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Wind farms operating at sea:

A sanctuary for marine fishes?

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Globally, there is an urgent need to move away from fossil fuels, like oil and gas. This will require a rapid expansion of our renewable energy capacity in the coming decades, including wind farms. Offshore locations offer a huge potential due to stronger and more consistent winds for wind farms.

However, tapping into this resource will increase our human footprint on offshore marine environments. In this article, we outline potential positive and negative effects that offshore wind farms may have on fish during the operational phase of the wind farm.

THE FAST-GROWING OFFSHORE WIND SECTOR

Our global demand for renewable energy is currently at a record high. The reason is a growing realization that the continued use of fossil fuels will pose great threats to our long-term survival. Threats include worsening air pollution, extreme weather events and global food and drinking water shortages. Likewise, fossil fuel emissions continue to accelerate the loss of natural habitats, sea ice cover and biodiversity. Nations across the globe are therefore heavily investing in renewable energy, including the use of offshore wind farms (OWF). For example, member states of the European Union have pledged to increase their OWF capacity to 300 gigawatt by 2050. This will require at least a 10-fold upscaling of the current offshore wind capacity in Europe. Clearly, such a rapid expansion of the offshore wind industry will increase the human footprint on offshore marine environments. It is therefore crucial to assess the potential positive and negative effects of the expansion on inhabitant marine life, including fish.

At present, the lifespan of an offshore wind turbine is between approximately 25 to 35 years, depending on environmental conditions and maintenance procedures. The construction phase of an OWF is generally of most concern when it comes to potential impacts on the marine environment. However, there may also be effects occurring during the operational phase of a wind farm, yet our knowledge on some of these effects remains limited. This is a surprise, because the operational phase is the longest phase within the lifecycle of a wind farm. Over the 20+ years of operations, the underwater structures of OWF may develop into diverse ecosystems hosting a wide variety of fish and other marine species. On the other hand, OWF will also be a continuous source of man-made emissions that could impact nearby marine life. Emissions during the OWF operational phase include electromagnetic fields, underwater noise, particle motion and vibration (Svendsen et al., 2022).

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WIND AND REEFS

One of the most well-established effects of OWF on marine ecosystems is the provision of new habitats for species associated with hard structures (e.g., reefs). The majority of wind turbines are constructed in soft-bottom areas (e.g., sand). In these areas, there are few places to hide for fish species that are unable to camouflage or bury themselves in the sand. However, after a turbine is constructed, different types of new hard substrates are provided that can function as habitat for fish. The monopile itself provides a hard structure running all the way through the water column. Here, many different biofouling communities (such as mussels, barnacles and anemones) can develop, depending on the water depth (Degraer et al., 2020). These communities may provide an abundant food source for higher trophic levels, such as fish. Research is showing that commercially important species such as Atlantic horse mackerel (*Trachurus trachurus*) and Atlantic cod (*Gadus morhua*) often spend prolonged periods of time near offshore structures in search of food (Fig. 1; Degraer et al., 2020).

In addition to the vertical structure created by the monopile, a wind turbine also provides complex horizontal habitats near the seabed. Because the turbine is often constructed on a soft bottom, water currents may over time create a large hole in the seabed around the turbine foundation (also called a “scour pit”). The hole in the seabed can cause the turbine to become unstable. Therefore, to maintain stability, scour protection can be installed around the monopile. The scour protection often consists of a layer of small-sized rocks

*Figure 1: Atlantic cod (*Gadus morhua*) swimming around the underwater structures of an offshore platform. Credit: C. Kuyvenhoven*

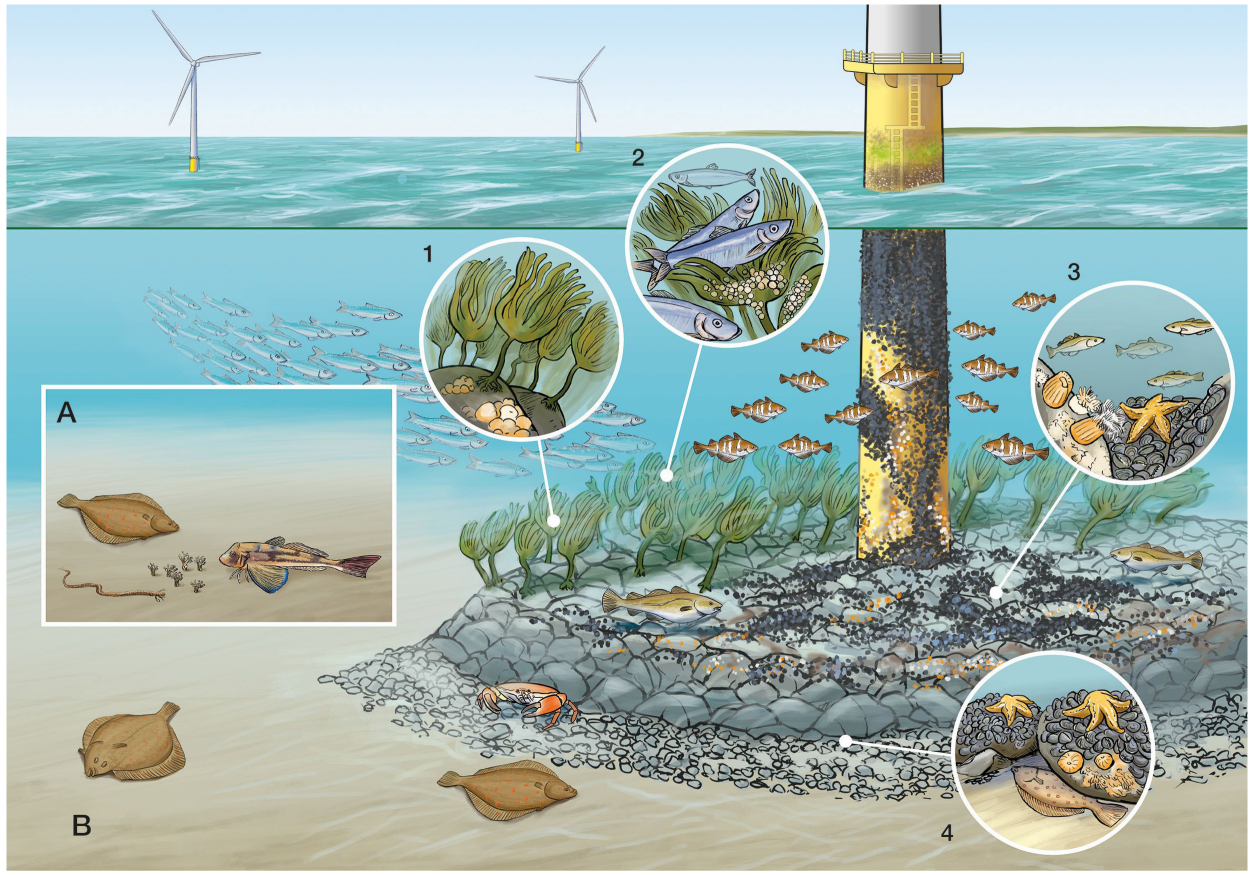


Figure 2: OWF are most often constructed on a sandy seabed, inhabited by a number of soft-bottom species that are adapted to living in environments of low structural complexity (A). After a wind turbine has been constructed, the monopile structure and scour protection offer different complex habitats for a range of fish species (B). The monopile structure can be colonized by a diverse biofouling community that goes through different successional stages, often becoming more dominated by mussels in later stages (Degraer et al., 2020). Biofouling species on the monopile offer a rich food source for different species of fish such as the pouting (Trisopterus luscus). In addition, the scour protection around the base of the turbine introduces hard substrate to the seabed. The availability of hard substrate may allow for the settlement and growth of macroalgae (here Laminaria sp.) which require hard surfaces to attach themselves (1). The macroalgae can provide a refuge for fish but may also be used by herring for deposition of their adhesive eggs (2). The rocks used in the scour protection provide shelter for juvenile fish, such as cod. This shelter availability can increase the survival of juvenile cod by protecting them from predation and also allows juvenile cod to save energy (3). Finally, the colonization of mussels may extend down to the scour protection layers. Mussels on the scour protection could offer a food source for benthic fish species, including soft-bottom species like flatfish (4). Note that the turbine in this illustration represents a shallow water turbine, constructed at depths between 20 and 30 m. The development of macroalgae on the scour protection depends, among other conditions, on adequate light penetration through the water column. Low light conditions at OWF in deeper areas may therefore not allow for any macroalgae development on the scour protection. Illustration by Hendrik Gheerardyn.

covered by larger rocks around the foundation (Fig. 2). Apart from offering stability, the scour protection typically functions as an artificial reef (Glarou, Zrust, & Svendsen, 2020) The artificial reef effects include provision of food for higher trophic levels, energy saving mechanisms (Schwartzbach, Behrens, & Svendsen, 2020), and spawning and sheltering opportunities for reef-associated fish species. Likewise, bivalves (mussel and oyster) may attach to the hard surfaces of the scour protection. Crustaceans (crab and lobster) may utilize shelters available between the rocks associated with the scour protection. Scour protection designs may be further optimized to benefit certain species of fish of a particular life stage. For example, holes and crevices of different sizes can host a variety of small- and large-bodied fishes. In addition, the scour protection may be designed with a combination of different materials such as boulders, gravel, and synthetic fronds (mimicking seagrasses). The different materials can offer diverse habitat types for a range of species.

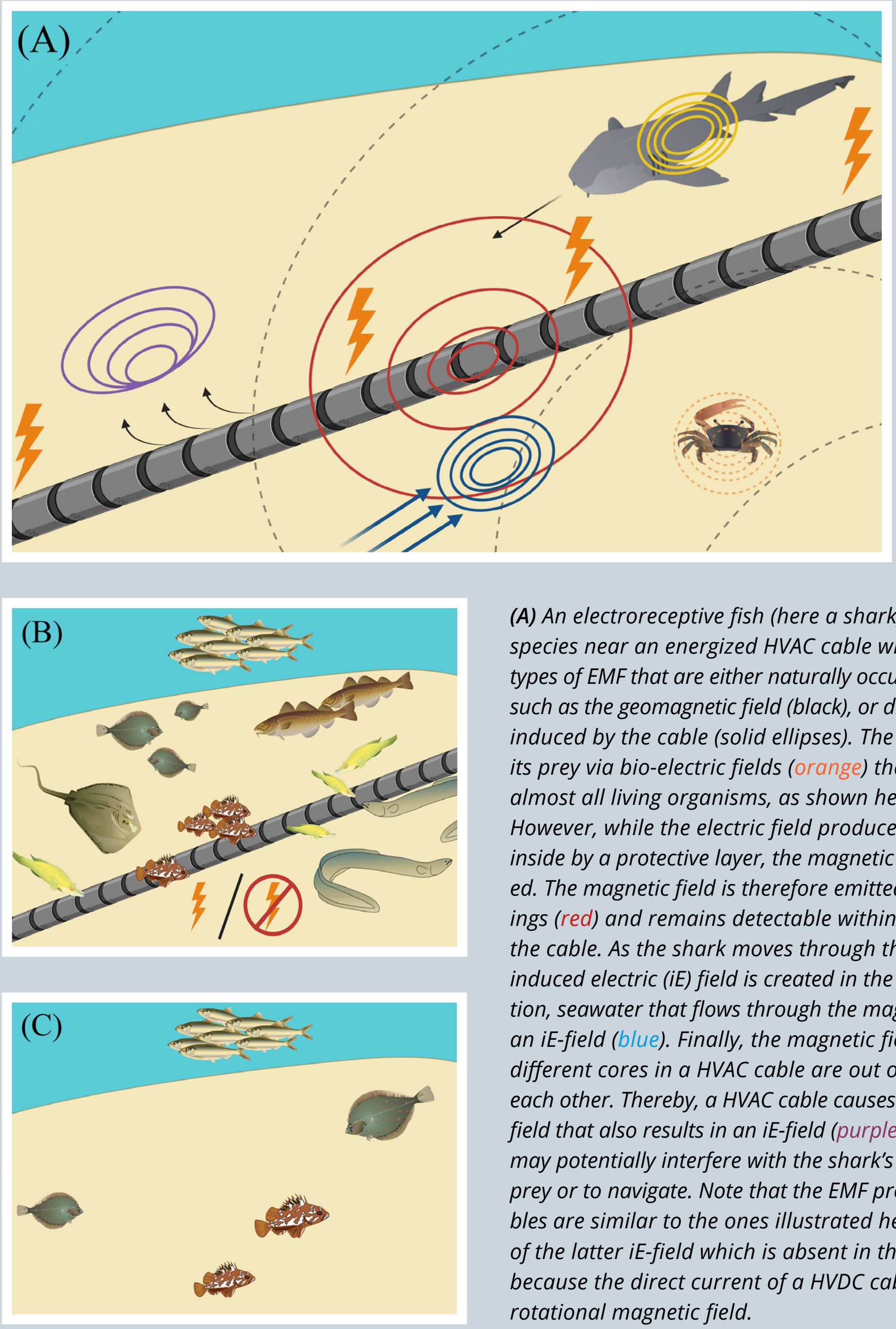
"Emissions during the OWF operational phase include electromagnetic fields, underwater noise, particle motion and vibration."

Finally, in relatively shallow waters with suitable light conditions, macroalgae (seaweed) may settle and grow on the hard surfaces of the scour protection. Seaweed often provides various benefits to fish. For example, the Atlantic herring (*Clupea harengus*) often deposit their adhesive eggs onto vegetation, and canopy-forming seaweed can function as a suitable nursery habitat for juvenile fish (Fig. 2).

ELECTROMAGNETIC FIELDS AROUND CABLES – ARE FISH AFFECTED?

The geomagnetic field (GMF) is a natural property of the Earth system. The GMF is formed within our planet's outer core. Here, convection currents of molten iron and nickel generate electric currents that create a magnetic field. The magnetic field extends from Earth's interior all the way into outer space. The GMF can be detected and used by numerous animal species on Earth, including a diverse range of marine fishes. One example is the scalloped hammerhead shark (*Sphyrna lewini*). During the day, these sharks can be found in large schools (Fig. 3) mostly around islands or seamounts. At night however, individual sharks swim along "highways" towards their feeding grounds to hunt for prey such as mackerel or squid. The hammerhead sharks are very accurately following these highways by detecting small distortions in the GMF. The sharks use the small distortions as "landmarks" for navigation. This is similar to humans using a map to get to a destination. Although the GMF gradually changes in strength over time, it still provides a reliable source of navigation for many marine species on Earth. However, subsea cables used in OWF to transport electricity to land also emit electromagnetic fields (EMF) into the surrounding environment (see Information Box 1). These anthropogenic EMF have the potential to impact fish in

*Figure 3 – Scalloped hammerhead sharks (*Sphyrna lewini*) swim in large schools during the day, yet during the night individual sharks use a "magnetic compass" to navigate from seamounts to their feeding grounds and back. Credit: © Dream69 | Dreamstime.com*



***(A)** An electroreceptive fish (here a shark) looking for prey species near an energized HVAC cable will encounter different types of EMF that are either naturally occurring (dashed ellipses), such as the geomagnetic field (black), or directly or indirectly induced by the cable (solid ellipses). The shark tries to locate its prey via bio-electric fields (orange) that are produced by almost all living organisms, as shown here around the crab. However, while the electric field produced by the cable is kept inside by a protective layer, the magnetic field cannot be shielded. The magnetic field is therefore emitted into the surroundings (red) and remains detectable within tens of meters from the cable. As the shark moves through this magnetic field, an induced electric (iE) field is created in the shark (yellow). In addition, seawater that flows through the magnetic field also creates an iE-field (blue). Finally, the magnetic fields produced by the different cores in a HVAC cable are out of phase with each other. Thereby, a HVAC cable causes a rotating magnetic field that also results in an iE-field (purple). All of these iE-fields may potentially interfere with the shark's ability to locate its prey or to navigate. Note that the EMF produced by HVDC cables are similar to the ones illustrated here, with the exception of the latter iE-field which is absent in the HVDC cable. This is because the direct current of a HVDC cable does not create a rotational magnetic field.*

***(B & C)** Research thus far indicates that fish communities near energized and non-energized cables have a similar composition. However, in absence of the cable, the species diversity and density of fish was found to be lower (Love et al., 2017), likely because the uniform soft-bottom away from the cable offers limited shelter and feeding opportunities for fish. Figure A redrawn from Newton et al. (2019). Note that the species shown in Figure B and C are not representative of the species surveyed in the study by Love et al. (2017). Symbols courtesy of the Integration and Application Network (https://ian.umces.edu/media-library/symbols/). Created with BioRender (www.biorender.com).*

Figure 4 – Illustrations of the effects of EMF produced by underwater cables on the surrounding environment.

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various ways, including their early life development and migratory behavior.

Experiments on Northern pike (*Esox lucius*) and rainbow trout (Oncorhynchus mykiss) have indicated that embryos have a smaller yolk sac, absorb the yolk sac faster and that the eggs hatch earlier when consistently exposed to an EMF in the laboratory (Fey et al., 2019). The results could indicate that fish larvae developing very close to cables may have reduced health conditions by the time they first start feeding, compared to larvae that developed further away from cables. However, these experiments used EMF intensities equal to or exceeding the maximum intensity found near underwater cables. Therefore, it remains very unlikely that such local effects could have any significant impact on fish populations at a wider scale.

Apart from early life stage development, underwater cables could affect the feeding and migratory behavior of various fish species that can detect EMF. Sharks, rays and skates use the weak electric fields produced by living organisms to locate their prey (Information Box 1) and may not be able to distinguish artificial electric fields from natural electric fields. This might explain why some species are known to bite at underwater cables. The little skate (Leucoraja erinacea) was found to significantly increase its exploratory behavior searching for prey when exposed to an artificial EMF in a tank experiment (Hutchison et al., 2020). Other species such as eels or salmon use the GMF for migration and have been observed to slightly change their swimming speed (eels swam slower and salmon faster) when appro-

BOKS 1

Underwater cables produce different kinds of electric and magnetic fields depending on the material and type of the cables. There are two main cable types used in OWF today, the high-voltage alternating current (HVAC) cables used to inter-connect individual turbines within a wind farm, and the high-voltage direct current (HVDC) cables that transport the electricity to land.

Fig. 4a illustrates the different electric and magnetic fields associated with a HVAC cable, from the perspective of an electroreceptive shark. Importantly, research has shown that fish communities living near energized cables are similar to fish communities living near non-energized cables.

These results suggest that the electromagnetic fields produced by energized cables do not affect overall fish communities. In fact, the diversity and density of fish was found to be higher near both energized and non-energized cables relative to natural soft-bottom habitats nearby (Love et al., 2017). This finding is likely explained by the physical presence of the cable, which creates more complex habitats. The more complex habitats near the cable can be used by various fish species, compared with the relatively uniform sandy bottom in the surrounding area (Fig 4b; Fig. 4c).

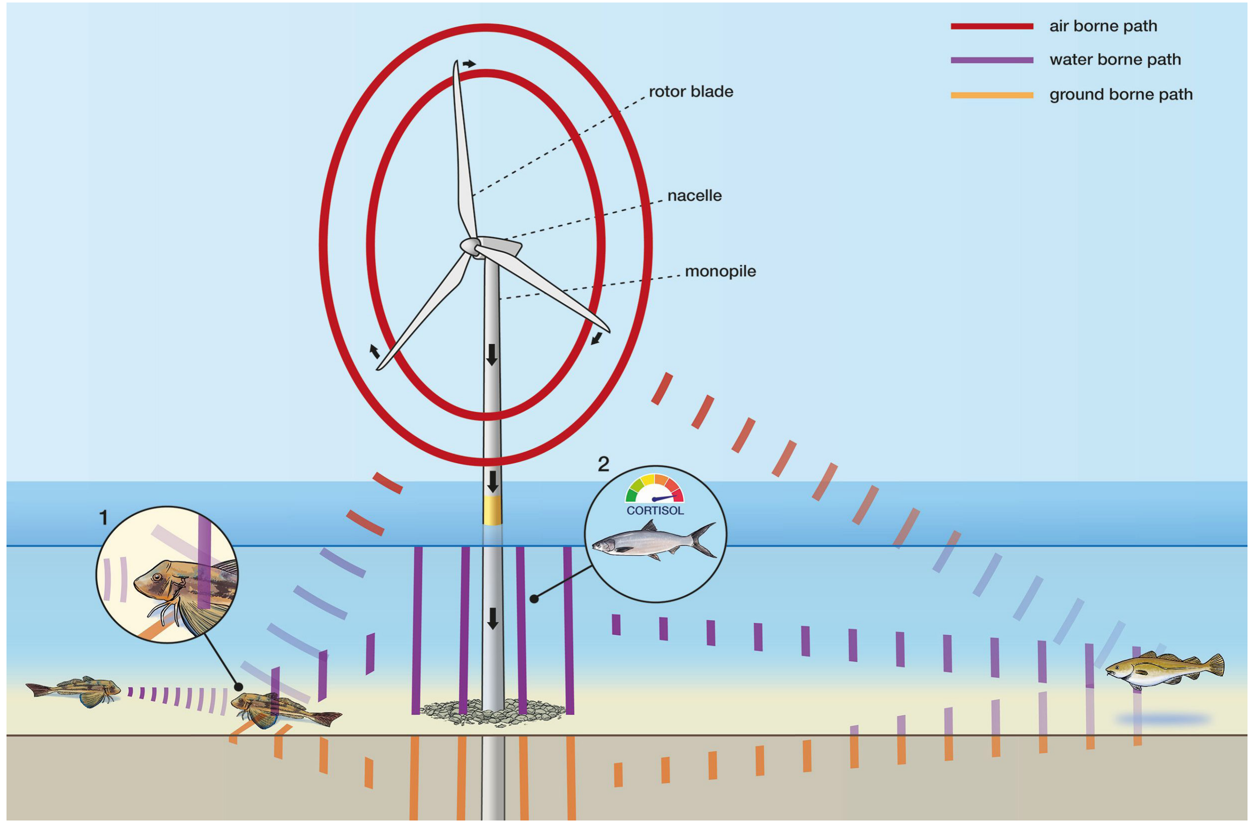
aching cables. However, to date, no studies have reported impacts of artificial EMF that would likely lower the migration success of these species in a significant fashion.

A NOISY UNDERWATER ENVIRONMENT?

Many think of the marine environment as a silent underwater world. This is, however, far from the truth. Many fish species use sound to communicate underwater. All fish species studied to date can detect sounds underwater, suggesting underwater sound plays an important role within a fish' life. Some fish species are known to produce sound while defending their territory. Other species mainly use sound to attract mates, ensure access to food items, or for strengthening group cohesion.

The marine environment is becoming noisier than it used to be, which started more than a century ago. Human activities have taken place in or near the marine environment for a long time, but the noise is increasing dramatically with elevated shipping traffic, commercial fishing and offshore resource extraction. Here, it is important to clearly distinguish the words "sound" and "noise".

Figure 5: Illustration of the different pathways through which the noise generated by a wind turbine can reach fish. For clarification purposes, airborne sound waves are shown in red, waterborne waves in purple and ground borne waves in orange. Transparency of the wave lines represents the intensity of the sound waves. The rotor blades of the turbine generate aerodynamic noise as they rotate through air. These airborne sound waves become waterborne after the sound waves hit the water surface and can reach a fish by traveling further down the water column. In addition, mechanical vibrations generated in the nacelle are transmitted downwards along the monopile (black arrows) and will pass the air-water interface. Here, the vibrations directly induce underwater noise that travels to a fish in the water column. This direct, waterborne noise is believed to be the major source of underwater noise as perceived by a fish. Finally, the structural vibrations transmitted all the way down to the bottom induce vibrations within the seabed. These vibrations can potentially impact benthic fish directly or may travel upward into the water column and reach demersal or pelagic fish as waterborne waves. Underwater noise has the potential to mask sound signals used by fish, for example for communication (1), and may also increase stress levels in some fish positioned very close to the turbine (2). Note that the size and range of the soundwaves drawn here are reduced for clarification purposes while these waves are in fact transmitted along the entire length of the rotor blades and monopile. Redrawn from Nedwell & Howell (2004). Illustration by Hendrik Gheerardyn.



> **One of the most well-established effects of OWF on marine ecosystems is the provision of new habitats for species associated with hard structures (e.g., reefs)"**

From the perspective of an organism, "sound" refers to acoustic signals that are biologically relevant and can be used by the organism. In contrast, "noise" consists of signals that are of no biological relevance and can either originate from a natural source (e.g. waves or wind) or a man-made source (e.g. boat engine noise).

Research has indicated that noise from operating wind farms can affect fish in several ways (Fig. 5). Noise may interfere with sound detection in fish, for example by blocking mating calls. This is known as the "masking" effect. The noise produced by operating wind farms falls within the frequency range detected by fish, meaning there is a potential risk that this noise can affect social interactions between fish and change their behavior. In the laboratory, scientists have tested the effects of noise by exposing fish to playback sounds of operating wind farms for several days continuously. Results indicated that both the black porgy (*Acanthopagrus schlegelii*) and milkfish (*Chanos chanos*) showed signs of increased stress levels after prolonged exposure to the noise (Chang et al., 2018; Wei et al., 2018). However, laboratory experiments mimic an extreme situation where the fish cannot freely swim away from the noise source. Such extreme conditions are likely to be rare near OWF, where instead the real impact of noise will depend on the sound level, the duration, and the distance at which the fish is experiencing the noise. Therefore, there is limited evidence suggesting that the noise of operating wind farms is harmful to fish. It is worth mentioning that no fish died during any noise experiments conducted thus far.

TWO POSSIBLE STRESSORS THAT REMAIN LARGELY OVERLOOKED: PARTICLE MOTION AND VIBRATION

Particle motion (PM) and vibration have received much less attention than EMF and underwater noise, even though PM and vibration are closely related to underwater noise (see Information Box 2). Underwater noise from an operating wind turbine can reach a fish via different pathways (Fig. 5), involving PM and vibrations. The exposure of these potential stressors to fish varies between species, depending on their hearing mechanism. Our knowledge on the effects of PM on fish is still very limited to date, mainly due to the challenge of measuring PM in the field and the limited availability of suitable equipment. Still, PM levels generated by wind turbines can be detected by fish. Since PM is a main acoustic stimulus for fish, changes in PM levels caused by operating turbines are increasingly recognized as a risk, and the topic of PM should therefore be prioritized in future research (Popper & Hawkins, 2019).

Similarly, the effect of vibrations occurring within the substrate near an operating wind turbine remain largely unknown. Substrate vibrations have the potential to affect benthic fish species, of which some are known to bury themselves in the sediment. Substrate vibrations could also affect demersal fish species like cod, which live in close association with the seabed and may be highly sensitive to substrate vibrations. It has been previously suggested that there exists a rich environment of different vibrations in the ocean's seabed, a so-called "vibroscape". This phenomenon remains largely hidden to the human senses and is similar to the natural soundscape that exists in the water column. This vibroscape consists of different natural vibrations related to burrowing, moving and feeding of species living in the sediment, as well as vibrations caused by waves, turbulence and earthquakes. Operating wind turbines have the potential to locally change this vibroscape and thereby affect the way fish and other organisms interact with it. However, any impacts of such local changes remain poorly understood and should be investigated in future studies.

CONCLUDING REMARKS

Today, there is a scientific consensus that OWF can benefit a range of fish species and other marine organisms throughout the 20+ years of wind farm operations. The benefits are explained by OWF providing hard structures that can be colonized by different communities and may develop into rich ecosystems. These effects of OWF resemble artificial reefs, deployed for conservation purposes, commercial fisheries enhancement, recreational development, etc. While potential negative effects from operating OWF have received less attention, the topics of EMF and underwater noise are nonetheless relatively well studied. Research has thus far shown limited negative effects on fish species. Importantly, there is no scientific evidence to date indicating that EMF, underwater noise, particle motion or vibration, emitted by operating OWF, can directly kill fish. Still, it remains largely unknown if any of these potential stressors may have a long-term impact on fish populations.

The offshore wind industry is set to expand rapidly in the coming decades, both in the capacity of individual turbines and in the overall number of farms. It remains important to assess how this expansion is going to affect marine life. For example, how will an increase in power transmitted within underwater cables affect the EMF produced by the cables and their effect on fish nearby? What will be the combined effect for migratory fishes encountering multiple OWF on their migratory route? Such questions must be answered primarily through experimental research in the field, as well as laboratory studies that mimic the conditions that fish experience near wind turbines as best as possible. The topics of PM and vibration in particular require more scientific focus, as changes in these stimuli may significantly impact the way fish interact with their natural surroundings. It will only be through an improved understanding of these various topics, that we may ultimately be able to mitigate any negative effects. This advanced knowledge should be developed while we simultaneously optimize the design of OWF to fully harness the benefits they can offer to marine life.

BOKS 2

The potential stressors of underwater noise, particle motion and vibration are all related. When noise (or sound) is produced in a medium (like seawater), the medium particles next to the noise source start moving back and forth in a wave-like motion. By doing so, the particles cause a similar movement in neighboring particles, basically transporting the energy away from the source and thereby propagating the noise. The movement of these medium particles is called particle motion. Similarly, if the source is located on top or within the seabed, the particles are now moving within a solid medium to propagate the energy, a process also known as vibration. As such, the noise and vibrations produced by an operating OWF can reach a receiver, for example a fish, through different mediums and via several pathways (Fig. 5).

REFERENCES

Chang, H. Y., Lin, T. H., Anraku, K., & Shao, Y. T. (2018). The effects of continuous acoustic stress on ros levels and antioxidant-related gene expression in the black porgy (Acanthopagrus schlegelii). *Zoological Studies*, 57. doi:10.6620/ZS.2018.57-59

Degraer, S., Carey, D. A., Coolen, J. W. P., Hutchison, Z. L., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore wind farm artificial reefs affect ecosystem structure and functioning. *Oceanography*, 33(4), 48–57.

Fey, D. P., Greszkiewicz, M., Otremba, Z., & Andrulewicz, E. (2019). Effect of static magnetic field on the hatching success, growth, mortality, and yolk-sac absorption of larval Northern pike Esox lucius. *Science of the Total Environment*, 647, 1239–1244. doi:10.1016/j.scitotenv.2018.07.427

Glarou, M., Zrust, M., & Svendsen, J. C. (2020). Using artificial-reef knowledge to enhance the ecological function of offshore wind turbine foundations: Implications for fish abundance and diversity. *Journal of Marine Science and Engineering*, 8(5). doi:10.3390/JMSE8050332

Hutchison, Z. L., Gill, A. B., Sigray, P., He, H., & King, J. W. (2020). Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Scientific Reports*, 10(1), 1–15. doi:10.1038/s41598-020-60793-x

Love, M. S., Nishimoto, M. M., Snook, L., Schroeder, D. M., & Bull, A. S. (2017). A comparison of fishes and invertebrates living in the vicinity of energized and unenergized submarine power cables and natural sea floor off Southern California, USA. *Journal of Renewable Energy*, 2017. doi:10.3160/soca-116-02-61-87.1

Nedwell, J., & Howell, D. (2004). *A review of offshore wind farm related underwater noise sources*. COWRIE Report No. 544 R 0308: 1-57.

Newton, K. C., Gill, A. B., & Kajiura, S. M. (2019). Electroreception in marine fishes: chondrichthyans. *Journal of Fish Biology*, 95(1), 135–154. doi:10.1111/jfb.14068

Popper, A. N., & Hawkins, A. D. (2019). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. *Journal of Fish Biology*, 94(5), 692–713. doi:10.1111/jfb.13948

Schwartzbach, A., Behrens, J., & Svendsen, J. (2020). Atlantic cod Gadus morhua save energy on stone reefs: implications for the attraction versus production debate in relation to reefs. *Marine Ecology Progress Series*, 635, 81–87. doi:10.3354/meps13192

Svendsen, J. C. ., Ibanez-Erquiaga, B., Savina, E., & Wilms, T. J. G. (2022). *Effects of operational off-shore wind farms on fishes and fisheries. Review report*. National Institute of Aquatic Resources, Technical University of Denmark.

Wei, C. A., Lin, T. H., Chen, R. D., Tseng, Y. C., & Shao, Y. T. (2018). The effects of continuously acoustical stress on cortisol in milkfish (Chanos chanos). *General and Comparative Endocrinology*, 257, 227–234. doi:10.1016/j.ygcen.2017.07.018