Regional Assessment of Offshore Wind Development in Nova Scotia Committee Briefing: Potential Impacts of Electromagnetic Fields (EMFs) Caused by Offshore Wind Farms (OSW)

Purpose

The purpose of this briefing document is to provide information on Electromagnetic Fields (EMFs) caused by offshore wind farms (OSW) and the latest research findings that are either directly or indirectly related to offshore wind development and could be relevant to the Regional Assessment.

Background on Electromagnetic Fields (EMFs)

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 (SEER).

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 (SEER, 2022).

Key sources for this briefing:

- SEER Research Brief on OSW EMF: SEER Educational Research Brief: Electromagnetic Field Effects on Marine Life (pnnl.gov)
- BOEM Research Brief on OSW EMF: Electromagnetic Fields anElectromagnetic Fields from Offshore Wind FacilitiesMarine Life (boem.gov)
- EMF Impacts on Commercial Lobster and Crab: Harsanyi et al - The effects of Anthropogenic EMF on Early Development of Two Commercially important crustaceans, euro lobster and edible crab.pdf
- EMF Impacts on American Eel Movement and Migration from Direct Current Cables: BOEM_2021-083.pdf

Figure 1. Illustration of how electrical cables are used at fixed bottom and floating offshore wind farms (SEER, 2022, pg.1). Source: [SEER Educational Research Brief: Electromagnetic Field Effects on Marine Life (pnnl.gov)]()

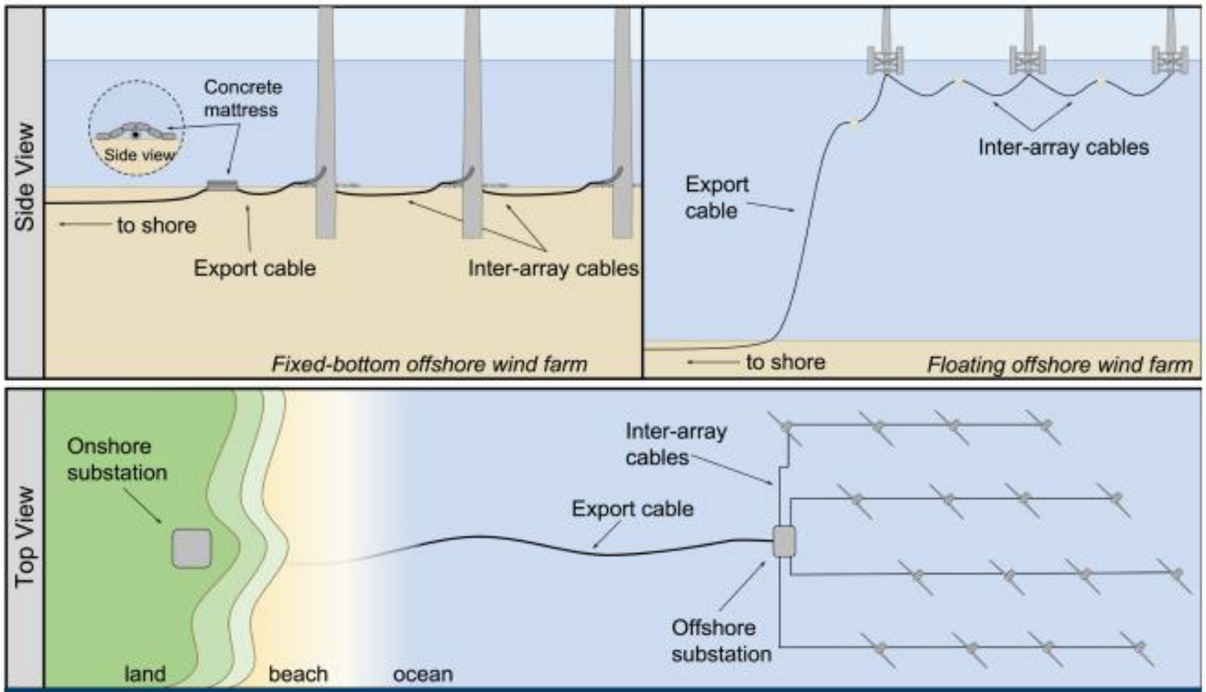


Figure 1. *An illustration of how electrical cables are used at fixed-bottom (top left) and floating offshore wind farms (top right). Inter-array cables connect between individual turbines and can be collected at an offshore substation to convert to a higher voltage export cable that connects to the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

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, these are described below and in Figure 1 (SEER, 2022).

- **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 (SEER, 2022).

Figure 1. Depiction of an EMF from an electrical cable and relative field strength from a snapshot in time (SEER, 2022).

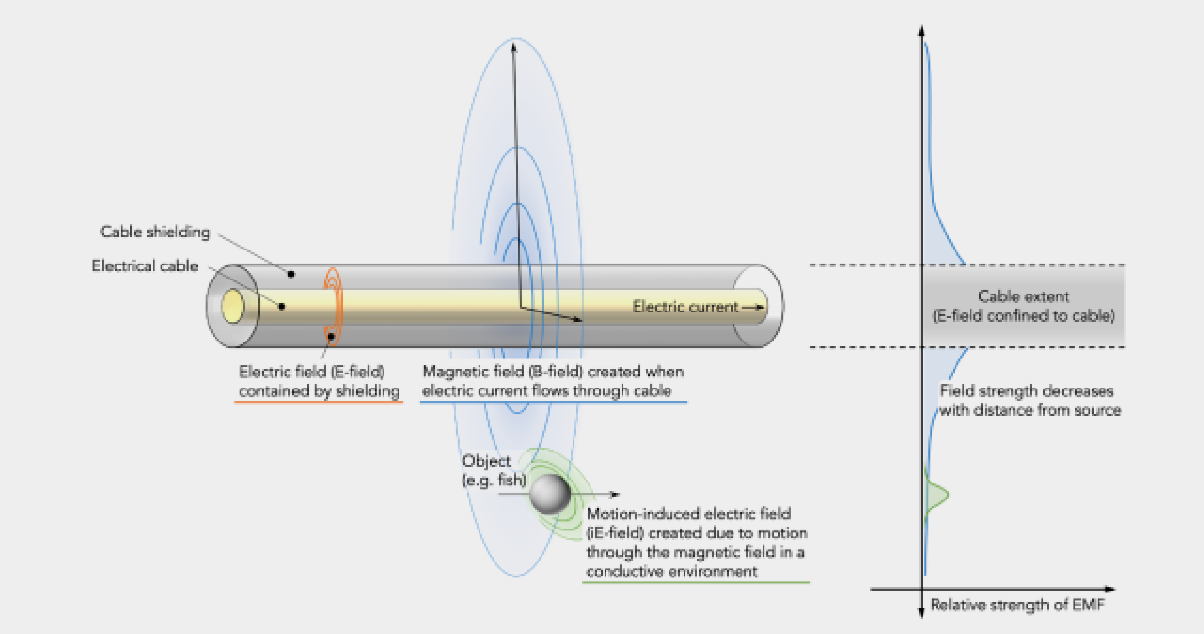


Figure 2. *Depiction of an EMF from an electrical cable (left) and relative field strength (right) from a snapshot in time. The electric field (orange) is contained by the cable shielding. The magnetic field (blue) is produced by both AC and DC cables. A motion-induced electric field (green) is created 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).*

Marine animals are exposed to natural EMF caused by sea currents traveling through the Earth's geomagnetic field. 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 (SEER, 2022). When in close proximity to subsea cables, some animals have demonstrated behavioral responses in a few studies, such as increased foraging and exploratory movements (SEER, 2022). 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 (SEER, 2022).

How are EMFs generated at offshore wind farms?

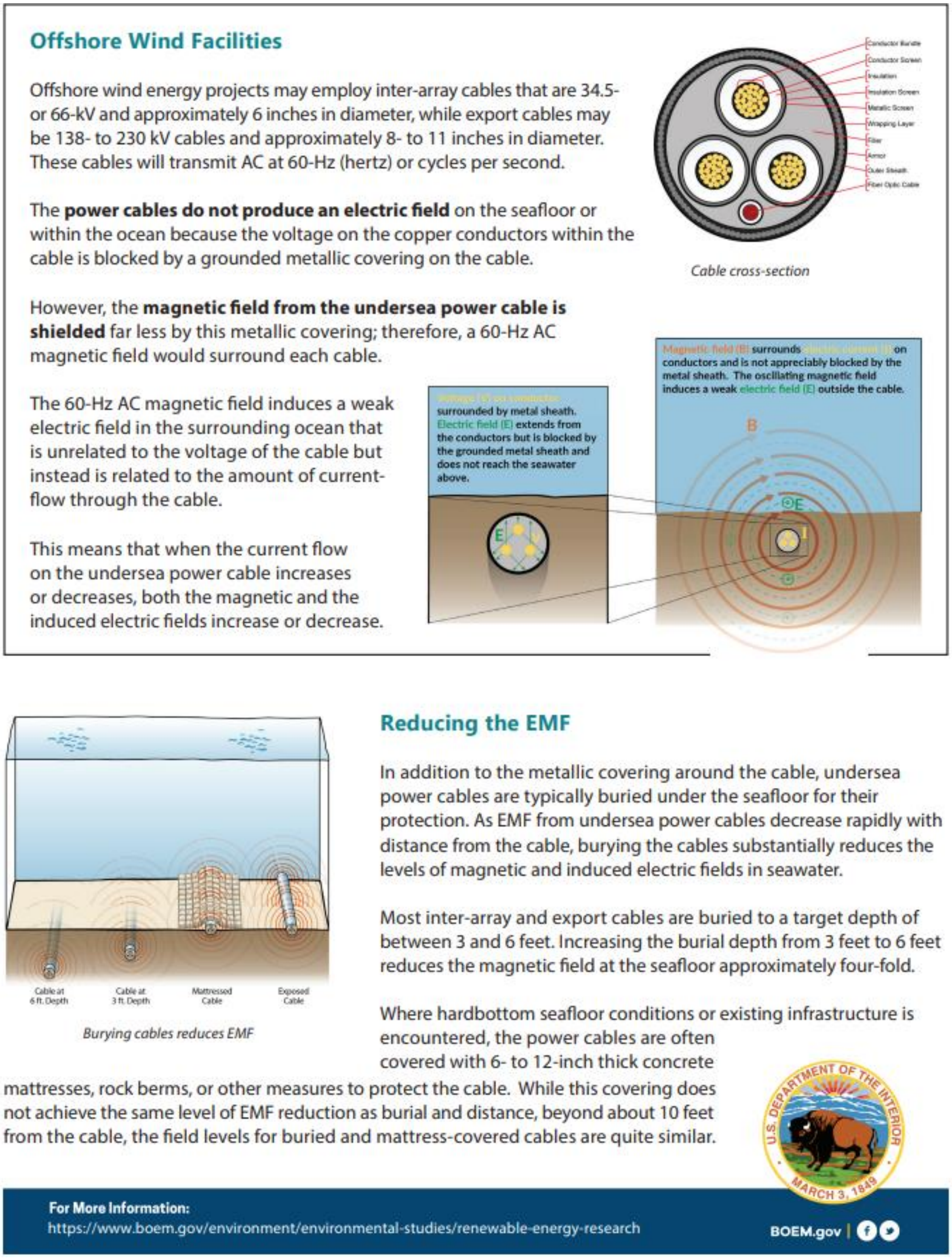
For offshore wind energy projects, the primary sources of EMF are inter-array cables that carry electricity from each wind turbine to the export cables, which carry that electricity to shore (BOEM, 2023). Subsea power cables are shielded and grounded, which eliminates most electric field emissions into the surrounding environment as long as the cable is undamaged. 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 (SEER, 2022).

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. 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., Btotal = Bearth + Bcable) 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. Description and diagrams of power cable cross-sections showing differences between a magnetic field (B) and an electric field (E) in BOEM's Factsheet on EMF below. Source: Electromagnetic

Fields anElectromagnetic Fields from Offshore Wind FacilitiesMarine Life (boem.gov)



Offshore Wind Facilities

Offshore wind energy projects may employ inter-array cables that are 34.5- or 66-kV and approximately 6 inches in diameter, while export cables may be 138- to 230 kV cables and approximately 8- to 11 inches in diameter. These cables will transmit AC at 60-Hz (hertz) or cycles per second.

The **power cables do not produce an electric field** on the seafloor or within the ocean because the voltage on the copper conductors within the cable is blocked by a grounded metallic covering on the cable.

However, the **magnetic field from the undersea power cable is shielded** far less by this metallic covering; therefore, a 60-Hz AC magnetic field would surround each cable.

The 60-Hz AC magnetic field induces a weak electric field in the surrounding ocean that is unrelated to the voltage of the cable but instead is related to the amount of current-flow through the cable.

This means that when the current flow on the undersea power cable increases or decreases, both the magnetic and the induced electric fields increase or decrease.

Cable cross-section

Voltage (V) on conductor surrounded by metal sheath. Electric field (E) extends from the conductors but is blocked by the grounded metal sheath and does not reach the seawater above.

Magnetic field (B) surrounds electric current (I) on conductors and is not appreciably blocked by the metal sheath. The oscillating magnetic field induces a weak electric field (E) outside the cable.

Burying cables reduces EMF

Reducing the EMF

In addition to the metallic covering around the cable, undersea power cables are typically buried under the seafloor for their protection. As EMF from undersea power cables decrease rapidly with distance from the cable, burying the cables substantially reduces the levels of magnetic and induced electric fields in seawater.

Most inter-array and export cables are buried to a target depth of between 3 and 6 feet. Increasing the burial depth from 3 feet to 6 feet reduces the magnetic field at the seafloor approximately four-fold.

Where hardbottom seafloor conditions or existing infrastructure is encountered, the power cables are often covered with 6- to 12-inch thick concrete mattresses, rock berms, or other measures to protect the cable. While this covering does not achieve the same level of EMF reduction as burial and distance, beyond about 10 feet from the cable, the field levels for buried and mattress-covered cables are quite similar.

MARCH 3, 1849

For More Information:
https://www.boem.gov/environment/environmental-studies/renewable-energy-research

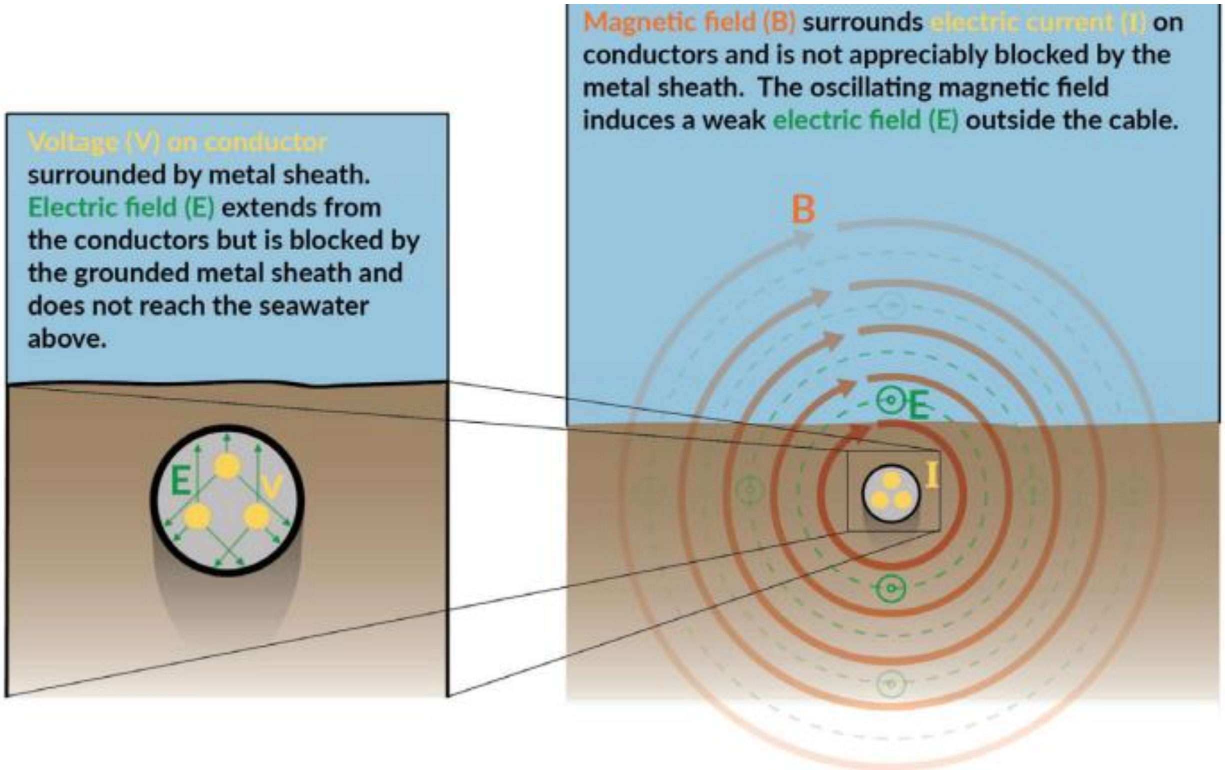
BOEM.gov

Components of the inter-array cables that may be employed by offshore wind energy projects are (BOEM, 2023):

1. An electric current that is contained within an insulated conductor and earthed metallic screen,
2. A magnetic field (B) which surrounds the electric current on conductors and is not appreciably blocked by the metal sheath, and
3. An oscillating magnetic field which induces a weak electric field (E) outside the cable.

For example, the magnetic field of a 60-Hz AC induces a weak electric field in the surrounding ocean that is unrelated to the voltage of the cable, but instead is related to the amount of current flow through the cable. This means that when the current flow on the undersea power cable increases or decreases, both the magnetic (B) and the induced electric fields (E) increase or decrease (BOEM, 2023).

Figure 4. Image showing differences between electric (iE) and magnetic (B) fields outside the power cable and how they are blocked by the metal sheath around the cable.



Voltage (V) on conductor surrounded by metal sheath. Electric field (E) extends from the conductors but is blocked by the grounded metal sheath and does not reach the seawater above.

Magnetic field (B) surrounds electric current (I) on conductors and is not appreciably blocked by the metal sheath. The oscillating magnetic field induces a weak electric field (E) outside the cable.

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 (SEER, 2022).

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 (SEER, 2022).

Figure 5. Examples of marine wildlife with the ability to sense EMFs (SEER, 2022).

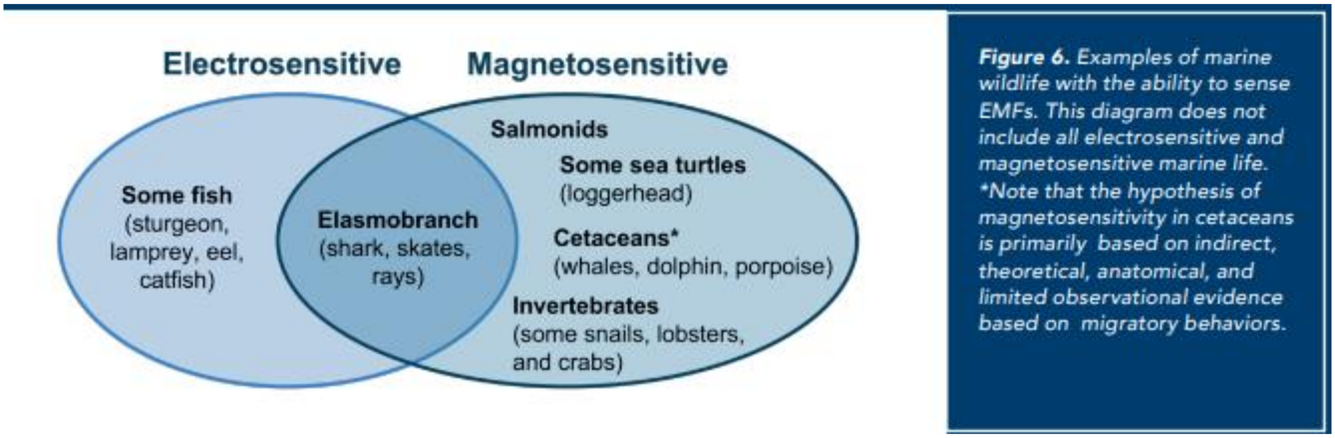


*Figure 6. Examples of marine wildlife with the ability to sense EMFs. This diagram does not include all electrosensitive and magnetosensitive marine life. *Note that the hypothesis of magnetosensitivity in cetaceans is primarily based on indirect, theoretical, anatomical, and limited observational evidence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

Species-specific interactions with EMFs from OSW subsea cables

Crustaceans

Lobster

- Summary of literature on impacts of EMFs on Lobsters (published by Hydro Quebec) here: [Leaflet summarizing the impact on lobster and snow crab of electric and magnetic fields generated by underwater cables produced as part of the project to connect Îles-de-la-Madeleine to the transmission system. (hydroquebec.com)]() (See Figure 6 below).
- When encountering EMFs, the American lobster exhibits an increased likelihood of exploratory behaviors. Another study shows a similar species, the European lobster, exhibits no attraction, foraging, or exploratory behaviors when exposed to a static EMF (SEER, 2022).
- Harsanyi et al. (2022) study found that significantly smaller larval parameters in both EMF treated species and a higher occurrence of larval deformities and lower swimming test success rate amongst lobster larvae. These results suggest that EMF may negatively impact larval mortality, recruitment and dispersal. In contrast, EMF exposure did not appear to impact

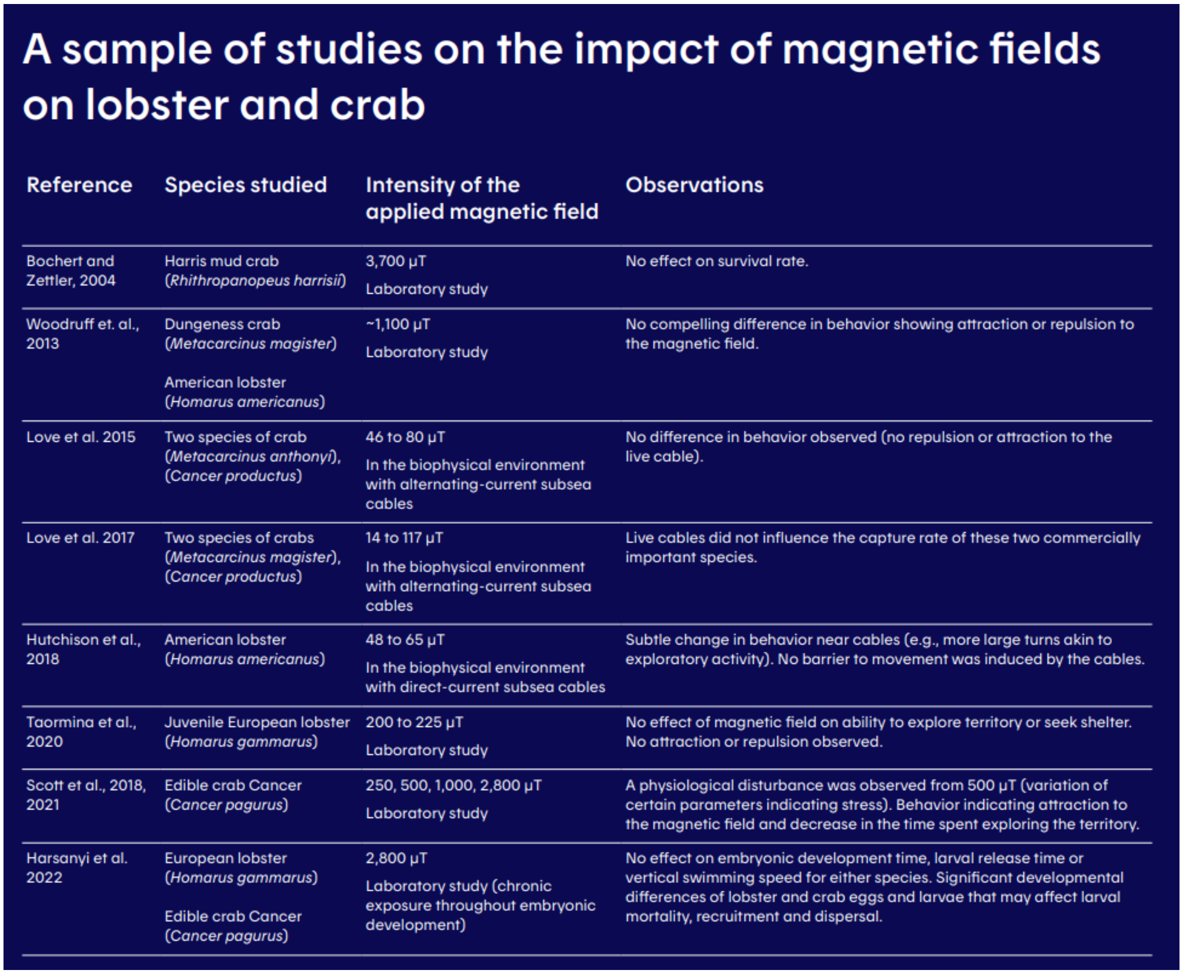
embryonic development time, larval release time, or vertical swimming speed for either species, or crab larval deformities and swimming test success. Differences found in this study on the effects of EMF on early development of European Lobster (H. gammarus) and European crab (C. Pagurus) highlight the importance of species-specific sensitivity to anthropogenic EMFs. As reproduction and early life stages represent a bottleneck of crustacean population, the vulnerability of such stages to anthropogenic EMFs expected around subsea power cables demonstrated in this study suggest that marine renewable energy developments could have a considerable impact on shellfish fisheries. To fully understand the population-level impacts of MREDs, further studies are required to assess the biological effects of EMFs along with other stressors and environmental changes expected around these sites on all life stages of European Lobster (Harsanyi et al., 2022). The model and materials used to demonstrate EMF effects on lobster and crabs does not mimic ocean or real-world conditions where lobster could migrate away from EMF cables (Hutchison et al., 2018).

  - There are gaps in the literature of the effects of EMF on crustaceans worldwide. **The few studies available on UK species were conducted using different types and strength of EMF, experimental methodology, and assessed different experimental parameters, making comparisons difficult.** The differences in results obtained between species that occupy similar biological niches such as edible crabs and European lobsters highlights the importance of species-specific studies as opposed to biological categorisation currently utilised within Environmental Impact Assessments (EIAs). More importantly however, is **the need for standardised methodology and EMF strengths to allow for easier comparisons and ultimately more informed management.** There is a **lack of in situ EMF measurements around subsea power cables and MRED deployments, which most likely accounts for the large variety in experimental values used in research.** To date most values have been derived from computer models designed to predict EMF discharge and subsequent field strengths based on cable type, length, current, and capacity (Scott et al., 2020). **Standardisation of experimental design perhaps encompassing a combination of field, caged, and laboratory-based studies** (to overcome the difficulties associated with each method) (Scott et al., 2020).

- Normandeau et al. (2011) study found that American lobsters were one of nine priority invertebrate species in US waters that could potentially be affected by exposure to EMF (Normandeau et al., 2011). The perceivable risk for lobsters is the potential delay or alteration to migration patterns/paths and homing behaviors. Lobsters (and other benthic decapods) were perceived to be a moderate risk group since their epibenthic habitat and relatively low mobility exposes them to the highest EMF from cables (Normandeau et al., 2011).
- Woodruff et al (2013) research article discusses that similar studies to those conducted on Dungeness crab were completed on American Lobster where the control tank had a stable magnetic field of 50 µT and the treatment peaked at 1.1 x 103 µT with boundary levels of 0.5 x 103 µT. Unfortunately, there were difficulties in assessing behavioral changes due to high individual variability and the fact that lobsters spent 76% of their time either burrowed, or in shelters (Woodruff et al., 2013). Lobsters that burrowed chose to do so in the low zones of EMF; however, the only shelter available was placed in the high zone of EMF and may have influenced this behavior. There was significantly more time spent in the area of high EMF than the downstream low EMF zone, but this did not hold true for the other tank and may have been either a tank effect, or could be attributed to individual variability. The results were somewhat inconclusive (Hutchison, 2018; Harsanyi et al, 2022).
- In other research discussed by Hooper et al. (2014), it has been suggested that it may be possible to co-locate decapod fisheries and OSW farms, which have seen much expansion in

European seas. It is possible that OSW may enhance coastal habitat for American Lobster. However, it was acknowledged that there is little understanding of decapod response to other influences such as electromagnetic fields (Hooper et al., 2014). Despite the potential for mutual benefits to developers and fisheries, the risk of displacement to fishing industries need to be addressed (Hooper et al., 2015). These concerns have also arisen during the planning for OSW in the USA, specifically for American Lobster. A first step to resolving potential conflict is determining if there is a risk of lobsters changing their behavior in response to EMFs from cables associated with marine renewable energy (Hooper et al., 2015).

Figure 6. Summary of studies on the impact of EMFs on lobster and crab prepared by Hydro Québec.



A sample of studies on the impact of magnetic fields on lobster and crab

Reference	Species studied	Intensity of the applied magnetic field	Observations
Bochert and Zettler, 2004	Harris mud crab (*Rhithropanopeus harrisii*)	3,700 µT Laboratory study	No effect on survival rate.
Woodruff et. al., 2013	Dungeness crab (*Metacarcinus magister*) American lobster (*Homarus americanus*)	~1,100 µT Laboratory study	No compelling difference in behavior showing attraction or repulsion to the magnetic field.
Love et al. 2015	Two species of crab (*Metacarcinus anthonyi*), (*Cancer productus*)	46 to 80 µT In the biophysical environment with alternating-current subsea cables	No difference in behavior observed (no repulsion or attraction to the live cable).
Love et al. 2017	Two species of crabs (*Metacarcinus magister*), (*Cancer productus*)	14 to 117 µT In the biophysical environment with alternating-current subsea cables	Live cables did not influence the capture rate of these two commercially important species.
Hutchison et al., 2018	American lobster (*Homarus americanus*)	48 to 65 µT In the biophysical environment with direct-current subsea cables	Subtle change in behavior near cables (e.g., more large turns akin to exploratory activity). No barrier to movement was induced by the cables.
Taormina et al., 2020	Juvenile European lobster (*Homarus gammarus*)	200 to 225 µT Laboratory study	No effect of magnetic field on ability to explore territory or seek shelter. No attraction or repulsion observed.
Scott et al., 2018, 2021	Edible crab Cancer (*Cancer pagurus*)	250, 500, 1,000, 2,800 µT Laboratory study	A physiological disturbance was observed from 500 µT (variation of certain parameters indicating stress). Behavior indicating attraction to the magnetic field and decrease in the time spent exploring the territory.
Harsanyi et al. 2022	European lobster (*Homarus gammarus*) Edible crab Cancer (*Cancer pagurus*)	2,800 µT Laboratory study (chronic exposure throughout embryonic development)	No effect on embryonic development time, larval release time or vertical swimming speed for either species. Significant developmental differences of lobster and crab eggs and larvae that may affect larval mortality, recruitment and dispersal.

Source: Leaflet summarizing the impact on lobster and snow crab of electric and magnetic fields generated by underwater cables produced as part of the project to connect Îles-de-la-Madeleine to the transmission system. (hydroquebec.com)

Crab

- When encountering EMFs, the brown crab reduces roaming and exhibits attraction behaviors to shelters where EMFs are present (SEER, 2022).

- Similarly to lobster, 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 (SEER, 2022).
- Controlled aquarium experiments of Dungeness crab showed a non-significant decrease in antennular flicking rate when exposed to 3 x 103 µT EMF (Woodruff et al., 2012). During the attraction/repulsion study there was evidence of a significant decrease in time buried and increase in changes in activity when exposed to an EMF with a peak of 1.1 x 103 µT (compared to control a of 0.12 x 103 µT), particularly in the first two days of exposure (Woodruff et al., 2012). In contrast, there was no obvious detection of EMF in the antennular flicking rate and no obvious difference in the detection of food in the presence of EMF compared to the control conditions (Woodruff et al., 2012). To specifically address potential effects on the catch of commercially important Dungeness crab (Metacarcinus magister) and rock crab (Cancer productus), Love et al., (2017) investigated catchability based on whether the crabs would cross over an energized subsea cable to a baited trap. No difference was found in the catchability of these two species in relation to an energized cable. Love et al., (2015) also reported no changes in behavior in response to powered (40-80 µT) and unpowered (0.2 µT) cables however behavioral responses were only measured at 1 and 24 hours. In previous studies, Love et al., (2015) compared caged rock crabs exposed to energized and unenergized cables and found no difference in their response. Further studies by Woodruff et al., (2013) again identified changes in behavior in response to EMF but they were confounded by other properties of the study e.g. tank, water flow direction, and individual variability (Hutchison et al., 2018).

Magnetosensitive Species

- Magnetosensitive species are thought to be sensitive to the Earth's magnetic fields (Wiltschko and Wiltschko, 1995; Kirschvink, 1997; Boles and Lohmann, 2003; McMurray, 2007; Johnsen and Lohmann, 2008). While the use of B-fields by marine species is not fully understood and research continues (Lohmann and Johnsen, 2000; Boles and Lohmann, 2003; Gill et al., 2002; Gill et al., 2005), it is suggested that magnetite deposits play an important role in geomagnetic field detection in a relatively large variety of marine species including turtles (Light et al. 1993), salmonids (Quinn, 1981; Quinn and Groot, 1983, Mann et al. 1988, Yano et al. 1997), elasmobranchs (Walker et al. 2003, Meyer et al. 2005), and whales (Fisher and Slater, 2010; Klinowska 1985, Kirschvink et al. 1986).
- Normandeau et al., (2011) reported on the magneto- and electrosensitivity of a wide range of marine organisms. The report noted that a magnetic sense is present for marine mammals, sea turtles, many groups of fishes (including elasmobranchs), and for several invertebrate groups (Hutchison et al., 2018).

Salmon

- Telost fish, including salmonids, also have an electric field sensitivity, but one that is orders of magnitude lower (less sensitive) than sharks (Fisher and Slater, 2010).
- A study by Klimley et al., (2017) looked at behavioral responses by migrating juvenile salmonids to a subsea high-voltage DC power cable, which showed cable energization did not significantly impact the proportion of fish that successfully migrated through the bay or the probability of successful migration (Wyman et al, 2018). However, after cable energization, higher proportions of fish crossed the cable location and fish were more likely to be detected south of their normal migration route (Wyman et al, 2018). Transit times through some regions were reduced during cable activity, but other environmental factors were more influential. Resource selection models

indicated that proximity to the active cable varied by location: migration paths moved closer to the cable at some locations, but further away at others (Wyman et al, 2018). Overall, cable activity appeared to have mixed, but limited effects on movements and migration success of smolts. Additional studies are recommended to further investigate impacts of subsea cables on fish migrations, including potential long-term consequences (Wyman et al, 2018).

Sharks

- The electrosensory system in elasmobranchs (sharks, skates, rays) is ubiquitous across the taxa (Murray, 1974). One of the primary uses of electroreception is to locate prey. Bioelectric fields of predators can also be detected by elasmobranchs when they are the prey. Electroreception also presents as a form of communication. Electroreception is also used to help find conspecifics and reproductive mates where in skates they may be buried in depressions during the day (Sisneros et al., 1998, Tricas et al., 1995). Elasmobranchs are capable of detecting and discerning important bioelectric signals from other biological noise (Bodznick et al., 2003), but it is not known if they can use the same approach to distinguish these signals from anthropogenic EMF 'noise' (Hutchison et al., 2018).
- Bellono et al. (2018) indicated that the electroreceptive sensitivity of some species of benthic shark appears to be adapted to a narrow range of electrical stimuli, such as those emitted by prey, whereas in some species of skate the EMF receptors are more broadly tuned, which may enable them to detect both prey stimuli and the electric organ discharges of other individuals (Hutchison et al., 2018).
- As reported by Normandeau et al., (2011), the perception of an EMF by an electro- and/or magnetosensitive species is complex and dependent upon several factors such as; cable characteristics, electric current, cable configuration, cable orientation relative to geomagnetic field, the swimming direction of the animal, local tidal movements and characteristics of the species life history and developmental stage. To address the primary objectives of the research, these parameters had to be carefully considered (Hutchison et al., 2018).

Eels

- Durif et al., (2013) showed that anguillid eels have a magnetic compass that enables adaptive behavior such as when encountering different water temperatures during migration or if displacement occurs. The eels appear to have the ability to resume the direction of movement along a previous compass bearing when they move away from either changed environmental conditions, or barriers. At the juvenile glass eel stage a magnetic compass is used for orientation and the orientation system appears to be linked to a circatidal rhythm (Cresci et al., 2017). Such an adaptive nature is important when considering the potential impact of changes to the magnetic/EMF environment (Hutchison et al., 2018).
- For the modeling of EMF encountered by the eels in the study by Hutchinson et al. (2018) it was essential to have information on cable characteristics, the power level in the cable, the interaction of the cable EMF with the geomagnetic field, and the horizontal and vertical proximity of the eel to the buried cable, to determine exposure. These aforementioned parameters allowed the speed of movement of migratory eels to be assessed in the response to the EMF and indicated that eels increased their speed and were more directed in their movement (Hutchinson et al., 2018).

Marine Mammals

Whales

- There is a significant lack of research into the potential impacts of EMF to sea turtles and marine mammals.
- Whales and dolphins form a useful "magnetic map" which allows them to travel in areas of low magnetic intensity and gradient ("magnetic valleys" or "magnetic peaks"; Walker et al. 2003). Many whale and dolphin species are sensitive to stranding when Earth's magnetic (B) field has a total intensity variation of less than 0.5mG (5 x 10-4 G). Species that are significantly statistically sensitive include common dolphin (Delphinus delphis), Risso's dolphin (Grampus griseus), Atlantic white-sided dolphin (Lagenorhynchus acutus), finwhale (Balaenoptera physalus), and long-finned pilot whale (Globicephala malaena) (Kirschvink et al., 1986).
- Live strandings of toothed and baleen whales have also been correlated with local geomagnetic anomalies (Kirschvink et al., 1986). It has been suggested that some cetacean species use geomagnetic cues to navigate accurately over long-distances of open ocean that do not have geological features for orientation. Valburg (2005) suggested that while sharks are unlikely to be impacted by low electric fields immediately around submarine electric cables, shifts in EMF have been significantly correlated to whale strandings (Fisher and Slater, 2010).
- Statistical evidence suggests that marine mammals are susceptible to stranding as a result of increased levels of EMF (Fisher and Slater, 2010).

Sea Turtles

- Much of what is known about animal response to the earth's magnetic field comes from studies of turtle migration. Putman et al., (2015) studied the magnetic navigation of the oceanic life stages of loggerhead turtles using a combination of field and lab studies. The study conclusion was that the navigation behavior of sea turtles is closely tied to the interplay between ocean circulation and the dynamics in the geomagnetic field. Fuxjager et al., (2014) further showed how the geomagnetic environment within which turtle eggs are incubated influences their magnetic orientation behavior during ontogeny (Hutchison et al., 2018).
- There is a significant lack of research into the potential impacts of EMF to sea turtles and marine mammals. Sea turtles do not appear to be as sensitive to EMF as marine mammals. Statistical evidence suggests that marine mammals are susceptible to stranding as a result of increased levels of EMF (Fisher and Slater, 2010).
- Sea turtles do not appear to be as sensitive to EMF as marine mammals (Fisher and Slater, 2010).

Mitigation Measures

Approaches for managing or mitigating 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 include siting, burial, cable characteristics, placement, and covering (BOEM, 2023; SEER, 2022).

1. **Siting**
   Cables should be routed to avoid habitat areas with electrosensitive and magneto-sensitive species of concern. This approach may increase the cable length and distance but would separate EMF sources from sensitive species (SEER, 2022).

2. **Burial**

Where hardbottom seafloor conditions or existing infrastructure is encountered, the power cables are often buried or protected with rocks or 6- to 12-inch-thick 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 (SEER, 2022). While this covering does not achieve the same level of EMF reduction as burial and distance, beyond about 10 feet from the cable, the field levels for buried and mattress-covered cables are quite similar (BOEM, 2023).

3. **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. 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 (SEER, 2022).

4. **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 (SEER, 2022).

5. **Covering around the cable**
   Blocking the voltage on the copper conductors of the subsea power cable by adding a grounded metallic covering to the cables can prevent them from producing an electric field on the seafloor or within the ocean. Where hardbottom seafloor conditions or existing infrastructure is encountered, the power cables are often covered with 6- to 12-inch-thick concrete mattresses, rock berms, or other measures to protect the cable. While this covering does not achieve the same level of EMF reduction as burial and distance, beyond about 10 feet from the cable, the field levels for buried and mattress-covered cables are quite similar (BOEM, 2023).

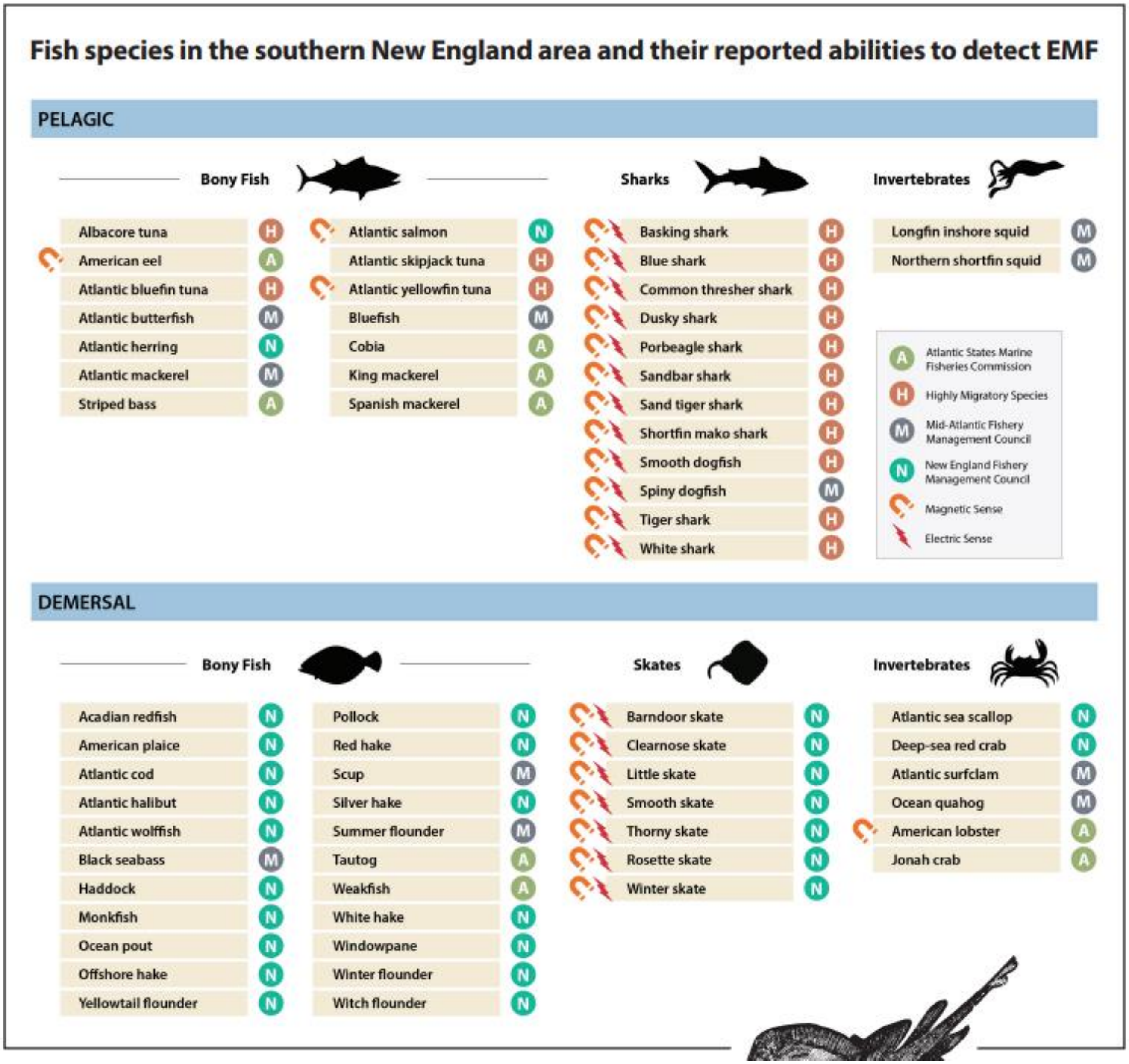
Data Gaps & Research Recommendations

- Field measurements of EMF intensity and its variability within the environment are required to better predict the actual EMF emitted. To date, some electromagnetic models predict EMFs similar to those of the small number of cables actually measured; however, where cables are not perfectly grounded or have leakage currents, further EMFs can also propagate, and models are not set up to predict these situations. These other EMFs may be relevant to the response of sensitive receptors and may require ambient measurements of EMFs at MRE development sites. Measuring the environmental EMF requires equipment that has the necessary sensitivity and accuracy to simultaneously measure the E- and B-fields. To date, only a handful of devices have been built to achieve these measurements, which are vital for validating EMF models. Therefore, affordable methods and equipment for measuring EMFs should be developed so that measurements taken with these instruments at MRE project sites can be compared to the power output of the devices (Gill and Desender, 2020).

- Understanding the relationship between EMFs and sensitive receptor species requires dose-response studies. If the effects are determined to be significant and negative, then appropriate mitigation measures may need to be developed. Given the current lack of sufficient evidence, additional studies of the most sensitive life stages of receptor animals to exposure to different EMFs (sources, intensities) are required and should be focused on the early embryonic and juvenile life stages of elasmobranchs, crustacea, mollusks, and sea turtles (Gill and Desender, 2020).
- Laboratory studies of species response to EMFs at different intensities and durations will be required to determine the thresholds for species-specific and life stage-specific dose responses. The threshold indicators could be developmental, physiological, genetic, and/or behavioral (Gill and Desender, 2020).
- Field studies using modern tagging and tracking systems will provide insight into behavioral and, in some cases, physiological evidence for determining the potential effects on mobile receptors of encountering multiple cables. These types of studies may be required when considering the installation of cable networks and large arrays of MRE devices. The findings should be collected with regard to their use in modeling the exposure likelihood for determining dose-response scenarios and applying population-based approaches (e.g., ecological modeling) (Gill and Desender, 2020).
- Data gaps exist between the interaction of pelagic species (like pelagic sharks, marine mammals or fishes) and dynamic cables (i.e., cables in the water column). These gaps remain in part because of difficulties in evaluating impacts at population scales around these deployments (Taormina et al. 2018). Field-tagging studies can be used to improve the knowledge base (Gill and Desender, 2020).
- Long-term and in situ studies are needed to address the question of the effects of chronic EMF exposure on egg development, hatching success, and larval fitness. Furthermore, because cables may be protected and stabilized with rock armor or artificial structures, the potential role of any habitat/refuge associated with subsea cables needs to be considered. Because some of these artificial structures are now being designed to attract species of interest (e.g., commercial species), an important question has arisen about determining whether their role as suitable habitat may be counteracted by potentially “negative” impacts of EMFs emitted by the electrical cable (Gill and Desender, 2020).
- To date, there are no environmental standards or guidelines for subsea cable deployment or the measurement of EMFs. Synthesizing current knowledge requires a number of assumptions and, because the nature of the knowledge is patchy, there are no apparent significant environmental impacts that require regulation. This interpretation and the associated assumptions will likely need to be reviewed in the future as the knowledge and understanding of subsea conditions expands, particularly when considering the planned larger power-rated cables, greater networks of MREs, and the subsea infrastructure (Gill and Desender, 2020).
- In terms of sources of EMF, there is a need to determine the characteristics of the EMF, the strength and type of fields produced by different cables, cable networks, number of devices, and associated hardware in different locations. These aspects then need to be considered in relation to the types of sensitive organisms that may be exposed to the EMFs. This approach will require

specific assessments of the EMF that marine animals may be exposed to in relation to source EMFs associated with power cables. Furthermore, dose-response studies would be useful to understand the level of response/effect on EM sensitive species in relation to their range of detection of different EMF sources and intensities (Hutchison et al., 2018).

Infographics on Electromagnetic Fields and Marine Animals from BOEM



Fish species in the southern New England area and their reported abilities to detect EMF

PELAGIC

Bony Fish

	Albacore tuna	H
🧲	American eel	A
	Atlantic bluefin tuna	H
	Atlantic butterfish	M
	Atlantic herring	N
	Atlantic mackerel	M
	Striped bass	A
🧲	Atlantic salmon	N
	Atlantic skipjack tuna	H
🧲	Atlantic yellowfin tuna	H
	Bluefish	M
	Cobia	A
	King mackerel	A
	Spanish mackerel	A

Sharks

🧲⚡	Basking shark	H
🧲⚡	Blue shark	H
🧲⚡	Common thresher shark	H
🧲⚡	Dusky shark	H
🧲⚡	Porbeagle shark	H
🧲⚡	Sandbar shark	H
🧲⚡	Sand tiger shark	H
🧲⚡	Shortfin mako shark	H
🧲⚡	Smooth dogfish	H
🧲⚡	Spiny dogfish	M
🧲⚡	Tiger shark	H
🧲⚡	White shark	H

Invertebrates

Longfin inshore squid	M
Northern shortfin squid	M

A	Atlantic States Marine Fisheries Commission
H	Highly Migratory Species
M	Mid-Atlantic Fishery Management Council
N	New England Fishery Management Council
🧲	Magnetic Sense
⚡	Electric Sense

DEMERSAL

Bony Fish

Acadian redfish	N
American plaice	N
Atlantic cod	N
Atlantic halibut	N
Atlantic wolffish	N
Black seabass	M
Haddock	N
Monkfish	N
Ocean pout	N
Offshore hake	N
Yellowtail flounder	N
Pollock	N
Red hake	N
Scup	M
Silver hake	N
Summer flounder	M
Tautog	A
Weakfish	A
White hake	N
Windowpane	N
Winter flounder	N
Witch flounder	N

Skates

🧲⚡	Barndoor skate	N
🧲⚡	Clearnose skate	N
🧲⚡	Little skate	N
🧲⚡	Smooth skate	N
🧲⚡	Thorny skate	N
🧲⚡	Rosette skate	N
🧲⚡	Winter skate	N

Invertebrates

	Atlantic sea scallop	N
	Deep-sea red crab	N
	Atlantic surfclam	M
	Ocean quahog	M
🧲	American lobster	A
	Jonah crab	A

Source: BOEM, 2020. [Ocean Wind 1 Offshore Wind Farm Environmental Impact Statement (boem.gov)]()

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