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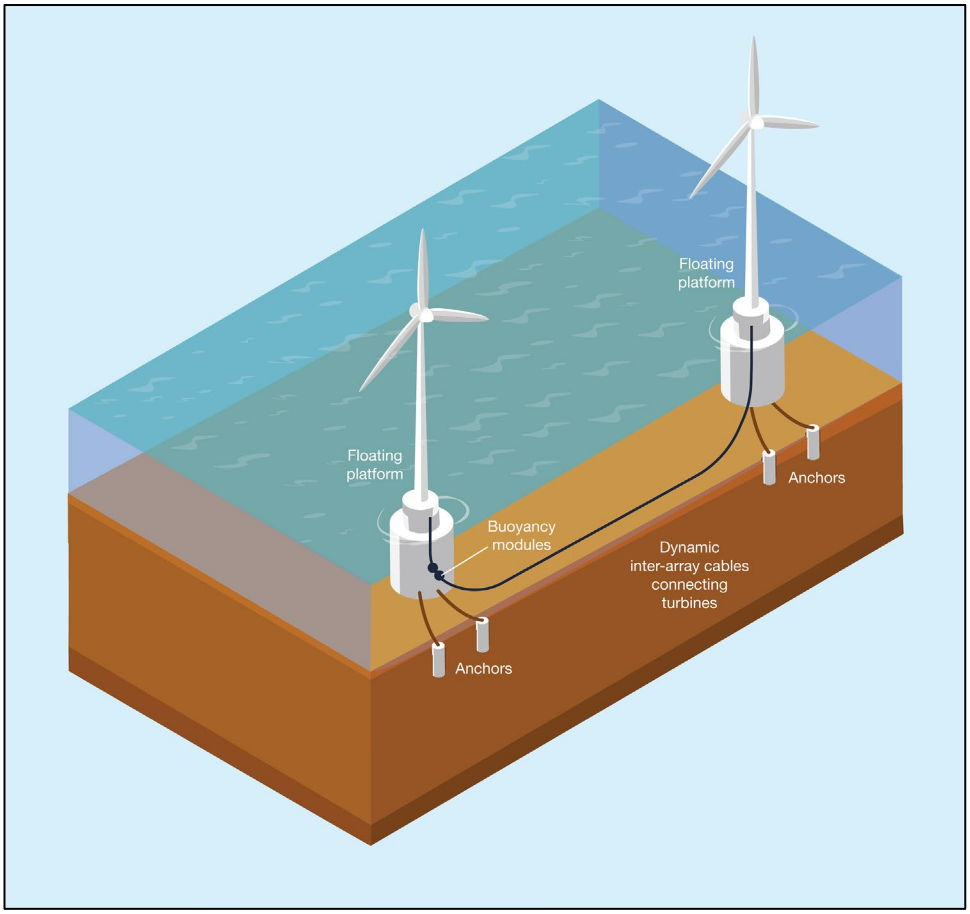
# Electromagnetic Fields: Background and Potential Impacts of Offshore Wind Farms on Marine Organisms




US Department of the Interior
Bureau of Ocean Energy Management
Gulf of Mexico Regional Office
New Orleans, LA

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# Electromagnetic Fields: Background and Potential Impacts of Offshore Wind Farms on Marine Organisms

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Authors:
Gulf of Mexico Regional Office
Office of Environment
Biological Sciences Unit

**US Department of the Interior**
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## List of Abbreviations and Acronyms

| Short Form | Long Form |
|---|---|
| μT | microtesla |
| AC | alternating current |
| BACI | Before-After-Control-Impact |
| B-field | magnetic field |
| COP | Construction and Operations Plan |
| EIS | environmental impact statement |
| EMF | electromagnetic field |
| DC | direct current |
| DTS | distributed temperature sensing |
| E-field | electric field |
| HDD | horizontal directional drill |
| HVAC | high voltage alternating current |
| HVDC | high voltage direct current |
| Hz | Hertz |
| iE-field | induced electric field |
| m | meter |
| mG | milligauss |
| MRED | Marine Renewable Energy Development |
| mVm | millivolts per meter |
| NOI | Notice of Intent |
| OFW | offshore wind farm |
| OSS | offshore substation |
| WTG | wind turbine generators |
| XLPE | cross-linked polyethylene |

# 1 Summary

Electromagnetic fields (EMFs) are areas of electric and magnetic energy moving together. The greater the electrical current, the greater the EMF emissions. Anthropogenic (i.e., human-induced) sources of EMFs have been introduced into the marine environment from offshore sources, mainly associated with power cables, but also with items such as ships, communication cables, and pipeline anti-corrosion systems. Offshore wind farms (OWFs) have submarine inter-array cables that collect electricity from wind turbine generators (windmills) and carry it to an offshore electrical substation (OSS). An export (transmission) cable(s) is then used to transfer electricity from the OSS onshore to the power grid. When energized, these cables are a source of EMFs in the marine environment. The EMFs generated by OWFs are of relatively low frequency and are not like higher frequency, ionizing EMFs (e.g., X-rays, microwaves) which are known to alter chemical bonds and damage biological molecules.

EMF levels are strongest around an energized cable and they decrease approximately as an inverse square of the distance from the cable. Elevated EMF levels from OWF cables are consistently estimated to return to background levels within 100 meters (m) or less (typically one to tens of m). There are currently no mitigation options to prevent EMF emissions from escaping the cable and entering into the surrounding environment. Cable burial is the most commonly discussed mitigation measure that will result in a lower EMF level at the sediment surface and in the lower part of the water column. The lower EMF level is due to increasing the distance between the cable and the seafloor and/or water column and not because burial itself dampens the intensity of the EMF. There are also other options and considerations to minimize EMF levels and/or exposure, including cable siting, cable design (e.g, sheathing), and cable management and monitoring. Currently, there is not enough information to determine what the appropriate EMF levels are to target with mitigation measures, or if specific mitigation measures are required.

For an organism to sense EMF emissions, they must possess a sensory system capable of detecting a magnetic field (i.e., magneto-sensitive), electric field (i.e., electro-sensitive), or both. Elasmobranchs (e.g., sharks, skates, and rays) appear to be the most sensitive to EMF and are both magneto- and electro-sensitive. Relevant available literature suggests that potential impacts from cable EMF emissions that could, if present, result in a reduction in an individual's fitness (i.e., ability to reproduce) and possible survival include altered migration and/or orientation, altered behavioral patterns (e.g., avoidance and/or attraction, predator and/or prey detection, conspecific communication), altered community structure and/or composition (e.g., species interactions such as prey availability, predator presence, competition), and physiological effects. However, exposure to elevated EMF levels equivalent to those expected from an OWF has not been observed to affect the survivorship of marine species. Effects, when observed in electro- or magneto-sensitive species, have been limited to minor changes in behavior or physiological effects. These effects are species-specific, sometimes individual-specific, and are not expected to result in population-level impacts.

A challenge in predicting future effects of EMFs from OWFs is extrapolating (i.e., scaling-up) current observations (both laboratory and field) to larger developments with higher electrical power and the possible cumulative effects of multiple OWFs in close proximity. This also includes predicting the potential effects of the new technology of floating OWFs. The area affected would need to be large to result in population level effects, but the region of influence of an individual OWF cable is relatively small (i.e., up to 100m but typically much less).

In addition to EMFs, even when cables are encased in a sheath, thermal radiation is emitted from electrified cables. However, the temperature increase is generally considered to be almost negligible in view of typical seasonal temperature variations. Therefore, similar to EMF exposure, it is not anticipated that enough individuals would be affected to result in population level effects.

Based on review of the available literature, exposure to EMF emissions from OWFs could elicit a response from electro- and magneto-sensitive species. However, any effects are anticipated to be species-specific, limited to individuals in the immediate vicinity, and biologically non-significant.

## 2 Offshore Wind Farms

*Summary: OWFs have multiple submarine electrical cables. Inter-array cables collect electricity from wind turbine generators (windmills) and carry it to an offshore electrical substation. An export (transmission) cable(s) is then used to transfer electricity from the offshore substation onshore to the power grid. When energized, these cables are a source of an EMF.*

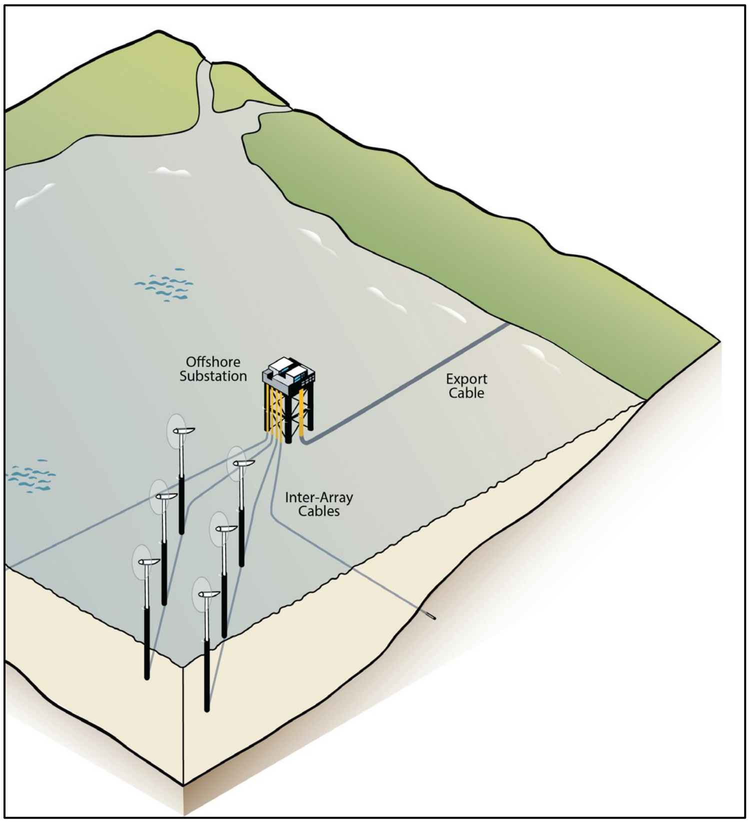


**Figure 1. Typical OWF.**
Inter-array cables in a fixed turbine design (i.e., monopile, jacket) are typically buried. In contrast, the inter-array cables in a floating turbine design (i.e., floating wind farm) are suspended freely in the water column to compensate for movement of the floating turbines. The export (transmission) cable is typically buried in both fixed and floating wind farms designs.

Offshore wind is an abundant domestic energy resource that is often located close to major U.S. coastal population centers. An OWF designed to capture that energy includes multiple wind turbine generators (WTGs, or turbines) placed in a grid-like array. The WTGs generate electricity with rotation of their fan blades. Inter-array cables link the individual WTGs and transfer the generated electricity to an OSS. From the OSS, an export cable(s), sometimes referred to as a transmission cable, carries the electricity to the onshore power grid. A depiction of an OWF is provided in Figure 1.

The design of an OWF depends on site-specific conditions, particularly water depth, geology, and oceanographic conditions. In general, within shallower waters the WTGs are fixed to the seafloor. In deeper waters a floating WTG design is typically utilized. An overview of the different WTG designs is provided in Figure 2. With fixed WTGs (i.e., monopile, jacket), the inter-array cables that connect the WTGs to each other and to the OSS are typically buried. In contrast, floating WTGs (i.e., tension leg, semi-submersible, spar) have dynamic inter-array cables that are suspended freely in the water column and designed to compensate for WTG movement due to wind and waves. The depth that the dynamic inter-array cables for the floating WTGs extend into the water column is a function of the specific OWF design. In some designs the inter-array cable may actually be buried (or weighted) between the floating WTGs that it connects. When buried (or weighted) the dynamic array cable may extend directly to the seafloor under its own weight or have a “lazy wave” shape with mid-line buoys (Maxwell et al. 2022), see Figure 3. For both fixed and floating OWF designs, the export cable is typically buried its entire length.

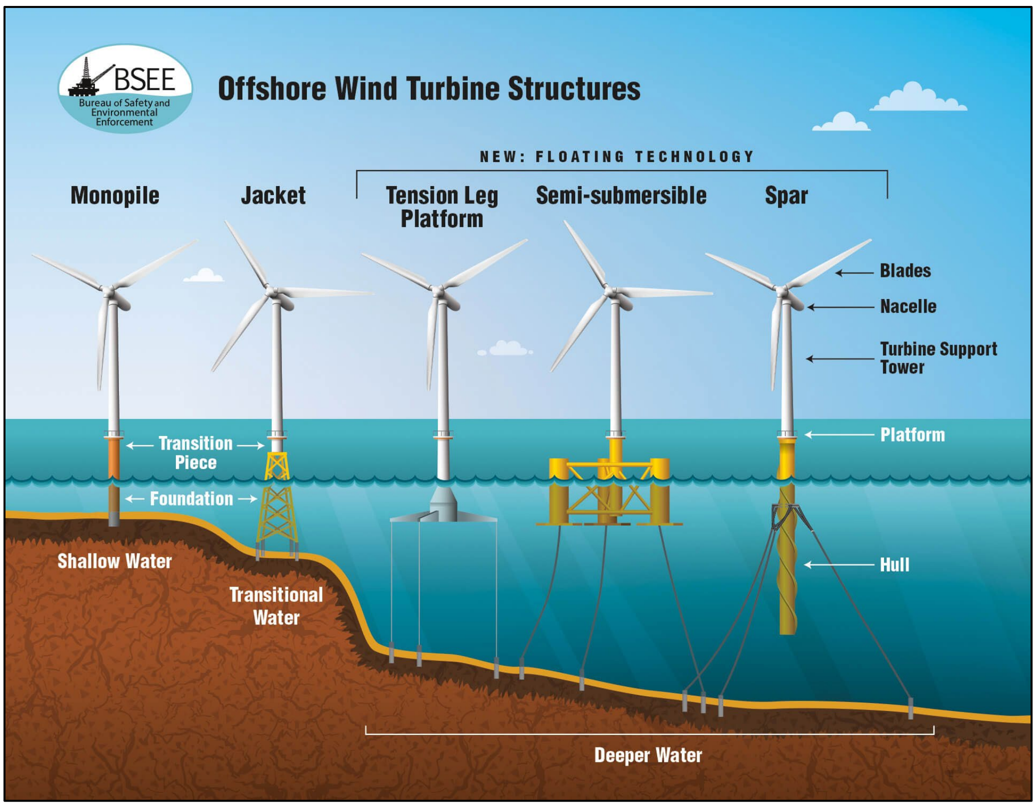


**Figure 2. An overview of the different types of fixed and floating WTGs.**

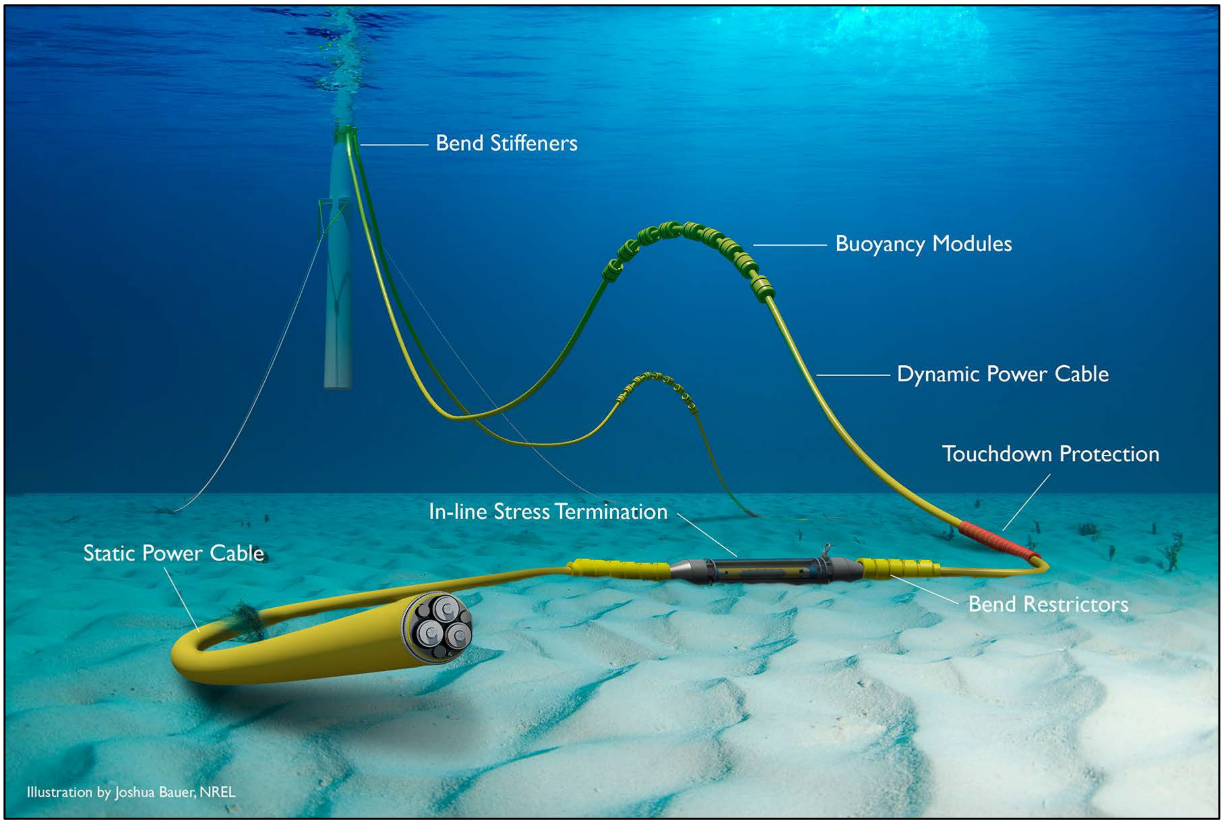


**Figure 3. Dynamic inter-array cable.**

# 3 What Are EMFs

*Summary: EMF emissions are electric and magnetic energy moving together. Anthropogenic (i.e., human-induced) sources of EMF have been introduced into the marine environment from offshore sources, mainly associated with power cables, but also ships, communication cables, pipeline anti-corrosion systems, etc. (Gill et al. 2014).*

EMFs are invisible waves of electric and magnetic energy moving together. There are two types of electric current: Alternating Current (AC) and Direct Current (DC). Details on the differences between the two are provided in Table 1. Electric fields are typically measured in units of millivolts per meter (mV/m), and magnetic fields in units of milligauss (mG) or microtesla (µT). For reference, 1 µT equals 10 mG (Snyder et al. 2019).

EMFs are invisible waves of electric and magnetic energy moving together. The EMFs generated by OWFs are of relatively low frequency. OWF-generated EMFs are not like higher frequency, ionizing EMFs (e.g., X-rays, microwaves) which are known to alter chemical bonds and damage biological molecules.

**Table 1. Overview of alternating and direct electrical currents**

| Type | Description | Typical Frequency |
|---|---|---|
| Alternating Current (AC) | AC changes direction (i.e., oscillates) and is identified by the number of times the strength and direction of the field alternates each second, which is measures in units of hertz (Hz). | Most natural AC fields in the marine environment occur at frequencies of less than 10 Hz and are produced by marine organisms. |
| Direct Current (DC) | DC has a constant direction (i.e., no oscillations). | DC fields have a frequency of 0 Hz. |

An overview of the electromagnetic spectrum is provided in Table 2. The primary sources of natural EMFs in the marine environment are listed in Table 3. Industrial and commercial interests have also introduced anthropogenic (i.e., artificial) sources of EMF into the marine environment. Offshore artificial EMF sources are mainly associated with power cables, but ships, communication cables, pipeline anti-corrosion systems, etc. contribute as well. Contributions from land-based EMF sources (e.g., bridges) is limited to nearshore and intertidal areas (Gill et al. 2014).

Naturally occurring EMFs are present everywhere in the oceans. Undersea cables used for power transfer are known sources of artificial EMF, but ships, telecommunication cables, pipeline corrosion systems, etc. also generate artificial EMFs.

**Table 2. Electromagentic spectrum**

| Energy Level[a] | Frequency[b] | Examples |
|---|---|---|
| Non-Ionizing | Very Low to Low Frequency<br>0 Hz (static) - 3 kHz | Earth's magnetic field<br>Brain waves<br>Electric power systems<br>AC power cables |
| Non-Ionizing | Radio Frequency -<br>Radiowaves<br>3 kHz - 300 MHz | TV and radio broadcasts<br>Laptop |
| Non-Ionizing | Radio Frequency -<br>Microwaves<br>300 MHz - 300 GHz | Cell phone<br>Microwaves<br>Radar<br>Wi-Fi |
| Non-Ionizing | Infra-red (IR)<br>300 GHz – 4.3x1014 | Thermal imaging<br>TV controllers<br>Security systems |
| Non-Ionizing | Visible<br>4.3x1014 – 7.5x1014 | Sunlight<br>Lightbulb<br>Photography |
| Non-Ionizing | Ultraviolet<br>7.5x1014 – 3x1017 | Radiant heater<br>Suntanning bed |
| Ionizing | X-Rays<br>3x1017 – 3x1019 | Medical X-rays<br>Airport security scanners |
| Ionizing | Radioactive<br>>3x1019 | Alpha, beta, gamma radiation<br>Nuclear reactor<br>Nuclear medicine |

Note:
[a] Ionizing energy acts by removing electrons from atoms and molecules of materials that include air, water, and living tissue. Non-ionizing radiation does not have enough energy to remove electrons from an atom.
[b] Frequency ranges are approximate.

**Table 3. Primary natural sources of EMFs in the marine environment**

| Natural EMF Source | Description |
|---|---|
| Earth's Geomagnetic Field | A DC magnetic field that originates from the flow of liquid metal in the earth's core and from local anomalies in the earth's crust. The intensity of this field varies with latitude, approximately 30 μT at the equator and 60 to 70 μT at the poles. |
| Induced Electric Fields | As ocean currents and organisms move through the earth's static geomagnetic field they produce a weak static electric field, the intensity of which depends on the velocity and direction of movement but generally does not exceed 0.075 mV/m. |
| Bioelectric Fields | All marine organisms produce AC and DC bioelectric fields due to their heart beats, gill movements, nerve impulses, uneven distribution of electrical charge along the body, etc. Values of up to 500 mV/m can be found at the organism's surface but quickly drop to much lower levels within inches of the source. Some marine organisms use bioelectric fields to locate members of the same species (i.e., conspecifics) and/or food (i.e., prey). |

Source: Klimley et al. 2021, Normandeau et al. 2011, NYSERDA 2021, Snyder et al. 2019.

# 4 Offshore Wind Cables and EMF Emissions

*Summary: EMF emissions from a cable are composed of an electric field (E-field) and a magnetic field (B-field) (Copping et al. 2021). Cable sheathing, unless damaged, retains the E-field but not the B-field, thus the B-field is emitted into the surrounding environment. An induced E-field (iE-field), is also produced from animal or water (e.g., eddy currents) movement through the B-field. The greater the electrical current, the greater the EMF emissions (Copping et al. 2021, Gill and Bartlett 2010, Hutchison et al. 2020a).*

Any anthropogenic activity that uses electrical cables in the marine environment is a source of EMF emissions (Gill and Desender 2020). Currently high-voltage AC (HVAC) cables (60 Hz) are typically used in OWFs for the connection between turbines (i.e., inter-array cables) and to the OSS. An HVAC or high-voltage DC (HVDC) export cable is then used to transport power to shore. An overview of the different cable types and sizes is provided in Table 4. EMF emissions from the inter-array and export cables will depend on a variety of factors including power supply type (HVAC or HVDC); cable design, including cable protection (e.g., sheath); and current.

EMF emissions from OWF cables depend on various factors such as power supply type (AC or DC), cable design/protection, and current.

**Table 4. OWF cable overview**

| Cable Type[a] | Typical Outer Diameter | Typical Voltage | Typical Core |
|---|---|---|---|
| Inter-Array (AC) | 110-200 mm | 33 - 72.5 kV | Aluminum (static), Copper (dynamic) |
| Export (AC) | 250-320 mm | 220 - 290 kV, up to 420 kV | Copper or Aluminum |
| Export (DC) | 150 mm | 320 - 600 kV | Copper or Aluminum |

Source: NYSERDA 2021, Middleton and Barnhart 2023, Offshore Wind Scotland 2024.
Note:
[a] Characteristics will change as larger projects are planned and technology advances.

A cable's EMF emissions are directly proportional to the amount of current being carried by the cable. Therefore, the design of the OWF will affect EMF emissions as described in Table 5 (Snyder et al. 2019).

**Table 5. OWF design influences on the amount of electrical current generated and subsequent EMF emissions**

| Design Consideration | Description of the Influence on EMF Emissions[a] |
|---|---|
| Generating Capacity of WTGs | As WTGs generate more power (i.e., increased megawatts) there is a proportional increase in cable current, increasing EMF emissions. |
| Number of WTGs Connected to a Cable | As the number of WTGs connected to the inter-array cable increases so does the cable current, increasing EMF emissions. |
| Number of Export Cables | The use of multiple export cables will reduce the current level needed per cable, decreasing EMF emissions per cable. |
| Voltage | Cables with a higher voltage design capacity require less current to deliver the same amount of power, thus higher voltages result in lower EMF emissions. |

Source: Snyder et al., 2019.
Note:
[a] EMF emissions are directly proportional to the amount of current being carried by the cable.

The EMF emissions generated from a cable are made up of two components: an E-field and a B-field (Copping et al. 2021). The E-field depends on the voltage. The B-field depends on the flow of current through the cable and increases with increasing current (Dhanak et al. 2016a). Modern cable sheathing, unless damaged, retains the E-field but not the B-field, thus the B-field is emitted into the surrounding environment (i.e., detectable outside of the cable). An induced E-field (iE-field) is also generated by the cable, produced from animal or water (e.g., eddy currents) movement through the B-field. An iE-field is also generated by the rotational nature of an AC B-field (Copping et al. 2021, Gill and Bartlett 2010, Hutchison et al. 2020a). A graphic of the B-field and iE-fields emitted from a cable is provided in Figure 4.

"Current" is the rate at which an electric charge flows past a point in a circuit. In other words, current is the rate of flow of electric charge.

"Voltage" is the potential difference in charge between two points and is what drives an electric current between two points.

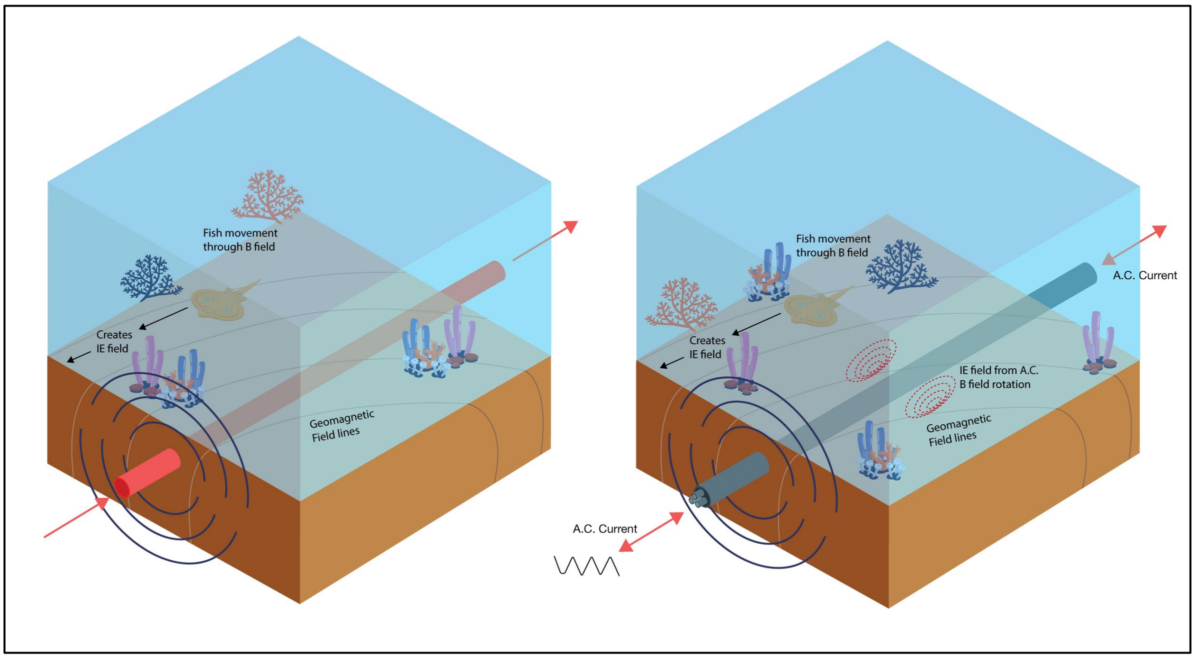


**Figure 4. Electromagnetic Fields Generated from an Energized Cable (Gill and Desender, 2020).**

As larger OWFs are planned, it is assumed that export cable corridors will contain multiple, parallel cables to bring the offshore-generated power to the onshore grid (NYSERDA 2001). When cables are in close proximity to each other, determining EMF levels becomes more complex due to the different orientations and geometries of the emissions. The expectation would be that some emissions cancel each other out while others will be additive (Gill et al. 2014, Hasselman et al. 2023). Possible mitigation measures to reduce EMF emissions are discussed in Section 7.

EMF emissions generated from a cable are made up of two components: an electric field (E-field) and a magnetic field (B-field). Modern cable sheathing, unless damaged, retains the E-field but not the B-field.

An induced E-field, referred to as an "iE-field", is also generated by animal or water (e.g., eddy currents) movement through a B-field.

> The primary underwater EMF sources from an OWF are the inter-array cables and export (transmission) cable. EMF emissions are directly proportional to the amount of current being carried by the cable.

Hutchison et al. (2018) found that AC currents can be generated by HVDC cables. As such, HVAC cables are less complex, since HVAC cables only emit an AC field, whereas HVDC cables generate both AC and DC fields[1]. In addition, unlike the B-field from an HVAC cable, the B-field from an HVDC cable can influence the intensity of the local (i.e., natural) geomagnetic field, as well as its inclination (see Figure 5). Thus, the placement of cables (i.e., side-by-side) as well as the geographic alignment of cables (i.e., north-south or east-west, etc.) should be accounted for when considering the potential effects of HVDC cables (Normandeau et al. 2011, Snyder et al. 2019).

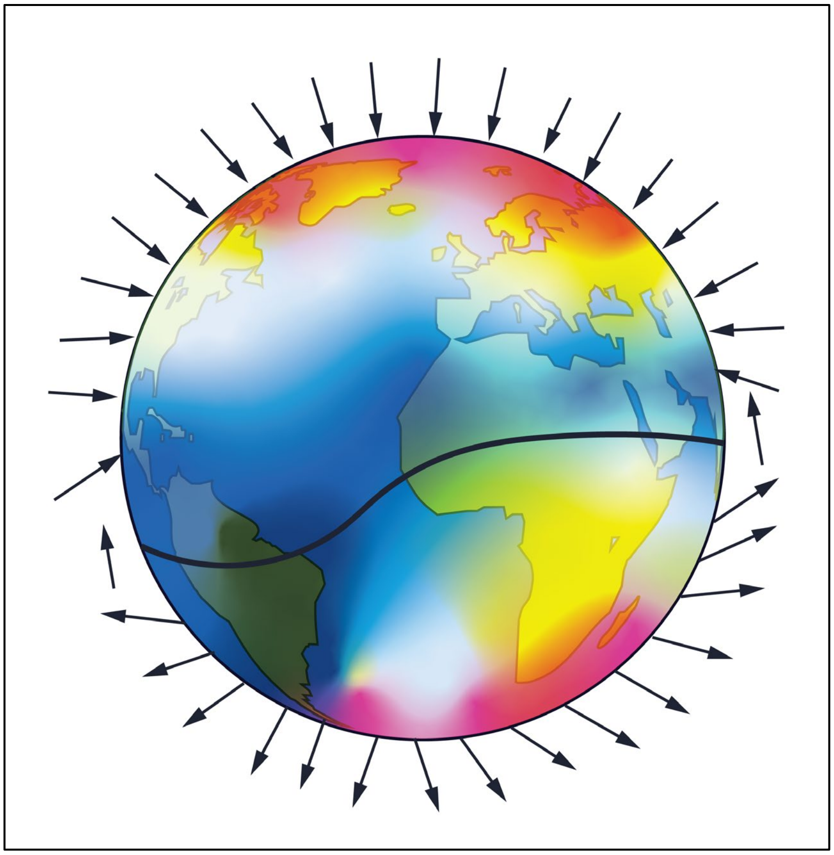

**Figure 5. Earth's geomagnetic field inclination and intensity**

[1] The AC to DC and then back to AC conversions that occur at the ends of an OWF's HVDC export cable produce side harmonics that are superimposed on the DC current. Hence, the cable is a source of both AC and DC currents (Hutchison et al., 2021b).

# 5 EMF Detection and Response

*Summary: EMF levels are strongest around an energized cable and decrease approximately as an inverse square of the distance from the cable. Elevated EMF levels from OWF cables are consistently estimated to return to background levels within 100 m or less (typically 1 to 10s of m) (BOEM 2020, BOEM 2021, Gill and Desender 2020, SEER 2022, Snyder et al. 2019). For an organism to sense EMF emissions, they must possess a sensory system capable of detecting a magnetic field (i.e., magneto-sensitive), electric field (i.e., electro-sensitive), or both. Elasmobranchs (e.g., sharks, skates, and rays) appear to be the most sensitive to EMF and are both magneto- and electro-sensitive (Gill et al. 2014, Snyder et al. 2019). Relevant, available literature suggests that potential impacts from cable EMF emissions which could, if present, result in a reduction in an individual's fitness (i.e., ability to reproduce) and possible survival include altered migration/orientation, altered behavioral patterns (e.g., avoidance/attraction, predator/prey detection, conspecific communication), altered community structure/composition (e.g., species interactions such as prey availability, predator presence, competition), and physiological effects (Gill and Desender 2020, Klimley et al. 2021, Hutchison et al. 2020b, Normandeau et al. 2011, Taormina et al. 2018).*

EMF levels are strongest around an energized cable and decrease approximately as an inverse square of the distance from the cable. Elevated EMF levels from OWF cables are consistently estimated to return to background levels within 100 m or less (typically 1 to 10s of m) (BOEM 2020, BOEM 2021, Gill and Desender 2020, SEER 2022, Snyder et al. 2019). Thus, marine organisms can either encounter OWF EMF emissions by: (1) being in close proximity to an inter-array or export cable on the seafloor (e.g., benthic species or those that forage near the seafloor); or (2) floating or swimming near cables in the water column (i.e., cables running from the surface to the seafloor or connecting floating WTGs) (Copping et al. 2021). WTGs and power equipment on OSS platforms are too far above the water's surface to result in noticeable EMF sources of exposure to marine species within the water column (Snyder et al. 2019).

> An individual organism will only be affected by EMF if: (1) they are close to the cable since elevated levels do not extend far from an energized cable (<100m); (2) they possess a sensory system capable of detecting EMF; and (3) the emitted EMF levels are within the threshold of the system's sensitivity.

In the event that a marine organism is close enough to the cable to be exposed to EMF emissions, the individual will only sense an elevated EMF level if they possess a sensory system capable of detecting it and it is within the threshold of that system's sensitivity to EMF emissions (Snyder et al. 2019). Animal movement and distribution as well as life stage also influence the probability of EMF exposure (Gill and Desender 2020). Based on the relevant, available literature, species that live on or in the seafloor, travel near the seafloor, or forage on or near the seafloor will have greater exposure to EMF emissions (Normandeau et al. 2011). However, with the introduction of dynamic inter-array cables for floating OWFs, exposure to pelagic species within the water column will need to be considered as that technology becomes deployed (see Figure 6; Hutchison et al. 2020b). Further, the potential for cumulative impacts due to either an individual's repeated exposure to the same cable or exposure to multiple cables (e.g., migrants) should be considered (Normandeau et al. 2011).

> Power transmission does influence if an organism will encounter a cables' EMF. For example, an individual passing over a buried cable several meters above the seafloor while the cable operates at a high current level may encounter a stronger field than an animal passing over a cable while swimming close to the seafloor when the current level is low.

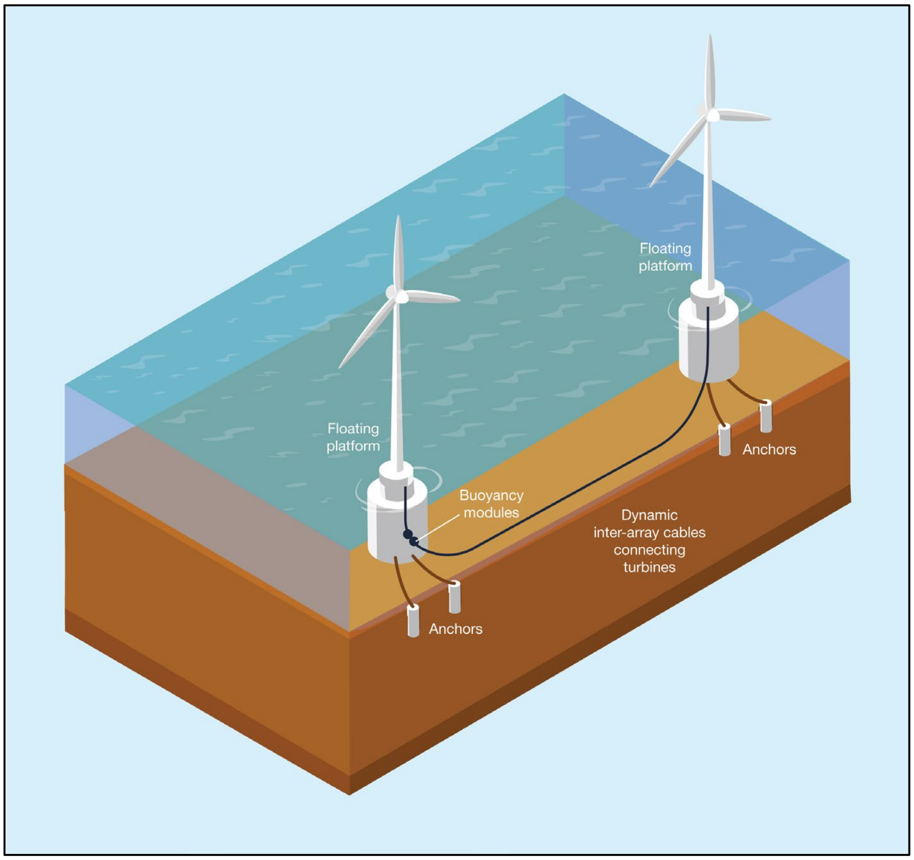


**Figure 6. Floating OWF dynamic inter-array cable between two turbines.**

Electro-sensitive species have the ability to perceive naturally occurring electric fields. An animal's ability to detect and respond to the earth's natural magnetic field is called magneto-sensitivity. Many species use the earth's magnetic field as guidance for navigating, including during migration.

If an organism can sense EMF emissions from a cable, its response will depend on the following: the duration of exposure; the intensity and frequency of the encountered EMF emissions; and the species-specific threshold levels at which a specific response will occur. Further, responses to EMF emissions will be dependent upon if the species possesses either magneto-sensitivity (i.e., B-field sensitivity) capabilities, electro-sensitivity (i.e., iE-field sensitivity) capabilities, or both (Gill and Desender 2020). Due to differences in the EMF emissions generated by AC and DC cables, an organism's response will not necessarily be the same to both types of cable (Claisse et al. 2015). DC cables can disrupt the earth's natural geomagnetic field, potentially leading an individual to misinterpret where they are at. Whereas an AC cable can cause disorientation by masking (i.e., unable to effectively identify biologically important signals) the natural geomagnetic field (Putnam 2022). For example, misinterpreting where an organism is might lead to their orienting in an atypical direction (e.g., orienting to the north versus south) while disorientation via masking might lead to a random orientation. However, the resulting effects could be the same and would be limited to the area of the cable's influence.

> Typical AC cables for OWFs operate at 60 kHz. This frequency is outside of what is considered the general range of marine species detection.

Arguments have been made that the fields detected by marine organisms are within a very limited frequency range, which includes the static magnetic field of the earth (frequency of ~0 Hz); the near 0-Hz iE-fields produced by ocean currents and organism movement within the earth's static magnetic field; and the E-fields produced by biological processes of bony fish and invertebrates with frequencies from 0 Hz to approximately 10 Hz (Bedore and Kajiura 2013, Snyder et al. 2019). This places the 60 Hz AC frequency that is typical of OWFs outside of the general range of marine species detection (Hutchison et al. 2020b, Snyder et al. 2019).

Marine animals thought to have magneto-sensitivity and electro-sensitivity capabilities are listed in Table 6. Although there have been suggestions that pinnipeds (seals) and sirenians (manatees) are capable of geomagnetic navigation, it is currently thought that their migrations are based on olfactory or mechanosensory cues (Gill et al. 2014). Similarly, although information on the potential magneto- or electro-sensitivity of horseshoe crabs (*Limulus polyphemus*) was not identified, they appear to use multiple sensory cues for mating migrations, such as visual, chemical, and/or physical (e.g., currents, temperature) cues (Barlow et al. 1986, Cheng and Chabot 2016, Saunders et al. 2010, Smith et al. 2010). The ability to use more than one sensory system provides a back-up for processing location information and would lessen the potential impact of any interference (i.e., environmental noise) created by artificial EMF.

**Table 6. Marine species thought to have the capability to sense EMFs**

| Magneto-Sensitivity Capabilities | Electro-Sensitivity Capabilities |
|---|---|
| Cetaceans (whales, dolphins and porpoises)<br>Sea turtles<br>Some teleost fishes (flatfish, salmonids, and eels)<br>Elasmobranch fishes (sharks, skates, and rays)<br>Crustaceans (lobsters, crabs, prawns, and shrimps)<br>Mollusks (snails, bivalves, and cephalopods) | Elasmobranch fishes[a]<br>Holocephalans (chimaeras)[a]<br>Elephantfish<br>Catfish<br>Electric eel<br>Sturgeon[a]<br>Salmon[b]<br>Tuna[b]<br>Plaice[b]<br>Cod[b] |

Source: Gill et al. 2014, SEER 2022, Snyder et al. 2019.
Notes:
[a] Have specialized electroreceptive organs called Ampullae of Lorenzini.
[b] Do not possess specialized electroreceptors and are thought to be able to detect induced voltage gradients associated with water movement through magnetic fields, such as tidal movements.

Three mechanisms have been theorized for animal detection of magnetic fields including: (1) mechanical, with a biogenic magnetite based magnetoreceptor; (2) a chemical-based mechanism (cryptochromes) associated with light sensitivity; and (3) electromagnetic induction in accessory structures (Hutchison 2018, Putman 2022). However, these remain theories with the exact mechanism(s) still unknown (Putman 2022).

Elasmobranchs (e.g., sharks, skates, and rays), holocephalans (e.g., chimaeras), and sturgeon have specialized electroreceptive organs called Ampullae of Lorenzini. These organs allow individuals to sense electric signals from prey (e.g., heartbeat) at close range (<1.5 ft).

Elasmobranchs (e.g., sharks, skates, and rays), holocephalans (e.g., chimaeras), and sturgeon have electro-sensitivity capabilities due to their specialized electroreceptive organs called Ampullae of Lorenzini (see Figure 7). These organs are jelly-filled tubes that open on the surface of the skin where there are hundreds of them. Each tube ends in a bulb, the ampulla. The jelly in the tube is highly conductive, which allows the electrical potential at the pore opening to be transferred to the ampulla at the base of the tube. Voltage differences across the membrane lining the ampulla cause attached nerves to be activated, sending signals to the brain. These organs are so sensitive that they can even detect a beating heart. But their detection distance to the electric potential of their prey (i.e., bioelectric field) is generally less than 1.5 ft (Bedore and Kajiura 2013, Snyder et al. 2019). Bioelectric fields are complex and multipolar in nature (Bedore and Kajiura 2013) and their short detection distance presumably assists with zeroing in on the prey.

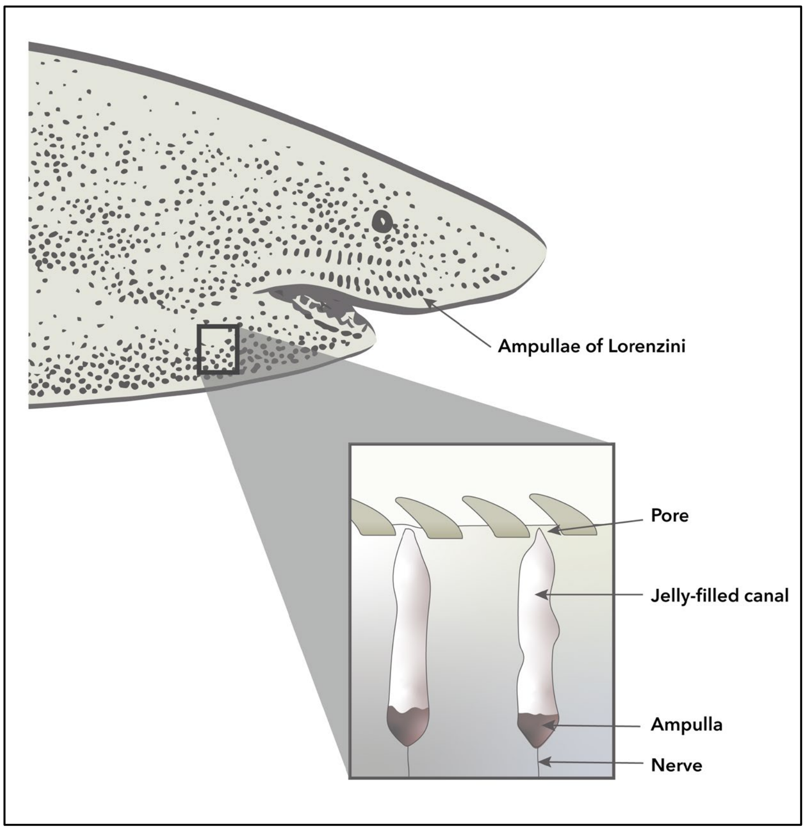


**Figure 7. Ampullae of Lorenzini.**

Table 7 includes descriptions of potential effects due to exposure to cable EMF emissions which could, if present, result in a reduction in an individual’s fitness (i.e., ability to reproduce) and possible survival. A graphic is provided in Figure 8 of the key elements which need to be considered when assessing the overall impacts of EMF exposure.

**Table 7. Potential effects to marine organisms from exposure to EFM emissions**

| Potential Effect | Possible Implications to an Individual's Fitness and/or Survival |
|---|---|
| Acute Injury or Death | Exposure to EMFs causing direct injury and/or death. |
| Altered Migration and/or Orientation | If a species' navigational capabilities are compromised (e.g., problems with magnetic cues or magnetoreceptor function), the cable essentially acts as a barrier to movement, or the cable serves as an attractant. Migratory species may be slowed or deviate from their natural routes, which could lead to their not reaching essential feeding, spawning, or nursery grounds and also result in additional energy expenditure. |
| Altered Behavioral Patterns | Species that use EMFs for foraging may spend time hunting the artificial EMFs instead of prey, thus reducing daily food/energy intake. Species that use EMFs to detect predators or members of the same species (conspecifics) could experience masking effects (i.e., unable to effectively identify biologically important signals). Other behavioral changes in response to EMFs (e.g., increased swimming speed, increased burrowing) could also result in changes in energy expenditure. |
| Altered Communities | Changes in community structure/composition could also occur which could affect species interactions (e.g., prey availability, predator presence, species competition). |
| Physiological | Developmental, genetic, and other physiological or biochemical changes. |

Source: Gill and Desender, 2020, Klimley et al. 2021, Hutchison et al. 2020b, Normandeau et al. 2011, and Taormina et al. 2018.

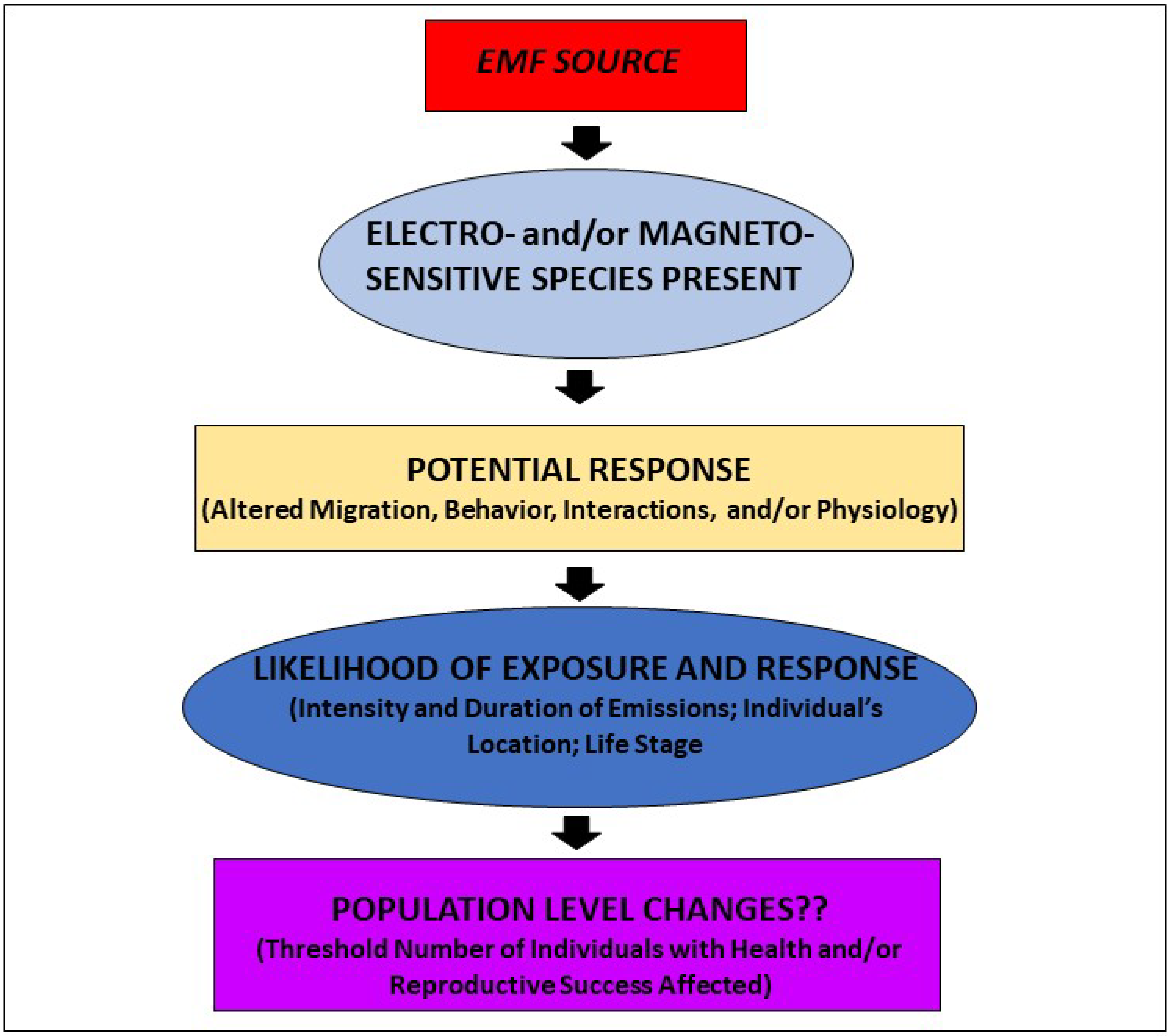


**Figure 8. Key elements for assessing potential environmental impacts due to EMF exposure.**

Adapted from Gill and Desender 2020.

Based on a literature review on the effects of exposure of marine species to artificial EMF emissions, an overview of some of the key findings is provided in the subsections below by taxa and summarized in Table 8. Caution should be taken in extrapolating from documented responses to EMFs in a laboratory setting (Love et al. 2017a). An advantage of laboratory studies is that the type (AC/DC) and intensity of the field can be controlled (Hutchison et al. 2020b). However, detection of a laboratory-based response to an electrical or magnetic stimulus does not necessarily mean there will be an actual change in behavior in situ (i.e., in a species' actual habitat). Species responses to stimuli and behavior in general are controlled by complex interactions of environment, hormones, and physiology (Gill and Bartlett 2010). Further, the level of stimulus that has been applied in the laboratory is often times not realistic of actual field conditions (Emma 2016, Albert et al. 2020). Therefore, when exposure values were provided, a screening level (i.e., threshold) of a maximum of 100 µT and/or 10 mV/m

> Detection of a laboratory-based response to an electrical or magnetic stimulus does not necessarily mean there will be an actual response when a species is in its natural habitat.

was selected for determining the laboratory studies to be included in the synthesis below. These values were selected as they appear to be overly conservative of the anticipated electrical and magnetic fields from an OWF cable based on the literature (see Table 9) and should account for cables potentially carrying higher currents (i.e., larger EMF levels generated) in the future.

When evaluating field studies, it is also cautioned that if not examining a comparison of energized versus non-energized cables, it can be difficult to differentiate the effects of a cable's EMF emissions versus the effects of the cable's structure (i.e., habitat alteration). It is also important to evaluate if other environmental factors exist which are more important than EMFs (Love et al. 2016).

**Table 8. Overview of the observed effects of EMF exposure by taxa**

| Effect | Taxa[a] | Potential Evidence of an Effect Upon EMF Exposure? | Section |
|---|---|---|---|
| Acute Injury and/or Death | Marine Vegetation<br>Invertebrates<br>Fish<br>Sea Turtles<br>Marine Mammals<br>Aerial Species (Birds, Bats, and Insects) | No supporting evidence for survivorship effects to any taxa. EMFs from OWFs are low frequency, unlike radiofrequencies (e.g., microwaves, X-rays) which are typically considered a potential health threat. | 6.1<br>6.1<br>6.2<br>6.3<br>6.4<br>6.5 |
| Altered Migration / Orientation | Marine Vegetation | Not applicable. | N/A |
| Altered Migration / Orientation | Invertebrates | Species-specific but some evidence that invertebrate species will change their orientation in response to manipulation of the magnetic field in a laboratory setting. No evidence of altered migration patterns or that in-situ cables represent a barrier to movement. | 6.1 |
| Altered Migration / Orientation | Fish | Species-specific but some evidence that fish species will change their orientation in response to manipulation of the magnetic field in a laboratory setting. No evidence of altered migration patterns or that in-situ cables represent a barrier to movement. Some evidence that migration can be delayed due to the presence of in-situ cables but not to a level that appears ecologically significant. | 6.2 |
| Altered Migration / Orientation | Sea Turtles | There is evidence that hatchlings can become disorientated in response to manipulation of the magnetic field on nesting beaches. The duration of disorientation is currently unknown. Adults and juveniles can still successfully migrate following disruption of the magnetic field, magnetic cues are not essential for reaching the normal migration end point. | 6.3 |
| Altered Migration / Orientation | Marine Mammals | No evaluations identified. | 6.4 |
| Altered Migration / Orientation | Aerial Species (Birds, Bats, and Insects) | No evidence of altered migration patterns or that sources of EMF act as a barrier to movement. Other cues (e.g., sun, stars) can be used to navigate and/or calibrate the geomagnetic compass if there is disorientation caused by EMF emissions. | 6.5 |
| Altered Behavioral Patterns | Marine Vegetation | No evidence of attraction to or avoidance of the EMF generated by an in-situ cable. | N/A |

| **Effect** | **Taxa[a]** | **Potential Evidence of an Effect Upon EMF Exposure?** | **Section** |
|---|---|---|---|
| Altered Behavioral Patterns | Invertebrates | No consistent evidence of attraction to or avoidance of EMF generated by an in-situ cable. Species-specific but there is evidence that limited behavioral effects (e.g., increased burrowing) can occur upon EMF exposure. No evidence of changes in behavior that would result in population level effects. | 6.1 |
| Altered Behavioral Patterns | Fish | No consistent evidence of attraction to or avoidance of the EMF generated by an in-situ cable. Species-specific but there is evidence that limited behavioral effects can occur upon EMF exposure (e.g., increased/decreased swimming). No evidence of changes in behavior that would result in population level effects. However, there is some evidence that elasmobranchs could potentially waste time and energy trying to forage on artificial EMF, incorrectly assuming it is prey. | 6.2 |
| Altered Behavioral Patterns | Sea Turtles | No evaluations identified. | 6.3 |
| Altered Behavioral Patterns | Marine Mammals | No evaluations identified. | 6.4 |
| Altered Behavioral Patterns | Aerial Species (Birds, Bats, and Insects) | No convincing evidence of attraction to or avoidance of artificial EMF emissions. Other habitat features (e.g., roosting places on powerlines) appear to be more important. | 6.5 |
| Changes in community structure/composition (e.g., prey availability, predator presence, species competition) | Marine Vegetation | No clear evidence of altered communities as a result of energized in-situ cables. | 6.1 |
| Changes in community structure/composition | Invertebrates | No consistent evidence of altered communities in the presence of in-situ cables or OWFs. Other habitat features appear to be more important. | 6.1 |
| Changes in community structure/composition | Fish | No consistent evidence of altered communities in the presence of in-situ cables or OWFs. Other habitat features appear to be more important. | 6.2 |
| Changes in community structure/composition | Sea Turtles | No evaluations identified. | 6.3 |
| Changes in community structure/composition | Marine Mammals | No evaluations identified. | 6.4 |
| Changes in community structure/composition | Aerial Species (Birds, Bats, and Insects) | No consistent evidence of altered communities in the presence of in-situ cables or OWFs. Other habitat features appear to be more important. | 6.5 |
| Physiological | Marine Vegetation | No evaluations identified. | 6.1 |
| Physiological | Invertebrates | Species-specific but there is evidence of limited physiological effects, including developmental effects. When observed in laboratory settings, effects have predominantly been at EMF emission levels that are not realistic of an OWF cable. | 6.1 |
| Physiological | Fish | Species-specific but there is evidence of limited physiological effects. When observed in laboratory settings, effects have predominantly been at EMF emission levels that are not realistic of an OWF cable. | 6.2 |

| Effect | Taxa[a] | Potential Evidence of an Effect Upon EMF Exposure? | Section |
|---|---|---|---|
| Physiological | Sea Turtles | No evaluations identified. | 6.3 |
| Physiological | Marine Mammals | No evaluations identified. | 6.4 |
| Physiological | Aerial Species (Birds, Bats, and Insects) | Species-specific but there is evidence of long-term exposure causing physiological effects in birds nesting by powerlines. Drosophila also have been documented to reduce egg production when exposed to EMF emissions. | 6.5 |

Note:
[a] Above water EMFs will be produced by the OWF's WTGs and OSS. For this reason, a discussion of birds, bats, and insects has been included.

**Table 9. Estimates of maximum EMF levels from OWF export cables**

| Source | B-Field (μT) | E-Field (mV/m) |
|---|---|---|
| Vineyard Wind Estimates[a,b] (BOEM 2021; Page 3-88, 3-111) | <0.05 | Not Provided |
| South Fork Wind Farm[a] (BOEM 2020; Table 3.4.2-6, buried) | 3.0 | 2.1 (Buried) |
| Revolution Wind Farm[a] (BOEM 2022; Table 3.6-10, buried) | 21 (Buried) | 6.3 (Buried) |
| Sea2Shore Cable, Block Island Wind Farm[b] (Gill and Desender 2020; Table 5-1) | 0.3 | 0.025 |
| Estimated Typical OWF[c] (Snyder et al. 2019; Table 3) | 16.5 | 3.7 |
| Existing and Proposed OWF AC Cables[a] (SEER 2022, adapted from Normandeau et al. 2011) | <18 | Not Provided |
| Literature Review in Hermans et al. 2024[b] | 6.54 (AC), 72.0a (DC) | Not Provided |

Note:
[a] Based on a modeling estimates.
[b] Based on field measurements.
[c] Source of estimate (i.e., modeling or field measurements) not specified.

## 5.1 Invertebrates and Marine Vegetation

*Summary: Laboratory study results indicate that some invertebrate species respond to magnetic and/or electric stimulation. However, research supports that EMF exposure has either no effect or results in only minor behavioral effects on invertebrates (Gill and Desender 2020). To date, there is no compelling evidence that the EMF levels that are produced by energized OWF cables will either attract or repel invertebrate species nor act as a barrier to movement (e.g., Love et al. 2016/2017a,b, Hutchison et al. 2018/2020a). Based on the limited area of elevated EMF emissions around a cable, even if there are individual behavioral effects, it is expected that not enough individuals would be affected to result in population level effects.*

> Observed effects of EMF emissions on invertebrates are species-specific.

> There is no indication that EMFs act as a barrier to invertebrate movement or significantly affect community structure.

Field and laboratory studies have been conducted to evaluate invertebrate responses to EMF exposure. As indicated by the studies and reviews included in Table 10, research on invertebrates supports that there is either no effect or only minor behavioral effects (e.g., increased burrowing, exploratory movements) due to EMF exposure, with some finding of effects ambiguous (i.e., open to interpretation) (Gill and Desender 2020). Further, the behavioral effects, if observed, generally do not appear to result in attraction or avoidance (see Table 10). There is also no evidence that EMF exposure can result in invertebrate mortality or present a barrier to normal movement. Based on the limited extent of elevated EMF emissions around a cable (100 m or less, typically 1 to 10s of m: BOEM 2020, BOEM 2021, Gill and Desender 2020, SEER 2022, Snyder et al. 2019), even if the behavioral effects were to continue to the point that they reduced an individual's fitness, population level effects would not be expected as not enough individuals would be affected.

**Table 10. Highlighted studies evaluating potential effects from EMF exposure to invertebrate species and marine vegetation**

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Albert et al. (2020) | Literature Review | Review paper providing a summary of results from 18 different studies which included looking at the response of crustaceans, molluscs, polychaetes, and echinoderms to EMF exposure. The analysis evaluated if there were any indications of a survival, physiological, or behavioral response. A copy of the summary table from this review is provided in Appendix A.<br><br>A key conclusion from the review is that studies that evaluated survival found no effects. Further, reviewed field studies did not show any significant ecological effects of EMFs associated with in-situ power cables. Any observed responses, both in the laboratory and field, were species-specific due to tolerance thresholds and include physiological/developmental and/or behavioral responses. Most of the reviewed laboratory studies were conducted with relatively high magnetic field values that are not expected of typical conditions in the vicinity of an OWF cable. Of the five studies reviewed (laboratory and field) that were within the threshold set for this analysis (i.e., a maximum of 100 uT and/or 10 mV/m), two indicated behavioral responses (Hutchinson et al., 2018; Tomanova and Vacha, 2017); one indicated a developmental response (Zimmerman et al., 1990); and two indicated no response (Love et al., 2015; Love et al., 2017). These studies have been included in this table. | Crustaceans<br>Mollusks<br>Polychaetes<br>Echinoderms | Effects are species-specific.<br><br>EMF exposure was not found to result in invertebrate mortality. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Albert et al. (2023) | Laboratory Study | This laboratory study included an evaluation of the behavior when the velvet crab (*Necora puber*) following short-term exposure (30 minutes) to alternating and direct magnetic fields of increasing intensity (72–304 μT). The study evaluated potential attraction and repulsion behavioral responses and exploratory, feeding, and sheltering behaviors. | Velvet crab | No attraction to or avoidance of EMF.<br><br>No alteration in movements relative to exploratory, feeding, and sheltering behaviors. |
| Jakubowska et al. (2019) | Laboratory Study | This laboratory study included an evaluation of EMF exposure levels of 1 mT, which is above the threshold screening level. However, since it is assumed that benthic organisms, especially infauna, have the highest probability of encountering underwater cables (both laid on the seafloor and buried in the sediment) and thus are particularly vulnerable to the generated EMFs, the study is included here.<br>An experiment was conducted on an infaunal polychaete (*Hediste diversicolor*) to look at EMF exposure and attraction/avoidance behavior, burrowing behavior, and physiology (i.e., food consumption and assimilation, respiration, and excretion of ammonia). The polychaete did not exhibit attraction/avoidance behavior and no significant effects were found on the rate of food or oxygen consumption. Exposure to EMF emissions did result in an increase in burrowing activity and decreased ammonia excretion. However, a positive energy balance was maintained (i.e., energy intake is greater than energy expenditure). | Polychaete | No attraction to or avoidance of EMF.<br><br>Limited burrowing behavioral effects upon EMF exposure.<br><br>Limited physiological effects upon EMF exposure. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Stankeviciute et al. (2019) | Laboratory Study | This laboratory study included an evaluation of EMF exposure levels of 1 mT, which is above the threshold screening level. However, since it is assumed that benthic organisms, especially infauna, have the highest probability of encountering underwater cables (both laid on the seafloor and buried in the sediment) and thus are particularly vulnerable to the generated EMFs, the study is included here.<br>The common ragworm (*Hediste diversicolor*) and Baltic clam (*Limecola balthica*) were exposed to elevated EMF levels for 12 days. To evaluate genotoxicity and cytotoxicity responses, assays of nuclear abnormalities in the coelomocytes of the common ragworm and gills of the Baltic clam were performed. Genotoxicity effects were found for both species. Cytotoxicity effects were found for the Baltic clam but not the common ragworm. | Polychaete clam | Genotoxicity and cytotoxicity effects are species-specific. Note, the level of exposure was higher than anticipated conditions for an OWF, so extrapolation to an actual field setting is not clear. |
| Tomanova and Vacha (2017) | Laboratory Study | The goal of this study was to determine if an amphipod (*Gondogenia antartica*) is using the earth's magnetic field for orientation. They found that the amphipod did use the magnetic field for orientation. Further, they found that a relatively small (2nT) anthropogenic electromagnetic change is enough to be disruptive, resulting in a random orientation. | Amphipod | Amphipods are magneto-sensitive. |
| Zimmerman et al. (1990) | Laboratory Study | The goal of this study was to evaluate any developmental effects to sea urchins (*Strongylocentrotus purpuratus*) from exposure to an artificial magnetic field (0.1 mT). Embryos which were exposed to the artificial magnetic field had a 1-hour delay in development from the gastrula to mid-gastrula state. There were no observed developmental abnormalities. | Sea urchin | Delayed development (no developmental abnormalities). |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Andrulewicz et al. (2003) | Field Study | The primary objective of this study was to evaluate impacts to invertebrate community structure from cable installation. Benthic samples were collected along an HVDC power transmission cable (SwePol Link) and also in reference areas in the Baltic Sea. Four study areas were established for benthic sampling based on different sediment types and depths. Box core samples were collected along the cable route and in reference areas both pre- and post- cable installation. Reference areas were located from 0.1 to 1 nautical mile from the cable. Although high variability in the data was observed, the authors indicate that there were no obvious changes in infaunal species composition, abundance, or biomass one-year post-construction. Elevated EMF levels did not extend beyond 20m from the cable. | Infaunal community structure | No avoidance of or attraction to an in-situ cable.<br><br>Elevated EMF levels extend up to 20m from cable. |
| De Backer et al. (2020) | Field Study | The objective of the study was to assess the invertebrate community in a Before-After-Control-Impact (BACI) design at two OWFs in the North Sea off of Belgium (C-Power and Belwind). Beam trawls were collected at both eight- and nine years post-construction, respectively. Epibenthos average density and biomass over the long-term were very similar in the impact and reference areas. However, in comparison to reference areas, there is an apparent reef effect happening with increased abundance of hard-bottom taxa inside of the OWFs. The species originally inhabiting the sandy bottom are still present and remain dominant in both OWFs. There is no indication of avoidance of the OFWs. | Benthic invertebrate community structure | No avoidance of an OWF.<br><br>Possible attraction (e.g., reef effect) of hard-bottom taxa to OWF. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Dunham et al. (2015) | Field Study | This field study's objective was to assess a dictyonine glass sponge (order Hexactinosa) reef community following installation of three 230 kV HVAC power transmission cables between British Columbia and Vancouver Island. Video and still imagery were collected along transects twice a year for four years following cable installation. Control transects were located 100m away and parallel to the cable. Sponges were found to recover to within 15 percent of baseline within 3.5 years. This was through both regrowth and recruitment, including growth on the cable. Megafaunal density and diversity, including squat lobster (*Munida quadrispina*) and spot prawn (*Pandalus platyceros*), had a non-significant trend to be slightly lower along the cable transects. | Glass sponge reef community | No significant avoidance of or attraction to an *in-situ* cable. |
| Lohmann et al. (1995) | Field Study | The objective of the study was to decipher if the migrating Caribbean spiny lobster (*Panulirus argus*) has an inclination magnetic compass (i.e., does not distinguish north versus south, rather the inclination angle) or polarity magnetic compass (i.e., distinguishes north versus south). Lobsters were subjected in the field to a reversal of the horizontal field and vertical field. Lobsters changed their orientation in response to a reversal of the horizontal field, indicative of a polarity magnetic compass. | Caribbean spiny lobster | Lobsters are a magneto-sensitive species. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Love et al. (2015) | Field Study | The objective of the study was to evaluate the orientation of yellow rock crabs (*Metacarcinus anthonyi*) and red rock crabs (*Cancer productus*) when caged in the vicinity of an unburied energized and unenergized power cable. The AC cables are associated with offshore oil and gas on the Pacific coast off California. Values of 46.2 μT to 80.0 μTb were recorded from the energized cable and have been previously noted to dissipate to background levels within approximately 1 meter. Each enclosure was placed so that one end was in contact with the cable. A panel was used to remove any visual cue of the cable. The crabs responded no differently in the enclosures along the unenergized versus energized cable. No behavioral effects were observed as the presence of an energized cable did not influence where the crabs were located within the enclosure. | Rock crabs | Avoidance of or attraction to an *in-situ* cable is not evident. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Love et al. (2016) | Field Study | The objective of the study was identifying any differences in the invertebrate community structure found in the vicinity of an energized AC power cable (EMF level around 100 μTb), an unenergized cable, and a reference area. The cables evaluated are associated with offshore oil and gas on the Pacific coast off California. Belt transects were made using a submersible along the cables and nearby seafloor. EMF was found to dissipate to background levels within approximately 1m of the cable at three of four locations. There was no statistical difference between the invertebrate assemblages along the energized and unenergized cables. The natural habitat community of invertebrates (reference) was significantly different from both the energized cable and unenergized cable communities. Several species were found to be more abundant around the cables (both energized and unenergized) than within the reference area due to the structure created by the presence of the cables.<br>There was a slight but statistically significant difference in species density for two of nine species when researchers compared the species' densities that comprised at least 1 percent of individuals observed. Sand star (*Luidia* spp.) abundance was greater near unenergized cables and black crinoids (Crinoidea) near energized cables; however, both species were present in each location. | Benthic invertebrate community structure | No attraction to or avoidance of EMF generated by an *in-situ* cable. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Love et al. (2017a) | Field Study | The objective of the study was identifying any differences in the invertebrate community structure found in the vicinity of an unburied pipeline, unburied energized AC power cable, and reference area. The reference area was 24m away from the cable. It had been previously noted that the EMF dissipates to background levels within approximately 1m of the cable. The cables used are associated with offshore oil and gas on the Pacific coast off California and had average EMF levels of 73 µT and 91.4 µTb. Divers made observations of invertebrates and macrophytes along continuous 30m long sections.<br>Biologically significant differences were not detected in the invertebrate community found in the vicinity of either the energized cable, the pipeline, or the reference area. There was no compelling evidence found that the EMF level produced by an energized cable was either attracting or repelling invertebrate species (i.e., disproportionate numbers). Any differences observed were contributed to the morphology differences of the habitats. In addition, seagrass was observed growing within the vicinity of the exposed energized cables and algae actually on the cables. | Benthic invertebrate community structure | No attraction to or avoidance of EMF generated by an *in-situ* cable.<br><br>Seagrass and algae will grow in the vicinity of an energized cable. |
| Love et al. (2017b) | Field Study | A field experiment was conducted in Puget Sound and Southern California with the objective of determining if the presence of an energized (35 kV and 69 kV) power cable would affect the likelihood of catching Dungeness crab (*Metacarcinus magister*) or red rock crab (*Cancer productus*). Crabs were given a choice of a baited trap that required crossing an energized cable versus a trap that did not require crossing the cable. Researchers found no evidence suggesting that crabs would not cross an energized cable to get to a baited trap. | Dungeness crab<br>Rock crab | An *in-situ* cable is not a barrier to movement. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Hutchison et al. (2018) & (2020a) | Field Study | The objective of the study was to determine how the American lobster (*Homarus americanus*) reacts to an energized cable. The field study was performed using enclosures placed over an energized HVDC cable (Cross Sound Cable, treatment enclosure) and within a reference area. Lobsters within the treatment enclosure were observed, on average, to be closer to the seabed than when in the control enclosure and exhibited a greater proportion of large turns, which was interpreted to be an exploratory response. There was no evidence of preference for either zones of high (>52.6 μT) or low (<49.7 μT) EMF within the treatment enclosure. The cable did not present a barrier to lobster movement, and it was concluded that individuals would have most likely moved freely past the cable had they not been confined. | American lobster | An *in-situ* cable is not a barrier to movement.<br><br>Minor behavioral changes in response to being enclosed over an in-situ cable. |
| Sherwood et al. (2016) | Field Study | The primary objective of this study was to evaluate impacts from HVDC transmission cable installation and operations after two years. The field study was conducted off of the coast of southern Australia. Diver surveys of the epibenthic community were made at six different sites. Diver transects were taken along the cable and at 10 and 50 m away. Within a year of installation in the non-reef areas, qualitatively there were no visible differences in the general nature of the assemblages close to the cable compared to the more distance reference transects, with abundance naturally relatively low. Similarly, the armored portion of the cable (cast iron half shell) that is located within a reef area was colonized within 3.5 years of installation by a species composition comparable to the surrounding reef. At 5 m above the buried cable, magnetic field strengths were less than 1 percent of the natural background and were barely detectable at 20 m above the cable. | Benthic invertebrate community structure | No attraction to or avoidance of EMF generated by an *in-situ* cable. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Taormina et al. (2020) | Field Study | The objective of the study was to assess the epibenthic community along an AC (7.5kV) cable (Fromveur tidal energy test site) in France that was installed in 2015. The field study was conducted in 2019 and included diver monitored quadrats immediately adjacent to the cable and 5 m away (reference). The epibenthic community was found to be similar between the cable and reference area, but there were some statically significant differences in species abundances. Three red algae species were more abundant in the area by the cable. Twelve species were more abundant in the reference area including brown algae and red algae species and an echinoderm, cnidarian, polychaete, ascidian, and bryozoan. The authors attributed the differences in abundance to greater topography in the reference area. Kelp dominated both the cable and control areas. | Benthic invertebrate community structure | No clear evidence of attraction to or avoidance of EMF generated by an *in-situ* cable.<br><br>Kelp will grow in the vicinity of an energized cable. |
| Thatcher et al. (2023) | Field Study | The objective of the study was to assess European lobster (*Homarus gammarus*) movement within an OWF. Acoustic telemetry was used to monitor lobster position (n=25) within the Bwynt y Mor wind farm (160 turbines, 80 square km) in the United Kingdom. Lobsters tended to remain in one general area and within 35 m of the scour protection. However, movement out of the area and between turbine locations was observed. This was interpreted to be likely a reef effect. No restriction of movement or avoidance of the area was noted. | European lobster | No avoidance of an OWF.<br><br>Possible attraction (e.g., reef effect). |
| Wilber et al. (2022) | Field Study | The objective of the study was to assess the invertebrate community in a BACI design at the Block Island Wind Farm off of the U.S. Atlantic coast. Seven years of trawl surveys were conducted within the OWF construction footprint and two reference areas (>1 km away) that have similar habitat characteristics. Two trawls were conducted monthly in each area. No evidence was found that invertebrates, including squid, were avoiding the Block Island OWF area. | Benthic invertebrate community structure | No avoidance of EMF generated by an *in-situ* OWF. |

| Reference[a] | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Williams et al. (2023) | Field Study | This study supplements and builds upon the findings from Love et al. (2017b) on red rock crab behavior. The primary objective was to verify the response of rock crab in the presence of energized cables associated with MRE installations, while also controlling for environmental conditions. Local magnetic fields near an energized cable were quantified and mapped. Magnetic field strength near the seafloor was variable along the length of the energized cable, peaking at about 1.2 μT. Magnetic field strength measured near zero (background level) in all locations ≥ 0.9 m from the cable. It was found that the energized cable did not alter crab behavior with no preference for crossing/not crossing the cable. | Rock crab | No attraction to or avoidance of EMF generated by an *in-situ* cable. |

Notes:
[a] Within each study type, references have been provided in alphabetic order.
[b] These values are higher than expected from an OWF (see Table 9).

## 5.2 Fish

*Summary: Fishes are by far the most studied group relative to the potential effects of EMF emissions. To date, documented effects, if any, include sub-lethal behavioral responses of individuals in close proximity to an EMF source (Claisse et al. 2015). EMFs do not appear to be a barrier to fish movement nor significantly affect fish migration (e.g., Copping et al. 2021, Gill et al. 2009, Wyman et al. 2018). Further, multiple surveys have been conducted to determine if fish populations have declined following OWF installation. The surveys have overwhelmingly shown that EMFs from offshore wind energy projects and associated cables have no effect on fish populations (Snyder et al. 2019). Overall, the potential for any impacts is considered highest for elasmobranch fishes (i.e., sharks, rays, skates) that depend on electric cues to detect benthic prey (Fisher and Slater 2010, Hutchison 2018). If individuals do not "learn" that the cable's EMF emissions are not prey, stay in proximity to the cable, and consistently exhibit increased exploratory/foraging behavior, it could result in reduced fitness. However, the range over which these species can detect an electric field, and thus be attracted to an energized cable, is limited (Snyder et al. 2019). Population level effects are not expected.*

Observed effects of EMF emissions on fish are species-specific and life stage specific.

As indicated by the studies and reviews included in Table 11, effects of EMF emissions on fish species, if any, are minimal and temporary. When there are documented effects, they include sub-lethal behavioral responses of individuals in close proximity to an EMF source (Claisse et al. 2015). Overall, the potential for any impacts is considered highest for fish species that depend on electric cues to detect benthic prey (Fisher and Slater 2010, Hutchison 2018), specifically those which possess ampullae of Lorenzini (Snyder et al. 2019). If individuals do not "learn" that the cable's EMF emissions are not prey, stay in close proximity to the cable, and consistently exhibit increased exploratory/foraging behavior, it could result in reduced fitness. For example, Kimber et al. (2011) found that small-spotted catsharks (*Scyliorhinus canicular*) were either unable to discern or showed no preference for artificial versus natural E-fields of the same strength, suggesting the species' potential to waste energy hunting when in proximity to a cable. However, the range over which these species can detect an iE-field, and thus be attracted to a cable is limited (Snyder et al. 2019). Further, even for elasmobranchs (e.g., skates), which may be particularly sensitive to artificial EMFs, studies have shown no barrier effects due to EMF exposure (Copping et al. 2021, Hemery et al. 2021, Snyder et al. 2019). It is expected that individuals would move freely through an area of elevated EMF emissions and only be temporarily affected.

There is no indication that EMFs act as a barrier to fish movement or significantly affect community structure.

For the limited number of studies that have documented physiological (e.g., suppressed melatonin levels) and developmental effects, the implications of these results remain uncertain (Claisse et al. 2015). Scaling up from these laboratory studies to potential population-level effects has not been done. However, offshore wind energy projects, along with associated cables, have operated in Europe over a decade. During this time, multiple surveys have been conducted to determine if fish populations have declined following OWF installation. The surveys have overwhelmingly shown that EMFs from offshore wind energy projects and associated cables have no effect on fish populations (Snyder et al. 2019). This includes the results of a long-term, demersal gillnet study conducted at the 80 WTG Horns Rev 1 OWF in the North Sea. After a period of eight years following construction, it was found that there was a positive effect of the OWF on fish abundance close to the WTGs and no signs of any negative effects to key species or functional fish groups (Stenberg et al. 2015). It also includes eight and nine years of trawl surveys conducted in a BACI design at two OWFs in the North Sea off of Belgium (54 WTG C-Power OWF and 55 WTG Belwind OWF). Fish species richness and density over the long-term were found to be very similar in the impact and reference areas and the species originally inhabiting the sandy bottom are still present and remain dominant in both OWFs (De Backer et al. 2020). Similarly, seven years of trawl surveys have also been conducted in a BACI design at the five WTG Block Island Wind Farm along the U.S. Atlantic coast. The results of those surveys also do not indicate avoidance of the OWF by fishes (Wilber et al. 2022).

EMFs do not appear to be a barrier to fish movement nor significantly affect fish migration (e.g., Copping et al. 2021, Gill et al. 2009, Wyman et al. 2018). Laboratory studies of fish behavior suggest sensitivity to magnetic fields is common in many species of fish (Snyder et al. 2019). For example, salmon may make use of a "magnetic map" to navigate back to their natal areas possibly explaining their long-distance migration capabilities (Claisse et al. 2015). However, studies on migratory fish also suggest changes in the earth's magnetic field are combined with other environmental cues (e.g., water temperature, light, salinity) to guide migration routes (Snyder et al. 2019). For example, salmonids upon reaching freshwater use olfactory cues to locate their upstream spawning grounds (Bett and Hinch 2015). In addition, assessing impacts to a species' magnetoreception is challenging given that no magnetoreceptor has been definitively found in animals and thus a mechanistic understanding of how EMFs would disrupt that process is not yet known (Klimley et al. 2021).

As indicated above, potential developmental effects from EMF exposure are not as well studied as effects on fish behavior or community structure. Formicki et al. (2021) reviewed studies on the effects of exposure to EMF emissions during development (freshwater fishes [e.g., trout]). Any effects, if seen, were found to be species-specific and also specific to the intensity of the field and exact timing of the exposure during embryogenesis and larval development. Observed effects included changes in heart rate, respiration, pigmentation, movement, etc. However, significant effects on embryo and larvae survival were not observed. Further, the levels of EMF exposure were consistently above the threshold screening level (i.e., a maximum of 100 uT or 10 mV/m) used in this synthesis and exposure duration within a laboratory setting (e.g., constant exposure) is not necessarily representative of what might occur in the marine environment (e.g., transient exposure when passing over a cable).

Fisher and Slater (2010), Emma (2016), Snyder et al. (2019), and Klimley et al. (2021) provide a literature review of EMF exposure studies that include fish species. A copy of the summary tables from those reviews is provided in Appendices B through E, respectively. Any laboratory studies in these summaries which are below the threshold screening level of exposure set in this synthesis (i.e., a maximum of 100 uT or 10 mV/m) have been included in Table 11.

**Table 11. Highlighted studies evaluating potential effects from EMF exposure to fish species**

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Copping et al. (2021) | Literature Review | This paper provides a literature review of field studies and summarized that fish species responses to EMF vary. When in proximity to a cable, responses have included increased swimming speeds (thornback rays [Raja clavate]); decreased swimming speeds (eels, sharks [Selachimorpha], salmonids [Oncorhynchus spp.], sturgeon [Acipenser spp.]); attraction to the cable (catshark [*Scyliorhinus canicula*]); and changes in behavior (thornback rays, little skates [*Leucoraja erinacea*]). Changes in fish species abundance or occurrence have not been observed nor has a barrier to migration (Chinook salmon [*O. tshawytscha*], green sturgeon [*A. medirostris*]). | Multiple species | Effects are species-specific.<br><br>No movement barrier to migration.<br><br>Elasmobranchs appear to be the most affected. |
| Cresci et al. (2022) | Laboratory Study | Laboratory study evaluating lesser sandeel (*Ammodytes marinus*) larvae after B-field exposure (50 µT). The study involved simulating a scenario of larvae swimming or drifting near a HVDC cable of an OWF. Study observations did not indicate any spatial preference, which would infer attraction to or avoidance of a cable. In addition, there were no changes in swimming speed observed. Of note, the lesser sandeel is not part of the Anguilliformes order (e.g., eels and morays) and therefore their magneto-sensitivity may still be questionable. | Lesser sandeel | No behavioral effects, including no attraction or avoidance. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Cresci et al. (2023) | Laboratory Study | Laboratory study evaluating Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae after B-field exposure (22 - 156 μT). The study involved simulating a scenario of larvae swimming or drifting near a HVDC cable of an OWF. Study observations did not indicate any spatial preference, which would infer attraction to or avoidance of a cable. There were observed changes in swimming speed. Average swimming speed was reduced for non-exploratory larvae; however, there was no change for exploratory larvae. It is not clear if the exposure level was >100 μT for those with an increased swimming speed. | Atlantic cod<br>Haddock | No behavioral effects indicating attraction or avoidance.<br><br>Reduction in swimming speed depending on the activity being conducted (i.e., behavior- and individual-dependent). |
| Kalmijn (1966) | Laboratory Study | A laboratory study involving the conditioning of thornback ray, small-spotted catshark, and tope shark (*Galeorhinus galeus*) individuals to react to a low-electric stimuli (0.04 μVcm) making them think it was food. The heart rate slowed down with introduction of an electric current, even as low as 0.01 μVcm for the thornback ray, which was the measured response. The experiments demonstrate that sharks and rays are extremely sensitive to electric fields and use this sensitivity to locate food. | Thornback ray<br>Small-spotted catshark<br>Tope shark | Demonstrates that these species could potentially spend time and expend energy trying to forage on artificial EMF, assuming it is prey. |
| Kalmijn (1982) | Laboratory Study | This laboratory study evaluated the ability of the round stingray (*Urolophus halleri*) to orient relative to electric fields. The voltage applied (< 5nV/m) was very low, similar to those produced by ocean currents. The results appear to support an electromagnetic compass sense. | Round stingray | Stingrays are electro-sensitive. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Marino and Becker (1977) | Laboratory Study | This is a cross-reference to McCleave et al. (1974). In this laboratory study, Atlantic salmon (*Salmo salar*) were exposed to an electric (7 µV/cm to 70 µV/cm) and magnetic field (50 µT) as part of a cardiac conditioning experiment. None of the twelve salmon tested for sensitivity to magnetic fields had significant cardiac decelerations. Significant cardiac deceleration due to electric field exposure was only found in a few salmon individuals and was dependent on the direction of exposure (i.e., perpendicular versus parallel). There was no observed change in activity levels due to exposure.<br><br>American eel (*Anguilla rostrata*) were also exposed to an electric (7 µV/cm to 70 µV/cm) and magnetic field (50 µT) as part of a cardiac conditioning experiment. Only two of the sixteen eels tested for sensitivity to magnetic fields had significant cardiac decelerations. Significant cardiac deceleration due to electric field exposure was only found in a few eel individuals and was dependent on the direction of exposure (i.e., perpendicular versus parallel). There was no observed change in activity levels due to exposure. | Atlantic salmon<br>American eel | Magneto-and electro-sensitivity is species- and individual-specific. |
| McIntyre III (2017) | Laboratory Study | In this laboratory study, sub-adult Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) were exposed to varying EMF levels (5µT, 100 µT, and 1000 µT) to evaluate behavioral responses to both AC and DC currents. The fish were approximately 3 years old with a fork length of 40 centimeters. Exposure times were 1-hour. Different field orientations were used to simulate fish in the wild passing directly over, or parallel to, a cable. The time an individual spent in the generated field area, the number of it passed through the field area, and its swimming speed were used to assess any response to EMF. No evidence was found of a behavior response. | Atlantic sturgeon | No behavioral effects, including no attraction, avoidance or change in swimming speed. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Nishi et al. (2004) | Laboratory Study | In this laboratory study, Japanese eels (*A. japonica*) were exposed to EMF levels (12,663 nT to 19,2473 nT) to determine their orientation following conditioning with a flashing light. In response, a slower heartbeat was recorded. The result was indicative that Japanese eels are magneto-sensitive. The authors further discussed that the opposite has been found with other eel species. The American eel and European eel (*A. Anguilla*) have been found to not be magneto-sensitive. | Japanese eel | Magneto-sensitivity is species-specific. |
| Putman et al. (2014) | Laboratory Study | In this laboratory study, researchers reared steelhead trout (*Oncorhynchus mykis*s) in a spatially-distorted magnetic field (42.68 to 54.56 μT). Results found that they fail to properly orientate like they would naturally. They were randomly oriented instead. | Steelhead trout | Steelhead trout are magneto-sensitive. |
| Walker et. al (1984) | Laboratory Study | The objective of the laboratory study was to determine if yellowfin tuna (*Thunnus albacares*) can discriminate an altered magnetic field. Through conditioning with food, it was determined that yellowfin tuna can discriminate an altered magnetic field. | Yellowfin tuna | Yellowfin tuna are magneto-sensitive. |
| Bergstrom et al. (2013) | Field Study | The objective of this study was to assess any differences in the fish community within an OWF compared to two reference areas. The field study was conducted at the Lillgrund Wind Farm off of Sweden. The wind farm consists of 48 WTGs of 2.3 MW each, a grid of 36 kV AC inter-array cables, and an OSS transformation station which is connected to land by a DC cable. The reference areas are located 8 and 13 km away. Fyke nets, which target benthic and demersal fishes, were used to sample four years pre-construction and three years post-construction. The results indicate no major differences in benthic fish diversity or abundance when comparing the OWF to the reference areas. Avoidance of the WTGs (measured by lower densities close to the foundations) was not observed for any of the species. They concluded that any potential negative effects related to the presence of EMF emissions were not overriding fish attraction to the introduced structures (i.e., “reef effect”). | Fish community structure | No evidence of attraction to or avoidance of EMF generated by an *in-situ* OWF.<br><br>Any potential negative effects related to the presence of EMF emissions were not overriding fish attraction to the introduced structures. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| De Backer et al. (2020) | Field Study | A BACI design field study of two OWFs in the North Sea off of Belgium, C-Power and Belwind. Beam trawls have been collected for eight- and nine-years following construction, respectively. Fish species richness and density over the long-term are very similar in the impact and reference areas. The species originally inhabiting the sandy bottom are still present and remain dominant in both OWFs. There is no indication of avoidance of the OFWs. | Fish community structure | No avoidance of an OWF. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Dhanak et al. (2016b) | Field Study | This object of the study was to evaluate the reef fish community near underwater cable arrays. The study location was the U.S. Navy's South Florida Ocean Measurement Facility off Fort Lauderdale, which is a cabled in-water range that consists of several active submarine power cables and junction boxes. Observations of a cable area were made by divers and bottom-mounted video stations were also established. Three different areas were evaluated, inner-reef (5m depth), middle-reef (10m depth), and outer reef (15m). Differences in the fish community were assessed for both when a cable was on (energized) versus when it was off (unenergized). Overall, species richness was not significantly different between energized and unenergized cable states. For the outer reef site, species richness was significantly lower during energized conditions; however, few species were recorded during only one state (energized versus unenergized) when assessing all three areas. Only two elasmobranch species (the yellow stingray [(*Urobatis jamaicensis*)] and southern stingray [(*Dasyatis americanus*]) were encountered,. The yellow stingray was observed exclusively during unenergized conditions, although only five individuals were recorded. The southern stingray was observed once during energized conditions and once during unenergized conditions. Although fish abundance was higher during unenergized conditions, it was not statistically significantly higher. Behavioral responses of fishes or other organisms were not observed when the power was switched on and off (transition periods). | Reef fish community structure | No clear evidence of attraction to or avoidance of EMF generated by an *in-situ* cable. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Dunham et al. (2015) | Field Study | This field study's objective was to assess a glass sponge community following installation of three 230kV HVAC power transmission cables between British Columbia and Vancouver Island. Video and still imagery were collected along transects twice a year for four years following cable installation. Control transects were located 100m away and parallel to the cable. Rockfish (Sebastes spp.) abundance did not differ between cable and control transects. The authors noted that the spotted ratfish (*Hydrolagus colliei*), an electro-sensitive species, was encountered along control and cable transects with equal frequency. | Glass sponge fish community structure | No avoidance of or attraction to an *in-situ* cable. |
| Dunlop et al. (2016) | Field Study | The field study's objective was to evaluate the fish community along the Wolfe Island wind power project's 295 kV HVAC export cable in Lake Ontario. The cable is buried under rubble and sediment in proximity to shore, but otherwise sits on top of the lakebed. Sampling was done at various distances from the cable in order to determine if any effects of the cable's presence could be detected. Acoustic sampling, gill netting, and electrofishing were performed. Fish density did not vary significantly as a function of distance from the cable. Species richness was also not affected by the presence of the cable. Any differences in the fish community were related to habitat features (i.e., depth or substrate) rather than cable presence. Of note, American eel (*Anguilla rostrata*), a magneto-sensitive species, were encountered in close proximity to the cable. | Fish community structure | No attraction to or avoidance of EMF generated by an *in-situ* OWF cable. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Gill et al. (2009) | Field Study | The objective of the study was to conduct a mesocosm experiment (i.e., a hybrid of laboratory and field approaches) over an in-situ cable. In this field study individuals of the thornback ray (benthic species), spurdog (*Squalus acanthias*, free-swimming species), and small-spotted catshark/lesser-spotted dogfish (benthic species) were placed within large enclosures over an experimental power cable. Their behavior was then evaluating when the cable was energized versus unenergized. The cable was not observed to create a movement barrier. The small-spotted catshark was more likely to be found within the zone of EMF emissions and moved less when the cable was energized, which is consistent with their behavior of area-restricted searching associated with feeding. There were some indications of the thornback ray and spurdog responding when the cable was energized (e.g., increased swimming); however, the responses were both species- and individual- specific. | Thornback ray Spurdog, Small-spotted catshark / lesser dogfish | Species-specific response to in-situ energized cable.<br><br>An *in-situ* cable is not a movement barrier.<br><br>Limited behavioral effects (e.g., stimulated feeding behavior).<br><br>Demonstrates that the catshark could potentially spend time and expend energy foraging in response to the artificial EMF, assuming it is prey. |
| Hutchison et al. (2018) & (2020a) | Field Study | The objective of the study was to conduct a mesocosm experiment over an in-situ cable in Long Island Sound. This field study placed individuals of the little skate within large enclosures over a 300 kV HVDC transmission power cable (Cross Sound Cable) and within a reference area. The little skate responded with an increase in exploratory and/or foraging behavior within the treatment enclosure. However, the cable was not a barrier to skate movement. The change in exploratory/foraging behavior resulted in the skates traveling a significantly longer distance (up to several kilometers more) and exhibiting a greater number of large turns, which could represent an increased energetic expense. However, the skates generally moved at a slower speed and were closer to the seafloor, so it was concluded that the skates were likely shifting from a swimming to punting (a push-glide movement using modified pelvic fins) mode of movement, which is less energetically costly. | Little skate | An *in-situ* cable is not a movement barrier.<br><br>Limited behavioral effects (e.g., increase in exploration/ foraging).<br><br>Demonstrates that the little skate could potentially spend time and expend energy foraging by responding to the artificial EMF, assuming it is prey. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Hutchison et al. (2021b) | Field Study | The objective of the field study was to assess if an in-situ cable presents a barrier to normal movements of the American eel. Specifically, the field study evaluated the movements of tagged eels near a 300 kV HVDC transmission cable (Cross Sound Cable) in New Haven Harbor. The study also evaluated the likelihood of eels encountering elevated EMF levels based on their position within the water column. Eels made full use of the harbor area. Although individual based, there was a response observed of increased swimming speeds when encountering the cable's EMF. It was determined that EMF exposure for the eels ranged up to 86.9 nT for the DC and 147.7 for the AC generated by the HVDC cable. | American eel | An *in-situ* cable is not a barrier to movement.<br><br>Limited behavioral effects (e.g., increased swimming speed). |
| Kalmijn (1982) | Field Study | The objective of the study was to evaluate the role electric senses play in predation. The study involved feeding trials in the field. Prey fields were simulated by applying direct current to an electrode, either to the right or left of an odor source indicative of prey. The right or left electrode which was not energized was considered the control. The author then observed if there was a feeding response (biting of the energized electrode) at very low voltages. The specifics include:<br>Small smooth dogfish (*Mustelus canis*), dose <0.021 µV/cm, response was to attack from 18 centimeters (cm) or more away from the source.<br>Large smooth dogfish (90 to 120 cm), dose 5 nV/m, response was to attack from 38 cm or more away from source.<br><br>Blue shark (*Prionance glauca*), dose 2.5 nV/m, response was repeated circling and attack the source. | Smooth dogfish<br>Blue shark | Demonstrates that these species could potentially spend time and expend energy foraging by responding to the artificial EMF, assuming it is prey. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Klimley et al. (2017), Kavet et al. (2016) | Field Study | The objective of the study was to assess if an in-situ cable presents a barrier to normal movements of the Chinook salmon or green sturgeon. The study evaluated migration across an HVDC transmission power cable (Trans Bay Cable) that runs parallel and perpendicular to their migration routes in San Francisco Bay. Tagged fish movements were evaluated. The study found that bridges in the Bay actually produce a larger (in both intensity and area) magnetic anomaly than the cable. There was no evidence found that either the bridges or cable are a barrier to Chinook salmon or green sturgeon migration. | Chinook salmon | An *in-situ* cable is not a movement barrier. |
| Love et al. (2016) | Field Study | The objective of the study was to identify any differences in the fish community found in the vicinity of an energized AC power cable, unenergized cable, and reference area. The cables evaluated are associated with offshore oil and gas on the Pacific coast off California. Belt transects were made using a submersible along the cables and nearby seafloor. EMF was found to dissipate to background levels within approximately 1-m of the cable. There was no statistical difference between the fish assemblages along the energized and unenergized cables. The natural habitat community statistically differed from both the energized cable and unenergized cable communities. Total fish densities were significantly higher around the cables than within the reference habitat.<br><br>Species (or in several cases species-groups) that formed at least 1-percent of the fishes observed were found to have no differences in densities between areas with energized and unenergized cables.<br><br>The authors noted that they did not observe high densities of electro-sensitive fishes around energized cables or alternatively around the unenergized ones, suggesting that elasmobranchs, which are common in the area, are neither attracted to, nor repelled by the EMF emissions. | Fish community structure | No attraction to or avoidance of EMF generated by an *in-situ* cable. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Love et al. (2017a) | Field Study | The objective of the study was to identify any differences in the fish community found in the vicinity of an unburied pipeline, unburied energized AC power cable, and reference area. The reference area was 24m away from the cable. It had been previously noted that the EMF dissipates to background levels within approximately 1m of the cable. The cables evaluated are associated with offshore oil and gas on the Pacific coast off California. Divers made observations of fishes along continuous 30-meter-long sections. Biologically significant differences were not detected in the fish community found within the vicinity of the energized cable, pipeline, and reference area. There was no compelling evidence found that the EMF level produced by an energized cable was either attracting or repelling fish species (i.e., disproportionate numbers). The differences observed were contributed to the morphology differences of the habitats. In addition, one elasmobranch individual (*Urobatis helleri*) was found near an energized cable during the course of the study. The authors concluded that it would appear that the EMF generated by an energized cable is either unimportant to these organisms or that other environmental factors take precedence. | Fish community structure | No attraction to or avoidance of EMF generated by an *in-situ* cable. |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Vattenfall and Skov-og (2006) | Field Study | The objective of the study was to determine if the Nysted wind farm export cable in the Baltic Sea off of Denmark is a barrier to fish movement. Fish capture was done with two types of pound nets, bi-directional and quadri-directional. One bi-directional and two quadridirectional pound nets were placed on each side of the cable. This made it possible to detect the migration direction of the fish and estimate the number of fish crossing the cable, by looking at asymmetries in the catches across the cable route. Some evidence was found to suggest that migration of Baltic herring (*Clupea harengus*), common eel, Atlantic cod (*Gadus morhua*), and flounder (*Platichthys flesus*) across the cable may be impaired. However, migration was not blocked. Flounder was the only species found to primarily cross the cable when the strength of the electromagnetic field was estimated to be low. | Fish community migration | Species-specific response.<br><br>An OWF *in-situ* cable is not a barrier to movement. |
| Westerberg & Begout-Anras (2000) | Field Study | The objective of this study was to assess any effects of an in-situ cable on European eel migration off of Sweden. The cable evaluated was an HVDC power transmission cable (Baltic Cable). The cable crosses a part of the Baltic through which essentially all migrating eels have to pass. Sixty percent of tagged eels crossed the cable within a few hours of release. | European eel | An *in-situ* cable is not a barrier to movement. |
| Westerberg & Langenfelt (2008) | Field Study | The objective of this study was to assess any effects of an in-situ cable on European eel migration as they passed through a strait off of Sweden. The cable evaluated was a 130kV HVAC transmission cable that is perpendicular to the straight. The pathway of tagged eels was evaluated during their normal migration through the strait. Eels decreased their swimming speed in the middle section of the strait where the cable was located. Some individuals appeared to stop for several hours to up to a day in the section with the cable. The average delay was 40 minutes. There was a non-significant trend of decreased swimming speed with increased electrical current. The cable did not act as a barrier and the biological effect of the delay is considered insignificant. | European eel | An *in-situ* cable is not a barrier to movement.<br><br>Limited behavioral effect (e.g., decreased swimming speed delaying migration). |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Wilber et al. (2022) | Field Study | The objective of the study was to assess the fish community in a BACI design at the Block Island Wind Farm off of the US Atlantic coast. Seven years of trawl surveys were conducted within the wind farm construction footprint and two reference areas that have similar habitat characteristics. Two trawls were conducted monthly in each area. No evidence was found that fish species, including the little skate and winter skate (*L. ocellata*), are avoiding the Block Island OWF area. | Fish community structure | No attraction to or avoidance of EMF generated by an *in-situ* OWF cable. |
| Wyman et al. (2018) | Field Study | The objective of the study was to assess if an in-situ cable presents a barrier to normal movements of the Chinook salmon. The study evaluated migration across a 200 kV HVDC power transmission cable (Trans Bay Cable) that runs parallel and perpendicular to the migration routes of salmon in San Francisco Bay. Data were available to assess migration pre-cable installation compared to post-installation. Based on fish tracking data, there was no significant difference between the proportion of fish that successfully exited the Bay before compared to after the cable was activated, thus the cable does not pose a barrier to migration. Although cable energization may have affected some of the migration behaviors that occurred within the Bay (i.e., misdirection to a bridge), there did not appear to be any significant impact on overall survival. | Chinook salmon | An *in-situ* cable is not a barrier to movement.<br><br>Limited behavioral effects (e.g., movements that potentially delayed migration). |

| Reference | Study Type | Details | Taxa | Implications Relative to Artificial EMF Exposure |
|---|---|---|---|---|
| Wynman et al. (2023) | Field Study | The objective of the study was to assess if an in-situ cable presents a barrier to normal movements of the green sturgeon. The study evaluated migration across a 200 kV HVDC power transmission cable (Trans Bay Cable) that runs parallel and perpendicular to the migration route of the green sturgeon from Pittsburg to San Francisco, California. Acoustic arrays were located across the cable in and around San Pablo and San Francisco Bay as well as the across the passageway to the Pacific Ocean. Detections of 141 acoustically tagged adult sturgeon were analyzed for trends when the cable was energized versus when it was not. Migration success was not affected by the energized cable. There were some subtle indications that outbound transit times were longer and migration path alterations occurred when the cable was energized. However, the changes do not appear to be significant. | Green sturgeon | An *in-situ* cable is not a barrier to movement.<br><br>Limited behavioral effects (e.g., possible delayed outbound migration on the scale of hours). |

## 5.3 Sea Turtle

*Summary: The most vulnerable stage for sea turtle EMF exposure appears to be during the egg and hatchling stage (Fuxjager et al. 2014, Normandeau et al. 2011). EMF exposure has been linked to disorientation of hatchlings once they reach the water. However, it can reasonably be assumed that any cable that crosses a nesting beach would be horizontally directionally drilled (HDD) putting the cable at significant depths below any nests and reducing the potential for exposure of nests and hatchlings. Magneto-sensitivity experiments on migrating juvenile and adult sea turtles have found that magnetic cues are not essential for reaching normal migration end points (Pappi et al. 2000, Luschi et al. 2007). Juvenile and adult sea turtles rely on multiple senses during their migration, thus are not as sensitive to impacts from EMF exposure (Normandeau et al. 2011, Pappi et al. 2000).*

EMF exposure to nests and hatchlings can result in disorientation and is the primary concern for sea turtles.

Sea turtles are known to possess a geomagnetic sensitivity that is used for orientation, navigation, and migration but not electro-sensitivity (Irwin and Lohmann 2005, Normandeau et al. 2011). Their geomagnetic sense is important for their primary orientation when navigating to the general vicinity of a destination (e.g., nesting beaches, feeding grounds). Fine-tuning of the approach is thought to then be accomplished with the use of olfactory and visual cues. Displacement and sensory manipulation experiments have proven that changes in magnetic field intensity and inclination angle can cause turtles to deviate from their original direction (Normandeau et al. 2011). However, experiments on migrating green sea turtles (*Chelonia mydas*) have found that magnetic cues are not essential for reaching the normal migration end point (Pappi et al. 2000, Luschi et al. 2007). Although a disruption in the magnetic field can result in longer migration times while the individual readjusts (Luschi et al. 2007).

Based on the relevant, available literature, a primary concern relative to EMF emissions and sea turtles is the placement of cables within the vicinity of nesting areas (Normandeau et al. 2011). In experiments on loggerhead sea turtle (*Caretta caretta*) nests, experimental groups of nests were exposed to an altered magnetic environment. Hatchlings that developed within the altered magnetic environment were found to have a random orientation once in the water, not a defined orientation like the hatchlings that developed within the non-altered environment (Fuxjager et al. 2014, Salmon 2019). The altered magnetic environment did not appear to impact the hatchling's ability to reach the water (i.e., ocean finding ability) which is based on the visual cue of light (Fuxjager et al. 2014). Irwin and Lohmann (2003) identified a similar disorientation when magnets were attached to loggerhead hatchlings in a laboratory setting. Based on a comparable field study performed on leatherback turtle hatchlings (*Dermochelys coriacea*), they also appear to have a random orientation when a magnet was attached to them in the field (Kloc et al. 1998). Such random movements once within the water could have implications on the percent of young surviving. However, it is unknown how long the disorientation lasts (Fuxjager et al. 2014).

It can reasonably be assumed that any cable that crosses a sea turtle nesting beach would be HDD, eliminating the need to disturb the nearshore and beach environment. Use of an HDD puts the cable at significant depths below the beach surface, reducing the potential for exposure of nests, hatchlings, and nesting females. EMF levels decrease approximately as an inverse square of the distance from the cable regardless of the cable being buried or not. Cable depth when crossing the beach via HDD will typically be on the magnitude of 10s of m below the surface.

## 5.4 Marine Mammals

*Summary: Cetaceans do appear to be magneto-sensitive and use the earth's magnetic field for migration. However, EMF from an OWF cable is not expected to significantly alter any individual's migration route due to their high mobility and the limited duration of exposure, considering that a cable would not affect a large portion of the water column (Normandeau et al. 2011).*

Marine mammals are generally not thought to be electro-sensitive. There is also no indication of magneto-sensitivity within the Carnivora (e.g., polar bears, sea otters, sea lions, fur seals, walrus, and earless seals) or Sirenia (e.g., manatees) orders (Normandeau et al. 2011). Among marine mammals, magneto-sensitivity has been primarily investigated in cetaceans (e.g., whales, dolphins, porpoises), which appear to use the earth's magnetic field for migration (Kirschvink et al. 1986, Normandeau et al. 2011). The likelihood of cetaceans being affected by EMF emissions from OWF-associated cables is thought to be low due to their high mobility and the limited duration of exposure (Normandeau et al. 2011). The relevant, available literature does suggest some concern that significant EMF levels could result in disorientation and stranding (Fisher and Slater 2010, Klimley et al. 2021); however, any generated emissions from an OWF cable are not likely to affect a large enough area to elicit a significant course alteration (Normandeau et al. 2011) and a recent evaluation of stranding data indicates that geomagnetic disruptions (i.e., solar storms) do not appear to be a principal driver for mass stranding events (Pulkkinen et al. 2020).

## 5.5 Aerial Species

*Summary: Birds, bats, and insects are magneto-sensitive and appear to use the earth's magnetic field while migrating. However, if disorientated due to an anomaly in the magnetic field, such as an artificial EMF, they appear to be able to use other cues (e.g., stars, sun) to compensate and/or recalibrate (Etheredge et al. 1999, Greif et al. 2015, Guerra et al. 2014, Holland et al. 2010, Kashetsky et al. 2021, LaRue et al. 2006, Lindecke et al. 2019). Therefore, short term exposure to elevated EMF levels while in passing should not present a barrier or disrupt normal migration. Any observed effects from long-term exposure to elevated EMF levels have been species-specific and the EMF emissions from OWFs are not high radio frequencies, which are typically considered a potential threat (see Cucurachi et al. 2013).*

WTGs produce EMFs in the vicinity of the nacelle (Kunz et al. 2007), which is the part of the WTG that consists of a generator, low- and high-speed shafts, gearbox, brake, and control electronics (see Figure 9). EMFs are emitted by the generator and switching components in the nacelle (Krug and Lewke 2009). EMFs will also be produced by the OWF's OSS. For this reason, a discussion of birds, bats, and insects has been included here.

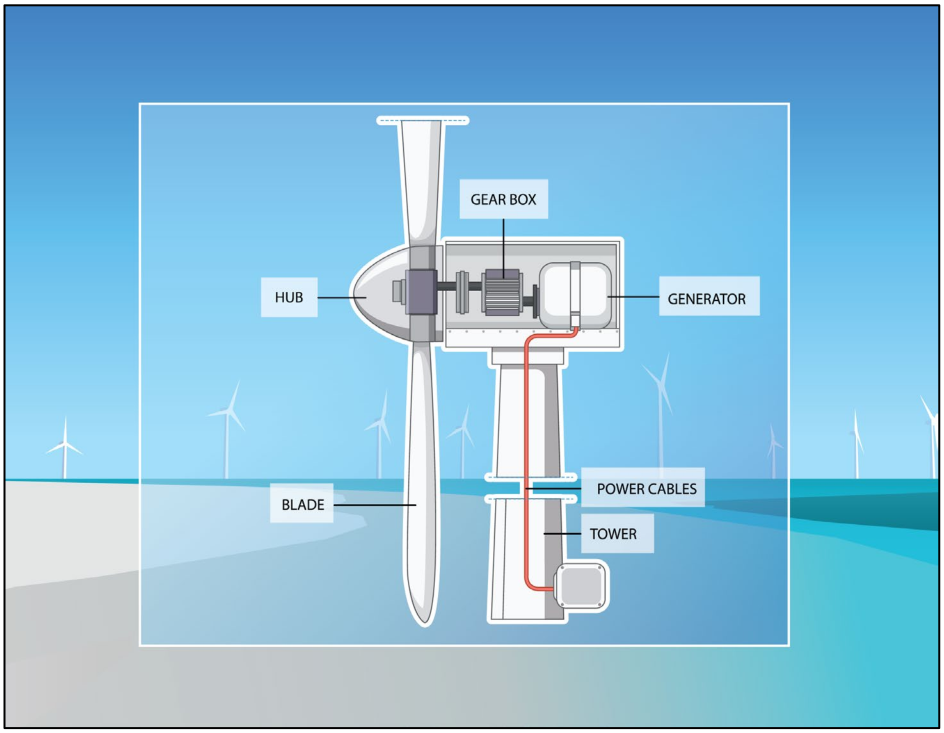


**Figure 9. Typical WTG nacelle.**

### 5.5.1 Birds

Birds typically use more than one type of compass (i.e., magnetic, sun, star) as well as other cues during migration.

There is evidence that birds can sense low-intensity electromagnetic fields (0.1 to 0.5 µT; 70 mV/m) (Larkin and Sutherland 1977, Wiltschko and Wiltschko 1996) and many bird species use the earth's magnetic field as a compass during migration (Gould and Gould 2012, Mouritsen 2015). If disorientated when encountering EMFs, individuals can adjust to the anomaly and successfully navigate as birds can use one compass mechanism to calibrate the other. For example, birds can use their star or sun compass to calibrate their magnetic compass (Gould and Gould 2012, Kashetsky et al. 2021). In addition, if one compass becomes unreliable (e.g., disorienting), birds appear to have the ability to switch to another compass system until normal conditions are restored as well as also rely on past learning and memory (Kashetsky et al. 2021). Therefore, with the capability of using multiple compass senses, any short-term exposure to elevated EMF levels and disorientation while in passing of a WTG or OSS should not present a barrier or disrupt normal migration.

There is no clear evidence that elevated EMF levels result in avoidance of an area. For example, it is common for birds to take advantage of the habitat that overhead powerlines provide. Hanowski et al. (1993) and (1996) conducted long-term bird counts along a low frequency antenna's overhead cable (55 to 566 mV/m; 0.21 to 1.02 µT) and in reference areas (0.3 to 2.3 mV/m; 0.0007 to 0.004 µT). Researchers did not find any consistent trends in bird community differences between the cable and reference areas. When observed, species-specific differences were more likely explained by habitat differences between the cable and reference areas (e.g., presence of edge habitat).

Long-term exposure to elevated EMF levels, such as a bird nesting adjacent to a powerline (e.g., on a power pole), has been observed to result in changes in behavior (e.g., alertness, time preening, time resting), reproductive success, growth and development, physiology (e.g., calcium ion movements) endocrinology (e.g., melatonin levels), and oxidative stress (Fernie and Reynolds 2005, Tomas et al. 2012). The effects, when observed, are species-specific and mostly adverse but not always (Fernie and Reynolds 2005). Long-term exposure to EMF levels from nesting or roosting on OWFs is not obvious. The U.S. Fish and Wildlife Service developed guidance for onshore wind farm avian and bat protection plans which indicates that using tubular support designs with pointed nacelle tops rather than lattice and avoiding the use of external ladders and support platforms minimizes bird perching and nesting opportunities (USFWS 2010).

### 5.5.2 Bats

> Short-term exposure to elevated EMF levels while in passing are not expected to present a barrier or disrupt normal migration of birds, bats, or monarch butterflies.

Bats are primarily associated with terrestrial environments, yet some species are known to migrate offshore (see review in Solick and Newman 2021). Bats are magneto-sensitive and use a magnetic compass for their migration (Kashetsky et al. 2021, Kunz et al. 2007). There is concern that the EMF from WTGs could cause bats to become disoriented and result in blade strikes (Kunz et al. 2007). Any effects due to artificial EMF exposure are expected to be localized to the WTG vicinity. Bats that have been disorientated experimentally in the field have been found to reorient themselves relatively quickly (Holland et al. 2006). Further, research has found that sunset cues (e.g., solar azimuth at sunset; pattern of polarized light) are used by some bat species to calibrate their magnetic compass (Greif et al. 2015, Holland et al. 2010, Lindecke et al. 2019). Therefore, with the capability of using multiple senses, any short-term exposure to elevated EMF levels and potential disorientation while in passing of a WTG or OSS should not present a barrier or disrupt normal migration.

Evidence of close-scale attraction based solely on physical phenomena (e.g., EMF, heat, or sound) generated by specific parts of the WTG has not been observed (Cryan et al. 2014). Alternatively, there is evidence that EMFs can act as a deterrent to bats, possibly due to the generation of heat. However, any deterrence from EMFs is at the high radio frequencies of the electromagnetic spectrum (e.g., microwaves) and of relatively high voltage (i.e., V/m versus mV/m). Specifically, bat activity was significantly reduced in habitats exposed to an EMF greater than 2 V/m compared to 0 EMF sites, but activity was not significantly different at lower EMF levels within 400 m of radar systems (i.e., air traffic control, military, and weather radars) (Nicholls and Racey 2007, Nicholls and Racey 2009). These frequencies and voltages are not representative of the EMF from an OWF cable.

### 5.5.3 Insects

Insects are magneto-sensitive. Some species like bees, moths, and butterflies are thought to use their magneto-sensitivity in support of orientation and navigation along with other equally important cues (e.g., odor, celestial information). It is thought that magneto-sensitivity evolved to compensate for times when the other cues are obscured (e.g., low light, poor weather) (Chicas-Mosier et al. 2020, Gould and Gould 2012). For example, monarch butterflies (*Danaus plexippus*), a candidate species for listing under the Endangered Species Act, are suggested to be capable of using both magnetic and sun compass information to orient and navigate when migrating (Etheredge et al. 1999, Guerra et al. 2014, LaRue et al. 2006). However, monarchs' use of a magnetic compass has come into question (Taylor et al. 2000), and the sun compass appears to be the primary source of navigational information, when available (Guerra et al. 2014, LaRue et al. 2006). Therefore, with the capability of using multiple senses, any short-term exposure to elevated EMF levels and potential disorientation while in passing of a WTG or OSS should not present a barrier or disrupt normal monarch butterfly migration.

Most discussion on EMF-related effects to insects revolves around high frequency EMF, which is considered a threat (Balmori 2021). These frequencies are not representative of the EMF from an OWF cable. However, a literature review by Thill (2020) found that effects from exposure to low-frequency EMF were observed in 26 of 29 studies. The taxa being evaluated in the 29 studies were primarily honeybees (11 studies) and fruit flies (13 studies), with locusts (one study), beetles (one study), and cockroaches (*Blaptica dubia*, *Periplaneta americana*, three studies) also included. At the upper end of the screening level adopted for this synthesis (100 µT), exposure to low frequency EMF, as noted in Thill (2020), caused changes in bee behavior with altered flight behaviors, increased aggression (stinging), reduced learning/memory formation (Shepherd et al. 2018), and reduced food intake/preference (Shepherd et al. 2018, Erdogan and Cengiz 2019) as well as a reduction in fruit fly egg production (Ramirez et al. 1983). A second review by Thill (2023) found that of 133 low frequency experiments, behavioral effects were found in 29 percent, metabolic effects in 12 percent, and reproductive impairment in 11 percent, with no effects being found in 6 percent. Since monarchs would only potentially encounter a WTG or OSS briefly while in passing during migration, no effects are expected to monarch foraging or reproduction.

## 5.6 Summary

*Summary: Exposure to elevated EMF levels has not been observed to affect the survivorship of marine species. Effects, when observed, have been limited to minor changes in behavior or physiological effects. These individual impacts are not expected to result in population-level impacts. Further, effects are species-specific and limited to electro- or magneto-sensitive species.*

A summary of potential effects to marine species from exposure to EMF emissions, based largely on the conclusions of the extensive reviews done by Albert et al. (2020), Normandeau et al. (2011), Gill et al. (2014), and Snyder et al. (2019), is provided in Table 12. A tabulation of results from the reviews included in Appendices A through D is also provided in Appendix F. Observed effects are species-specific and no direct link has been found between exposure to a cable's EMF emissions and a species' survival or population level effects.

A species' ability to detect EMF does not necessarily imply an adverse biological effect will occur.

**Table 12. Summary of key points concerning EMF effects by taxa**

| Taxa | General Conclusion on EMF Effects due to the Presence of Cables |
|---|---|
| Marine Plants | No effects. Found to grow on and in the vicinity of energized cables. |
| Marine Invertebrates | Does not appear to be any movement barrier effect on invertebrates, but there can be minor behavioral changes. The duration of the behavioral changes is unknown; however, it is expected that mobile species would only be temporarily affected.<br><br>Any observed effects (i.e., behavioral, physiological) are species-specific.<br><br>Based on field studies there appears to be no biologically significant effect on invertebrate communities (i.e., species composition, density).<br><br>No reduction in survival.<br><br>No marine invertebrates have been definitively demonstrated as being electro-sensitive. |
| Fish | Elasmobranchs are by far the most likely group of marine animals to be affected by the generated iE-fields. There is some evidence that the presence of a cable could result in an individual wasting time and energy hunting a cable's iE-field instead of prey; however, any effects would depend on the amount of time an individual remained within the region of influence of an OWF cable which is relatively small (i.e., up to 100 m but typically much less).<br><br>There does not appear to be any movement barrier effect on fish, but there can be minor behavioral changes. The duration of the behavioral changes is unknown; however, it is thought that mobile species would only be temporarily affected.<br><br>Any observed effects (i.e., behavioral, physiological) are species-specific.<br><br>Based on field studies there appears to be no biologically significant effect on fish communities (i.e., species composition, density).<br><br>No reduction in survival.<br><br>Migratory fish use the earth's magnetic field likely combined with other environmental cues (e.g., water temperature, light, salinity) to guide migration routes (e.g., olfactory cues in natal rivers to reach spawning grounds). |
| Sea Turtles | Consideration needs to be made for cables that approach nesting beaches and the potential for disorientating hatchlings.<br><br>Juvenile and adult sea turtle navigation relies on multiple cues and exposure is unlikely to prevent successful migration. |
| Marine Mammals | Cetaceans use geonavigation by detection of variation in magnetic fields. However, any disorientation due to short-term exposure to elevated EMF levels while in passing is not expected to affect migration. |
| Aerial Species (Birds, Bats, and Insects) | Species are magneto-sensitive, but typically use more than one type of compass (e.g., magnetic, sun, celestial) or cues during migration. Any disorientation due to short-term exposure to elevated EMF levels while in passing is not expected to affect migration.<br><br>Monarch butterflies are capable of using both magnetic and sun compass information to orient and navigate when migrating.<br><br>Any observed effects (i.e., behavioral, physiological) from long-term exposure to elevated EMF levels are species-specific and typically at frequencies not representative of OWFs. |

# 6 Mitigation

*Summary: Cable sheathing retains the E-field, but there are currently no mitigation options to prevent B-field emissions from escaping the cable and out into the environment (Copping et al. 2021). However, there are other mitigation options and considerations to minimize EMF levels and/or exposure, including: cable siting, cable burial/cover, cable design, and cable management and monitoring (see Gill et al. 2014, Hutchison et al. 2018, Maxwell et al. 2022, Normandeau et al. 2011, NYSERDA 2001, Snyder 2019, Taormina et al. 2018).*

Cable sheathing retains the E-field, but there are currently no mitigation options to prevent B-field emissions from escaping the cable and out into the environment (Copping et al. 2021). However, Table 13 outlines other mitigation options and considerations to minimize EMF levels and/or exposure. These include cable siting, cable burial/cover, cable design, and cable management and monitoring. Currently, there is not enough information to determine what the appropriate EMF levels are to target with mitigation measures, or if specific mitigation measures are required (SEER 2022).

> Cable burial and design are two of the main mitigative measures being considered relative to reducing EMF emissions.

**Table 13. Potential mitigation measures to minimize EMF levels and/or exposure**

| Category | No. | Description |
|---|---|---|
| Cable Siting | 1 | Siting cable routes to avoid sensitive habitats (e.g., sea turtle nesting areas, key migration routes). |
| Cable Siting | 2 | Placing multiple cables in proximity to each other. Greater mutual cancellation of the B-fields from cables is achieved by placing the cables close together because of the vector nature of B-fields. Placing the cables close together not only reduces the peak B-field but it increases the rate at which the field diminishes with distance from the cables. Of note, there is a trade-off with cables in close proximity having a higher chance of being damaged at the same time (e.g., trawl damage). |
| Cable Siting | 3 | Consideration of HVDC cable orientation since they can interact with the earth's magnetic field. |
| Creation of Distance Between Organisms and the Cable | 4 | Cable burial will result in a lower EMF level at the sediment surface and in the lower part of the water column. The lower EMF level is due to increasing the distance between the cable and the seafloor/water column and not because burial itself dampens the intensity of the EMF. Of note, there is a trade-off with burial depth and overheating of the cable. In addition, there is also a trade-off with increasing burial depth as this leads to an increase in seafloor disturbance during construction. |
| Creation of Distance Between Organisms and the Cable | 5 | Where hardbottom seafloor conditions or existing infrastructure are encountered, the cable would be laid on the seafloor and likely covered with concrete mattresses, rock berms, or other coverings to protect the cable. Similar to burial within the seafloor, this increases the distance between the cable and marine organisms. |
| Creation of Distance Between Organisms and the Cable | 6 | HDD sensitive sea turtle nesting areas, placing the cable far underground[a]. |

| Category | No. | Description |
|---|---|---|
| Cable Design | 7 | Use of grounded metallic shielding (e.g., metal armor) for the cable. The metal sheath around the cable shields the E-field produced by the voltage on the conductors and confines it to the cable's interior. Steel wires also partially shield the B-field from the outside environment due to opposing eddy currents induced in the armor and ferromagnetic shielding (ferromagnetism is a property of some substances [e.g., iron] in which application of a weak magnetic field within a certain temperature range induces high magnetism). |
| Cable Design | 8 | Twisting of the three individual copper conductor bundles within an AC cable. In this configuration, the B-field from each twisted conductor will more effectively cancel out the field from each of the other two conductors, resulting in a lower B-field near the cable. In addition, the B-field from the twisted conductors will decrease more rapidly with distance than a cable with straight conductors. |
| Cable Design | 9 | Use of three-phase AC cables and bipolar HVDC transmission systems. |
| Cable Design | 10 | Consideration of the permeability of the cable sheath/armor. As the permeability of cable armor increases, the resultant EMF strength outside of the cable has been shown to decrease; similarly, as the conductivity of cable sheath and armor increases, the resultant EMF strength outside of the cable decreases. |
| Best Management Practices During Operations | 11 | Manage current flow since the B-field varies directly with current flow on a cable, the greater the current the higher the B-field. |
| Best Management Practices During Operations | 12 | Monitoring of cables to ensure they are in good condition (lack of wear and tear). Of note, suspended cables are more vulnerable to wear through hydrodynamic stress (fatiguing pressure and twist) and biofouling. |

Source: Gill et al. 2014, Hutchison et al. 2018, Maxwell et al. 2022, Normandeau et al. 2011, NYSERDA 2001, Snyder 2019, Taormina et al. 2018.
Notes:
[a] To construct the HDD a pit needs to be excavated offshore (subtidal) for the drill string to either be drilled into or for the drill string to pop out of depending on if it is a water-to-shore or shore-to-water drill. Alternatively, the required width of an open trench that crosses a sandy shoreline is typically rather wide due to the instability of the sediments. Thus, it is generally accepted that HDD leads to less offshore disturbance since the intertidal isn't open trenched.

An overview of cable characteristics for planned OWFs along the U.S. Atlantic coast is provided in Table 14. To date, mitigation proposed specifically for EMF levels is generally cable burial (Gill et al. 2014). Cable burial is done for cable protection (e.g., trawl damage). This also increases the distance between the cable and the seafloor, and the greater this distance is the less EMF exposure to organisms on the seafloor surface and in the lower water column. A study prepared for the Bureau of Ocean Energy Management, Enforcement and Regulation Technology Assessment and Research Branch, titled "Offshore Electrical Cable Burial for Wind Farms: State of the Art, Standards and Guidance & Acceptable Burial Depths, Separation Distances and Sand Wave Effect" concludes that the "norm" for burial depth is 15ft (4.5m) in an anchorage area or channel with sizeable ship traffic, where considerable maneuvering is required and vessels might need to deploy an anchor (e.g. port entry), and 3 to 6 feet (1 to 2m) in all other areas. Deeper burial may be required in soft sands where trawl nets can penetrate further (Sharples 2011), resulting in increased seafloor disturbance.

**Table 14. Characteristics of planned OWF cables and EMF implications**

| Name<br>(Current Status[a]) | Available Details[b]<br>(Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| Atlantic Shores Offshore Wind<br>(BOEM DEIS available) | Cables will be buried 5 to 6.6ft (1.5 to 2m) below the seafloor or have secondary protection (e.g., rock).<br><br>HVAC cables are expected to have three stranded-core conductors made of aluminum or copper that are encapsulated in a cross-linked polyethylene (XLPE) insulation system, a metallic screen, and a core jacket. The three power cores will be bundled together and protected by an armor layer.<br><br>HVDC cables are expected to have single-core stranded conductors made of aluminum or copper each encapsulated in an XLPE insulation system, a metallic screen, a core jacket, and protected by an armor layer.<br><br>A minimum separation distance of approximately 330ft (100m) is planned between the HVAC export cables installed within each export cable corridor.<br><br>The export cable design will likely include a Distributed Temperature Sensing (DTS) System and may include other monitoring systems such as Distributed Acoustic Sensing System or Online Partial Discharge Monitoring to constantly assess the status of offshore cables and detect anomalous conditions, insufficient or excess cable depth, or potential damage.<br><br>Landfall of an offshore export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10)<br><br>Monitoring during operations (Mitigation No. 12) |
| Coastal Virginia Offshore Wind<br>(Operational) | Cables will be buried 3.3-16.4 feet (1-5 meters) below the seafloor or have secondary protection (e.g., rock).<br><br>The HVAC inter-array cables will consist of strings of three-core copper and/or aluminum conductor.<br><br>The HVAC export cables will be a three 3-core copper and/or aluminum-conductor cable.<br><br>A DTS System will provide a real time monitoring of temperature along the export cable. Temperature changes could be the result of scouring of material and cable exposure.<br><br>Landfall of an offshore export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable design (Mitigation No. 8)<br><br>Monitoring during operations (Mitigation No. 12) |

| Name (Current Status[a]) | Available Details[b] (Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| Empire Wind<br>(BOEM Approved) | Cables will be buried to a minimum target burial depth of 6 feet (1.8 meters) outside of federally maintained (e.g., anchorages and shipping channels) areas or have secondary protection (e.g., rock). In locations where the cable must cross federally maintained areas, the cable will be buried to a minimum burial depth of 15 feet (4.7 meters) below the current or future authorized depth or depth of existing seafloor (whichever is deeper).<br><br>HVAC submarine export cables will consist of three-core cable with copper conductors, XLPE insulation system, and armoring package. The armoring package made of an armoring bedding and a layer of steel, or a combination of steel and polymeric armor wires flushed with bitumen will be applied over the bundle. Finally, an outer serving made of polypropylene yarns will be applied over the armoring package.<br><br>Surveys of the export and inter-array cable routes will be made to confirm that the cables have not become exposed or that the cable protection measures have not worn away. Following the full coverage as-built survey, annual, risk-based inspections will be conducted for the first three years. After that, risked-based burial depth surveys will be conducted every five years, with coverage to be determined using DTS and Distributed Acoustic/Vibration Sensing systems.<br><br>Landfall of at least some of the offshore export cables will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10)<br><br>Monitoring during operations (Mitigation No. 12) |

| Name (Current Status[a]) | Available Details[b] (Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| SouthCoast Wind (formerly Mayflower Wind) (BOEM DEIS available) | Inter-array cables will be buried to a target burial depth of 3.2 to 8.2ft (1.0 to2.5m) below the seafloor or have secondary protection (e.g., rock). Export cables will be buried to a target burial depth of 3.2 to 13.1ft (1.0 to4.0m) below the seafloor or have secondary protection (e.g., rock).<br><br>The AC inter-array cables are a three-core (three separate conductors/cores) armored cable. The power cores will either be an aluminum or copper stranded conductor with a XLPE insulation system, copper wire screen with lead sheath (or aluminum foil or copper tape screen), and polyethylene over-sheath. Each cable will contain a stainless-steel tube that houses and protects the fiber optic cable, the stainless-steel tube is coated with a polyethylene jacket. The power core fillers and fiber optic tube are covered with armor bedding and galvanized or stainless-steel wire armor outer jacket, which will be polypropylene yarns soaked in bitumen (i.e., corrosion protection).<br><br>Each HVAC export cable will be a three-core (three power cores) armored cable. Each cable will contain a stainless-steel tube coated with a polyethylene jacket that houses and protects the fiber optic cable. The power cores, fillers, and fiber optic tube are covered with armor bedding and galvanized or stainless-steel wire armor. The outer serving will be polypropylene yarns soaked in bitumen.<br><br>Each HVDC export cable will be a single-core (one power core) armored cable. The cable will be covered with galvanized, stainless-steel wire armor, and an outer serving of polypropylene yarns soaked in bitumen. Fiber optic wires may be embedded within the armor layer of the cable. The HVDC cables will be installed in a bundled configuration where practicable, with each cable bundle consisting of two power cables and one dedicated communications cable.<br><br>Target horizontal separation between each cable is approximately 328ft (100 m).<br><br>Landfall of an offshore export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10) |

| Name (Current Status[a]) | Available Details[b] (Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| New England Wind (formerly Vineyard Wind South) (BOEM Approved) | Cables will be buried to a target depth of 5 to 8 ft (1.5 to 2.5m) below the seafloor or have secondary protection (e.g., rock).<br><br>They will be a three-core cable. The three cores of the cable will consist of copper or aluminum conductors.<br><br>Expected to be encapsulated by steel armoring, XLPE insulation, and waterproof sheathing which is typical of current cable designs. However, the inter-array cables may not include a water-impervious lead sheath and may have different armoring (e.g., high-density polyethylene).<br><br>High resolution geophysical surveys will be used to monitor cable exposure and/or depth of burial. It is expected that the cables will be surveyed within six months of commissioning, at years one and two, and every three years thereafter.<br><br>The cable design may include a DTS System, so that the temperature of the cable is always monitored.<br><br>The export cables will typically be separated by 164 to328ft (50 to 100m).<br><br>Landfall of an offshore export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10)<br><br>Monitoring during operations (Mitigation No. 12) |
| Ocean Wind (2 Year Suspension of Operations) | Cables will be buried to a target depth of 4 to 6 ft (1.2 to 1.8m) below the seafloor or have secondary protection (e.g., rock).<br><br>Typical inner-array cable separation of 328ft.<br><br>They will be a three-core cable and surrounded by layers of insulating material as well as material to armor or protect the cable from external damage. | Creation of distance between organisms and the cable via burial (Mitigation Nos. 4 & 5)<br><br>Cable design (Mitigation Nos. 7-9) |

| Name (Current Status[a]) | Available Details[b] (Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| Revolution Wind (Construction) | Cables will be buried to a target depth of 4 to 6 ft (1.2 to1.8m) below the seafloor or have secondary protection (e.g., rock).<br><br>HVAC inter-array and export cables will consist of three bundled copper or aluminum conductor cores surrounded by layers of XPLE insulation and various protective armoring and sheathing.<br><br>Export cables will typically be spaced, where practical, greater than 164ft (50m) apart.<br><br>Landfall of an offshore export cable will be completed via HDD.<br><br>Cables will be inspected within 6 months of commissioning and subsequently in years 1 and 2 post-construction, every 3 years thereafter, and after a storm event.<br><br>A DTS System will provide real time monitoring of the export cable. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10)<br><br>Monitoring during operations (Mitigation No. 12) |
| South Fork (Operational) | Cables will be buried to a target depth of 4 to 6ft (1.2 to 1.8m) below the seafloor or have secondary protection (e.g., rock).<br><br>An AC inter-array cable will contain three conductors, screens, insulators, fillers, sheathing, and armor.<br><br>The AC export cable will include a continuous three-conductor and fiber optic bundle that will be encased in a water sealed jacket, which is wrapped in either a single or double-steel armor wire. The bundle will be wrapped in a polyester yarn. The power conductors will be made of either copper or aluminum alloys and XPLE insulated.<br><br>Remote surveys will be taken to confirm that the cables remain buried and that rock placement and concrete mattresses remain secured and undamaged. Surveys will be conducted annually for the first three years and biennially thereafter.<br><br>The export cable will be monitored continuously with an as-built DTS System that will indicate burial conditions.<br><br>Landfall of an offshore export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10)<br><br>Monitoring during operations (Mitigation No. 12) |

| Name (Current Status[a]) | Available Details[b] (Additional Measures Might Be Planned) | Applicable EMF Mitigation Measure[b,c] |
|---|---|---|
| Sunrise Wind (BOEM Approved) | Cables will be buried to a target depth of 3 to 7ft (1 to 2m) below the seafloor or have secondary protection (e.g., rock).<br><br>AC inter-array cables will consist of three bundled copper or aluminum conductor cores surrounded by layers of XPLE or ethylene propylene rubber insulation and various protective armoring and sheathing.<br><br>The DC export cable bundle will be comprised of two cables. Each cable within the single bundle will consist of one copper or aluminum conductor core surrounded by layers of XLPE insulation and various protective armoring and sheathing.<br><br>Landfall of an export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable armor/sheath and design (Mitigation Nos. 7-10) |
| Vineyard Wind 1 (Operational) | Cables will be buried to a target depth of 5 to 8 ft (1.5 to 2.5 m) below the seafloor or have secondary protection (e.g., rock).<br><br>The AC export cable will have three copper or aluminum conductors encapsulated by XPLE insulation.<br><br>The AC inter-array cable will be the same three-core AC cable to be used for the export cables.<br><br>Initial inter-array and export cable inspections will be carried out within 6 months of commissioning and subsequent inspections will be carried out the first two years post-construction and then every three years thereafter. Inspections will also be done after a major storm event.<br><br>The export cable will be monitored continuously with an as-built DTS System. The DTS data will indicate if burial conditions have deteriorated or changed significantly, and remedial actions are warranted.<br><br>A typical separation distance of 100m (330 ft) will be maintained between the two export cables.<br><br>Landfall of an export cable will be completed via HDD. | Creation of distance between organisms and the cable via burial and HDD (Mitigation Nos. 4-6)<br><br>Cable design (Mitigation Nos. 8 & 9)<br><br>Monitoring during operations (Mitigation No. 12) |

Source: Atlantic Shores Offshore Wind 2021, BOEM 2020, BOEM 2021, BOEM 2022a, BOEM 2022b, Dominion Energy 2021, Equinor 2021, Mayflower 2021, Ocean Wind 2021, Park City Wind LLC 2022, Revolution Wind 2021, South Fork Wind 2021, Sunrise Wind 2021, Vineyard Wind LLC 2020.
Notes:
[a] Status as referenced in Northeast Ocean Data (2022).

[b] Additional measures might be planned which would lead to reduced EMF levels; however, the measures identified within this table are based on the publicly available details to date.
[c] Mitigation number as identified in Table 13. Assumed general design considerations relative to mitigation numbers 7 to 10.

# 7 Key Challenges

*Summary: One of the key challenges to assessing potential impacts of EMFs includes collecting field data to calibrate models that predict EMF emission levels. Currently, there is no off-the-shelf technique that can be used to assess EMF levels in the marine environment. Another key challenge is extrapolating (i.e., scaling-up) current observations (both laboratory and field) to assess the potential impacts of larger developments with higher electrical power and the possible cumulative effects of multiple OWFs in close proximity. This also includes predicting the potential effects of the new technology of floating OWFs.*

Predicting potential EMF effects can be challenging based on the current level of understanding. Some of the key challenges are identified in Table 15. Although there have been no clear, significant impacts found so far from OWF generated EMFs, one of the key challenges is extrapolating (scaling up) current observations to larger developments with higher electrical power and evaluating cumulative effects of multiple OWFs in close proximity. This will most likely be done through modeling.

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**Table 15. Key challenges regarding the assessment of potential EMF effects**

| Category | No. | Description |
|---|---|---|
| Estimated EMF Levels and Accurate Measurements | 1 | For an accurate estimation of a cable's EMF emissions, numerical models are needed that include a realistically described environment and cable design. It is essential to have detailed information on the characteristics of the cable and the geological properties of the stratum, as well as the conductivity of the water column. However, estimates of EMF emissions from cables are usually concluded based on approximate calculations of an infinite and straight cable in a homogenous environment (Ohman et al. 2007, Hutchison et al. 2021, Scott et al. 2023). Further, measuring actual EMF levels in the field is challenging. At present, there is no off-the-shelf technique that can be used to assess EMF levels in the marine environment. Although there are commercially available sensors for measuring magnetic fields (magnetometers), measuring EMF levels 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 (Hutchison et al. 2018, Gill and Desender 2020). |
| Estimated EMF Levels and Accurate Measurements | 2 | Wind levels are not constant, therefore neither are the EMF levels. It is currently unknown how this may affect the significance of any behavioral or physiological effects (SEER 2022). |
| Dynamic Arrays with Floating OWFs | 3 | There is a limited understanding of the potential effects that could occur from cables suspended in the water column, as will be the configuration of the dynamic inter-array cables associated with floating OWFs (Maxwell et al. 2022). The suspended inter-array cables will increase EMF emissions within the water column and potentially interact with a greater diversity and abundance of marine organisms than with traditional OWFs (Farr et al. 2021). |

| Category | No. | Description |
|---|---|---|
| Application of Existing Information | 4 | It is difficult to draw comparisons between controlled laboratory studies and those that are field-based (Gill et al. 2014). The variety of observed responses to EMF emissions does not clearly suggest which specific species or biological changes might be most suitable as general bioindicators of potential impacts (Otremba et al. 2019). Gill et al. (2009) and Gill et al. (2014) suggest that further research include a hybrid of laboratory and field approaches (i.e., mesocosm studies) to address specific research questions. The proposed mesocosm approach includes controlled experiments within large enclosures deployed over cables and reference areas. Within these experiments, collection of fine scale telemetry data will be necessary (Hutchison et al. 2020b). |
| Application of Existing Information | 5 | Most of the evaluations conducted to assess a species' sensitivity are based on B-field responses. There is not as much information concerning iE-field responses (SEER 2022). |
| Application of Existing Information | 6 | Often it is unclear when/if other senses (e.g., sight, smell) become more important than EMF receptors, reducing the concern over potential EMF impacts (Emma 2016). |
| Application of Existing Information | 7 | There is no information available on the potential habituation of a species to artificial EMF emissions (Emma 2016, SEER 2022). |
| Application of Existing Information | 8 | DC and AC cables should not necessarily be treated the same in terms of environmental considerations. Species will most likely perceive DC and AC fields in different ways (Ohman et al. 2007). |
| Scaling Up & Cumulative Impacts | 9 | Although there have been no clear, significant impacts found thus far, how to extrapolate the current observations to larger developments with cabling of higher power and to multiple OWFs in close proximity (i.e., cumulative effects) is uncertain (Gill et al. 2014). Modelling will most likely be required to help assess those types of impacts/concerns (i.e., scaling up and cumulative impacts) (Putnam 2022). |
| Limited Data | 10 | Data are limited specific to EMF emissions, especially applicable field studies for OWFs. This is compounded by the fact that effects are species-specific, when observed. |
| Limited Data | 11 | Data are limited specific to EMF emissions from above water OWF components and area of aerial influence. In addition, data on the detection distance of any EMF sensitive species (e.g., bats) are also limited. |

# 8 Thermal Effects

*Summary: Although encased in a sheath, in addition to EMFs, thermal radiation is emitted from electrified cables. Heat transfer to the water column is influenced by sediment cover when the cable is buried (Hughes et al. 2015). The only field measurements for an offshore wind farm cable found a maximal temperature increase of about 2.5ºC at 50 cm from the cable. The temperature increase is generally considered to be almost negligible in view of typical seasonal temperature variations (Henry et al. 2022, Taormina et al. 2020). Therefore, similar to EMF exposure, it is not anticipated that enough individuals would be affected to result in population level effects.*

Although encased in a sheath, in addition to EMFs, thermal radiation is emitted from electrified cables. For offshore cables, the presence of a large body of water above acts as a heat sink. Heat transfer to the water column is influenced by sediment cover when the cable is buried (Hughes et al. 2015). The resulting degree of temperature change due to the presence of an energized cable will also be a result of cable characteristics (e.g., AC/DC, size), power levels being transmitted, and ambient conditions (e.g., currents, temperature) (Meibner 2006, Hogan et al. 2023). Further, over its entire length, an offshore cable is likely to go through a variety of sediment types with differing thermophysical properties (e.g., conductivity, resistance) (Hughes et al. 2015).

A localized increase in temperature could modify oxygen concentration, affect species physiology (e.g., respiratory rate, metabolic functioning, growth, reproduction), and/or affect local species distribution (i.e., attraction, repulsion) (Henry et al. 2022, Taormina et al. 2018). The potential for impacts could be higher for sessile deep-water species (e.g., coldwater corals) which are adapted to constant temperatures (Henry et al. 2022, Taormina et al. 2020).

> There is no indication that thermal effects from an OWF cable would significantly affect any populations.

Any impacts due to temperature elevation are expected to be localized around the cable (Taormina et al. 2018). Only a few field measurements of temperature near offshore power cables are available (see Table 16). Of note, only one study was available assessing the temperature increase near a buried cable. Based on the values in Table 16, sediments in close proximity (cms) to the cable would only be expected to be elevated by a few degrees Celsius or less. The temperature increase is generally considered to be almost negligible in view of typical seasonal temperature variations (Henry et al. 2022, Taormina et al. 2020). Therefore, similar to EMF exposure, it is not anticipated that enough individuals would be affected to result in population level effects.

**Table 16. Key challenges regarding the assessment of potential EMF effects**

| Cable Details | Buried at Temperature Measurement Site | Temperature Details | Reference |
|---|---|---|---|
| 33 and 132 kV cables (Nysted offshore windfarm) | Yes (approximately 1 meter) | Maximal temperature increase of about 2.5 ºC at 50 cm from the cable | Carlier et al. 2019 as summarized in Henry et al., 2022 |
| 7.5 kV (tidal energy), 20kV (offshore test site), and 90 kV (electricity supply) | No | <0.06°C (below measurement sensitivity level) | Taormina et al. 2020 |

# 9 Conclusions

*Summary: Exposure to EMF emissions from OWFs could elicit a response from electro- and magneto-sensitive species. However, any effects are anticipated to be species-specific, limited to individuals in the immediate vicinity, and biologically non-significant.*

The submarine inter-array and export cables of OWFs, when energized, are a source of EMFs in the marine environment. The EMFs generated by OWFs are of relatively low frequency and are not like higher frequency, ionizing EMFs (e.g., X-rays, microwaves) which are known to alter chemical bonds and damage biological molecules (Middleton and Barnhart 2023). EMF levels are strongest around an energized cable and decrease approximately as an inverse square of the distance from the cable. Elevated EMF levels from OWF cables are consistently estimated to return to background levels within 100 m or less (typically 1 to 10s of m) (BOEM 2020, BOEM 2021, Gill and Desender 2020, SEER 2022, Snyder et al. 2019). There are currently no mitigation options to prevent EMF emissions from escaping the cable and out into the environment (Copping et al. 2021). Cable burial is the most commonly discussed mitigation measure that will result in a lower EMF level at the sediment surface and in the lower part of the water column. The lower EMF level is due to increasing the distance between the cable and the seafloor/water column and not because burial itself dampens the intensity of the EMF. There are also other options and considerations to minimize EMF levels and/or exposure, including cable siting, cable design (e.g, sheathing), and cable management and monitoring (see Table 13). Currently, there is not enough information to determine what the appropriate EMF levels are to target with mitigation measures, or if specific mitigation measures are required (SEER 2022).

> Laboratory and field studies have found species-specific altered behaviors in response to EMFs for some sensitive species. However, the level of effect appears to be limited, not significantly affecting migration patterns, or resulting in avoidance of preferred habitat.

The potential impacts to marine fauna from anthropogenic (i.e., human-induced) EMF emissions discussed in the relevant, available literature primarily include: impairment of orientation/navigation affecting migration; repulsion of animals causing a barrier effect to natural movement and migration; attraction or masking resulting in changes in migration behaviors, predator and/or prey relationships, or interactions with conspecifics; confusion with bioelectric fields affecting prey detection; and changes in physiology and development (Gill and Desender 2020, Gill et al. 2014, Taormina et al. 2018; see Table 7). There have been multiple comprehensive reviews evaluating the potential vulnerability of marine species to EMFs produced by cables. These reviews found that both field and laboratory studies have been undertaken, but the results are generally ambiguous (i.e., open to interpretation). Any observable effects have been highly species-specific and, when found, typically involve behavioral responses from individuals (see Appendix F, Tables 8 and 12). The observed effects on animal behavior are unlikely to substantially alter survival or reproduction. Further, field studies have generally not identified any ecologically significant effects. In agreement with the conclusions of Emma (2016) and Copping (2020), there does appear to be enough evidence to indicate that species within several taxa (e.g., elasmobranchs) can detect and sometimes respond to anthropogenic EMF emissions. However, there is no evidence to suggest a significantly detrimental biological effect which would be harmful to a population. The overall risk from EMF emissions from OWFs appears to be low unless in the future there is a significant cumulative effect of large OWFs, including OWFs operated in areas already significantly affected by other EMF sources.

Love et al. (2017a) suggests that one possible reason that studies have only found negligible effects, or ambiguous ones, is that marine organisms respond to anthropogenic EMFs differently from those produced in nature. An anthropogenic EMF is inherently different from a naturally produced EMF, with naturally produced EMFs being polarized and consequently more biologically active. Thus, it is possible that most sensitive species are able to differentiate between the two types and therefore respond differently. Further, Snyder et al. (2019) points out that in general species are not tuned into the 60 Hz frequency typical of OWF AC cables.

> When found, effects from EMF exposure, of the levels anticipated from OWF cables, typically involve sub-lethal behavioral responses that are unlikely to have any ecologically significant effects.

There is little evidence in the material reviewed that EMF emissions from OWFs will cause changes in marine species movements (e.g., migration) (see Tables 10 and 11). Elasmobranchs are both electro- and magneto-sensitive (SEER 2022) and do represent a group of species that appear to show responses to anthropogenic EMFs, particularly in behaviors related to foraging (see Table 11). The effects on energetics and overall fitness are not clear. However, based on their limited detection range (< 1 meter) (Snyder et al. 2019), the area affected would need to be large to result in population level effects, while the region of influence of an OWF cable is relatively small (i.e., up to 100m but typically much less) (BOEM 2020, BOEM 2021, Gill and Desender 2020, SEER 2022, Snyder et al. 2019).

For those laboratory studies that met the threshold used in this review (maximum of 100 µT and/or 10 mV/m), researchers have found some species-specific and life-stage-specific effects on development and physiology, but no significant effects on survivorship (see Tables 10 and 11). How these observed developmental and physiological effects might affect fitness (i.e., ability to reproduce) is not clear. However, the limited distance that EMF emissions are elevated around a cable will result in a relatively small area in which exposure can occur. Therefore, it is not anticipated that enough individuals would be affected to result in population level effects.

Predicting potential EMF effects can be challenging based on the current level of understanding (see Table 15). For example, to obtain an accurate estimation of a cable's EMF emissions, numerical models are needed that include a realistically described environment and cable design. It is essential to have detailed information on the characteristics of the cable and the geological properties of the stratum, as well as the conductivity of the water column. However, estimates of EMF emissions from cables are usually concluded based on approximate calculations of an infinite and straight cable in a homogenous environment (Ohman et al. 2007, Hutchison et al. 2021, Scott et al. 2023). Further, measuring actual EMF levels in the field is challenging. At present, there is no off-the-shelf technique that can be used to assess EMF levels in the marine environment.

Another challenge in predicting future effects of EMFs from OWFs is extrapolating (i.e., scaling-up) current observations (both laboratory and field) to larger developments with higher electrical power and the possible cumulative effects of multiple OWFs in close proximity. This also includes predicting the potential effects of the new technology of floating OWFs (i.e., dynamic inter-array cables). However, the area affected would need to be large to result in population level effects, while the region of influence of an OWF cable is relatively small (i.e., up to 100m but typically much less).

Although encased in a sheath, in addition to EMFs, thermal radiation is emitted from electrified cables. However, the temperature increase is generally considered to be almost negligible in view of typical seasonal temperature variations (Henry et al. 2022, Taormina et al. 2020). Therefore, similar to EMF exposure, it is not anticipated that enough individuals would be affected to result in population level effects.

In conclusion, based on review of the relevant, available literature, exposure to EMF emissions from OWFs could elicit a response from electro- and magneto-sensitive species. However, any effects are anticipated to be species-specific, limited to individuals in the immediate vicinity, and biologically non-significant.

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# Appendix A: Table 2 from Albert et al. (2020)

**Table A-1. Table 2 of Albert et al. (2020): Summary of studies investigating the effects of artificial magnetic fields**

| Type of Response Considered | Group | Species | Life Stage | Lifestyle | Characteristics of AMF Exposure Duration / Magnetic Induction (mT) | Observed Effects | References |
|---|---|---|---|---|---|---|---|
| Survival | Crustacean | North Sea prawn (*Crangon crangon*) | Adult | Vagile epifauna | 49 days / 3.7 mT DC | None | Bochert and Zettler (2006) |
| Survival | Crustacean | Isopod (*Saduria entomon*) | Adult | Vagile epifauna | 93 days / 3.7 mT DC | None | Bochert and Zettler (2006) |
| Survival | Crustacean | Isopod (*Sphaeroma hookeri*) | Adult | Vagile epifauna | 34 days / 3.7 mT DC | None | Bochert and Zettler (2006) |
| Survival | Crustacean | Round crab (*Rhithropanopeus harrisii*) | Adult | Vagile epifauna | 57 days / 3.7 mT DC | None | Bochert and Zettler (2006) |
| Survival | Mollusc | Blue mussel (Mytilus edulis) | Adult | Sessile epifauna | 52 days / 3.7 mT DC | None | Bochert and Zettler (2006) |
| Survival | Mollusc | Baltic clam (*Limecola balthica*) | Adult | Sedentary endofauna | 12 days / 0.85 to 1.05 mT 50 Hz AC | None | Jakubowska et al. (2019) |
| Survival | Polychaete | Ragworm (*Hediste diversicolor*) | Adult | Sedentary endofauna | 12 days / 0.85 to 1.05 mT 50 Hz AC | None | Jakubowska et al. (2019) |
| Physiological | Crustacean | North Sea prawn (*Crangon crangon*) | Adult | Vagile epifauna | 3 hours / 3.2 mT DC and 50 Hz AC | No effects on oxygen consumption rate | Bochert and Zettler (2006) |
| Physiological | Crustacean | Baltic prawn (*Palaemon squilla*) | Adult | Vagile epifauna | 3 hours / 3.2 mT DC and 50 Hz AC | No effects on oxygen consumption rate | Bochert and Zettler (2006) |
| Physiological | Crustacean | Edible crab (*Cancer pagurus*) | Juvenile | Vagile epifauna | 6 hours / 2.8 mT DC | No effects either on oxygen consumption rate | Scott et al. (2018) |

| Type of Response Considered | Group | Species | Life Stage | Lifestyle | Characteristics of AMF Exposure Duration / Magnetic Induction (mT) | Observed Effects | References |
|---|---|---|---|---|---|---|---|
| | | | | | | and haemocyanin concentrations<br><br>Suppression of night rises in D-lactate and D-glucose concentrations | |
| Physiological | Mollusc | Mediterranean mussel (*Mytilus galloprovinciallis*) | Adult | Sessile epifauna | 15-30 Minutes / 0.3-1 mT 50 Hz AC | Disruption of cellular processes | Ottaviani et al. (2002); Malagoli et al. (2003, 2004) |
| Physiological | Mollusc | Blue mussel (*Mytilus edulis*) | Adult | Sessile epifauna | 93 days / 3.7 mT DC | No effects either on the condition index nor the gonad development index | Bochert and Zettler (2006) |
| Physiological | Mollusc | Baltic clam (*L. balthica*) | Adult | Sedentary endofauna | 12 days / 1 mT 50 hz AC | Increase in genotoxic and cytotoxic effects | Stankevičiūtė et al. (2019) |
| Physiological | Echinoderm | Sea urchin (*Strongylocentrotus purpuratus*) | Embryo | Pelagic fauna | 23 hours / 0.1 mT 60 Hz AC (permanent magnets) | Delay in cell division | Zimmerman (1990) |
| Physiological | Echinoderm | Sea urchin (*S. purpuratus*) | Embryo | Pelagic fauna | 26 hours / 30 mT DC (permanent magnets) | Delay in cell division | Levin and Ernst (1997) |
| Physiological | Echinoderm | Sea urchin (*Lytechinus pictus*) | Embryo | Pelagic fauna | 48-94 Hours / 30 mT DC (permanent magnets) | Delay in cell division Increase in development abnormalities | Levin and Ernst (1997) |

| Type of Response Considered | Group | Species | Life Stage | Lifestyle | Characteristics of AMF Exposure Duration / Magnetic Induction (mT) | Observed Effects | References |
|---|---|---|---|---|---|---|---|
| Physiological | Echinoderm | Sea urchin (*L. pictus*) | Embryo | Pelagic fauna | 48-94 Hours / 0.39 mT AC 60 Hz (permanent magnets) | Increase in development abnormalities | Levin and Ernst (1997) |
| Physiological | Polychaete | Ragworm (*Hediste diversicolor*) | Adult | Sedentary endofauna | 8 days / 1 mT 50 Hz AC | No effects on food consumption and respiration rates but increase in ammonia excretion | Jakubowska et al. (2019) |
| Physiological | Polychaete | Ragworm (*Hediste diversicolor*) | Adult | Sedentary endofauna | 12 days / 1 mT 50 Hz AC | Increase in genotoxic and cytotoxic effects | Stankevičiūtė et al. (2019) |
| Behavioural | Crustacean | Edible crab (*Cancer pagurus*) | Juvenile | Vagile epifauna | 7 hours / 2.8 mT DC | Attraction behaviour | Scott et al. (2018) |
| Behavioural | Crustacean | Edible crab (*Cancer pagurus*) | Juvenile | Vagile epifauna | 24 hours / 2.8 mT DC | Suppression of side selection behaviour | Scott et al. (2018) |
| Behavioural | Crustacean | Spiny cheek crayfish (*Oronectes limosus*) | Adult | Vagile epifauna | 24 hours / 0.8 mT | Attraction behaviour | Tanski et al. (2005) |
| Behavioural | Crustacean | Spiny lobster (*Panulirus argus*) | Adult | Vagile epifauna | 15 minutes / 703.1 mT | Repulsion behaviour | Ernst and Lohmann (2018) |
| Behavioural | Crustacean | Freshwater crab (*Barythelphusa canicularis*) | Adult | Vagile epifauna | 2 hours 30 minutes / 50 Hz AC | Attraction and aggregation behaviour | Rosaria and Martin (2010) |
| Behavioural | Crustacean | North Sea prawn (*Crangon crangon*) | Adult | Vagile epifauna | 1.5 hours / 2.7 mT DC | No effects on spatial distribution | Bochert and Zettler (2006) |
| Behavioural | Crustacean | Isopod (*Saduria entomon*) | Adult | Vagile epifauna | 1.5 hours / 2.7 mT DC | No effects on spatial distribution | Bochert and Zettler (2006) |

| Type of Response Considered | Group | Species | Life Stage | Lifestyle | Characteristics of AMF Exposure Duration / Magnetic Induction (mT) | Observed Effects | References |
|---|---|---|---|---|---|---|---|
| Behavioural | Crustacean | Round crab (*Rhithropanopeus harrisii*) | Adult | Vagile epifauna | 1.5 hours / 2.7 mT DC | No effects on spatial distribution | Bochert and Zettler (2006) |
| Behavioural | Crustacean | American lobster (*Homarus americanus*) | Adult | Vagile epifauna | 12-24 hours / In situ<br>Real cable: 0.01 to 0.1 mT | Behavioural changes | Hutchison et al. (2018) |
| Behavioural | Crustacean | American lobster (*H. americanus*) | Adult | Vagile epifauna | 24 hours / 1.01 mT DC | No effects on spatial distribution | Woodruff et al. (2012,2013) |
| Behavioural | Crustacean | Dungeness crab (*Metacarcinus magister*) | Adult | Vagile epifauna | 3-4 days / 1.01 mT DC | No effects on spatial distribution and no effect of the level of agitation | Woodruff et al. (2012,2013) |
| Behavioural | Crustacean | Dungeness crab (*M. magister*) | Adult | Vagile epifauna | Not provided / In situ<br>Cable 1: 0.014 to 0.12 mT 60 Hz AC<br><br>Cable 2: 0.025 to 0.043 kV 60 Hz AC | No effect on catchability | Love et al. (2017) |
| Behavioural | Crustacean | Red crab (*Cancer productus*) | Adult | Vagile epifauna | Not provided / In situ<br>Cable 1: 0.014 to 0.12 mT 60 Hz AC<br><br>Cable 2: 0.025 to 0.043 kV 60 Hz AC | No effect on catchability | Love et al. (2017) |
| Behavioural | Crustacean | Red crab (*Cancer productus*) | Adult | Vagile epifauna | 1 hour / In situ<br>Real cable: | No effect on spatial distribution | Love et al. (2015) |

| Type of Response Considered | Group | Species | Life Stage | Lifestyle | Characteristics of AMF Exposure Duration / Magnetic Induction (mT) | Observed Effects | References |
|---|---|---|---|---|---|---|---|
| | | | | | 0.042 to 0.08 mT 60 Hz AC | | |
| Behavioural | Crustacean | Yellow rock crab (*M. anthonyi*) | Adult | Vagile epifauna | 1 hour / In situ Real cable: 0.042 to 0.08 mT 60 Hz AC | No effect on spatial distribution | Love et al. (2015) |
| Behavioural | Crustacean | Amphipod (*Gondogenia antartica*) | Adult | Vagile epifauna | 1 minute / 2.10-9 to 20.10-9 mT 1 MHz AC | Disruption of orientation abilities | Tomanova and Vacha (2017) |
| Behavioural | Echinoderm | Common starfish (*Asturia rubens*) | Adult | Vagile epifauna | 1.5 hours / 2.8 mT DC | No effect on spatial distribution | Bochert and Zettler (2006) |
| Behavioural | Mollusc | Snail (*Elimia clavaeformis*) | Adult | Vagile epifauna | 48 hours / 36 mT DC | No effect on spatial distribution | Cada et al. (2011) |
| Behavioural | Mollusc | Clam (*Corbicula fluminea*) | Adult | Sedentary endofauna | 48 hours / 36 mT DC | No effect on spatial distribution | Cada et al. (2011) |
| Behavioural | Polychaete | Ragworm (*Hediste diversicolor*) | Adult | Sedentary endofauna | 1.5 hours / 2.8 mT | No effect on spatial distribution | Bochert and Zettler (2006) |
| Behavioural | Polychaete | Ragworm (*H. diversicolor*) | Adult | Sedentary endofauna | 8 days / 1 mT 50 Hz AC | No effect on spatial distribution but behavioural changes | Jakubowska et al. (2019) |

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## Appendix B: Table 4 from Snyder et al. (2019)

**Table B-1. Table 4 of Snyder et al. (2019): Relationship between static geomagnetic field detection, electrosensitivity, and the ability to detect 50/60-Hz AC fields in common marine species**

| Species Group | Detect Static (DC) Geomagnetic Field? | Detect Bioelectric Fields or Electric Fields at <20 Hz? | Evidence from Laboratory Studies of 50/60-Hz EMF from AC Power Cables | Evidence from Field Studies of AC Power Cables |
|---|---|---|---|---|
| Lobsters and crabs | Yes, for some lobster species [61,2] | Not tested [1] | No effect at 800,000 μT [62] | Distribution unaffected by 60-Hz AC cable operating up to 800 mG [63] |
| Salmon | Yes, for multiple species [64,65] | Not tested [1] | No effect of 950 mG magnetic field at 50 Hz on swim behavior [66] | Not surveyed |
| American and/or European eels | Yes, for multiple species [1] | Mixed evidence [1] | No effect of 950 mG magnetic field at 50 Hz on swim behavior or orientation [67] | Unburied AC cable did not prevent migration of eels [68] |
| Tunas and mackerels | Yes, for some species [69] | Not tested [1] | Not tested | Some evidence of attraction of mackerel to monopile structure, but no effect from cables [70] |
| Flounders | Potentially, due to observed orientation behaviors [71] | Not tested [1] | Not tested | No population-level effects, but some evidence of delayed cable crossing. It is unclear whether effect was due to cable EMF or prior sediment disturbance [72] |
| Black sea bass | Unlikely, based on lack of attraction or repellence by magnetic field source [73] | Not tested | Not tested | Not surveyed |
| Atlantic croaker | Unlikely, based on lack of attraction or repellence by magnetic field source [73] | Not tested | Not tested | Not surveyed |
| Bluefish | Unlikely, based on lack of attraction or repellence by magnetic field source [73] | Not tested | Not tested | Not surveyed |
| Striped bass | None demonstrated [74] | Not tested | Not tested | Not surveyed |

| | | | | |
|---|---|---|---|---|
| Skates | Yes, multiple species [1] | Yes, multiple species [1] | No responses expected at 60 Hz [43,44] | No attraction observed at California AC cable sites operating at up to 914 mG [4] |

Notes: The text in Snyder et al. (2019) does state “that electrosensitive fish contain specialized organs that alert the fish when it is in proximity to electric fields associated with other organisms. These organs are mostly “tuned” to frequencies between 1 and 20 Hz [43,44]”.

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# Appendix C: Table 1 from Fisher and Slater (2010)

**Table C-1. Table 1 of Fisher and Slater (2010): Summary of electromagnetic field impacts to marine species[a]**

| Species Type | Species | Tested For | B-Field | E-Field | Frequency | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Benthic Species | North Sea prawn (*Crangon crangon*)<br><br>Round crab (*Rhithropanopeus harrisi*)<br><br>Blue mussel (*Mytilus edulis*) | Survival | 3.7mT (37G) | - | - | No detection | Bochert and Zettler (2004) |
| Benthic Species | Blue mussel (*Mytilus edulis*) | Biochemical parameters | 5.8, 8, and 80 mT (58, 80, 800 G) | - | - | 20% decrease in hydration and a 15% decrease in amine nitrogen values | Aristharkhov et al. (1988) |
| Benthic Species | Sea urchins | Developmental abnormalities | 10 mT – 0.1 T (100G - 1000G) | - | - | Delayed mitotic cycle of early embryos and great increase in the incidence of exogastrulation (Note, exposure was continuous for 5 hours with samples taken every 15 minutes) | Levin and Ernst (1997) |
| Teleost Fish | Flounder (*Plathichthys flesus*) | Survival | 3.7mT (37G) | -- | -- | No detection | Bochert and Zettler (2004) |
| Teleost Fish | Salmonids (general) | Bradycardia | -- | 7 μV/cm to 70 μV/cm | -- | Elevated heart rate | Marino and Becker (1977) |
| Teleost Fish | Salmonids (general) | First Response | -- | 0.5 to 7.5 V/m | -- | Shuddering of gills and fins | Marino and Becker (1977) |

| Species Type | Species | Tested For | B-Field | E-Field | Frequency | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Teleost Fish | Salmonids (general) | Anode reaction | - | 0.025 V/m to 15 V/m | - | Swims towards an electrically charged anode | Marino and Becker (1977) |
| Teleost Fish | Salmonids (general) | Electro-narcosis or Paralysis | - | 15 V/m | - | Electro-narcosis or Paralysis | Balayev (1980), Balayev and Fursa (1980) |
| Teleost Fish | Eels (general) | Bradycardia | - | 7 to 70 µV/cm (0.007 to 0.07 V/m) | - | Elevated heart rate | Marino & Becker (1977) |
| Teleost Fish | Eels (general) | First Response | - | 0.5 to 7.5 V/m | - | Shuddering of gills and fins | Marino & Becker (1977) |
| Teleost Fish | Eels (general) | Anode reaction | - | 25 µV/m (0.025 V/m) to 15 V/m | - | Swims towards an electrically charged anode | Marino & Becker (1977) |
| Teleost Fish | Eels (general) | Electro-narcosis or Paralysis | - | 15 V/m | - | Electro-narcosis or Paralysis | Balayev (1980), Balayev & Fursa (1980) |
| Teleost Fish | Silver eels (*Anguilla anguilla*) | Migration | Same order of magnitude as the Earth's geomagnetic field at a distance of 10m | - | - | Approximately 60% crossed the cable | Westerberg & Begout-Anras (2004) |
| Teleost Fish | Japanese eel (*Anguilla japonica*) | Magneto-sensitivity | 12,663 nT (0.12663G) to 192,473 nT (0.192473 G) | - | - | Exhibited significant conditioned response | Nishi et al. (2004) |
| Elasmobranchs | Sharks (general) | AC current sensitivity | All | All | 1/8 Hz and 8 Hz | Effects basic function | Kalmijin (2000b), Walker et al. (2003) |
| Elasmobranchs | Blue shark (*P. glauca*) | Sensitivity to electric fields | -- | 8 µA | -- | Repeated circling and attacked apparatus. | Kalmijn (1982) |

| Species Type | Species | Tested For | B-Field | E-Field | Frequency | Effect | Reference |
|---|---|---|---|---|---|---|---|
| Elasmobranchs | Small dogfish (*Mustelus canis*) | Sensitivity to electric fields | - | <0.021 µV/cm | - | Attacked from 18 cm or more away from the source | Kalmijn (1982) |
| Elasmobranchs | Large dogfish | Sensitivity to electric fields | - | 5 nV/m | - | Attacked from 38 cm or more away from source | Kalmijn (1982) |
| Elasmobranchs | Skates (general) | Cardiac response | - | 1 x 10-9 V/m | 5 Hz (uniform square wave) | Cardiac responses | Kalmijn (1966) |
| Elasmobranchs | Skates (*Raja clavata*) | Respiratory and cardiac responses | - | 10-6 V/m | 5 Hz (uniform square wave) | Respiratory and cardiac rhythms are affected | Kalmijn (1966) |
| Elasmobranchs | Skates (*Raja clavata*) | Cardiac response | - | 4 x 10-5 V/m | 5 Hz (uniform square wave) | Slowing down of the heartbeat | Kalmijn (1966) |
| Elasmobranchs | Stingray (general) | Orientation | - | Similar to those produced by ocean currents < 5nV/m (5 x 10-9 V/m) | - | Ability to orient relative to uniform electric fields similar to those produced by ocean currents | Kalmijn (1982) |
| Turtles | Green sea turtle (*Chelonia mydas*) | Navigation | Variable | - | - | No detection | Papi et al., 2000 |
| Marine mammals | Whales and dolphins (general) | Navigation | Earth's magnetic field ±0.5mG | - | - | Use of magnetic maps to travel in areas of low magnetic intensity and gradient | Walker et al. (2003) |
| Marine mammals | Common Dolphin (*Delphinus delphis*) Risso's dolphin (*Grampus griseus*) Atlantic white-sided dolphin (*Lagenorhynchus acutus*) Finwhale (*Balaenoptera physalus*) Long-finned pilot whale | Sensitivity to stranding | Earth's magnetic field ±0.5mG | - | - | Significantly statistically sensitive to stranding | Kirschvink et al. (1986) |

| Species Type | Species | Tested For | B-Field | E-Field | Frequency | Effect | Reference |
|---|---|---|---|---|---|---|---|
| | (*Globicephala malaena*) | | | | | | |

Notes:
[a] Includes both anthropogenic and natural sources

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# Appendix D: Table 1 from Emma (2016)

### Table D-1. Table 1 of Emma (2016)

Example range of species in groupings that have been assessed for responses to EMFs and the range of microteslas (μT) they are exposed to. "Untested" signifies the impact was not tested for. 'Lab cond.' signifies laboratory conditions as described in the research method

| Species Assessed | Location | Exposed EMF (μT) | Behavior Impact | Physiological Impact |
|---|---|---|---|---|
| Rock crab (*Metacarcinus anthonyi*) | California | 46-80 | None found | Untested |
| Rock crab (*Cancer productus*) | California | 46-80 | None found | Untested |
| Round crab (*Rhithropanopeus harrisii*) | Lab cond. | 3,700 | Untested | None found |
| Dungeness crab (*Cancer magister*) | Lab cond. | 314-1,103 | Attraction to EMF and increased activity | Untested |
| Shrimp (*Crangon crangon*) | Lab cond. | 3,700 | Untested | None found |
| Blue mussel (*Mytilus edulis*) | Lab cond. | 3,700 | Untested | None found on gonads or fitness |
| Isopod (*Saduria entomon*) | Lab cond. | 3,700 | Untested | None found |
| Flounder (*Plathicthys flesus*) | Lab cond. | 3,000-3,700 | Untested | None found |
| Coho salmon (*Oncorhynchus kisutch*) | Lab cond. | 3,000 | Predator avoidance behaviour | None found |
| Atlantic halibut (*Hippoglossus hippoglossus*) | Lab cond. | 3,000 | None found | None found on larval development |
| California halibut (*Paralichthys californicus*) | Lab cond. | 3,000 | None found | None found on larval development |
| European eel (*Anguilla anguilla*) | Baltic Sea | >5 at 60 m distance | Decreased swim speed | None found |
| Japanese eel (*Anguilla japonica*) | Lab cond. | 13-19 | Untested | Decreased heart rate |
| Blue shark (*Prionace glauca*) | NE Atlantic | 464,000-885,000 | Attraction to magnet | Untested |

# Appendix E: Table 1 from Klimley et al. (2021)

### Table E-1. Table 1 of Klimley et al. (2021)

Examples of documented impacts of anthropogenic EMFs on navigational abilities of marine species

| Species | Anthropogenic EMF | Observed Impact | References |
|---|---|---|---|
| European eels (*Anguilla anguilla*) | Energized undersea cable, altering magnetic intensity by ~10% | Telemetered animals decreased swimming rates | Westerberg and Lagenfelt (2008) |
| Chinook salmon (*Oncorhynchus tshawytscha*) | Energized underwater cable, altering magnetic intensity by ~10% | Alterations to migratory routes and timing | Klimley, Wyman, and Kavet (2017) |
| Little skate (*Leucoraja erinacea*) | Energized undersea cable under housing cage that distorted local field intensity by up to 27.2% | The presence of EMFs resulted in more exploratory activity | Hutchison, Gill, Sigray, He, and King (2020) |
| American lobster (*Homarus americanus*) | Cable under rearing cage that distorted local field intensity by up to 27.2% | The presence of EMFs resulted in more exploratory activity | Hutchison, Gill, et al. (2020) |
| Steelhead trout (*Oncorhynchus mykiss*) | Iron pipe near rearing tank, altering magnetic intensity by 24% and inclination angle by 12% | Fish failed to differentiate “magnetic displacements” in lab assays that show use of a magnetic map; controls did | Putman, Meinke, and Noakes (2014) |
| Loggerhead Sea turtle (*Caretta caretta*) | Magnets placed around nests, altering magnetic intensity by a mean of 71% (range 23–564%) | Turtles failed to differentiate “magnetic displacements” in lab assays that show use of a magnetic map; controls did | Fuxjager, Davidoff, Mangiamele, and Lohmann (2014) |

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# Appendix F: Summary

**Table F-1. Summary of Appendix A through D**

| Citation | Taxa | Number of Taxa or Species Groups Evaluated for Behavioral Effects | Number of Observed Behavioral Effects | Number of Taxa or Species Groups Evaluated for Physiological Effects | Number of Observed Physiological Effects | Number of Taxa or Species Groups Evaluated for Survivorship Effects | Number of Observed Survivorship Effects |
|---|---|---|---|---|---|---|---|
| Albert et al. (2020), Appendix A | Invertebrates | 16 | 6 | 9 | 6 | 7 | 0 |
| Snyder et al. (2019), Appendix Ba | Invertebrates | 1 | 0 | - | - | - | - |
| Snyder et al. (2019), Appendix Ba | Teleost Fish | 4 | 1 (possible) | - | - | - | - |
| Snyder et al. (2019), Appendix Ba | Elasmobranch Fish | 1 | 0 | - | - | - | - |
| Fisher and Slater (2010), Appendix Cb | Invertebrates | - | - | 2 | 2 | 3 | 0 |
| Fisher and Slater (2010), Appendix Cb | Teleost Fish | 2 | 2 | 2 | 2 | 1 | 0 |
| Fisher and Slater (2010), Appendix Cb | Elasmobranch Fish | 4 | 4 | 2 | 2 | - | - |
| Fisher and Slater (2010), Appendix Cb | Sea Turtle | 1 | 0 | - | - | - | - |
| Emma (2016), Appendix D | Invertebrates | 3 | 1 | 4 | 0 | - | - |
| Emma (2016), Appendix D | Teleost Fish | 4 | 2 | 6 | 1 | - | - |
| Emma (2016), Appendix D | Elasmobranch Fish | 1 | 1 | - | - | - | - |

Notes: The results from the review in Appendix E (Klimley et al., 2021) are not included as that paper only included studies that were considered to demonstrate impacts.

[a] Evidence from laboratory studies of 50/60-Hz EMF from AC power cables or field studies on AC power cables.

[b] Species groups (general) responses were tallied versus individual species when there was overlap. This review provided information on marine mammals but the conclusions appeared theoretical and were not included here.

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