What are the potential effects of the electromagnetic fields produced by offshore wind farm power cables on marine organisms?

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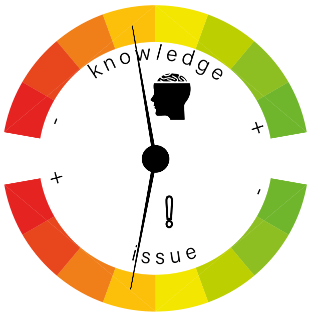
COME3T

LABEL COME3T

The **COME3T label** aims to promote research projects designed to enhance knowledge of the environmental and socio-economic issues arising from the development of offshore renewable energies.

It comes under the COME3T initiative, a committee of experts for environmental issues related to offshore renewable energies, which brings together neutral, independent experts to provide scientific knowledge and recommendations in response to these issues.



Question deemed by the experts to be "an issue of intermediate concern with regard to current knowledge—considered moderate—of the potential effects of EMFs in natural environments"

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Introduction

Electromagnetic fields (EMFs) occur naturally in the environment, including the marine environment. Many living organisms are capable of detecting them. Many marine species (cetaceans, sharks, rays, fish, sea turtles, crustaceans, etc.) show sensitivity to magnetic fields and certain species, such as rays and sharks, have electroreceptive organs with which they are able to sense electric fields.

Artificial EMFs can exist alongside natural EMFs and can disturb these so-called magnetosensitive and electroreceptive species. In the marine environment, the main source of man-made EMFs is power cables in operation, which are used for a number of purposes (connecting islands to the mainland power grid, supplying power to offshore platforms, etc.). With the development of offshore wind farms (and offshore renewable energy at large) off the coast of France, the number of power cables installed in the marine environment is set to rise over the coming decades, raising questions within the scientific community about the potential effects of these cables on marine organisms and the environment.

Cross-section of a power cable

Definitions

Voltage and current

To understand the difference between electrical "voltage" and "current", an analogy can be made between water systems and electricity grids. The pressure exerted in a water system can be likened to the voltage in an electricity grid, while the flow of water can be compared to the electric current. An electric current is the flow of electrons through a conductive material and is characterised by its intensity (expressed in amperes, A). When a lamp is plugged into mains electricity, for example, it is supplied with electric power (expressed in Volts, V) and emits an **electric field** (expressed in Volts/meter, V/m). When the lamp is switched on, an electric current flows through the supply cables at a certain intensity and generates a **magnetic field** (Fig. 1). This magnetic field may be static (in the case of a direct current) or alternating (in the case of an alternating current) (see box on next page). The combination of the electric field and the magnetic field is known as an **electromagnetic field**[1].

Fig. 1 *Illustration of the example of the lamp and the units of measurement used to define electric current – Voltage (in V) and intensity (in A). Adapted from RTE*[1].

Electromagnetic waves and fields

An electromagnetic wave or field is characterised by a **frequency** (number of repetitions of a pattern in one second, expressed in Hertz, Hz) and a **wavelength** (i.e. the distance travelled for the duration of the pattern, expressed in metres, m). The shorter the wavelength (in other words, the higher the frequency), the greater the energy carried by the wave. In the case of high propagation, we use the term **electromagnetic waves**. This is the case for instance of the high frequencies used in telecommunications. For low frequencies, the term **electromagnetic field** applies.

Conductivity

Capacity of a material to carry an electric current, expressed in Siemens (S) as a function of distance (S/m). The opposite of conductivity is **resistivity**, i.e. the ability to resist the flow of an electric current, expressed in Ohms (Ω) as a function of distance (Ω.m).

Effect

Objective consequence of the introduction of one or more pressures liable to generate **impact** on the marine living environment. An effect may or may not generate an impact on the different compartments of the marine ecosystem according to their **sensitivity** (capacity to tolerate changes to the environment – resistance, and the time required for it to recover following these changes – resilience)[2].

[1] MOOC "Comprendre les champs électromagnétiques d'extrêmement basses fréquences" by RTE: https://mooc.cem-50hz.info/

[2] Adapted from definitions given by the working group on cumulated effects (GT ECUME) under the French Ministry in charge of the environment and derived from the French order of 17 December 2012 relating to the definition of good ecological status

What is the difference between alternating current and direct current?

An electric current is a flow of electrons through conductive material. Depending on how the electrons flow, the current will be referred to as either alternating or direct current.

In the case of alternating current, the flow of electrons regularly reverses direction. Its frequency, expressed in Hertz (Hz), indicates the number of times the flow changes direction per second. In Europe for example, the frequency used for alternating current is 50 Hz, which means that the electric charge reverses direction 50 times per second. This type of current is characteristic of alternator generation systems, in which the rotor turns to produce energy.

Direct current carries the electric charge in one direction only. It is characteristic of currents delivered by batteries or accumulators, with a unidirectional current flowing from the positive terminal to the negative terminal.

Cumulative effect

Combination in time and/or space of several effects (resulting from one or more different anthropogenic activities) which may be **additive** (the sum of the effects is equal to the sum of each effect acting individually), **antagonistic** (the effects observed will be less than the sum of each effect acting individually), **synergistic** (the effects observed will be greater than the sum of each effect acting individually) or **masking** (one effect dominates the signal and masks the other effects) on an **ecological receptor** (i.e. an individual, species, group of species or habitat)[3].

Benthic

Relating to the seabed. A **benthic** organism is an organism that spends the majority of its life cycle (or even its entire life cycle) on or near the bottom or in the sediment. Conversely, a **pelagic** organism is an organism that spends all or part of its life cycle swimming or floating in the water column.

[3] Adapted from the definition of "cumulative effects" proposed by the OES-Environmental: https://tethys.pnnl.gov/about-oes-environmental

Electromagnetic fields in the marine environment

What characterises an electromagnetic field in the marine environment?

An **electromagnetic field (EMF)** is generated when electrical charges are set in motion. It comprises two components: an **electric field** and a **magnetic field**. The **electric field (EF)** is directly related to the electric voltage. Its strength therefore depends on the voltage and the distance from the emitter (expressed in Volts/m). The **magnetic field (MF)** occurs together with the electric field and is generated by the flow of an electric current. The magnetic field depends on the intensity of the electric current and the distance from the emitter (expressed in Amperes/m or, more often, in µTesla based on the equivalence 1 A/m = 1.25 µT). In the presence of a conductor (marine current, passing animal, etc.), the magnetic field can lead to an **induced electric field (IEF)** of a few µV/m (Fig. 2).

The specificity of the diffusion of EMFs in the marine environment is due to the relatively high **conductivity** of seawater (between 3 and 5 S/m) compared with soil (around 0.001 S/m) or freshwater (between 0.02 and 0.08 S/m). This is directly correlated to the **seawater's physico-chemical properties**, in particular its salinity, temperature and depth.

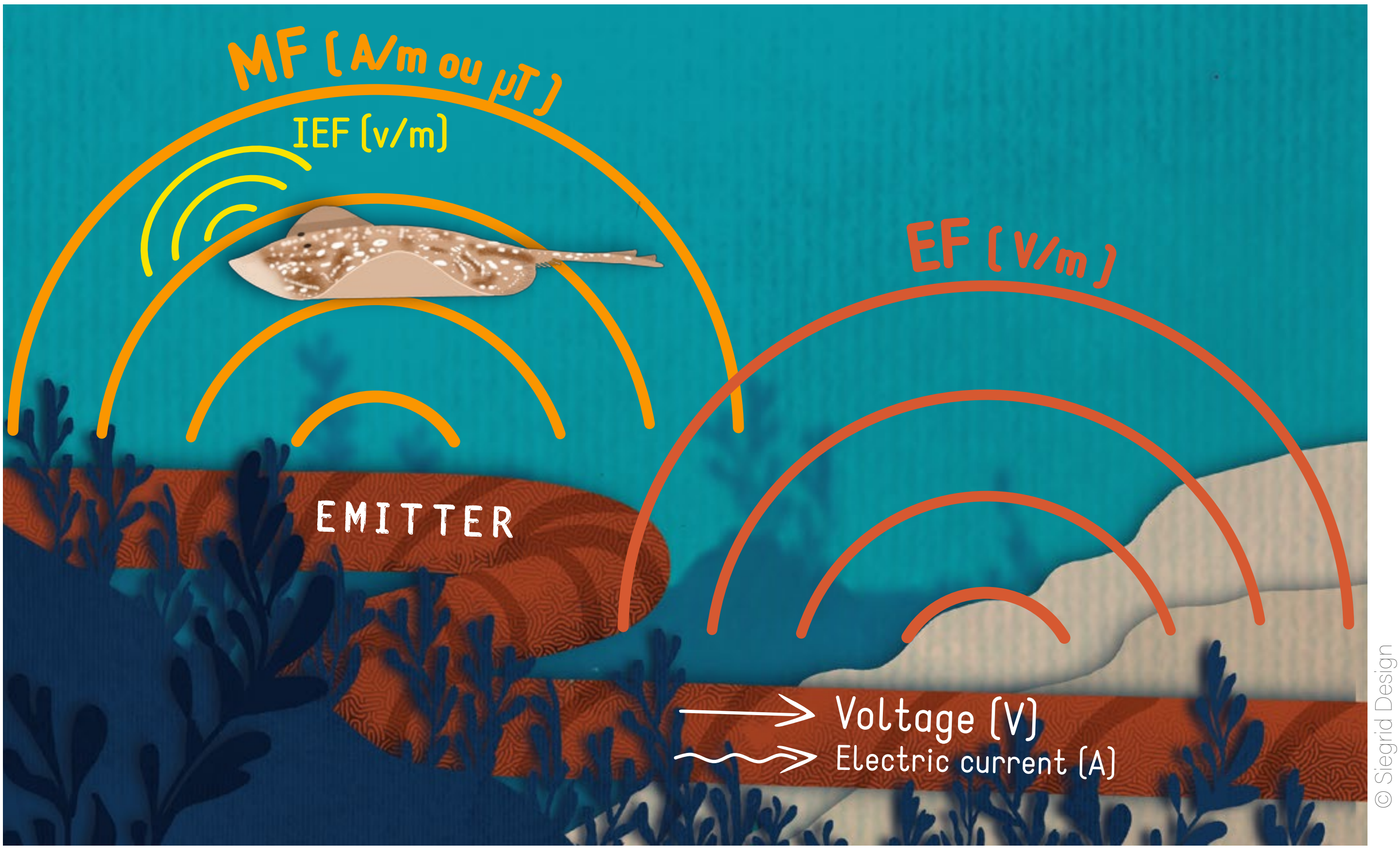


Fig. 2 *Components of the electromagnetic field in the marine environment.*

EMFs occur naturally in the environment. The Earth's magnetic field (also known as the **geomagnetic field**) is the best known example. Present around the entire globe, its intensity varies from 20 µT at the equator to 70 µT at the poles, and is around 50 µT in Europe. This geomagnetic field originates in the Earth's core (at a depth of between 3,000 and 5,000 km) and is considered to be relatively stable. Marine organisms themselves can also be considered natural sources emitting weak, highly localised electric fields, known as **bioelectric fields**.

Human activities also generate EMFs. In the marine environment, artificial EMFs are mainly induced by shore-based activities (close to the coast) and submarine cables.

Measuring electromagnetic fields

Man-made EMFs can be monitored and measured using different types of instruments that are sensitive to minor variations in magnetic and electric fields. Given the low resistivity of seawater, these measurements are difficult to make in the marine environment and require specialised measurement instruments. The **electrometer** measures voltage and the **magnetometer** gives an indication of the magnetic field by measuring the induced electric field (conversion of the magnetic field into an induced electric field using a transconductor).

Between 2017 and 2020, two innovative EMF measurement systems were deployed as part of the SPECIES project[4]: the PASSEM and STATEM systems. The PASSEM towed measurement system contains a magnetometer and electrodes to measure magnetic and electric fields in the water and identify the emitting zones. The STATEM measurement station, installed on the seabed, contains magnetic and electric sensors. It is able to (i) measure electromagnetic signals near to the source, (ii) monitor EMFs over time and (iii) combine them with on-site biological observations.

[4] SPECIES project: Characterisation of the potential impacts of subsea power cables associated with offshore renewable energy projects (2017- 2020)

Electromagnetic fields and offshore wind farms

What are the sources of EMF emissions in wind farms?

Within offshore wind farms, the main sources of EMFs are the cables used to transport the electricity generated during the farm's operational phase. There are two main categories of cable used in offshore wind farms. The characteristics of these cables (type of current, power, length, etc.) can vary considerably from one wind farm to another (Fig. 3):

- **inter-array cables**
- **export cables**

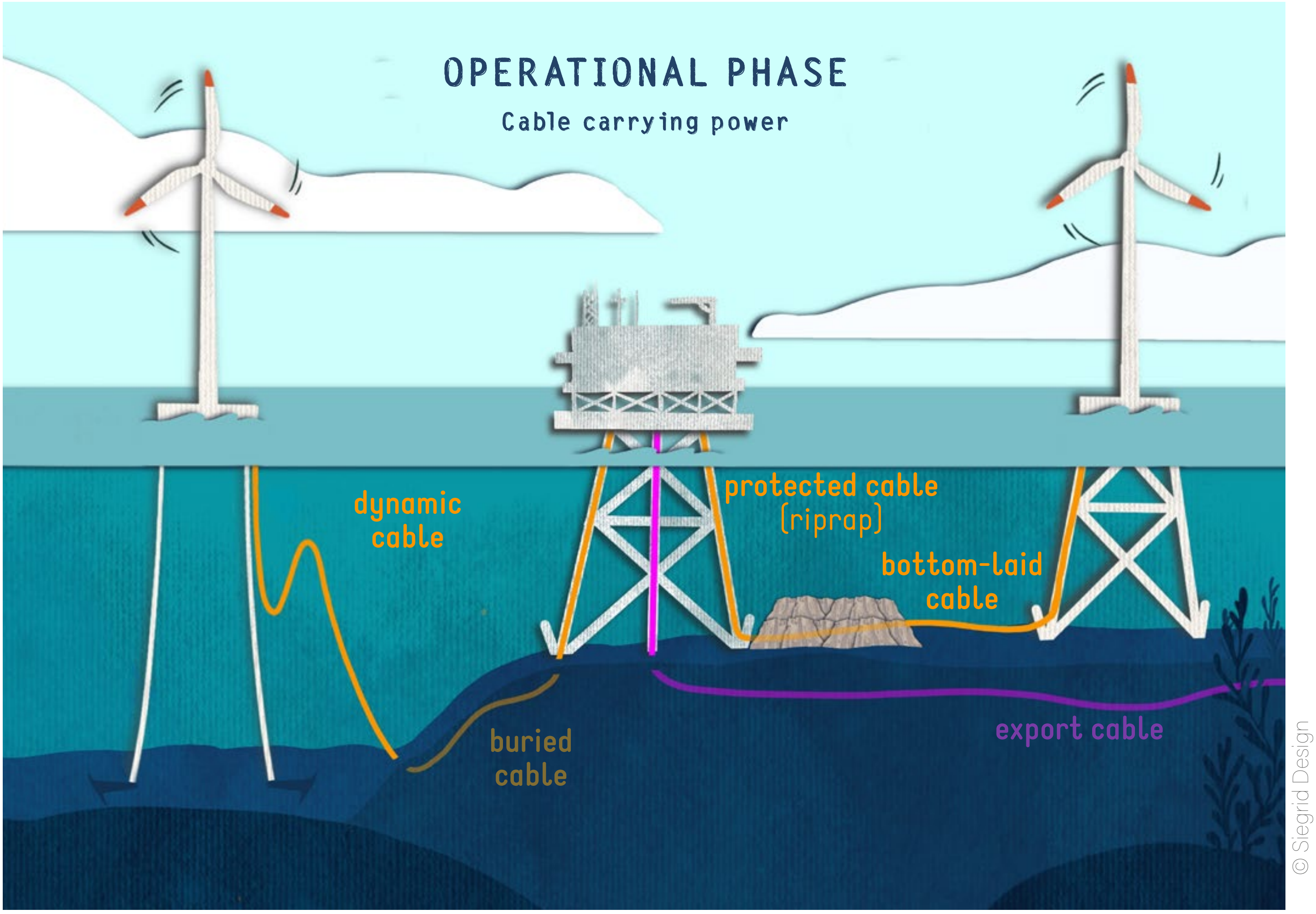


Fig. 3 *Overview of the different sources of EMFs from offshore wind farms. Depending on the type of infrastructure, inter-array cables (in orange) may be dynamic, buried, protected or laid, while export cables (in purple) will necessarily be buried, protected or laid.*

Inter-array cables carry the electricity generated by the wind turbines to the offshore substation, where the voltage is stepped up to high voltage (above 200 kV) by electrical transformers. This operation reduces potential electrical losses during long-distance transmission and reduces the number of cables needed to transport electricity from sea to shore (connection to the public electricity grid). Inter-array cables generally carry alternating current and have a capacity of 10 to 36 MW and a small diameter (around 15 cm).

Export cables carry the electricity generated by the wind farm to the onshore electricity grid, by connecting the offshore substation to the onshore substation. Depending on the distance to the onshore substation, these export cables may transmit power in the form of **alternating current** (short distance < 50 km) or **direct current** (distance > 50 km).

Alternating current cables are preferred, as the use of direct current cables requires prior conversion of the alternating current from the inter-array cables to direct current. Export cables are generally larger in diameter (20 to 30 cm) and can carry a current with a typical voltage of 230 kV[5].

What are the conditions surrounding EMF emissions in wind farms?

During operation, inter-array cables and export cables will generate electric and magnetic fields. Despite the differences in diameter and voltage between these two types of cable, the current flow and the resulting EMF are relatively similar. The electric fields inherent to the voltage running through the cables remain confined inside the cables as they are protected by metal sheaths. **The cables therefore do not directly generate electric fields in the marine environment.**

However, these metal sheaths do not confine the magnetic fields inside the submarine cables. The cables will therefore emit magnetic fields, whose level will depend on the intensity of the current flowing through the cables and their installation parameters (how the cables are arranged in relation to each other). The **intensity of the magnetic fields** emitted by the different cables studied (direct current cable, alternating current cable, etc.) **is localised and decreases with distance from the cables**.

The **magnetic field** levels emitted by cables would appear to be the same whether the cables are suspended in the water column (in the case of dynamic inter-array cables used by floating offshore energy production systems), laid on the seafloor, buried in sediment or protected by cable protection systems. However, magnetic field exposure levels can vary depending on the type of cable and species' lifestyles. Exposure to the magnetic fields emitted by dynamic inter-array cables may, for instance, be higher for certain pelagic species. In the case of buried cables, the magnetic field exposure level varies depending on the species. Exposure will be lower for benthic species, whereas it will be higher for burrowing species and substrate-dependent species, even if, according to Clavier (1984), between 1 and 1.5 m deep (i.e. the average depth for cable burial) the abundance of burrowing species is considered to be low.

[5] SPECIES project: Characterisation of the potential impacts of subsea power cables associated with offshore renewable energy projects (2017- 2020)

Electromagnetic fields and marine fauna

The cables carrying power from offshore wind farms can generate magnetic fields whose intensity exceeds that of the Earth's geomagnetic field. Although their intensity decreases with distance from the cable, man-made EMFs may contribute to the localised masking or alteration of natural electromagnetic signals.

What mechanisms do marine species use to detect EMFs?

In cartilaginous fish such as rays and sharks for example, the mechanism for sensing electric fields is well known. These species have electroreceptor cells called "ampullae of Lorenzini" (Fig. 4). These specialised cells are composed of a tube filled with a thick, conductive substance that enables an electrical signal to be transferred from the mouth of the tube (which forms a pore at the skin surface) to its base which is connected to the nervous system. Ampullae of Lorenzini are sensitive to variations of 0.5 µV/m and essentially enable cartilaginous fish to sense and capture prey. Marine organisms' heartbeat, breathing or movements in the water generate a bioelectric field and/or an induced electric field that is liable to be detected.

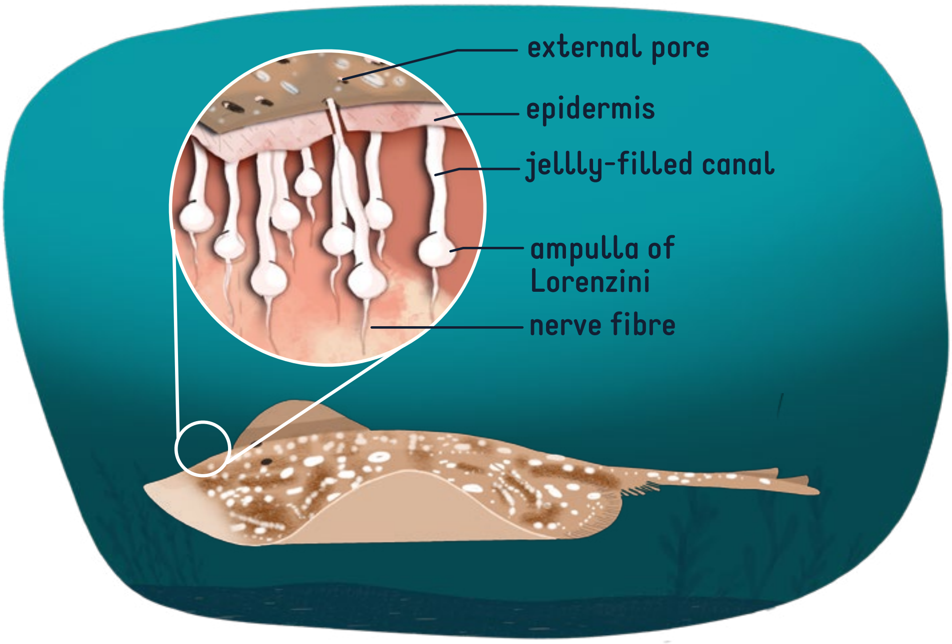


Fig. 4 *Diagram of ampullae of Lorenzini, electro-sensory cells in cartilaginous fish.*

However, the mechanisms by which marine organisms sense the magnetic fields involved in magnetoreception remain unknown, and various hypotheses have been put forward by the scientific community (presence of specialised receptors, etc.). Although the mechanisms used to detect magnetic fields remain uncertain, the phenomenon of magnetoreception has been recognised and demonstrated in many marine species, particularly migratory species (sea turtles, fish, crustaceans, amphipods, etc.).

What are the potential effects of EMFs on marine organisms?

In general terms, studies on the perception of artificial magnetic fields by marine organisms have only been carried out at the scale of individuals. In this respect, according to Boehlert and Gill (2010), only the notion of **potential effects** can be addressed here, as there is insufficient scientific evidence to support the claim that the EMFs generated by power cables induce impacts on populations, communities or ecological processes.

In addition, studying potential effects is particularly complex as it depends on a number of factors such as: the sensitivity of the species and of each individual within that species, the probability of an encounter between an individual and a power cable, the distance of the individual from the artificial magnetic field, etc.

The potential effects identified by the scientific community for all marine organisms capable of detecting EMFs can be summarised as follows (Fig. 5):

- Behavioural changes [1] including attraction/repulsion effects [2];
- Impairment of navigation and orientation capacities [3];
- Physiological effects [4].

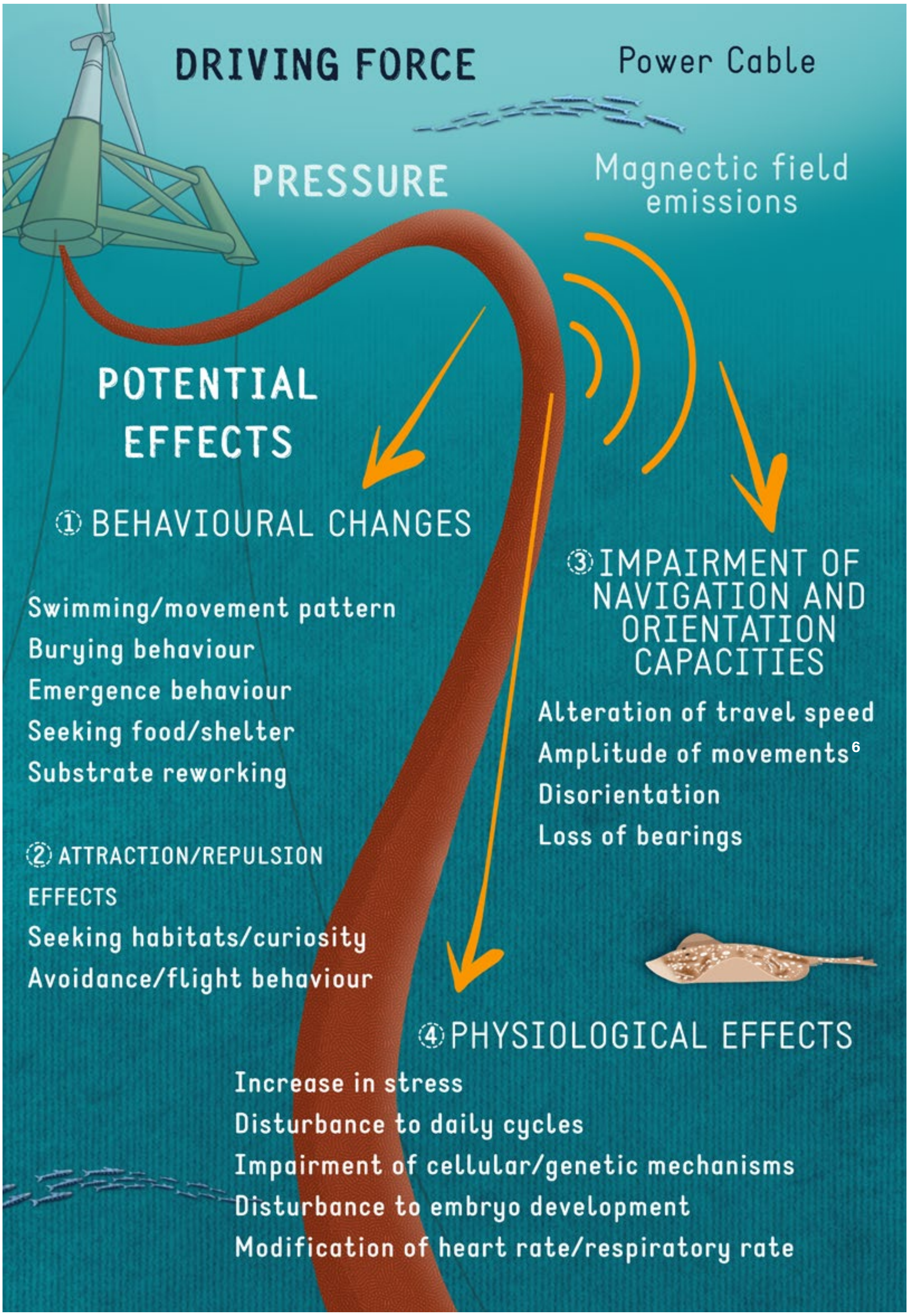


Fig. 5 *Overview of the potential effects of man-made EMFs on marine organisms (the list of examples given for each category of potential effects is not exhaustive and draws on the results of experiments carried out in controlled environments for selected species and life stages).*

[6] Corresponds to the amplitude of shell movements observed in bivalves such as mussels, oysters and scallops.

What knowledge gaps currently remain?

According to the current state of knowledge, magnetic fields can induce species-specific, and even individual-specific, responses. It is therefore important to be cautious when extrapolating results obtained for a single species to other species. Research into the evaluation of these potential effects is still incomplete for a number of reasons:

- Fundamental knowledge about magnetosensitivity and electrosensitivity is still lacking for many species. The sensitivity of a single species to EMFs can vary according to its life stage (eggs, larvae, juveniles, adults), which hinders our understanding of the potential effects;
- The majority of studies have been carried out in the laboratory under controlled conditions and have focused only on exposure to man-made magnetic fields. The intensities tested in the laboratory are often high and are not always representative of the levels of exposure found in the natural environment. They are limited according to the methodological choices made for the experiment (choice of species, parameters measured, field levels tested, etc.);
- Most studies focus on the potential effects of magnetic fields, while few investigate induced electric fields;
- The magnetic fields studied are generally those emitted by laid or buried cables. Few studies have investigated the EMFs emitted by dynamic cables; these EMFs propagate through the water column and can affect pelagic species. This gap is mainly due to a lack of feedback on wave and floating wind technologies;
- The experiments carried out to monitor and assess the potential effects of EMFs focus mainly on behavioural changes, with few monitoring studies conducted on organisms' sensitivity thresholds and the long-term effects.

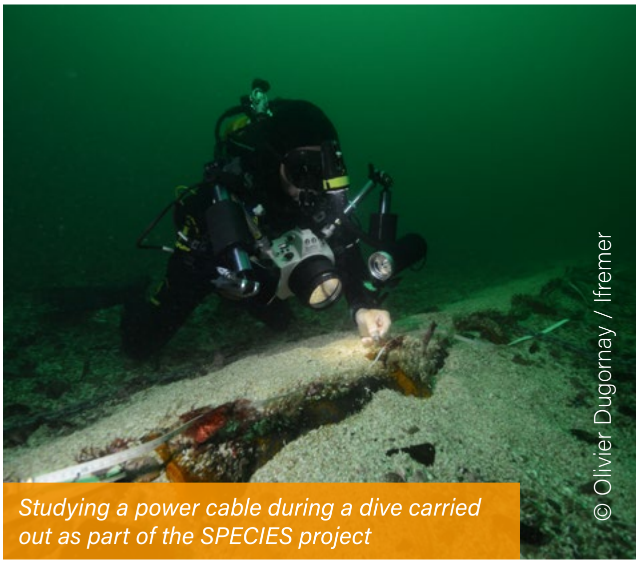
Recommendations

Generally speaking, all the experts involved emphasised the lack of scientific feedback on the effects of EMFs on marine organisms and the need to improve knowledge in order to respond to current environmental concerns. To fill these gaps, a number of recommendations based on various scientific reports (see bibliography) on the effects of EMFs are put forward here:

- Focus research on the species that are potentially most exposed to EMFs, such as burrowing species or species with a benthic life stage (eggs, larvae, etc.), which migrate along the seabed or are liable to use cables and their protection systems for shelter or attachment;
- Improve our knowledge of species-specific EMF detection capabilities in order to define sensitivity thresholds;
- Take measurements in the field and select the relevant magnetic and electric field values in order to study potential effects. Few *in-situ* measurements currently exist and most of the values used to study potential effects draw upon theoretical emission values established from cable performance data. High (megatesla-order) values are generally tested and are not representative of real emissions;
- Identify areas with a high density of power cables and where there may be potential cumulative effects, which could affect a larger surface area than simply the cable route. This is the case, for instance, of areas around offshore substations, where all the inter-array cables converge, leading to a potentially higher risk of cumulative effects;
- Characterise EMFs, taking into account the characteristics of the current (AC or DC), the cable configuration and density, etc.
- Characterise the potential effects of inter-array cables and develop appropriate reduction measures in the case of proven impacts;
- Develop and implement long-term monitoring within wind farms to assess the potential cumulative effects on species at different life stages.

Outlook

The development of offshore wind farms off the French coastline will mean an increase in the number of power cables installed in the marine environment. Regulatory environmental monitoring will be conducted on these sites, which, in addition to dedicated research projects, could help to improve knowledge of the potential effects of EMFs in the natural environment. These specific monitoring initiatives will require the development of appropriate, specialised EMF measurement instruments. They may draw on existing research infrastructures developed as part of other research projects to study the effects of offshore wind farms on marine fauna. The aim in doing so would be to combine approaches and pool efforts to study the pressures generated by offshore wind farms.



Studying a power cable during a dive carried out as part of the SPECIES project

Conclusion

While there is solid knowledge of the effects of man-made EMFs on land, gaps currently remain in our understanding of their effects in the marine environment. Various studies on the effects of EMFs on different species have been carried out in experimental conditions, however *in-situ* studies are still too scarce and cover too limited a range of species. Furthermore, laboratory experiments are often carried out with high magnetic field emission levels, which are not representative of the emission ranges likely to be encountered in the marine environment. Based on the current state of knowledge, it is difficult to anticipate any cumulative effects, particularly in areas with a high density of cables (offshore substations, for example), making this issue one of relatively high concern.

IN SHORT

EMFs are naturally present in the environment and some marine organisms are able to detect them. Within offshore wind farms, power cables generate EMF emissions that are liable to be sensed by certain "magnetosensitive" species. Thanks to the protective metal sheaths surrounding the cables, only magnetic fields, which have a localised intensity that decreases with distance from the cable, will be emitted into the marine environment. The level of exposure of species to these magnetic fields will depend on the type of cable (dynamic, laid, protected, buried), its characteristics (type of current, power, etc.) and the species' lifestyle (benthic, pelagic, burrowing, etc.). The potential effects of EMFs on marine fauna can be divided into three main categories: (1) behavioural changes, including attraction and repulsion phenomena; (2) impairment of navigation and orientation capacities; (3) physiological effects. Further knowledge, in particular of EMF sensing mechanisms by marine species and the assessment of potential effects in real-life conditions, is essential in order to gain a better understanding of the potential effects of EMFs on marine fauna.

Find out more

Read the SPECIES project report, available online:

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