U.S. OFFSHORE WIND SYNTHESIS OF ENVIRONMENTAL EFFECTS RESEARCH

ELECTROMAGNETIC FIELD EFFECTS ON MARINE LIFE

MAIN TAKEAWAYS

- Subsea power cables are sources of electromagnetic fields (EMF), which are made up of induced electric fields and magnetic fields.
- EMFs from natural sources also exist in the marine environment. Some marine animals, such as sharks, salmon, and sea turtles, can detect naturally occurring electric and/or magnetic fields and use those signals to support essential life functions, such as navigating and searching for prey.
- When in close proximity to subsea cables, some animals have demonstrated behavioral responses in a few studies, such as increased foraging and exploratory movements.
- So far, behavioral responses of individuals have not been determined to negatively affect a species population, but further research is needed to refine our understanding of the effects of EMFs on wildlife.

Please visit **Tethys** to view the literature reviewed to inform the development of this research brief.

TOPIC DESCRIPTION

Electric power cables, such as those used in offshore wind (OSW) farms, are sources of electromagnetic fields (EMFs) that may add to and interact with other sources of electric and magnetic fields that are present on land, in the atmosphere, and underwater. Some marine animals have specialized receptors that can detect electric and/or magnetic fields. They use these senses for navigation, orientation, or detection of other organisms. While a small number of scientific experiments have shown that some animals have the ability to respond to EMFs, there is no conclusive evidence to determine that EMFs from an OSW farm will cause any impacts to an individual animal or population.

Similar to existing submarine power cables and to a lesser extent telecommunication cables, electrical cables at OSW farms are a source of EMFs in the marine environment. Over the past 50 years, most subsea power cables have been operated to transmit electricity across bodies of water. At OSW farms, submarine power cables are used to connect individual wind turbines together (i.e., inter-array cables) and to transmit power back to shore (i.e., export cables) (Figure 1). Inter-array cables transmit power using alternating current (AC) systems, and export cables can transmit power using AC or, for longer distances, direct current (DC) systems. Most power cables are buried in the seabed or protected with a concrete mattress or other coverings, but some cables for floating OSW farms are deployed in the water column (top-right in Figure 1).

> Submarine power cables are used to connect individual offshore wind turbines together and transmit power back to shore.

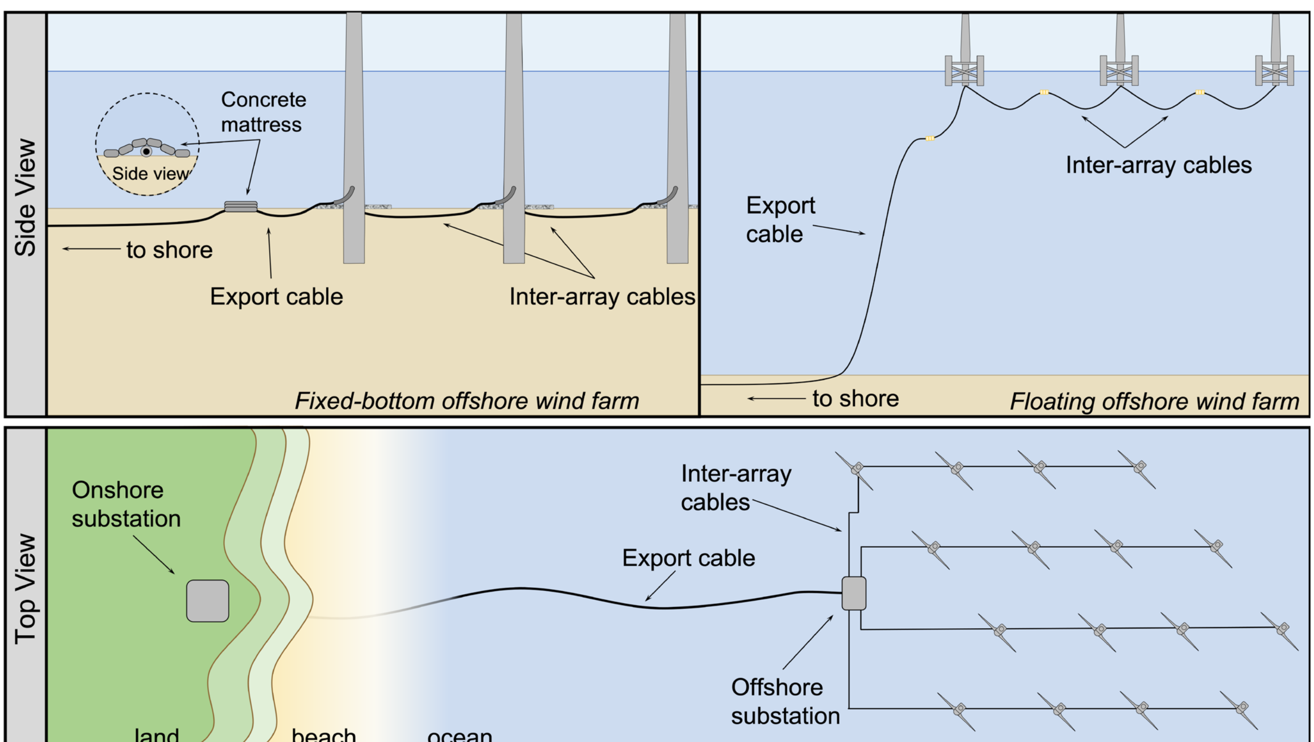

Figure 1. *An illustration of how electrical cables are used at fixed-bottom (top left) and floating offshore wind farms (top right). Inter-array cables connect between individual turbines and can be collected at an offshore substation to convert to a higher voltage export cable that connects to the onshore electrical system (bottom). Drawings are not to scale.*

What are EMFs?

Electromagnetic radiation is present in the environment across a spectrum of frequencies including radio waves, microwaves, visible and ultraviolet light, and X-rays. EMFs are a type of low-frequency electromagnetic radiation generated from natural and anthropogenic sources such as the Earth's geomagnetic field, thunderstorms, power cables, and electronics. The type of power cable that is used (AC or DC) influences the types of EMFs that are created. Low frequency EMFs from power cables include both magnetic and electric fields (Figure 2), which are described below.

- **Electric Field:** When a subsea power cable is electrically charged, it produces an electric field, or E-field. When perfectly grounded, the electrical shielding prevents E-fields from entering the surrounding environment.
- **Magnetic Field:** When an electrical current flows through a cable, it produces a magnetic field, or B-field.
- **Induced electric Field:** The oscillation of an AC magnetic field creates an induced electric field, or iE-field. Induced electric fields have the same properties as an electric field produced by the voltage on the conductors within the cable (E-field), except they are generated through a different mechanism.
- **Motion-Induced Electric Field:** When a conductive object or an electric charge moves through a magnetic field, it produces a motion-induced electric field. For example, a motion-induced electric field is created when seawater or aquatic animals pass through a static magnetic field, such as the Earth's geomagnetic field or a B-field around a subsea cable.

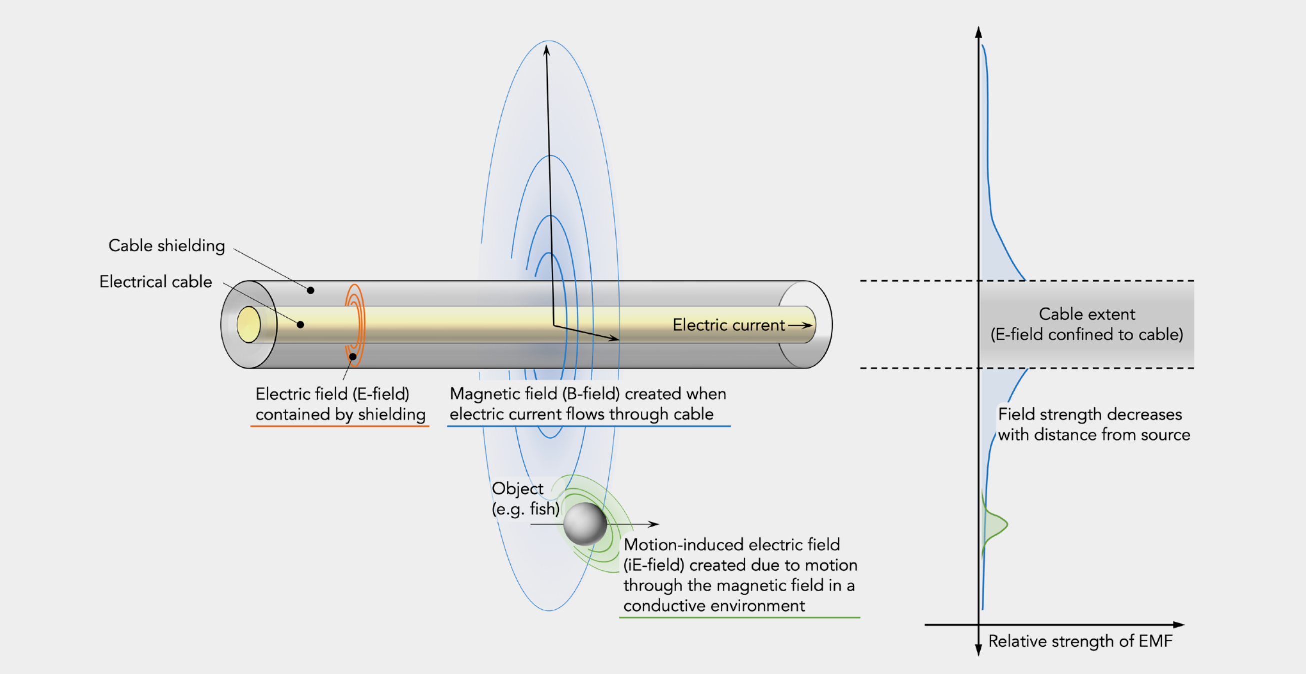

Figure 2. *Depiction of an EMF from an electrical cable (left) and relative field strength (right) from a snapshot in time. The electric field (orange) is contained by the cable shielding. The magnetic field (blue) is produced by both AC and DC cables. A motion-induced electric field (green) is created as a conductive object moves through the static DC magnetic field of the Earth or the magnetic field from a subsea cable. The figure does not show an induced electric field that would be created around an AC cable due to the rotating magnetic field (AC only).*

How are EMFs generated at offshore wind farms?

Subsea power cables are shielded and grounded, which eliminates most electric field emissions into the surrounding environment as long as the cable is undamaged (Figure 3). However, magnetic fields cannot be eliminated through cable design and will surround the area of the cable. Local motion-induced electric fields then are produced when an animal or seawater moves through a magnetic field.

Power cables from OSW farms can carry either AC or DC power. AC power typically is used for export cables from existing OSW farms, but because of lower cable costs and lower power losses, DC systems may become more economical as projects move farther from shore even though their terminal converter costs are higher. Both AC and DC systems produce magnetic fields, but DC cables are capable of carrying higher power levels that may result in the generation of stronger B-fields than those generated from an AC cable.

EMFs are strongest immediately adjacent to the cable. The strength of the magnetic field and an associated induced electric field decreases with distance from the cable (Figure 4). The highest intensities of magnetic fields typically are observed within the first few meters around a subsea power cable; however, this distance will increase as higher electric current levels are carried in these cables. In certain scenarios, magnetic fields beyond the first 5 meters (16 feet) from to the cable have decreased to less than 10% of the magnitude of the initial magnetic field. The magnitude of the total magnetic field (i.e., $B_{total} = B_{earth} + B_{cable}$) also depends on the interaction with the local geomagnetic field intensity and its orientation, which results in both positive and negative deviations in the field.

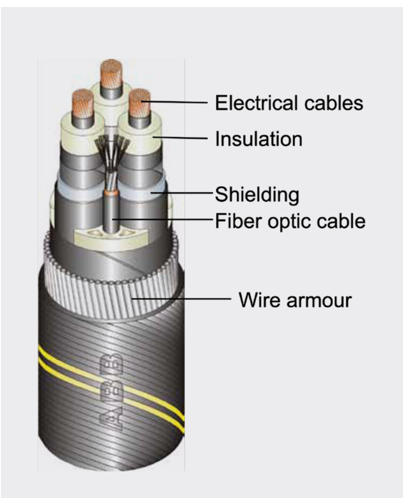

Figure 3. *Subsea AC electrical cable, adapted from* ***ABB (2019)***

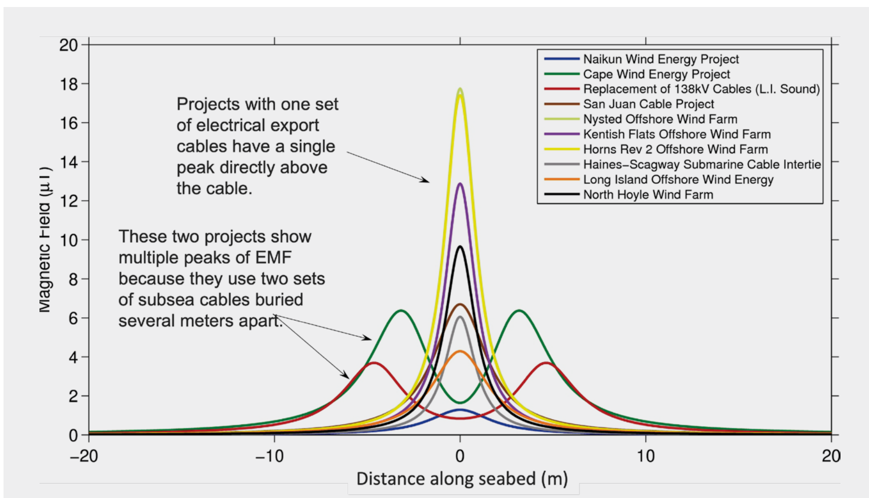

Figure 4. *Modeled spatial distribution of the modeled magnetic field strength on the seabed from existing and proposed offshore wind AC cables (figure adapted from* ***Normandeau et al., 2011****). The spatial range shown here extends on both sides of the cable and would be present along the entire length of the subsea cable; often several kilometers or longer. Note that this plot shows the magnetic field strength from subsea cables, not the induced electric field from AC cables.*

How do animals sense EMFs?

The ability to sense either electric or magnetic fields has been identified or theorized for a range of marine wildlife including some fish species, elasmobranchs (i.e., sharks, skates, and rays), cetaceans (i.e., whales and dolphins), some sea turtles, and invertebrates (i.e., some snails, lobsters, and crabs). Electroreceptive species detect electric fields using special sensory organs, known as the Ampullae of Lorenzini, in sharks, skates, rays, and relatives of those species (Figure 5). The biological mechanisms for magnetoreception—or the ability to detect magnetic fields—are not completely understood despite years of research. Experts currently believe that magnetoreception occurs either when an animal detects an induced electric field or when animals have internal magnetic minerals that sense a magnetic field and send signals through their nervous system. Regardless of how a marine animal detects forms of EMFs, these abilities allow some electrosensitive and magnetosensitive species to respond to an EMF from electrical cables if the field is within their sensory range.

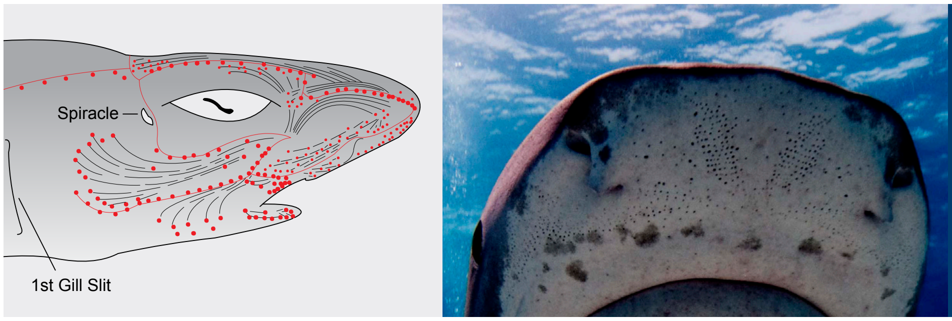

Figure 5. *Ampullae of Lorenzini are electroreceptors located within pores on the head of a shark. Images from Wikimedia Commons (left, right).*

EMF Detection

An animal's sensory abilities determine the EMF components that it can detect (i.e., E-field, B-field, iE-field). Their sensitivity to an EMF and the minimum and maximum intensity thresholds at which they can sense the field will determine whether it responds to an EMF emitted from an electrical cable. Sensitivity to an EMF is specific to each species (Figure 6), and the range of detectable EMFs is difficult to generalize for all animals within one group without a focused study. The frequency of an EMF also is important. It has been demonstrated that DC and low-frequency (e.g., <10 Hz) fields can be detected by some species, but there is less evidence that sensory mechanisms of marine species in North America respond to fields at higher frequencies of 50–60 Hz associated with AC power cables.

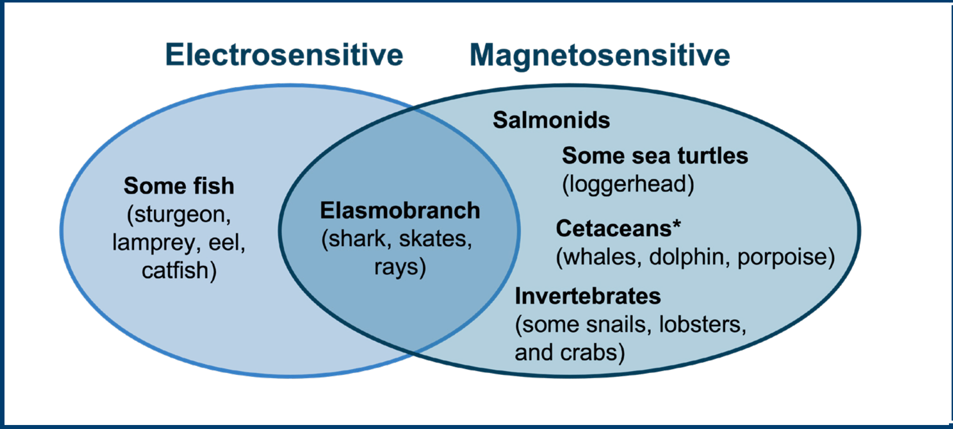

Figure 6. *Examples of marine wildlife with the ability to sense EMFs. This diagram does not include all electrosensitive and magnetosensitive marine life. *Note that the hypothesis of magnetosensitivity in cetaceans is primarily based on indirect, theoretical, anatomical, and limited observational evidence based on migratory behaviors.*

MAIN RISKS AND EFFECTS

The ability to detect electric or magnetic fields supports essential life functions in some marine animals, such as locating predators or prey and navigating and orienting through water. Although the physical interactions between cable-induced EMFs and naturally occurring EMFs are not well-understood, EMFs from subsea cables also may disguise or distort natural EMF cues that animals use for important life functions. It has been hypothesized that adding anthropogenic EMFs to the marine environment would interfere with the reception of electrical and magnetic signals by sensitive marine species and perhaps interfere with their ordinary response to natural electric or magnetic signals. Most scientific research has used laboratory or field experiments to understand electrosensitivity or magnetosensitivity of species. This research helps provide a greater understanding of how some animals use electric and magnetic fields for essential life functions, but specific studies, including experiments, are needed to understand whether EMFs from subsea cables will have a significant effect on the life outcomes of an individual or population.

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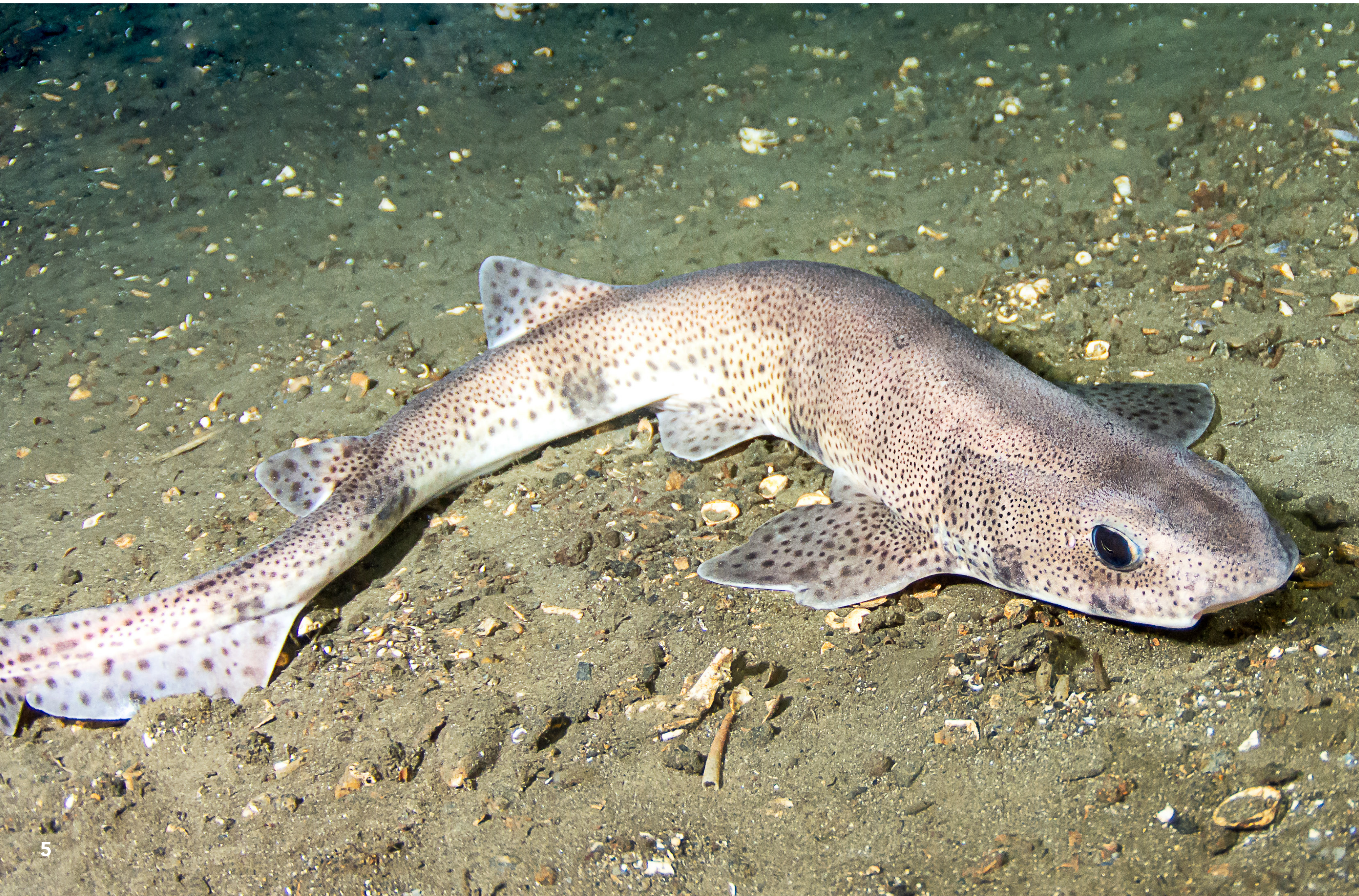

How does marine life respond to EMFs?

Some marine life can detect electric and magnetic fields. Different species will respond to EMFs in different ways depending on how that animal uses EMFs in the natural world. Some behavioral responses are described below.

- **Navigation and Orientation:** Some invertebrates, sharks, stingrays, sea turtles, eels, and salmon have been observed to use their sense of the geomagnetic field to help navigate during migrations and orient themselves to return to a specific location. Loggerhead sea turtles, which are present on both the Atlantic and Pacific Coasts, use magnetosensitivity to navigate during their migration and then reorient to return home. Sockeye salmon have been found to use the Earth's magnetic field, in addition to chemical signals, to navigate through the ocean back to their home river to spawn. Local magnetic anomalies or additional sources of EMFs are not known to disrupt an animal's sense of location, but there is limited evidence to confirm this. Field observations show that some species are able to navigate through a complex magnetic landscape with anthropogenic magnetic fields. For example, young Chinook salmon and green sturgeon in San Francisco Bay appear to detect magnetic fields from high-voltage DC power cables and large static magnetic anomalies produced by metal bridges as they moved through the bay to the ocean, but their migration was not affected.

- **Predator and Prey Interactions:** Some electroreceptive predators use the ability to sense electric fields to detect prey, and some electroreceptive prey use the same ability to detect the location of predators. Sharks, rays, and skates use their sense of electric field for close-range detection of prey, especially when the target is outside their line of sight. Additionally, some prey in the embryonic state (e.g., rays and sharks) will initiate a freeze response to avoid detection when predators are present. During this time, gill movement, tail beating, and all ventilatory behaviors stop. However, it is unknown whether anthropogenic EMFs from subsea cables or other sources might influence this freeze response. Some species, such as the little skate, have shown increased exploration/foraging behaviors when exposed to EMFs from DC cables. When encountering AC cables, another study found that small-spotted catshark more frequently visited the area and exhibited less movement nearby the AC cables, which are behaviors typically are associated with feeding patterns in benthic catsharks.

- **Avoidance, Attraction, and Behavioral Effects:** The ability of some marine life to detect EMFs can lead to attraction or avoidance behaviors when these fields are present. In a natural setting, some species use EMFs to locate the opposite sex during mating season, whereas others use it to detect prey, predators, or other individuals. Higher-strength EMFs may elicit avoidance behavior in some species whereas lower-strength fields, which could mimic EMFs from prey, may attract other electrosensitive species. Studies show that species respond to EMFs with different behaviors. When encountering EMFs, the American lobster exhibits an increased likelihood of exploratory behaviors, and the brown crab reduces roaming and exhibits attraction behaviors to shelters where EMFs are present. Another study shows a similar species, the European lobster, exhibits no attraction, foraging, or exploratory behaviors when exposed to a static EMF. Similarly, yellow rock crab and red rock crab also did not exhibit attraction or repulsion when exposed to EMFs. The range of results from these behavioral studies helps illustrate how animals may or may not respond to different types of EMFs.

- **Changes Throughout Life Cycle:** EMFs can elicit anatomical responses during an animal's entire life cycle. For example, in one study rainbow trout hatched a day earlier after exposure to a static magnetic field, and in another study they displayed a faster growth rate and enhanced immunity and resistance to disease when exposed to a low-frequency (i.e., 15-Hz) magnetic field. In both cases, the EMF had no effect on the mortality of larval or embryonic fish. Steelhead trout raised in natural magnetic fields are able to orient themselves better than steelhead raised in a distorted, static magnetic field (i.e., a hatchery). Physiologically, it has been shown that juvenile benthic organisms are affected cellularly when they are exposed to a high-strength (i.e., 50-Hz) AC EMF field. An animal's response and sensitivity to EMFs also can change during different life stages. Skates and rays use their electrical sense in early ages to find prey and then adapt to use electrosensitivity for social communication and to find mates during later life stages. Understanding potential effects of EMFs from subsea cables requires knowledge of how a cable intersects different ecosystems and life stages of animals and how often animals will encounter EMFs at frequencies and intensities within their detection range.

Anthropogenic EMFs can stimulate behaviors in marine life that would occur normally in response to natural EMFs (e.g., attraction to a subsea cable because it is mistaken for prey) or it can temporarily disrupt an animal's ability to use existing EMFs in their environment (e.g., a subsea cable locally distorting a geomagnetic field used by some animals for navigation). Behavioral responses to EMFs would be anticipated only in species that can sense these fields, such as those shown in Figure 6. Animals with the ability to detect an EMF does not mean they will respond to, or be affected by, new EMF sources in their environment.

To understand the potential for EMFs to affect marine life, we must consider several technical, geographic, and biologic factors:

- **Cable Characteristics:** The type of subsea cable (AC or DC) influences the characteristics of the EMF as well as its detectability by different species. Additionally, while inter-array and export cables both emit EMFs, inter-array cables typically operate with lower electrical current, which generate lower-strength EMFs than export cables because the strength of the magnetic field is directly linked to the amount of current flowing through the cable. The distance or range that the EMF extends from the cable depends on several factors including the cable design and amount of power flowing through the cable. A model developed for existing subsea cables found that the strongest EMF is within the first 2 meters (7 feet) of the cable and then decreases to lower levels beyond 10 meters (33 feet) from the cable (Figure 4). Because of engineering limitations, multiple parallel export cables occasionally are installed to carry lower power loads per cable instead of using a single high-power export cable. In this case, a lower-intensity EMF may be emitted across a wider footprint depending on spacing and the electrical current flowing through the cables.

- **Marine Life Detection Range:** Electrosensitive and magnetosensitive species are able to detect particular intensities and frequencies of EMFs. To sense an EMF from a subsea cable, an animal's range of detection must overlap with the intensity and frequency of the EMF emitted from the cable. Distinct detection ranges of electric and magnetic fields are not well known for different species. Magnetosensitive species are considered to be responsive to very small changes in the magnetic field, as these species can use small deviations in the geomagnetic field over relatively long periods of time and distances for orientation and navigation. In contrast, electrosensitive species have receptors that can detect electric fields from low-frequency, low-voltage AC signals where the need for detection is immediate and the range of detection is limited to less than 1 meter (3 feet). Some species such as sharks, skates, rays, invertebrates, and some fish have the greatest sensitivity to electric fields less than 25 Hz. AC cables used for electric power transmission, which operate at 60 Hz in the United States (50 Hz in Europe), appear to be less detectable by electrosensitive species. Overall, the intensity of EMFs does not directly correlate to potential environmental effects in which higher intensity means more likely effects. Instead, lower-intensity EMFs that are within the frequency detection range of marine organisms may be more likely to elicit a response.

- **Location of Cables and Likelihood of Encounter:** Subsea cables cross through different marine ecosystems as they route back to shore. EMFs from subsea cables also need to be considered in the context of local geomagnetic field properties (intensity and orientation) to determine the level of EMF change that may be detected by migrating species. Site-specific studies help determine which EMF-sensitive species may use or migrate across a cable route. Marine animals that spend time on or near the seafloor are more likely to encounter EMFs than animals in the water column. Individual marine animals that frequently pass a subsea cable will encounter more EMFs during their life cycle, but the long-term effects from multiple encounters on survivability and reproductive success, if any, are not known.

- **Response to EMF:** Responses to EMFs will vary based on how a species uses fields from natural sources. Animals may exhibit natural responses to EMF stimuli when they encounter

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EMFs from subsea cables. Species that use the Earth's static magnetic fields for navigation or to derive locational cues may lose track of their direction temporarily as they pass through a magnetic field around a cable. Animals that use EMFs to detect predators or prey may begin foraging for food around EMFs of the appropriate frequency and intensity.

- **Mechanisms of Impact to an Individual Animal or Population:** Recent research has shown that a variety of marine species can detect and react to electric and magnetic fields. However, there is no conclusive evidence that shows whether or not an EMF from a subsea cable will cause negative impacts to an individual animal or population. Continued research and field studies are needed to understand potential impacts.

Despite behavioral effects observed for some species in the experimental studies, EMFs generally have been considered to have negligible or minor impact to marine species during environmental reviews of OSW farms or other scientific reviews. A regional evaluation of EMF effects in southern New England found that those effects would be negligible to fish and invertebrates. During surveys on the Pacific Coast of California, community structures of fish and invertebrates near existing AC subsea cables were found to be similar to their structure in a natural habitat, suggesting there was no response to the magnetic field. However, the evidence base to evaluate population level impacts is limited and requires extrapolating experimental studies; therefore, confidence in these assessments is considered low by some researchers.

EMFs from Floating Offshore Wind Farms

For floating OSW farms developed on the Pacific Coast or other deep-water locations, inter-array cables and a portion of export cables suspended in the water column will generate EMFs (Figure 1). Most of these cables are inter-array cables, which carry less power than export cables and produce lower-strength EMFs that may be within the detection range of some species. While at present there is little evidence to illustrate an animal's EMF detection range, floating cables have the potential to affect a different group of species (i.e., animals that move throughout the water column) that should be considered when identifying a project's potential risk.

Cumulative Effects

Increased numbers of subsea cables from future OSW farm projects and other marine industries possibly could lead to cumulative effects in heavily developed regions. The potential for cumulative effects from EMFs has not been characterized from studies or research. Still, an EMF from a single cable needs to be considered in the context of other cables in the area (i.e., existing and proposed cables) and other activities that might occur in the region. For example, the addition of new cables might increase the number of subsea cables a migratory species could encounter along its migratory route. These scenarios need to be studied to understand the actual interactions that may occur.

Status of Knowledge

Overall, there is no conclusive evidence that EMFs from a subsea cable creates any negative environmental effect on individuals or populations. To date, no impacts interpreted as substantially negative have been observed on electrosensitive or magnetosensitive species after exposure to EMFs from a subsea cable. Behavioral responses to subsea cables have been observed in some species, but a reaction to EMFs does not necessarily translate into negative impacts. Continued research and monitoring are required to understand the ecological context within which short-term effects are observed and if species experience long-term or cumulative effects resulting from underwater exposure to EMFs.

MONITORING & MITIGATION METHODOLOGIES

Measuring or modeling the strength and extent of EMFs is an important step toward understanding if a specific cable has the potential to induce environmental effects. Magnetic fields can be modeled using specific information about the cable design and oceanographic conditions along the cable route. Model results can show how EMFs spread into the surrounding water horizontally and vertically from the cable (for example, Figure 7).

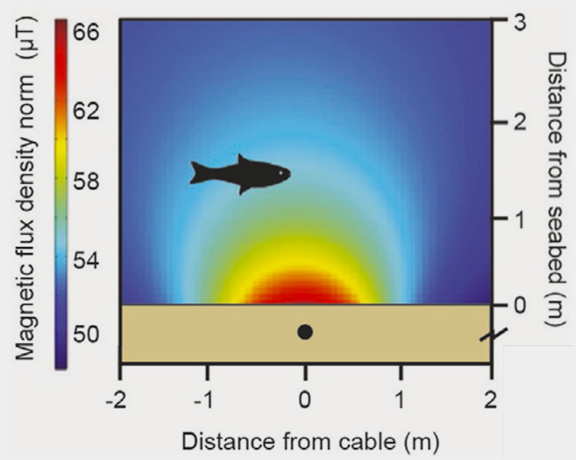


Figure 7. *Modeled magnetic field strength of a DC cable buried 1.5 meters beneath the seafloor. The magnetic field strength is highest just above the cable and then decreases with distance from the source. Fish not to scale. Image adapted from* ***Hutchison et al. 2021.***

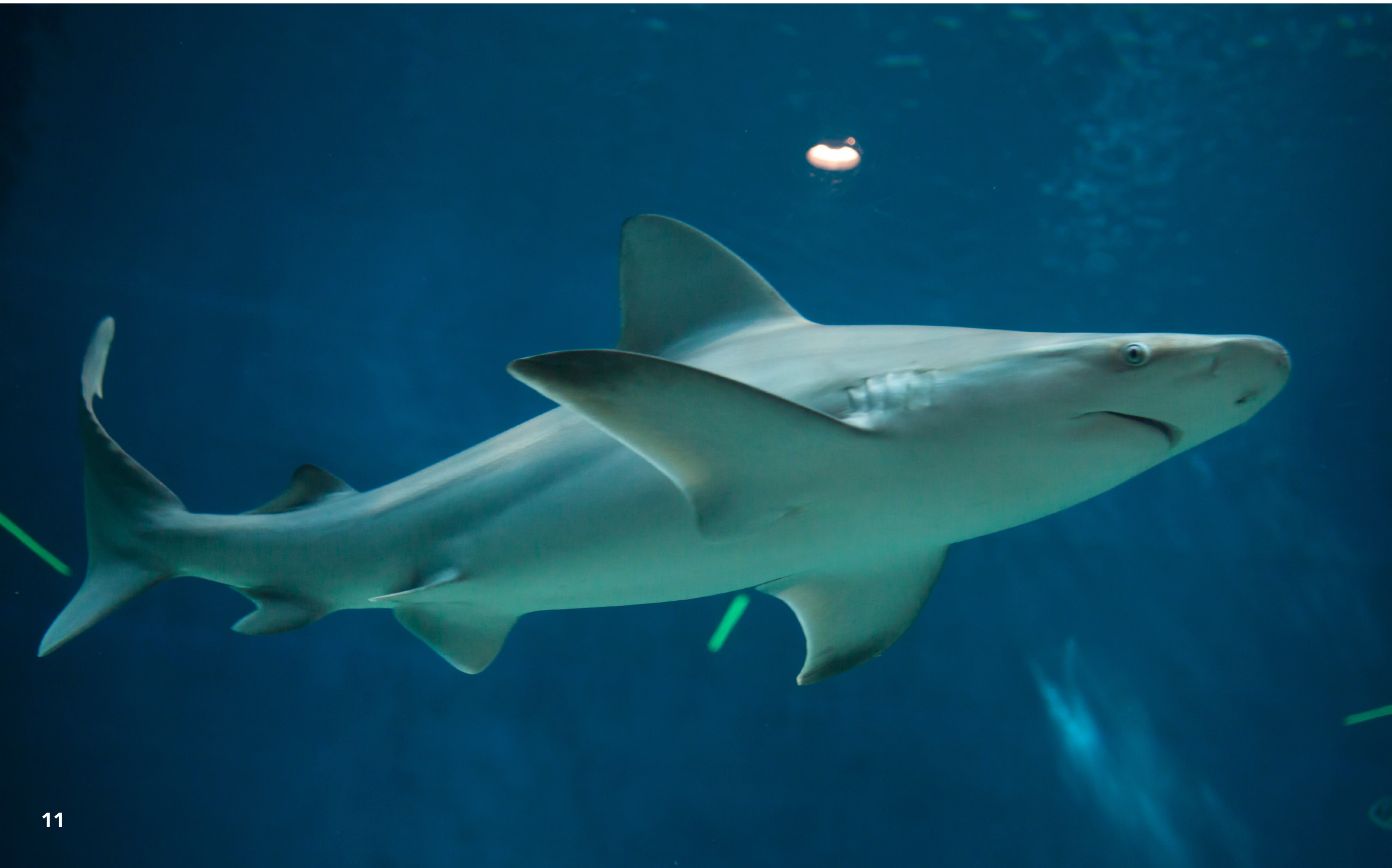
Measuring the electric and magnetic components of underwater EMFs is not a common practice. The strength of DC magnetic fields can be measured using a magnetometer, but custom instrumentation is needed to measure induced electric fields. Measurement devices can be towed behind a boat, attached to a remotely operated vehicle, or deployed at a stationary location near the cable. Marine animals can be tracked and monitored to identify behavioral changes in the presence of EMFs. While challenging to implement, experiments could be conducted at OSW farms where a cable is producing an EMF and also at a controlled location where no EMFs are present to evaluate response differences within a species.

Approaches for managing the effects of EMFs currently focus on reducing the amounts of these fields in areas of concern. Approaches that can be used to reduce EMFs are described below:

- **Siting:** Cables should be routed to avoid habitat areas with electrosensitive and magnetosensitive species of concern. This approach may increase the cable length and distance but would separate EMF sources from sensitive species.
- **Burial:** Cables typically are buried or protected with rocks or concrete mattresses to lower the risk of external damage. Cable burial plans are reviewed and approved as part of the Construction and Operation Plan and permitting phases of an OSW farm in the United States. In suitable seabed conditions, cables can be buried 1–2 meters (3-7 feet) below the seafloor to provide physical separation between the highest levels of EMFs adjacent to the cable and organisms that live near the bottom of the water column. However, burying the cable does not reduce the strength of the B-field in the soils directly adjacent to the cable; therefore, benthic organisms living below or at the seabed surface would still be exposed to the higher EMF intensities.
- **Cable characteristics:** The intensity of a magnetic field increases with the amount of electrical current passing through a cable. Cables operating at higher voltages will produce lower-intensity EMF because higher voltage cables can transmit the same amount of power using lower electrical current.

- **Placement:** When multiple, parallel cables are used, decreasing the distance between cables will reduce the area of the magnetic field. However, there are practical and technical limits to how close cables can be placed together due to physical conditions, such as the seabed type, or operational constraints, such as providing enough space for maintenance and repair of each cable. On the other hand, EMFs from separate transmission cables placed closer together will interact with one another, which may increase or decrease overall EMF strength.

EMFs are evaluated as part of the environmental review process for permitting OSW farms. In the United States, these fields have been described in Environmental Impact Statements and Construction and Operations Plans as having negligible-to-minor impacts. The environmental reports cite the burial depth, cable shielding, and limited range of EMFs as factors that contribute to a highly localized environmental condition that does not affect the entire habitat range for an animal. Mitigation or monitoring of EMFs has not been required for OSW projects in the United States. However, during its permitting process, the Block Island Wind Farm project modeled the EMF around subsea cables to predict the expected strength of the magnetic field. After project construction, researchers conducted field surveys to characterize the EMF from the AC export cable during operation and found that the magnetic field was 10 times lower than the modeled values commissioned by the grid operator. Without EMF detection or exposure thresholds for aquatic animals established by regulatory agencies, it is difficult for OSW projects to quantify environmental impacts. Further research can help determine if EMFs pose a potential risk to marine life, and if so, the frequency and intensity that would elicit a response and the ecological context of that response.



KNOWLEDGE GAPS & RESEARCH NEEDS

Scientific studies related to EMFs in the marine environment have progressed significantly over the past 20 years to inform how wildlife detect and respond to these fields. Overall, the effects of EMFs have been considered minor-to-negligible and a less significant issue than other environmental effects at OSW farms; however, confidence in this assessment remains low. EMFs should be considered in more depth on a site-specific basis if electrosensitive species are present and the cable design does not reduce EMFs below perceptible levels. Further research is needed to understand if EMFs from subsea cables ultimately produce long-term or cumulative effects on marine life. These research gaps could be addressed through continued analysis of subsea cables and observations of the behavior of sensitive species around cables. Because the risk of EMFs causing population damage is currently considered low, research could be accomplished by monitoring throughout the operation of new subsea cables. OSW farms provide new opportunities to strengthen the scientific understanding of EMF effects by incorporating environmental monitoring into ongoing field studies. Focus areas for further research and specific study types are discussed below.

Cable Characteristics

EMFs from different cables have been characterized through computer models and, in a few cases, field measurements. EMF models (e.g., submitted as part of a Construction and Operation Plan) often are carried out both for average loading conditions and the maximum output of an OSW farm to provide a range of potential EMF levels based on varying wind conditions. In contrast, measurements of EMFs are, by definition, a specific snapshot in time and space. Measurements are valuable in that they can and have been validated to be able to extrapolate measured EMF to other power generation levels so conditions along the full length of the cable at all power levels and ocean conditions can be understood. As-built information (i.e., cable burial depths along the entire route) along with minute-by-minute monitoring of power generated by OSW farms can therefore be combined to evaluate EMF models at any time and location. This would be a valuable tool for marine researchers involved in monitoring the activity of marine species around OSW farm cable installations. Research in this area could focus on developing real-time sensors to monitor the response of marine species to EMFs over time and to correlate those data with the properties and power flow through the cable.

Biological Studies

From a biological perspective, field studies in controlled environments or at operating cables help support laboratory research by identifying if EMF-sensitive species react to the signals in the field. While research should continue to study how individuals respond to EMFs at different stages of their life cycle, the overarching concern is whether specific observed behavioral responses to EMFs are likely to result in population-level impacts. Research toward this goal has been ongoing and is supported by basic research focused on identifying the detection range and sensitivity of marine wildlife to EMFs.

For more information on the literature reviewed to develop this Research Brief, visit: Tethys

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