological valorisation is a method for assessing an area's importance to the ecosystem, independent of human economic and social interests. The factors enhancing an area's ecological value include its uniqueness, the density of species and individual organisms, the health condition of organism communities, and the role of specific species as habitat constructors or for other ecosystem functions (Figure 1). Some areas in Polish waters are sparse in species yet hold significant biological and economic value, such as clean, well-oxygenated moving sands on shallow coastal shelves, which support a high population of crustaceans essential as prey for commercially valuable fish species. The richest zones in terms of species diversity are located in the euphotic zone and transition zones between sediment types, where diverse faunal communities intersect (ecotone zones). Species richness is generally higher in the western Baltic than in the eastern Baltic, as salinity decreases eastward. The Gulf of Gdańsk area, one of the species-richest regions, is also adjacent to a landfill (Figure 2). The complexity of habitats associated with the presence of OWFs is influenced by several factors:

- material protection measures applied,
- local species pools,
- reduced fishing pressure,

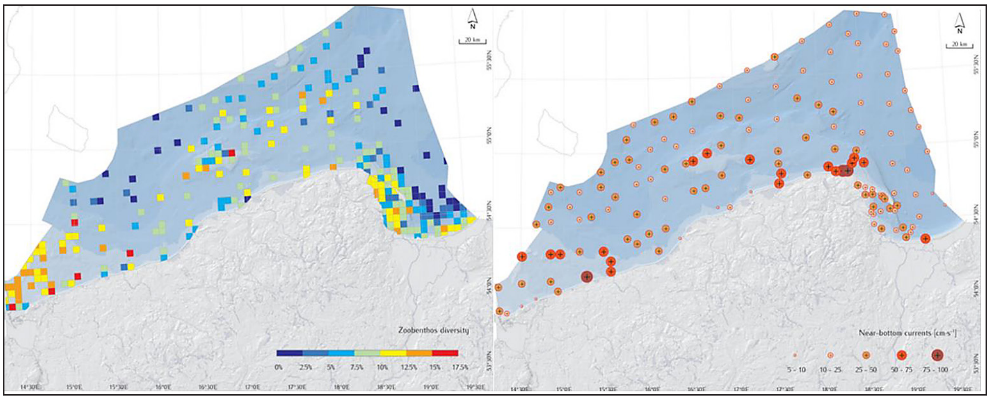

Figure 1. Dependence of zoobenthos (right) on near-bottom currents (left) [Atlas of Polish marine area bottom habitats]

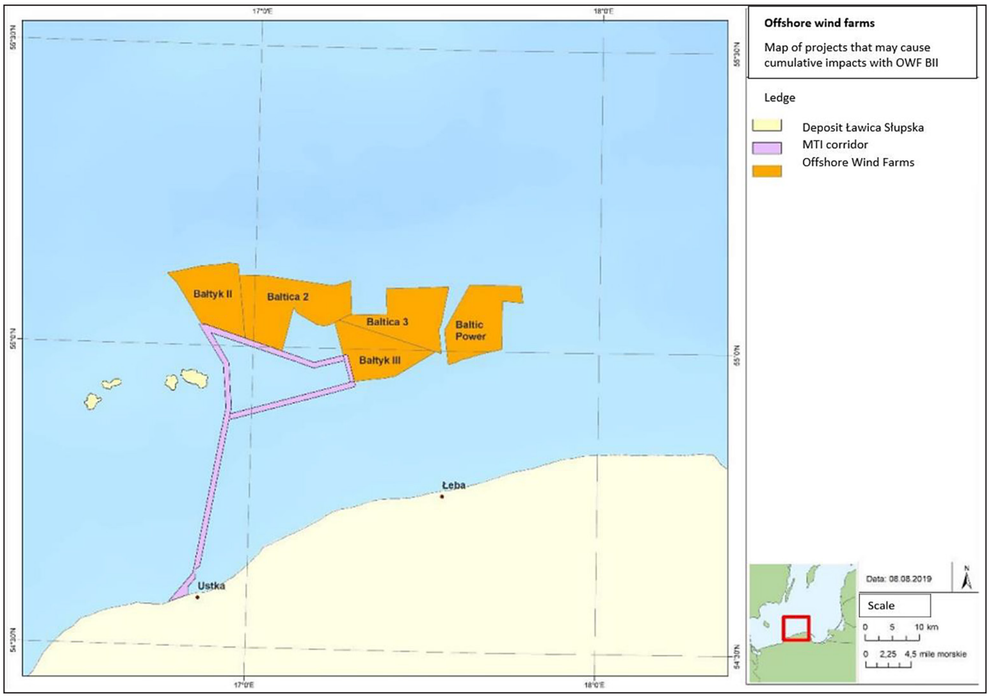

Figure 2. Offshore Wind Farms scheduled for completion by 2027 in the vicinity of the Słupsk Bank [Environmental Impact Report for the amendment of the decision on the environmental conditions of the BAŁTYK II OWF project – prepared by RDOŚ (Regional Directorate for Environmental Protection) for MFW Bałtyk II Spółka z o.o. MIP – Maritime Transmission Infrastructure]

- vibrations generated by turbine towers through the gearbox and generator (80–150 dB at 1 μPa), usually limited to the local area,
- increased boat traffic for maintenance and servicing,
- electromagnetic fields generated by transmission cables,
- components used in turbine and cable construction.

The presence of benthic fauna is strongly linked to near-bottom currents, mainly found in shallow waters. Water flow over the seabed significantly shapes marine habitats. On one hand, it induces sediment movement, such as rolling sand grains along the seabed, which limits the presence of delicate, firmly-bonded organisms. On the other, water flow is essential for the efficient feeding of filter-feeding organisms. The highest current speeds, above 50 $cm \cdot s^{-1}$, occur in the western shallows, the coastal edge of the Bay of Pomerania, and at the base of the Hel Peninsula, with the slowest currents found in the deep, flat areas of the Gulf of Gdansk. The Słupsk Bank area, relatively shallow and far from shore, is characterized by relatively high near-bottom current speeds, supporting rich epiphytic fauna communities.

Seabed and habitats in areas of strong currents are marked by the absence of fine sediments and the presence of well-washed stones and hard clay deposits with gravel. In Polish waters, there are both species-rich areas and those sparse in species yet of significant biological and economic importance, such as clean, well-oxygenated mobile sands on shallow coastal shelves, supporting large populations of crustaceans crucial as prey for commercial fish species. The richest zones in terms of species diversity are located in the euphotic zone and transition zones between sediment types, where diverse faunal communities intersect (ecotone zones). The number of species in the western part of the Baltic is higher than in the eastern part (it is decreasing with decreasing salinity) – the Bay of Pomerania area is one of the most species-rich areas. The number of zoobenthos species in the Baltic Sea is significantly lower compared to other seas, with species numbers also depending on salinity levels. Zooplankton thrives in large quantities in late spring, feeding on phytoplankton, which includes microscopic plant organisms, algae, and cyanobacteria classified as bacteria.

The impact of OWFs on zoobenthos depends on foundation types, salinity, near-bottom currents, and the abundance of specific microorganisms and vertebrates that feed on them. Among zoobenthos species, the blue mussel (Mytilus edulis), a dominant invertebrate on rocky substrates, is frequently observed on turbine foundations.

At the construction stage, it is essential to consider potential disturbances to zoobenthos communities. Key parameters influencing impact levels include:

- type, size, and number of foundations built, as well as the length of cables installed,
- type of rock material constituting the seabed.

IMPACT OF OWF ON ICHTHYOFAUNA

Vertebrates in the fish class inhabit the water column. In the Baltic Sea, there are 26 marine fish species and several species that sporadically appear in the western Baltic. These include marine, freshwater species (mainly in bays), and migratory fish. The highest fish species density is in the bays, particularly the Bay of Puck, with the lowest density found in open waters. Fish species identified as vulnerable to negative OWF impacts include:

- cod (*Godus morhua*),
- herring (*Clupea harengus*),
- European eel (*Anguilla anguilla*),
- flatfish (*Pleuronectiformes*).

The RDOŚ (Regional Directorate for Environmental Protection) has conducted studies on OWF impacts, including research at the Bałtyk II OWF site in 2012–2013. These studies consisted of five series of observations over ten survey cruises. Only pelagic fish species, or those living in the pelagic zone, were found in areas planned for offshore wind farm construction.

During these surveys, 15 species were identified. Among them, eight species (sprat, herring, cod, flounder, plaice, turbot, salmon, and sand eel) are commercially harvested. However, only four (sprat, cod, herring, and flounder) were found in significant numbers, while the remaining species appeared in very low quantities. Sprat was the most abundant, accounting for 71.7% of all catches, followed by herring at 14.9% and cod at 10.6%, with the rest representing only 2.8%. No protected species were identified during the study. Of the 8 identified pelagic fish species, sprat and herring were the most frequently observed. Although the OWF area does not serve as a feeding ground for pelagic fish, it lies on their migratory paths. The spatial distribution of sprat and herring is large enough that the construction of the OWF will not present a significant obstacle. For juvenile herring, the northern edges of the proposed project could serve as a secondary feeding area, but only at depths below 30 meters during the second half of the year. The highest diversity of pelagic fish was observed in summer, with the lowest in winter. The bottom set catches recorded the presence of 13 fish species, of which cod, flounder and plaice were the most abundant in all survey periods. Their numbers varied across different study seasons. The area around the wind farm has a favourable seabed structure and food base, making it a feeding ground for young cod. However, adult cod generally avoid this region as they migrate to their spawning grounds in the Bornholm Basin. The planned wind farm area is also on the winter migration route of flounder, but it does not serve as a spawning ground due to the low salinity in the region.

Ichthyoplankton, which includes the early life stages of fish suspended in the pelagic zone, was observed as well, comprising 11 taxa. The most abundant component of ichthyoplankton was sprat eggs and larvae, indicating an intense spawning ground in the area during the previous summer. This was unusual, as sprat typically spawn in deep waters (50 m) at a salinity of 6 ‰. The second most common taxon was flounder larvae from spawning grounds near the Słupsk Bank. Shallow areas at the wind farm sites may serve as spawning grounds for a small portion of the population, though they are less significant compared to deep-water spawning grounds. Additionally, two taxa of eggs belonging to protected species – the common seasnail and the small goby – were identified. The former prefers vegetative substrates for spawning, typically found in deeper waters or the eastern Baltic, while the latter prefers shallow waters with sandy substrates. Their presence may have been due to the proximity to the Słupsk Bank.

The Regional Directorate for Environmental Protection also conducted ichthyofauna surveys for the Baltica OWFs project from 2017 to 2018, revealing the presence of 19 fish taxa, including eight stable groups, such as cod, flatfish, herring, sprat, and occasional appearances of species like the shorthorn sculpin, lumpfish, sand eel, and the viviparous eelpout. Ichthyoplankton surveys identified 12 taxa, with 27 goby larvae, some of which may have belonged to the protected small goby. Sixteen common seasnail larvae were also observed.

Following the surveys for Baltic II OWF (2012–2013) and Baltica OWF (2017–2018), an LFI (Large Fish Index) coefficient was calculated, revealing a significant decrease for all Polish marine areas in 2018. This decline is indicative of a deteriorating Baltic Sea environment, primarily driven by a decrease in the population of cod over 30 cm in length, followed by a reduction in flounder populations.

According to the article 'Effects of offshore wind farms on marine wildlife – a generalized impact assessment', the electromagnetic field (EMF) produced by transmission cables may negatively impact cartilaginous fish, which rely on electromagnetic signals to detect prey. Additionally, EMF could adversely affect fish migrations by disrupting their geomagnetic orientation abilities. However, cartilaginous fish are relatively rare in the Baltic Sea and were not observed in the planned investment area. The range of the electromagnetic field can potentially be minimized by using appropriate cable construction methods and following the guidelines outlined in the environmental approval obtained for the project.

IMPACT OF OWF ON MARINE MAMMALS

Marine mammals represent the least numerous group of animals in the Baltic Sea, with each species under strict protection. Four species of marine mammals are found in the Baltic Sea, along with a few that appear sporadically. The rarest marine mammal is the harbour porpoise *(Phocoena phocoena)*, the only cetacean species in the Baltic Sea. Its population is estimated at around 500 individuals and is declining, making it critically endangered. As part of OWF installation procedures, companies like PGE are required to conduct marine mammal monitoring. MEWO, a company recently awarded a monitoring contract, will conduct harbour porpoise monitoring 18–20 km from the farm and within the Natura 2000 area 'Słowińska Refuge' (Ostoja Słowińska) until 31 December 2029. Seals represent the second group of marine mammals in the Baltic Sea, with three species present:

- grey seal (*Halichoerus grypus*),
- ringed seal (*Phoca hispida*),
- harbour seal (*Phoca vitulina*).

The protection of marine mammals is a significant aspect of environmental preservation and is often featured in various advertising campaigns.

The populations of all Baltic seal species are considered threatened or endangered. Fish populations are heavily impacted by overfishing. Research conducted in UK waters by scientists from the Swedish University of Agricultural Sciences, the University of Gothenburg, and the University of Southern Denmark in 2013, detailed in the article 'Effects of offshore wind farms on marine wildlife—a generalized impact assessment', indicates that the noise generated by pile-driving for monopile OWF foundations has significant effects on marine mammals, causing them to flee and leading to tissue damage in fish and high mortality rates. The environmental impact is reduced near turbines on gravity base structures, although the primary source of acoustic disturbance in this case comes from preparatory work to position the foundation. Increased traffic from transport and installation vessels is also more disruptive to marine mammals, an effect unavoidable with all types of offshore wind turbines. It is also worth mentioning that, as we can infer from the maps in the figures, the locations of the planned OWF are significantly remote from the seal area and the occurrence of the harbour porpoise in Polish waters is not much more extensive. The study detailed that the use of gravity foundations is associated with a greater impact of sediment dispersion as a result of bottom dredging. However, it might be expected that animals inhabiting a shallow enough sea would be more tolerant of turbidity. In contrast, other studies indicate that this may harm young, vulnerable fry. Nevertheless, the impact of sediment dispersion is assessed as low to moderate. No negative electromagnetic field effects from the offshore sector have been demonstrated to date.

THE IMPACT OF OWF ON AVIFAUNA

Avifauna is the animal group that will be most strongly affected by the establishment of offshore wind farms. Information on the deaths of birds caused by wind farms is inconclusive and varies depending on the region where observations were made. It also depends on the species; large birds of prey and migratory birds are most at risk, while Passeriformes as well as Anseriformes and Turniciformes are least at risk. Offshore wind farms may displace seabirds from their natural feeding grounds. Many Polish bird species are classified as vulnerable or they have recently reappeared off the Polish coast. A bird may also be thrown off balance and crash by falling into turbulence caused by the rotor blades. The possibility of a collision with a wind turbine is determined by the specifics of the species and by how it uses the airspace. The potential risk increases across migration corridors, which run along the coast as well as the largest valleys and forest areas. The activity of birds increases in autumn and spring.

The first measures taken in the USA, Germany, France and Spain, after significant bird fatality was observed as a result of collisions with wind turbines, included the introduction of permanent monitoring of birds during migration and the introduction of restrictions on the planning of investment locations. In Poland, an organisation called Stowarzyszenie Wspierania Inwestycji Przyjaznych PTAcom (English: PTAcom Association for the Support of Bird-Friendly Investments] was established and is active in the development of technology towards the protection of birds by sharing knowledge and scientific research and helping birds that have collided with architectural elements.

The areas characterised by a very high susceptibility to collisions with birds in Poland represent 0.5% of the country's area, while areas with a moderate risk of collisions represent 5.8% of Poland's area. Available research indicates that the most frequent collision victims at wind farms include:

- buzzard (*Buteo buteo*),
- red kite (*Milvus milvus*),
- kestrel (*Falco tinnunculus*),
- white-tailed eagle (*Haliaeetus albicilla*),
- griffon vulture (*Gyps fulvus*) (in other European countries).

The share of bird of prey species in the number of collisions with onshore wind turbines in Poland is 30.5% of all collisions, however, the study is based on a very small sample. According to a study conducted by Aleksandra Szurlej-Kielańska, Lucyna Pilacka and Dariusz Górecki of PTAcom in 2021, the total number of birds was 85, which included 25 birds of prey. In Spain, Germany and France, higher values can be observed from the wider scale of wind turbine investments, namely 47% out of 5525 birds, 40.6% out of 4196 birds and 21% out of 1391 birds, respectively.

As it was already mentioned, the characteristics of the accidents in question result from the characteristics of the region, the time of year in which the observations were made, and the characteristics of the species in question, primarily predator hunting. Territorial birds fly in a specific area and may be exposed to collisions with one turbine several times a day. For example, a white-tailed eagle may search for prey by circling near a power station, which exponentially increases the risk of an accident. The collision mechanism is related to the 'motion swear' phenomenon. From a distance, a working rotor appears to move slowly, but the speed of the blades increases with their length. Birds are unable see the tips of the blades because of anatomical conditions related to eye positioning and the area of blurred peripheral vision. Large birds, moreover, find it more difficult to manoeuvre than smaller birds. It is, therefore, the contractors' responsibility, as set out in the environmental decision, to paint the tips of the blades to make them more visible. It is also important to leave a clearance between the lower position of the blade and the sea level, which should be no less than 20 metres.

As described in the article 'Expected Effects of Offshore Wind Farms on Mediterranean Marine Line', vulnerability indices have been developed in studies of seabird populations in Northern Europe to indicate which seabirds are likely to be impacted by OWFs. The Regional Directorate for Environmental Protection has carried out studies and prepared reports on the impact on the marine environment for all offshore investments in Poland.

The distribution of birds along the coast is uneven and is primarily associated with feeding grounds and species specificity. The greatest number of birds can be found in the areas of the Puck Bay, the Słupsk Bank and the Gulf of Gdańsk, which significantly reduces the list of species that could come into contact with the rotor.

Above all, and this is included in the environmental decision if the company is granted planning permission, no work can be carried out during the bird breeding season. The breeding season lasts from April to June (although in the area of OWF, a decrease in the number of avifauna is observed already in May) - this is when birds mate and build nests. One of the birds hatches the eggs and the other flies off to hunt. This is particularly true of gull species, which during the breeding season often form colonies of several hundred individuals. A permit for the erection of artificial islands and structures in the Polish maritime area requires a buffer zone of 500 m of free space to be set up. During the construction phase, it is logical to assume that the birds will be scared away. Birds will mostly bypass the construction site. The distance they keep depends on the species. Gulls, especially the Silver Gull, which are often seen during construction works, use the protrusions to rest, despite the noise. In addition, during the construction phase, avifauna is also affected by the lighting of the investment site, which may attract birds that are active at night. However, there is no data confirming impact on bird species other than Procellariiformes, which only pass through the Baltic Sea and are not regular visitors to the water area. The lighting may furthermore attract migratory birds and thus increase the likelihood of collisions with the blades. The larger the power plant, the greater the environmental impact. The impact of lighting depends on the number of turbines and the intensity of light related to the length of the cables laid.

During construction, the large number of vessels associated with transport and installation will result in a barrier effect, reducing the possibility for birds to move between stopover areas during migration. The scale, as in the case of turbines, will depend on the number of vessels, size, light configuration and duration of construction. In addition, the launching of foundations will cause dispersal of sediments, which will make it more difficult for birds to hunt for fish, or can even affect the food base of avifauna in the OWF area. According to the guidelines stipulated in the environmental decisions, the turbines must be equipped with systems to stop them at night during bird migration and haze. Therefore, some contractors, namely the Baltica 2 and Baltica 3 OWFs, the Baltic Power OWF and the BC-Wind OWF are obliged to use a concrete foundation structure instead of a jacket one. The Bałtyk II, Bałtyk III and Baltic Power OWFs are subject to the restriction on strong position light. In addition, the environmental decisions for the Bałtyk III, Baltica 2 and 3, Baltic II and BC-Wind OWFs include an obligation to create a migration corridor. However, the migration corridor between the Baltic II and Baltic II wind farms will be extended by excluding the north-western area from construction, due to possible impact on the Słupsk Bank.

Wind turbines during their operational period cause changes in the use of airspace by birds. There is a possibility of collision; however, the vast majority of wind turbines have a deterrent effect on birds. The animals can evade the equipment at distances of 100 to 4.000 m, so that areas close to the turbines are used sparsely or not at all for the purpose of foraging. Bird fatalities associated with the presence of wind farms on water bodies are low. The risk increases with the size of the bird. Birds either fly very low, further lowering their flight as they approach the turbine, or very high above the turbines. According to the Regional Directorate of Environmental Protection, the physical structure of the OWF, light and noise emissions can be a source of disturbance to some sensitive bird species, causing them to fully or partially move out of the farm area, which may unfortunately lead to habitat loss. The level of disturbance depends on the size of the wind farm, the number of wind turbines and the noise and light emitted. Investors are allowed to drive foundation piles only between May and September or October, with the exception of the Baltic Power OWF and BC-Wind OWF, however, construction must be carried out under ornithological supervision. It is also a requirement to carry out the work using a 'soft smart' method, starting the work at low noise levels. During the construction phase for the Baltic Power, BC-Wind, Bałtyk II and Baltic II OWFs, a gradual build-up of the area is to be carried out, in the case of Baltica 2 and 3 OWFs and BC-Wind OWF, piling is required to be limited to a maximum of two, and one at a time in the case of Baltic Power OWF, due to work being carried out on nearby wind farms. It has been shown that intensive crane migration takes place in the Baltic Power and BC-Wind OWFs area.

The introduction of bird monitoring and implementation of collision avoidance systems is crucial for the protection of rare species; just a few dead individuals of e.g. Fulmar *(Fulmarus glacialis*), a bird extremely rare in Poland, observed again over the Polish coast only in 2024 after 70 years, could affect the local population. It requires the use of periodic automatic shutdowns of individual, or groups of, turbines during the bird migration period from 15 March to 30 April and 1 September to 15 October.

Currently, 15 detection-reaction systems, i.e. systems that temporarily shut down turbines for approaching birds or bats, are available for sale on the market. Out of those, seven systems are dedicated to offshore wind farms. It should be noted, however, that on the scale of human architectural

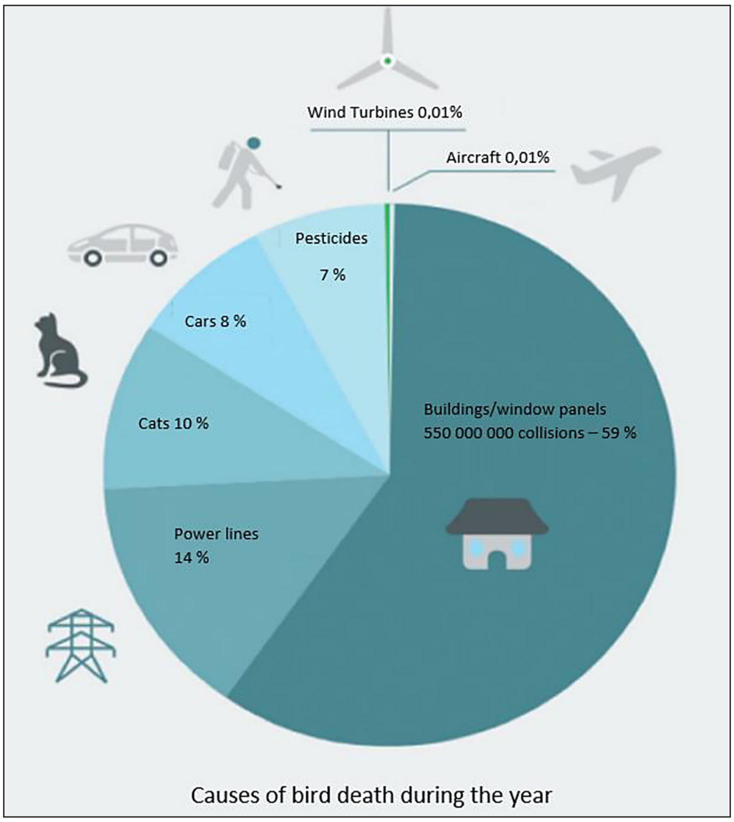

Figure 3. Causes of bird deaths per year. Comparison of the scale of estimated anthropogenic bird mortality. [Protection of birds from collisions with wind turbines – Dariusz Górecki, Aleksandra Szurlej-Kielańska, Lucyna Pilacka]

and economic development, the impact of the offshore and onshore sector has a marginal impact on bird mortality (Figure 3).

The highest number of fatal collisions per building is observed with glass surfaces of tall buildings. Most birds collide with a building between 4 and 11 storey high, statistically 16 birds/building/day, which gives approx. 245 million collisions per year with 15 million such structures. For 12-storey and higher high-rise buildings, 500.000 collisions per year are recorded, which gives approx. 24 collision/day/building per year. It should be noted that not every collision necessarily results in the death of a bird, but the vast majority of birds at least sustain injuries. Other causes of high bird mortality are high voltage lines and free-roaming cats. In contrast, the main threats to seabirds' existence are oil spills and the loss of food base, that is is fish, due to overfishing.

OWF FAILURES

Weather phenomena at sea are much stronger than on land. Their occurrence obviously carries risks for offshore facilities. These risks include fog, storms and gusts. The worst possible scenario is damage to the turbine with components detaching and falling into the sea. The presence of wind turbines also poses a previously non-existent threat of falling pieces of ice.

When carrying out maintenance or decommissioning work on a wind turbine, it is necessary to wait for suitable weather as such work is dangerous due to the size of the components being transported. A potential failure, however, will not cause significant damage to the environment. The only possibility is water pollution through spillage of oil and lubricants.

Current turbine models use the following estimated quantities of oils:

- gearbox oil – 750 to 1000 l/turbine,
- hydraulic oil – approx. 250 l/turbine,
- transformer oil – 1500 to 2000 l/turbine.

Oil spills are harmful to the environment due to the formation of an oil film, a stain that rapidly spreads in a large area. In the case of a 1.8 m^3 stain, it can expand over an area of up to 1 km^2 in one day. The spreading oil patch impedes gas exchange between the water and the atmosphere, and then it causes a 5–10% decrease in light intensity below the water surface, which reduces photosynthesis and ultimately causes the water temperature to rise during the day. Low molecular weight hydrocarbons are also released and the heavier fractions are sorbed with organic and mineral suspended solids; then, they sink to the bottom and destroy bottom sediments. The events that can cause oil spills include collisions and damage to vessels transporting components. Possible incidents also include a collision between a vessel and a standing wind turbine at a power station site, and a failure involving an oil spill, for example, from an offshore wind farm transformer station. The worst-case scenarios envisage an oil spill of 80 m^3, which is not feasible for investments in Poland, as this assumption is based on the largest turbines in the UK. In addition, the risk of ship collisions in the Baltic Sea was estimated as unlikely. The greatest risk is in the area of the Danish Straits and the South West Baltic, where the ship traffic is heavy and the sea is narrower. Despite this, there is a need to meet the requirements for technical safeguards and to draw up methods of eliminating the consequences of a possible accident, which results not only from European Union regulations, but also from the vicinity of the Słupsk Bank. There is also a list of failure prevention measures, starting from design, technological and organisational safeguards and finishing with prevention of accidents at the decommissioning stage.

According to the Environmental Impact Assessment Report for the Baltic Power Offshore Wind Farm, the failure prevention measures include:

- preparation of plans for safe construction, operation and decommissioning of the OWF in accordance with the applicable provisions of law for the period of project implementation;
- the development of rescue plans and trainings for crews and personnel;
- the preparation of the plan for the prevention of hazards and pollution generated during the construction, operation and decommissioning of the OWF;
- the selection of suppliers and certified components and components of the OWF;
- the designation of protection zones;
- the precise marking of the OWF area, its facilities and vessels moving within the OWF area;
- the application of the standards and guidelines of the International Maritime Organization (IMO), recognized classification societies, and recommendations of the maritime administration;

- the preparation of plans for the safe navigation within the OWF, and for traveling to ports;
- the continuous monitoring of vessel traffic within the OWF, direct or remote throughout the period of construction, operation and decommissioning of the OWF;
- the maintenance of permanent communication lines between the OWF coordination center and the coordinator of offshore works and other coordination centers (Maritime Rescue Coordination Center in Gdynia, maritime administration).

In the event of an uncontrollable failure, for example as a result of a violent storm, 200m^3 of oil at most will enter the sea. This is considered not to be a harmful value for the environment, as it will dissipate within 12 years.

The most important safeguards against the entry of undesirable substances include. During the construction and decommissioning phases:
- closure of the water body affected by the works,
- establishment of safety zones,
- delineation of fairways for vessels,
- equipping a minimum of one vessel with flexible barriers and packaged sorbents for oil spill containment in case of accidents and spills.

During the operation phase:
- establishment of safety zones as well as works and equipment of vessels as at the construction stage,
- monitoring the wind farm,
- sealing of turbine housings,
- equipping offshore transformer stations with oil sumps with an oil capacity equal to 110% of the oil in the transformer.

Vessel traffic is prohibited in or near the Słupsk Bank Natura 2000 area, which applies to the Baltic II, Baltica 2 and 3 OWFs and Baltic II OWF due to emissions of pollutants and noise associated with scaring birds wintering in the area.

POSITIVE ASPECTS OF OWF

During the operation phase of offshore wind turbines, the local natural conditions are important for the occurrence of negative or positive environmental impacts, which demonstrates the need for regular surveys to be carried out under different conditions. Colonisation and aggregation have been documented in the vicinity of OWF foundations in the first years after the installation of the farm. This enables acquisition of new habitats for marine animals, and is not different in this respect from other anthropogenic structures intentionally created for colonisation by invertebrates, fish and mammals. Also, an increased number of species has been observed due to the absence of fishing. This effect, however, may also have undesirable consequences if the platforms created serve alien species or if, through them, selected species gain dominance over others. Increased populations of one fish or mammal species may contribute to increased mortality of those that are more poorly adapted to change.

Nowadays, corporations involved in the construction of offshore wind farms financially support the projects and the environmental organizations behind them (Figure 4). Examples include the support by Ørsted and Eversource for research on marine mammals and turtles (stress and metabolism, stranding during farm construction, behavioral tracking, etc.) and support for the coastal restoration project 'Coastal life', i.e. reducing nitrogen leaching into coastal waters. The corporation supported the project with DKK 40 million, that is approx. PLN 23.2 million.

An example of a direct positive effect of the OWF on marine fauna is the unintended formation of reefs on turbine foundations. The best example is the Swedish offshore wind farm Lillgrund, located in the area of the Øresund Strait between Sweden and Denmark. The development of the reef effect there has been described and photographed by Marine Environmental Inspector Kjell Andersson, and according to the diver, there is no negative impact on marine fauna at the foot of the OWF. This is very readily presented by the investor Vattenfall who also adds that there are no fishing practices in the area of the farm. Therefore, Vattenfall has modified the modern offshore wind farm to make it even more wildlife-friendly. To avoid stagnant water at the Hollandse Kust Zuid Farm in the North Sea, refuges for aquatic animals were created in the replenishment holes, making sure at the same time that the holes fulfilled their technical function. Reef habitats are formed not only by concrete or metal foundations, but above all by rocks used to prevent structural elements from moving. The larger the size of the rocks, the better protection they provide for cod and lobsters.

OWFs have a moderate impact on marine fauna. By applying the requirements imposed by EU

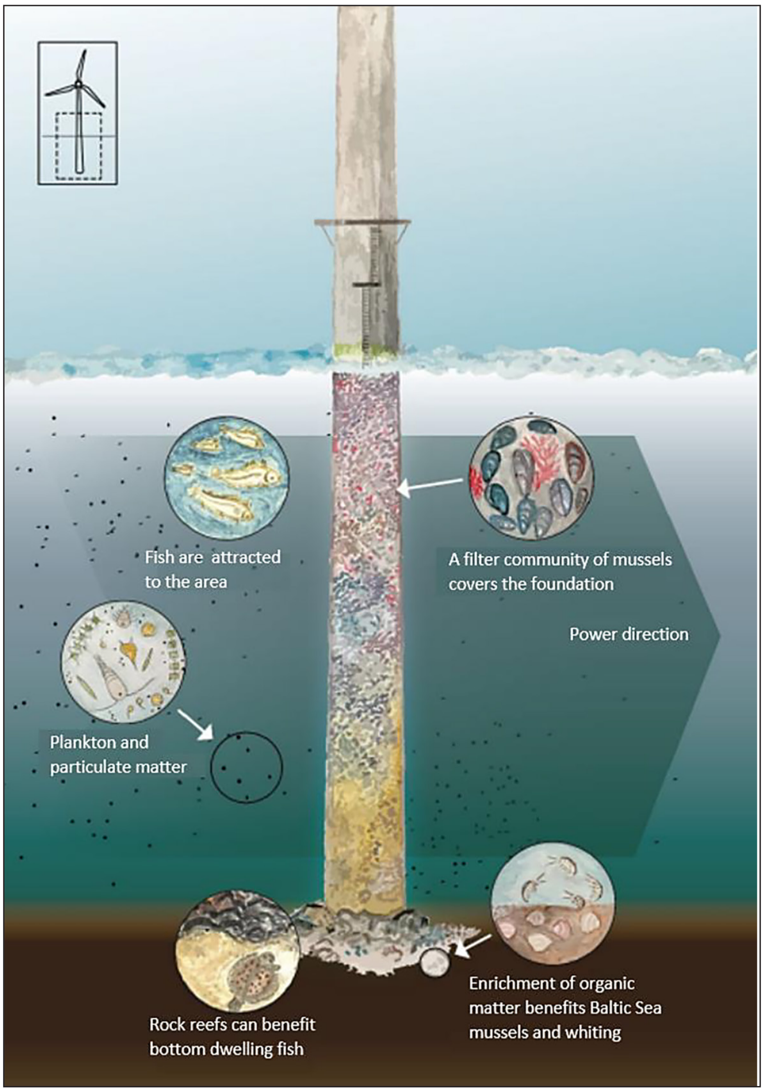

Figure 4. Illustration of a possible reef effect on the foundation of a wind turbine with species present in the Baltic Sea, prepared by Lena Kautsky [Effekter av havsbaserad vindkraft på marint liv – En syntesrapport om kunskapsläget 2021]

and Polish standards, it is possible to reduce the undesirable effects of erecting turbines and maximize the positive ones. The most intensive part of the OWF construction process that interferes with the marine environment is the launching of the foundations and the accompanying noise. Hence, the OWF investments are carried out in areas with low biodiversity. Foundations are a good base for zoobenthos and fish during the operation of wind turbines. As shown by the observations, seabirds avoid wind turbines. A potential threat could be an oil spill during a wind turbine failure. An overall analysis of the studies from a number of independent sources shows that in none of the aspects discussed, OWF investments are a greater threat to marine animals than overfishing, land-based emissions and potential UXO leakage.

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