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Chapter authors: Andrew B. Gill, Marieke Desender
Contributor: Levy G. Tugade

Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices

Interest in the potential effects of anthropogenic electromagnetic fields (EMFs) within the marine environment has increased in recent years, in part as a result of advanced knowledge gained from conducting dedicated research studies. To understand and interpret the potential environmental interactions of marine renewable energy (MRE)-related EMF emissions, it is necessary to consider the source of the EMFs and address the source within the context of the knowledge about the electro- and magneto-sensitivity of marine species.

5.1. IMPORTANCE OF THE ISSUE

Any anthropogenic activity that uses electrical cables in the marine environment is a primary source of EMFs. The cables emit EMFs along their entire lengths, whether transmitting high-voltage direct current (DC) or alternating current (AC). Currently, high-voltage AC (HVAC) electrical cables are used to connect all types of offshore and MRE devices both among units in an array and to marine substations; and HVAC or high-voltage DC (HVDC) can be used to export power to shore. The interactions between EMFs emitted by MRE power generation with the naturally occurring geomagnetic field (GMF) can potentially alter the behavior of marine animals that are receptive to these fields (Figure 5.1), including potentially altering avoidance or attraction behaviors. It is important to know the intensity of the emitted EMF, which depends on the type of current (DC or AC), the cable characteristics, the power transmitted, the local GMF, and surrounding environmental factors (Figure 5.1). The EMF scales with the energy produced by multiple and/or larger MRE devices and higher power-rated cables. The response of receptor animals fundamentally depends on the sensitivity of the animals, which is determined by the sensory systems they possess (Snyder et al. 2019). The movement and distribution of the animals also plays a role in the probability of an encounter with an EMF and may depend on the species life stage, as well as the spatial and temporal use of the environment where the EMF occurs (Figure 5.1).

An EMF has two components: electric fields (E-fields) and magnetic fields (B-fields[1]). The Earth creates its own GMF and has E- and B-fields associated with natural phenomena (e.g., lightning), while also being permeated by EMFs from outside the Earth's atmosphere (Gill et al. 2014). In seawater, natural E-fields are produced by the interaction between the conductivity of the water, the Earth's rotation of the B-field, and the motion of tides/currents (Stanford 1971), which creates localized motion-induced fields.

The primary source of anthropogenic EMF emissions associated with MRE systems is the cables used to transmit the electricity produced, and their emissions depend on the cable configurations in relation to the ambient environment. EMF emissions may also be associated with offshore substations receiving multiple cables and, in some cases, transforming voltages between AC and DC. Current interest is focused on EMFs generated within the cable and existing along its length, propagating perpendicular to the cable axis into the surrounding environment, and decaying with distance from the source. In DC cables, the EMF emitted is a static field, whereas in AC cables, the EMF is normally a low-frequency sinusoidal field. E-fields are contained within the cable by shielding and grounding that allow the field to dissipate quickly, but a B-field is still emitted in the outside environment. When an animal or water current causes motion through a B-field, secondary induced electric fields (iE-fields) are generated (Figure 5.1). AC current passing through a standard, three-core cable will also create iE-fields (Figure 5.1).

In Figure 5.1, the separate E-field and B-field components of the EMFs emitted by a buried subsea cable (red) are shown, as well as the ambient geomagnetic field (black) and bioelectric fields from living organisms (orange). Figure 5.1a shows the EMF associated with a DC cable; Figure 5.1b shows the EMF associated with a standard three-phase AC subsea cable with the current following a typical sine wave back and forth through each core. For both cables the direct E-field is shielded by cable material (black outer cable), but B-fields (blue) are not shielded and propagate to the surrounding environment. An iE-field is created in the fish (yellow) as it moves through the B-field emitted by the cable. Localized iE-fields will also be induced by seawater moving through the B-field and the GMF. In addition, for the AC cable, the out-of-phase B-field emitted by each core of the cable causes a rotation in the magnetic emission, which induces an iE-field in the surrounding conductive seawater (red), that is emitted into the environment above the seabed.

1. B-field is the accepted nomenclature for the magnetic field. It is technically termed the magnetic flux density. The B-field is easily measured (in the International System of Units unit of Tesla) and takes account of the permeability of the medium.

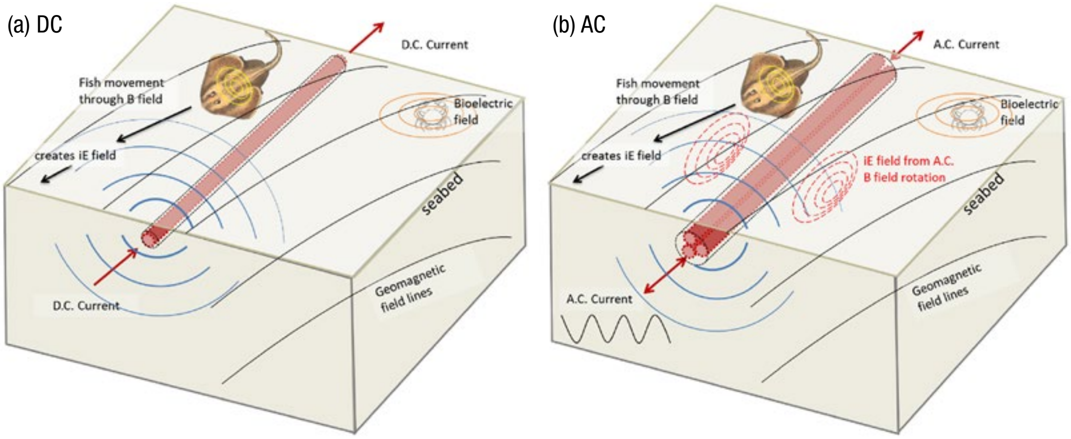

Figure 5.1. Diagrams summarizing the natural and anthropogenic electric fields (E-fields), induced electric fields (iE-fields) and magnetic fields (B-fields) encountered by an electromagnetic-sensitive fish moving across the seabed. (Adapted from Newton et al. 2019)

5.2. SUMMARY OF KNOWLEDGE THROUGH 2016

Some marine animals are capable of sensing EMFs to aid in their orientation, migration, and prey location (Kirschvink 1997; Tricas and New 1998; Walker et al. 1992). As of 2016, studies have focused on a diversity of organisms such as elasmobranchs (sharks, skates, and rays), agnatha (lampreys), crustacea (lobsters and prawns), mollusks (bivalves, snails, and cephalopods), cetaceans (whales and dolphins), bony fish (teleosts and chondrosteans), and sea turtles (Copping et al. 2016). Anthropogenic EMFs may interfere with the ambient EMF, and anomalies in the behavioral patterns of animals have been observed (Gill et al. 2014). Some studies have shown that sensitive animals may respond to anthropogenic B-fields at or below the geomagnetic intensity or ambient conditions (in the range of 30 to 60 microtesla [μT] approximately). However, EMFs are currently considered unlikely to generate any ecologically significant impacts on receptive species at these low field intensities (Gill et al. 2014).

The strength of anthropogenic E-fields associated with MRE-type cables, that have been measured, are in the 1 to 100 μV/cm range, which is similar to the bioelectric fields emitted by prey species; such E-fields act as attractants for electroreceptive ocean predators (Kalmijn 1982; Peters et al. 2007; Tricas and New 1998). Cables associated with larger MRE arrays will produce greater B- and E-fields, potentially interfering with migratory movements due to a perceived barrier effect (Tesch and Lalek 1973; Westerberg and Begout-Anras 2000; Westerberg and Lagenfelt 2008) and possibly reaching the limit between animal attraction to and repulsion from EMFs (Huveneers et al. 2013). However, the state of the knowledge until 2016 was limited, which prevented further interpretation (Gill et al. 2014).

While most of the field and semi-natural studies conducted before 2016 focused on behavioral effects, none have shown any demonstrable significant impacts of EMF on sensitive species (e.g., Gill et al. 2014). However, a controlled laboratory experiment showed some adverse effects of prolonged exposure to high-intensity EMFs (in the millitesla [mT] range) on the physiology, development, and growth of several species of demersal fish and crustaceans (Woodruff et al. 2012). It is important to note that, to date, EMF levels similar to these experimental conditions have not been observed around deployed MRE devices. These effects would be more likely observed for sessile species that stay near undersea cables than motile species, but knowledge of the effects of EMF on these sessile species had not been established by 2016.

B-field patterns produced by different cable configurations can be detected and mapped using magnetometers (Normandeau et al. 2011), but it is more difficult to measure E-field emissions. As of 2016, only a few groups had developed or were developing the instrumentation to detect E-fields at the low-intensity levels expected to occur around MRE devices (e.g., Oregon State University, Swedish Defense Research Agency). Mathematical modeling has been used to complement field and laboratory measurements, because it is more cost-effective for predicting conditions over larger areas than measurements recorded under difficult field conditions. However, the measurement data needed to validate EMF models are lacking.

Based on the knowledge acquired up to 2016, there was insufficient reason to consider establishing definitive mitigation efforts. However, if mitigation was deemed necessary, technical design standards could be proposed, such as the use of helically twisted three-conductor cables to reduce EMF emissions (Petterson and Schönborg 1997). Burial of cables is not an effective mitigation measure for EMFs because the cables emit EMFs into the environment directly as B-fields and create iE-fields in the seawater and, therefore, have the potential to affect sea life. Cable burial does, however, separate most demersal and benthic animals from the maximum EMF emissions at the cable surface, owing to the physical distance between the seabed surface and the cable.

To fill significant knowledge gaps about EMFs, the *2016 State of the Science* report (Copping et al. 2016) recommended further efforts toward

- characterizing EMFs in AC vs. DC transmission systems, in single vs. multiple cables configurations, and in the electrical topology of various MRE devices
- measuring actual EMF levels linked to the location and depth of devices, as well as the spatial and temporal variability of EMFs to which animals would potentially be subjected
- carrying out dose-response studies to establish species-specific ranges of detections, and thresholds for and types of responses
- developing modeling tools that combine EMF models and dose-response studies with ecological models
- implementing long-term research and monitoring to assess cumulative impacts, especially impacts on vulnerable life-history stages.

5.3. KNOWLEDGE GENERATED SINCE 2016

In the *2016 State of the Science* report (Copping et al. 2016), the importance of differentiating the potential environmental effects of EMFs when assessing the interactions between MRE devices and receptors was highlighted (e.g., by Boehlert and Gill 2010). The present update focuses on whether an effect or response recorded in a study can be considered an impact.

In the four years since the publication of the *2016 State of the Science* report, interest in the topic of EMFs has grown, and some notable research projects have provided an improved understanding of the interactions between EMFs and aquatic life, with a focus on fish and invertebrate receptor species. The research has either involved laboratory-based controlled studies of B- or E-fields or field-based experiments or surveys of EMF-emitting subsea cables. Within the academic literature, some key reviews have been published, specifically about magnetoreception in fish (Formicki et al. 2019), electroreception in marine fish (Newton et al. 2019), the perception of anthropogenic electric and magnetic emissions by marine animals (Nyqvist et al. 2020), and the environmental impacts of subsea cables (Taormina et al. 2018).

These reviews demonstrate that when considering the potential response of an organism to EMFs, the topic should be divided into two categories: organisms that have the sensory capability to detect and respond to B-fields, and organisms that have the sensory capability to detect and respond to E-fields (although recent evidence suggests that some organisms may be able to detect both types of fields directly) (see Newton et al. 2019). The primary consideration for EMFs emitted by subsea cables is the B-field, which should be considered in relation to the ambient GMF and the iE-fields that occur. For organisms that detect E-fields, direct E-fields will only occur in the environment if a cable (AC or DC) is not properly grounded or if the design of the electrical system leads to electrical leaks; however, iE-fields will be associated with the B-field. Therefore, while understanding both elements of EMFs is important, the B-field is regarded as the primary focus for understanding organism response to MRE EMFs.

The predominant taxonomic groups discussed in the *2016 State of the Science* report were fish and invertebrates. The current review of recent literature includes consideration of new knowledge about the responses of electro- and magnetoreceptive organisms to changes in the magnetic and/or electric environment. An overview of knowledge generated since 2016 and a set of recommendations are covered in the remainder of this chapter.

5.3.1. RESPONSES TO EMF – FISH (ADULT)

Field Studies of EMFs

Studies of magnetosensitive species migration have continued to be a focus of field investigations. The migration success of Chinook salmon (*Oncorhynchus tshawytscha*) in San Francisco Bay, California (United States [U.S.]) was found to be largely unchanged after installation of a 200 kV HVDC subsea cable (Wyman et al. 2018). However, the proportion of salmon crossing the cable location was larger than the proportion not crossing it. Furthermore, fish were more likely to be detected on one side of their normal migration route. Fish migration paths moved closer to the cable at some locations, but farther away at others, which was attributed to other higher-intensity B-field sources, such as metal bridges. Together with other environmental factors, transit times through some parts of the bay were slightly reduced (Wyman et al. 2018).

The results of a field experiment conducted in Long Island Sound, Connecticut (U.S.) showed that little skates (*Leucoraja erinacea*) crossed over a 300 kV HVDC transmission cable. However, the skates showed a strong distributional response associated with the higher EMF zone, moved significantly greater distances along the cable route, and displayed increased turning activity (Hutchison et al. 2018).

Magnetic Fields

A number of species have the ability to detect and respond to B-fields, likely via a magnetite-based sensory process (Diebel et al. 2000; Kirschvink and Gould 1981; Kirschvink and Walker 1985), but other hypotheses remain to be demonstrated (Binhi and Prato 2017). Research on elasmobranch response to EMFs in the environment has considered that when an individual approaches an EMF, it experiences an iE- field, which stimulates its electroreceptive sensory apparatus. This hypothesized mechanism of indirect magnetic stimulus detection has been offered as a plausible explanation of the responses of yellow stingray (*Urobatus jamaicensis*), which learned to associate magnetic anomalies with food rewards up to six months after first exposure (Newton and Kajiura 2017). Other recent studies suggest that elasmobranchs can detect magnetic fields directly rather than via induction of E-fields (Anderson et al. 2017). To date, elasmobranchs have no known direct B-field receptors, but putative magnetoreceptive structures may reside within the naso-olfactory capsules of sandbar sharks (Anderson et al. 2017). Strong permanent magnets, used in shark-repellent studies, have been shown to induce avoidance behaviors in a number of elasmobranch species (Richards et al. 2018; Siegenthaler et al. 2016). However, it is unclear whether the avoidance effects were a result of the fish responding directly to magnetic stimuli or to iE-fields. Newton (2017) showed that the yellow stingray uses GMF polarity to solve spatial tasks and detect changes in GMF strength and inclination angle. These two magnetic cues may be used for orientation and to derive a location.

Electric Fields

The anatomy, physiology, and behavior of electroreceptive species have been the subjects of a number of studies over the past few decades. Most studies since 2016 have focused on determining whether electroreceptive species detect B-fields directly or indirectly by induction (see above). 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.

A number of fish can be affected adversely by high-intensity E-fields, such as those used in electric fishing (de Haan et al. 2016), but these E-fields are several orders of magnitude greater (30 to 100 V/m approximately 20 cm from electrodes) than those associated with subsea cables (Table 5.1) and are not regarded as relevant to MRE EMFs.

5.3.2. RESPONSE TO EMF – FISH (EMBRYONIC AND LARVAL)

The strongest effects of EMFs on an individual organism will most likely occur during either the embryonic or larval stages of species settling on the bottom, particularly for those species that have a long incubation period (see Nyqvist et al. 2020 and references therein). Most early life-history studies have been conducted on freshwater fish species and have focused on the B-field. The application of B-field studies will not differ between fresh and ocean water, but for E-fields, direct or iE-fields only propagate in seawater because of the conductivity of the medium.

In a study of rainbow trout (*Oncorhynchus mykiss*), demersal eggs and larvae were exposed under experimental conditions to static B-fields (10 mT, DC) and a low-frequency EMF (1 mT, AC) for 36 days (Fey et al. 2019a). No effect on embryonic or larval mortality, hatching time, larval growth, or swim-up from the bottom was found. However, both low-frequency and static exposures enhanced the yolk-sac absorption rate. Larvae with absorbed yolk-sacs were less efficient at first feeding, resulting in smaller weights at age. A smaller yolk sac and faster absorption rate were also observed in exposed (static magnetic, 10 mT, DC) freshwater Northern pike (*Esox lucius*) (Fey et al. 2019b). In addition, hatching was one day earlier, but no differences in hatching success and larval mortality or size of larvae were noted. The appearance of embryonic melanophores, a key developmental marker, in common whitefish (*Coregonus lavaretus*) and vendace (*Coregonus albula*) was delayed, while increased static field intensities caused a concentration of melanin in their cells (Brysiewicz et al. 2017). A low-intensity (hypo)magnetic field (i.e., weaker than the GMF) has been found to cause a decrease in the activity of intestinal enzymes, proteinases, and glycosidases in crucian carp (*Carasius carasius*) (Kuz'mina et al. 2015). Furthermore, the activity of intracellular calcium (Ca^{2+})-dependent proteinase (calpains) decreased, and this could have potential consequences for calcium signaling pathways leading to changes in the morphology and activity of cell organelles. These calpains were also inactivated in crucian carp, roach (*Rutilus rutilus*), and common carp (*Cyprinus carpio*) (Kantserova et al. 2017). A newer study investigating the genotoxicity and cytotoxicity responses during the early development of rainbow trout exposed to a low-frequency (50 Hz 1 mT) EMF for 40 days, showed nuclear abnormalities and alterations in the number of cell nuclei (Stankevičiūtė et al. 2019).

Even though these studies were conducted under controlled laboratory conditions, they highlight how exposure to B-fields in the millitesla range have implications for developmental, genetic, and physiological outcomes for early life stages. The laboratory-induced B-field intensities are high compared to microtesla or nanotesla fields measured around subsea cables (Table 5.1). However, with increased cable power transmission and subsequent B-field strength, the effects on the development of early life stages may become a consideration in the future.

No studies concerning E-fields in the predictive range associated with MRE devices have been conducted to date, largely because the industry is still emerging and power generation levels are relatively low and isolated, and EMF studies have seldom been required in the marine environment for established industries.

5.3.3. RESPONSE TO EMF – INVERTEBRATES

Relatively little is known about the effects of EMFs on marine benthic invertebrates, but some decapod crustaceans are known to be magnetosensitive. Research since 2016 concerning invertebrates generally supports previous studies that demonstrated no or minor effects of encounters with EMFs, but some findings are equivocal (Albert et al. 2020).

Field Studies

During a field experiment in southern California and the Puget Sound, Washington State (U.S.), no evidence was found that the catchability of two commercially important crab species (*Metacarcinus magister* and *Cancer productus*) was influenced by their having to traverse an energized low-frequency submarine AC power cable (35 kV and 69 kV, respectively) to enter a baited trap (Love et al. 2017a). Greater turning activity and altered distribution of American lobster (*Homarus americanus*) in the presence of static HVDC EMFs (Cross Sound Cable: 300 kV; Table 5.1) were highlighted recently in a field study using large enclosures above a domestic electrical power cable in Long Island Sound, Connecticut (U.S.) (Hutchison et al. 2018, 2020).

Magnetic Fields

In a laboratory study, Scott et al. (2018) observed a clear attraction of European edible crabs (*Cancer pagurus*) to shelters that had a relatively high B-field (2.8 mT, compared to nT- or μT-level EMFs measured in the field) associated with them, and the crabs spent less time roaming. The daily behavioral and physiological rhythmic processes (i.e., circadian rhythm) of the haemolymph L-Lactate and D-Glucose levels were disrupted. However, the EMF (2.8 mT and 40 mT) had no effect on stress-related parameters, such as haemocyanin concentrations, respiration rate, activity level, or the antennular flicking rate.

An experimental study by Taormina et al. (2020) exposed juvenile European lobsters (*Homarus gammarus*) to a DC or AC B-field (maximum up to 200 μT) and found no statistically significant effect on their exploratory and sheltering behaviors. They suggested that a behavioral response to B-fields, up to 200 µT, does not appear to be a factor influencing the European lobster's juvenile life stage, although there was a confounding influence of light affecting their sheltering behavior. The authors commented that higher magnetic values (which could be encountered while seeking shelter close to a cable) may need to be considered when studying the potential B-field effects on the behavior of this species.

A laboratory study assessing the effects of environmentally realistic, low-frequency B-field (1 mT) exposure on the behavior and physiology of the common ragworm (*Hediste diversicolor*) did not find any evidence of avoidance or attraction behaviors (Jakubowska et al. 2019). The polychaetes did, however, exhibit enhanced burrowing activity when exposed to the B-field. In addition, food consumption and respiration rates were not affected, but ammonia excretion was reduced in exposed animals, with plausible consequences for their metabolism; however, knowledge about the biological relevance of this response is currently absent (Jakubowska et al. 2019).

Stankevičiūtė et al. (2019) investigated potential genetic damage (i.e., genotoxicity) and damage or destruction of cells (i.e., cytotoxicity) in the common ragworm and Baltic clam (*Limecola balthica*) after a relatively long-term (12 days) exposure to a 50 Hz 1 mT EMF. The exposure affected both species, but the strongest response was elicited in the Baltic clam, for which six out of the eight measured parameters were significantly elevated in the gill cells. No cytotoxic effect was induced in common ragworm immune system cells, but the development of micronuclei and nuclear buds on filaments demonstrated a potential effect on the integrity of genetic material that may cause diseases.

Electric Fields

Relative to species navigation and prey detection, a limited number of previous studies indicated that some freshwater invertebrate species may be able to detect low-intensity E-fields comparable to those induced by subsea cables (Patullo and MacMillan 2010). However, no similar studies of marine invertebrate response to E-fields are found in the literature for the period from 2016 to 2019. Invertebrates have been shown to respond to high-intensity fields such as those used in electric fishing at sea (Polet et al. 2005; Soetaert et al. 2014). Although these fields have been shown to cause neuromuscular disruption, they are several orders of magnitude greater than those associated with subsea cables and so are not considered further in this report.

5.3.4. RESPONSE TO THE PRESENCE OF SUBSEA CABLES – FAUNAL COMMUNITIES

To assess the effects on the community of species inhabiting the environment on or adjacent to subsea cables, a small number of studies have conducted field surveys along cable routes.

Love et al. (2017b) used submersible surveys of energized cables (35 kV) to compare the invertebrate colonizing community and the fish assemblages present in southern California (U.S.). Magnetic fields of energized cables reached background levels within 1 m and no statistical differences in the faunal communities were found. Factors such as substrate or depth were more relevant than proximity to the cable in explaining the variation of fish community and density in association with a 245 kV HVAC transmission cable in Lake Ontario, Ontario (Canada) (Dunlop et al. 2016). Dunham et al. (2015) found that the abundance of decapods (principally the prawn and shrimp species) associated with the glass sponge reefs colonizing three 230 kV HVAC cables off Vancouver Island, British Columbia (Canada) differed from their abundance at control survey sites; they were less abundant around the cables. Diver and remotely operated vehicle surveys across Bass Strait in Tasmania (Australia) found a third of a cable route visually undetectable within two years; after three and a-half years, the colonizing benthic species were similar to the nearby hard-bottom species (Sherwood et al. 2016).

These studies collectively suggest that benthic communities growing along cables routes are generally similar to those in nearby areas, although some locations perhaps show a difference in the abundance of a few species. However, it is important to note that any observed changes could be the result of the physical presence of the cable or other features in the environment, rather than an EMF effect (see Chapter 6, Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices).

5.4. GUIDANCE ON MEASURING EMF FROM MRE DEVICES AND CABLES

Advancing our knowledge of the characteristics of EMFs emitted by cables or MRE devices is essential for understanding the possible consequences of exposure of the aquatic environment and for developing accurate predictive models of EMFs. Since the MaRVEN (Marine Renewable Energy, Vibration, Electromagnetic fields and Noise) project deployed the SEMLA (Swedish Electromagnetic Low-Noise Apparatus) device to measure *in situ* E-fields and B-fields emitted by subsea MRE cables (Thomsen et al. 2015), a few studies have continued to focus on quantifying the extent of anthropogenic EMFs using field measurements and modeling (Table 5.1). Field strengths and the depth and angle of buried HVDC power cables are parameters that determine the extent of the EMF above the seabed and can be modeled, but these models need to be validated in the field.

Dhanak et al. (2016) used an autonomous underwater vehicle equipped with a commercial magnetometer and custom-built, three-axis E-field sensor that simultaneously measured E-fields and B-fields by following a lawnmower-type survey path above AC and DC power cables on the east coast of Florida (U.S.). The values of the emitted fields were within the expected EMF intensity of these cables. The modeled B-fields for the Trans Bay Cable in San Francisco, California (U.S.) were very similar to field measurements and consistent with expectations (Kavet et al. 2016), as was the case for measurements of the B-field emitted by the Basslink HVDC across Bass Strait in Tasmania (Australia) (Sherwood et al. 2016). Nonetheless, the emissions from other B-field sources, such as metal bridge structures or geological deposits, might be up to a hundred times greater than the B-field emission from the cable and might distort the B-field, making it impossible to model and discern B-fields emitted by and measured around the cable in some locations (Kavet et al. 2016). Hence, in some cases the actual EMF emitted into the environment will not match the modeled outputs.

Table 5.1. Measurements from high-voltage alternative current (AC) and direct current (DC) subsea cables since 2016. The distances above the seafloor were extracted from studies when provided. The electromagnetic field (EMF) extent refers to the distance that EMF is measurable in relation to the ambient fields perpendicular to the cable axis.

Cable	Current	Location	Magnetic field (B-field)	Electric field (E-field)	Extent EMF	Reference
2 - 2.4 amps 0.98 - 1.59 amps, 60 Hz	DC AC	South Florida (U.S.)	Max: 150 μT Mean: 30 nT 2.2 m above seafloor	Max: 60 μV/m 4 m above cable	10s m (estimated) AC > DC	Dhanak et al. (2016)
Trans Bay Cable (200 kV, 400 MW, 85 km)	DC	San Francisco Bay, California (U.S.)	1.15 - 1.2 μT 3 m above seafloor	n/a	<40 m	Kavet et al. (2016)
Basslink (500 kV, 237 MW, 290 km)	DC	Bass Strait, Tasmania (Australia)	58.3 μT	5.8 μV/m	15 - 20 m	Sherwood et al. (2016)
Cross Sound (300 kV, 330 MW, 40 km)	DC	Connecticut (U.S.)	DC: 0.4 - 18.7 μT AC: max 0.15 μT	AC: max: 0.7 mV/m	AC-DC B-fields: 5 - 10 m	Hutchison et al. (2018)
Neptune (500 kV, 660 MW, 105 km)	DC	New Jersey (U.S.)	DC: 1.3 - 20.7 μT AC: max 0.04 μT	DC: 0.4 mV/m	AC: max: E-fields up to 100 m	Hutchison et al. (2018)
Sea2shore (502 amps, 30 MW, 32 km)	AC	Rhode Island (U.S.)	0.05 - 0.3 μT	1-25 μV/m	AC: B-field up to 10 m AC: E-field up to 50 m (estimated)	Hutchison et al. (2018)

Hutchison et al. (2018, 2020) discovered AC fields associated with two HVDC power cables (Cross Sound and Neptune Cables, Table 5.1) that extended tens of meters farther than the DC fields. This unexpected finding is most likely explained by harmonic currents created during AC-DC conversion at the converter station on each end of the cables. In the same study, an AC cable at a small wind farm emitted B-fields that were ten times lower than those modeled, suggesting self-cancellation inside the three-conductor cable owing to the twisted design of the cable.

Remote-sensing satellites have the potential to become a new tool for studying EMFs in the ocean. The European Space Agency (ESA) launched satellites in 2013 (as part of the SWARM mission) to study various aspects of the Earth's B-field. One of the goals of SWARM was to study ocean circulation based on its EMF signature. In 2018, electric currents generated in the world's oceans due to seawater movement through the Earth's B-field were detected by the ESA satellites. These large-scale datasets will provide further context for the electromagnetic environment relevant to marine life.

5.5. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

The *2016 State of the Science* report highlighted significant gaps in the current knowledge of the impacts of EMF from MRE on receptive species. In the intervening years, the conduct of more specific research has increased the knowledge base, allowing for further consideration of whether the interaction between receptive species and EMFs has any biological significance that could translate to ecological impacts. New research has shown evident effects and responses of individual species at behavioral, physiological, developmental, and genetic levels. However, based on the evidence to date, the ecological impacts associated with MRE subsea power cables may be weak or moderate at the scale that is currently considered or planned. Nonetheless, it is important to recognize that this assessment comes from studies of a small number of cables, and several researchers have acknowledged that data about impacts are scarce and many uncertainties concerning electromagnetic effects remain (Taormina et al. 2018). Furthermore, knowledge about how sensitive species will respond and adapt to an aquatic environment that is being increasingly altered by anthropogenic E- and B-fields, not just from MRE but other human activities, is lacking (Newton et al. 2019).

In general, the research concerning EMF effects requires an understanding of both the EMF environment in which the sensitive organisms will encounter EMFs and the context of their responses. With a growing number of cables being deployed, and increases in the power being transmitted, the extent of EMFs emitted into the environment will increase with additional MRE deployments and associated cables. Therefore, the likelihood of animals encountering EMFs in the aquatic environment will increase, as will the intensities experienced.

MRE installations currently are of relatively small scale and they are not the only sources of EMFs in the environment. Questions about the environmental effects of EMFs remaining to date can be addressed and management decisions can be supported by considering some key elements (Figure 5.2).

To date, although some of the study results suggest effects of EMFs on certain species (see Section 5.4), the lack of specific information has led to the general conclusion that EMFs associated with subsea cables are not harmful and do not pose a risk to biota. This would appear to be an appropriate conclusion for MRE devices and cables because their EMF signatures are low. However, the lack of evidence does not necessarily equate to a lack of impacts. Future increases in EMFs in the marine environment, due to the development of MRE arrays, may increase the potential risk to sensitive receptors and require additional investigation to enhance our knowledge and understanding of the emerging spectrum of effects.

If studies provide evidence that a given receptor organism responds to EMFs, then the next step toward the determination of any impact would be to investigate the likelihood of a receptor to encounter the EMF emission extent (Figure 5.2). For non-mobile receptors, the emission-response relationship will depend on the duration of the exposure, the intensity and frequency of the EMF, and the threshold levels at which a response will occur. Knowledge about thresholds is currently very poor and, therefore, requires more specific attention.

For mobile species, the most likely response is expected to be attraction to the EMF or avoidance of higher-level EMFs. However, physiological effects could occur within the receptor animal. With multiple cables (or sources of EMFs), the likelihood of encounter will be greater (Figure 5.2); hence, cumulative effects of an encounter with EMFs are plausible. To date, studies have been conducted in controlled settings (either in laboratories or field-deployed enclosures) or have involved visual observations around single cables. No EMF receptor interaction studies have been conducted in relation to multiple subsea cables, even around existing offshore wind farms, so there is no evidence to enable cumulative effects assessments to be undertaken, and no other data about this topic exist from other industries.

Additional research is needed to determine the specific environmental impacts of EMFs on the aquatic life highlighted in Figure 5.2. This knowledge will be required because the more extensive EMFs associated with future MRE and subsea cable deployments will require a greater degree of confidence than currently exists. The targeted priorities for future research include the following:

- The sources and intensity of EMFs emitted by subsea cables are directly determined by the cable characteristics and the power being transmitted. Quantifying these parameters in the aquatic environment is crucial for characterizing emissions and for accurate modeling. Deployment of small-scale devices is required to gather data to quantify the EMFs related to power transmission.
- Cables and MRE devices are part of a whole power system of electrical generation and transmission infrastructure. Each of the different parts will have a role in the variability of the EMFs emitted. Understanding the whole power system and how its different parts influence EMF variability is important for determining the EMF environment encountered by receptor species. In addition, evidence that wide AC fields are associated with DC cables (Hutchison et al. 2018) makes the interpretation of the biological effects of EMFs from DC cables more complex.

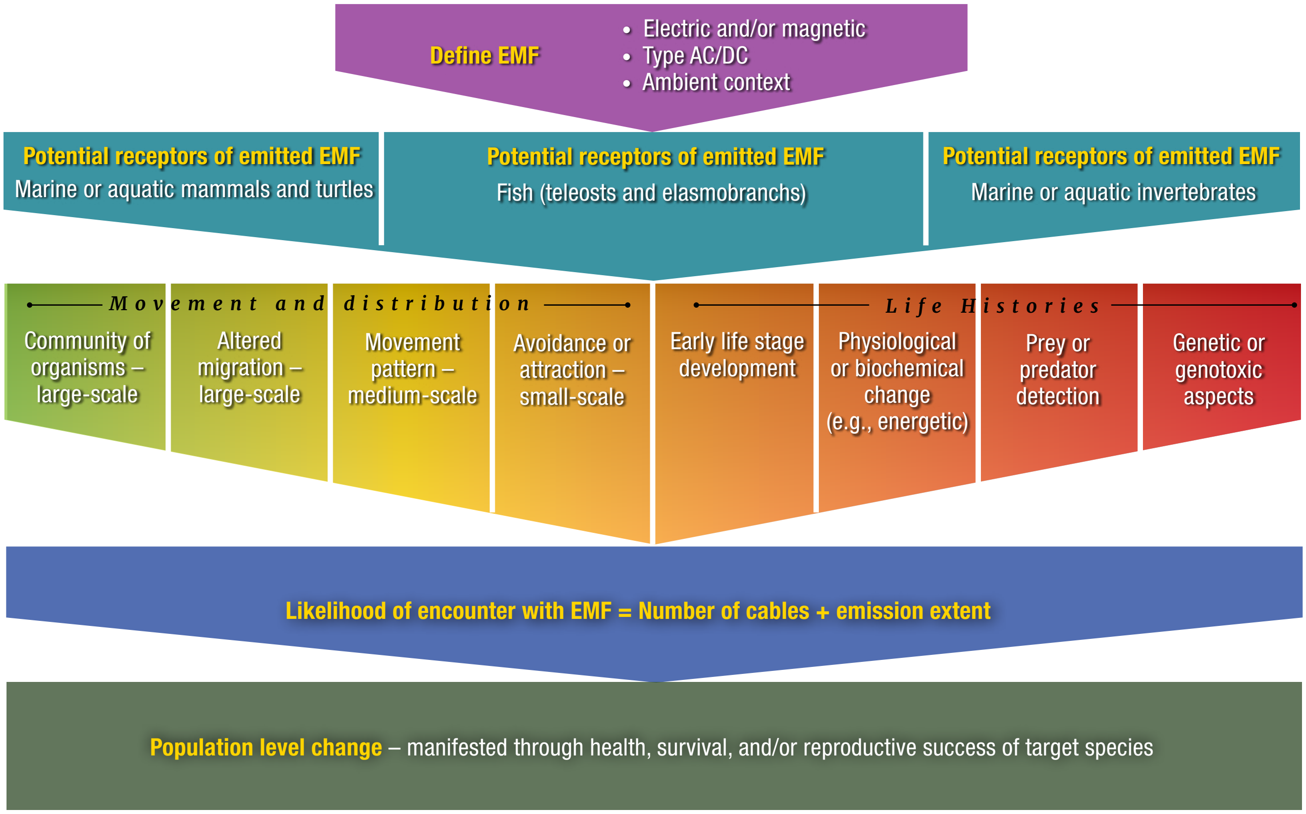

Figure 5.2. The key elements that need to be considered when assessing the environmental impact of electromagnetic fields (EMFs) on sensitive receptors. If a population-level change is demonstrated, there is the potential for cumulative or cascading effects at the ecological community level. (Graphic by Robyn Ricks)

- 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.
- 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.
- 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.
- 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).
- 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.
- 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.
- To determine whether an effect is negative, demonstration of the effect at the biologically relevant unit of the species population is required (Figure 5.2). Impacts can only be determined through replicated studies that show consistent evidence of a response.
- Because EMFs are associated with any subsea transmission cable, regardless of the MRE device, the collection and sharing of EMF characteristics should be encouraged and facilitated. If local conditions are also taken into consideration, their consideration will assist with assessments of similar cables in different environments.
- 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.

5.6. CONCLUSION

Since the publication of the *2016 State of the Science* report, which highlighted significant gaps in the knowledge of the impacts of EMFs from MRE on receptive species, more targeted research has increased the knowledge base. This has increased our understanding of whether the interactions between receptive species and EMFs have any biological significance that could translate into ecological impacts. New research, both field and laboratory studies, has shown measurable effects and responses to E- and/or B-fields on a small number of individual species (behavioral, physiological, developmental and genetic levels), but not at the EMF intensities associated with MRE. However, an effect or response to MRE EMFs does not necessarily mean there are impacts. Currently, conclusive evidence is insufficient and additional knowledge about receptor species (at different life stages), exposure to different EMFs (sources, intensities), and the determination of the EMF environment is needed. Based on the knowledge to date, biological or ecological impacts associated with MRE subsea power cables may be weak or moderate at the scale that is currently being considered or planned. It is important, however, to acknowledge that this assessment comes from a handful of studies and that data about impacts are scarce, so significant uncertainties concerning electromagnetic effects remain. Because EMFs are associated with any subsea transmission cable, the collection and sharing of EMF characteristics should be encouraged and facilitated, for example, by making these practices a condition of permissions being granted for MRE deployments. Taking local conditions into consideration will help with future assessments of similar cables in different environments to assist the MRE industry.

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NOTES

Risk to Animals from Electromagnetic Fields Emitted by Electric Cables and Marine Renewable Energy Devices

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REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2020

CONTACT

Andrea Copping
Pacific Northwest National Laboratory
andrea.copping@pnnl.gov
+1 206.528.3049

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