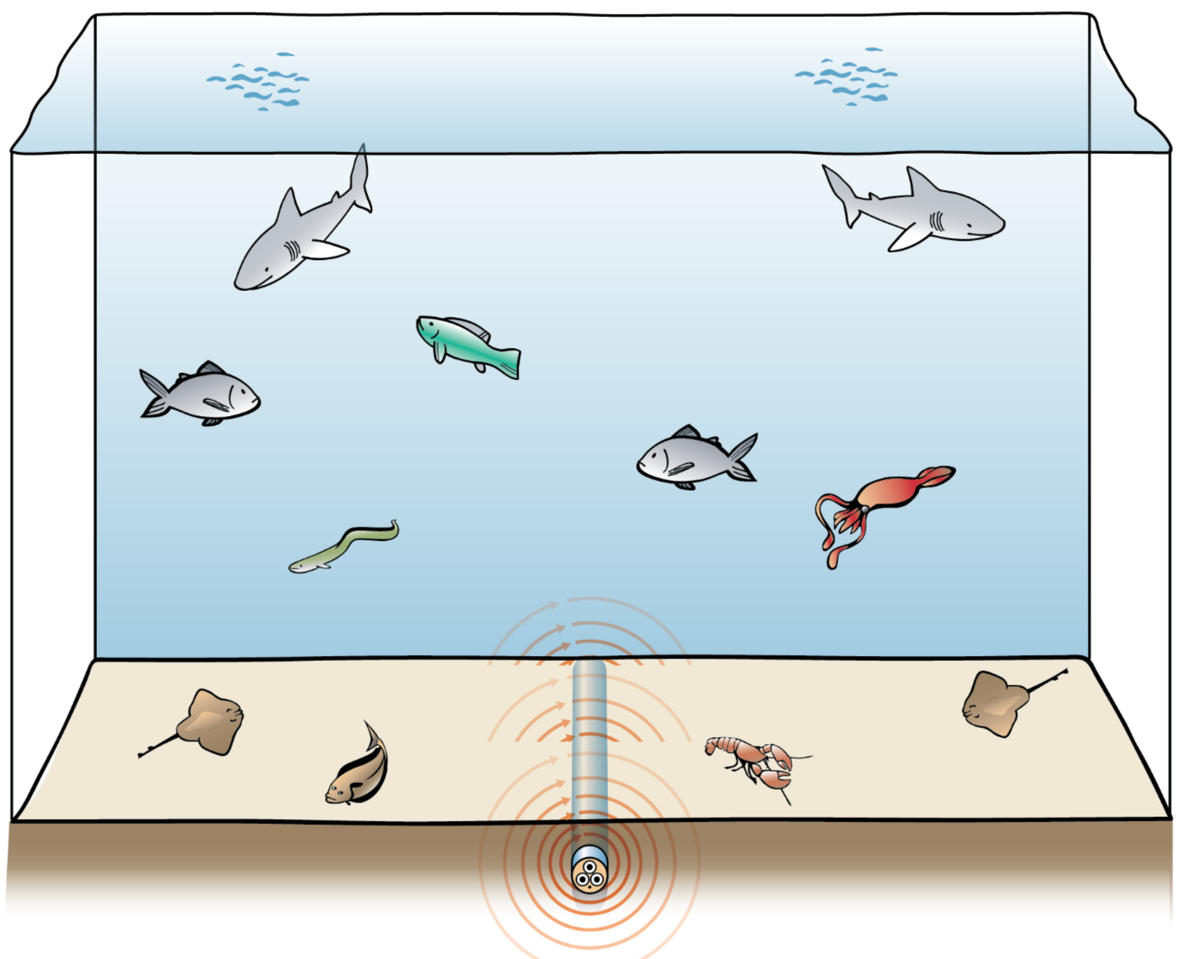
OCS Study
BOEM 2019-049

Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England



U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

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Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England

August 2019

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U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

DISCLAIMER

Study concept, oversight, and funding were provided by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), Environmental Studies Program, Washington, D.C., under Contract Number 140M0118A0003, BPA Call Order Number 140M0119F0012. This report has been technically reviewed by BOEM, and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

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CITATION

CSA Ocean Sciences Inc. and Exponent. 2019. *Evaluation of Potential EMF Effects on Fish Species of Commercial or Recreational Fishing Importance in Southern New England*. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA. OCS Study BOEM 2019-049. 59 pp.

ABOUT THE COVER

Cover graphic created by Kearns & West.

ACKNOWLEDGMENTS

Select graphics created by Kyle Vint and Jason Gershowitz with Kearns & West. The thoughtful review and comments from Robert Kavet are appreciated.

Executive Summary

Goals and Purpose

The development of offshore wind technology along the Atlantic coast of the United States (U.S.) has raised public concern about the potential effects of electric and magnetic fields (EMF) from undersea power cables on commercially and recreationally important fish species. This white paper provides a summary of the currently available science that addresses the potential effects of EMF from undersea power cables associated with offshore wind energy projects on fish species of concern. This summary has been developed to help the commercial and recreational fishing communities who have concern about the effect of EMF on fish. The report summarizes what is currently known about EMF issues, addresses common concerns and misconceptions, and provides background information about EMF in the environment and the relevance of EMF to fish species of concern in the southern New England area.

Public concern revolves around the potential impacts on fishes from EMF generated by the undersea power cables associated with offshore wind energy projects. Concerns include:

- Identification of species most and least likely to be affected by EMF;
- Potential EMF impacts on different species groups (e.g., closer to the surface [pelagic] or closer to the seafloor [demersal]);
- Potential EMF impacts on fishes during different life stages and behavioral activities (e.g., predation, mating, navigation);
- Cumulative or long-term impacts from EMF;
- Effectiveness of mitigation measures;
- European experience regarding fish impacts from EMF offshore wind energy projects; and
- Characterization of the existing ocean habitat regarding EMF levels.

The Bureau of Ocean Energy Management (BOEM) has completed multiple studies examining EMF issues and funded several field studies investigating the effects of EMF, the most recent of which include crab harvest and eel behavior. Other agencies and organizations worldwide also have funded studies and workshops to obtain additional data and understand the current level of knowledge regarding potential impacts on marine life from EMF. The current state of knowledge on this topic is summarized below.

Electric and Magnetic Fields

Natural Electric and Magnetic Fields

Naturally occurring EMF are present everywhere in the oceans. These fields are identified by the number of times the strength and direction of the field alternates each second, or hertz (Hz). Direct current (DC) fields have a constant direction (i.e., no oscillations); thus, their frequency is 0 Hz. DC fields are closely linked to the Earth’s magnetic field. While natural alternating current (AC) fields change direction many times per second, most natural AC fields in the marine environment occur at frequencies less than 10 Hz and are produced by marine organisms, including fish. Electric fields typically are measured in units of millivolts per meter (mV/m), and magnetic fields in units of milligauss (mG) and sometimes in units of microtesla (μT); 1 μT equals 10 mG.

Bioelectric fields are produced by all marine organisms (e.g., from a heartbeat or gill movement). Bioelectric fields are sources of natural AC and DC electric fields which are close to fish and may reach values as high at 500 mV/m, but these fields quickly drop within 10 to 20 cm (4 to 8 in.) from the source animal. Some marine organisms use these bioelectric fields to find each other or to locate prey (food).

The Earth's DC magnetic field causes a compass needle to align in a magnetic north-south direction. The strength of the Earth's DC magnetic field is approximately 516 mG (51.6 μT) along the southern New England coast. As ocean currents and organisms move through this DC magnetic field, a weak DC electric field is produced. For example, the electric field generated by the movement of the ocean currents through the Earth's magnetic field is reported to be approximately 0.075 mV/m (0.000075 V/m) or less.

EMF from Undersea Power Cables

Undersea cables used for power transfer are known sources of EMF, but telecommunication cables and undersea communication cables also generate AC and DC EMF. For offshore wind energy projects, the sources of EMF are inter-array cables that carry electricity from each wind turbine to the export cables, which carry that electricity to shore. To date, all proposed U.S. offshore wind energy projects plan to use AC electricity with a frequency of 60 Hz, the same as onshore electrical systems that power homes. In the U.S., DC power cables have not yet been proposed for offshore wind energy projects in southern New England but BOEM has received a proposal for an AC or DC collector system to bring power generated by multiple projects to shore.

Cables

As currently planned offshore wind energy projects will be larger than the existing Block Island Wind Farm, the associated cabling is expected to connect at one or more offshore substations. Based on past experience, such offshore wind energy projects' may employ inter-array cables that are 34.5- or 66-kV and approximately 155 to 165 mm (6.1 to 6.5 in.) in diameter while the export cables may be 138- to 230-kV cables and approximately 20 to 30 cm (7.9 to 11 in.) in diameter.

For these undersea power cables, the voltage on the copper conductors within the cable does not produce an electric field in the seafloor or ocean because it is shielded (blocked) by a grounded metallic covering on the cable. However, the magnetic field from the undersea power cable is shielded far less by this metallic covering; therefore, a 60-Hz magnetic field would surround each cable. The 60-Hz AC magnetic field induces a weak electric field in the surrounding ocean that is unrelated to the voltage of the cable, but instead is related to the amount of current flow on the cable. This means that when the current flow on the undersea power cable increases or decreases, both the magnetic and the induced electric fields increase or decrease.

The voltage, size, and operational characteristics of inter-array and export cables differ from one another and between offshore wind energy project designs. The cable size and voltage of AC inter-array cables are smaller than export cables, but the magnetic fields from each are quite similar. The export cables operate at a higher voltage, requiring less current to supply power, and less current means lower magnetic fields than otherwise would be expected as the export cable carries power generated by the entire wind energy project, not just a subset of the wind turbines. DC cables have not been proposed to export power from U.S. offshore wind energy projects to shore; however, DC EMF interact with organisms from AC EMF in different ways and cannot be compared directly.

Three major factors determine the exposure of marine organisms to magnetic and induced electric fields from undersea power cables: 1) the amount of electrical current being carried by the cable, 2) the design of the cable, and 3) the distance of marine organisms from the cable.

Cable Design and Electrical Current

AC undersea power cables are made with three copper conductors separated by layers of insulation and sheathing, bundled together, and twisted in a single armored (metallic-covered) cable. The outer layer is made up of small steel wires that partially shield the magnetic field from the outside environment due to opposing eddy currents induced in the armor and ferromagnetic shielding.

Each copper conductor bundle within a cable carries electricity with an associated magnetic field. The closer the conductor bundles are to each other, the greater the magnetic field cancellation and the lower the overall magnetic field. The combination of metal armor and twisting of the conductors results in considerably lower magnetic fields than bare straight cables. Ultimately, the EMF levels from this cable design are low and decrease rapidly with distance from the cable.

EMF from undersea power cables are directly proportional to the amount of current being carried by the cable. Higher voltage power cables have more insulation between conductors and require less current to deliver power. Therefore, the current and EMF are lower compared to a cable operating at a lower voltage.

Distance from the Cable

Undersea power cables typically are buried under the seafloor for their protection. As EMF from undersea power cables decrease rapidly with distance from the cable, burying the undersea cables substantially reduces the levels of magnetic and induced electric fields in seawater. Most inter-array and export cables are buried to a target depth between 0.9 and 1.8 m (3 and 6 ft). Increasing the burial depth from 1 to 2 m (3.3 to 6.6 ft) reduces the magnetic field at the seafloor about four-fold.

Where hardbottom seafloor conditions or existing infrastructure is encountered, the power cables are laid on the seafloor and often covered with 15 to 30 cm (6 to 12 in.) thick concrete mattresses, rock berms, or other measures to protect the cable. While this covering does not achieve the same level of EMF reduction as burial and distance, beyond approximately 3 m (10 ft) from the cable, the field levels for buried and mattress-covered cables are quite similar.

Fish Sensitivity to Electric and Magnetic Fields

The sensitivity of fish to EMF is based on the basic functions of their sensory organs. All animals' sensory organs receive signals from the surrounding environment; fishes also have abilities to detect water motion with their lateral lines, and some fish species can detect magnetic and sometimes electric fields with specialized sensory organs.

Marine animals are discussed by family groupings (cartilaginous fishes, bony fishes, invertebrates) as well as where in the water column they reside (closer to the surface [pelagic] or closer to the seafloor [demersal]). The cartilaginous group (elasmobranchs) is composed of sharks, skates, and rays. An important trait that binds the sharks and rays as a related group is the ability to sense electric fields. The bony fishes include basses, flounders, catfishes, eels, tunas, and others; however, the only bony fishes in the southern New England area known to be electrosensitive are Atlantic sturgeon (*Acipenser oxyrhynchus*) and shortnose sturgeon (*A. brevirostrum*). Overall, slightly less than one-third of the total list of species important to commercial and recreational anglers that reside in or around the southern New England area are electrosensitive.

Electrosensitive fish contain specialized organs that perceive naturally occurring electric fields and use them to locate prey or detect the presence of predators. The range over which these species can detect electric fields is limited to centimeters, not meters, around these species. Sharks, rays, and sturgeon possess specialized sensory organs called ampullae of Lorenzini, which are arranged in clusters, that can detect and process electric signals. In rays (and skates), ampullae tend to be clustered around the mouth and on the ventral side of the broad, flat body and along the wing (pectoral fin) margin on the dorsal side. In sharks, ampullae are distributed along the flanks and around the dorsal and ventral portions of the head. Sturgeon ampullae are clustered on the head.

Skates, because of their bottom-dwelling habitat preference would be the most likely of the regional fishery species to potentially detect electric fields. Skates feed on bottom-dwelling invertebrates and some fishes. Average bioelectric fields produced by invertebrates and bony fish can differ by a factor of 10; however, these all are produced at frequencies of 10 Hz or less, far lower in frequency than the electric fields from the AC power cables and hence outside the typical "tuned" range of species sensitivities. Skates likely rely on their electric senses to find mates more than larger, mobile sharks. There is little to no evidence that electrosensitive fish react to the weak levels of electric fields present around AC undersea power cables.

An animal's ability to detect and respond to the Earth's natural static magnetic field is called magnetosensitivity. Many fish species, including bony fishes and sharks, use the Earth's natural static magnetic field for guidance during migration and to navigate in the oceans. Magnetic senses work with other senses to help fish find food, habitat, and spawning locations. Of greater importance, these magnetic senses of fish are "tuned" to the frequency of the Earth's DC (0 Hz) magnetic field, not to the 60-Hz magnetic fields produced by undersea power cables associated with offshore wind energy projects; therefore, outside the known range of detection by magnetosensitive fish species. Species reported to be magnetosensitive include salmon, American eel (*Anguilla rostrate)*, sturgeons, yellowfin tuna (*Thunnus albacares)*, sharks, skates, and rays.

Figure ES-1 lists grouped fish species important to commercial and recreational anglers in and around the southern New England area that are sensitive to EMF and provides their general location within the water column, pelagic or demersal.

Water Column Preference of Fish Groups

The pelagic group in the southern New England area consists of 28 species: 12 sharks and rays, 14 bony fishes, and 2 invertebrates (squids). The demersal group is represented by 35 species: 6 invertebrates and 29 fishes (**Figure ES-1**). Of the fishes, 22 are bony fishes and 7 are skates.

The list of commercially and recreationally important fish species from the southern New England area (**Figure ES-1**) includes eight bottom-dwelling species that are electrosensitive or magnetosensitive. These species would vary in the likelihood of exposure to EMF produced by undersea power cables because of their habitat preferences. The 28 pelagic species (water column dwellers) are less likely to come close to buried power cables during normal migratory or foraging activities, which includes 12 shark species that are electrosensitive and magnetosensitive but are highly unlikely to detect weak electric fields emanating from undersea power cables because of their normal habits. There are 35 species on the list that are demersal (bottom dwellers) capable of very close proximity to buried undersea power cables associated with offshore wind energy projects. The eight bottom-dwelling electrosensitive or magnetosensitive species (seven skate species and the American lobster (*Homarus americanus*) in this group likely would encounter magnetic fields as well as electric fields induced by the magnetic field from undersea power cables.

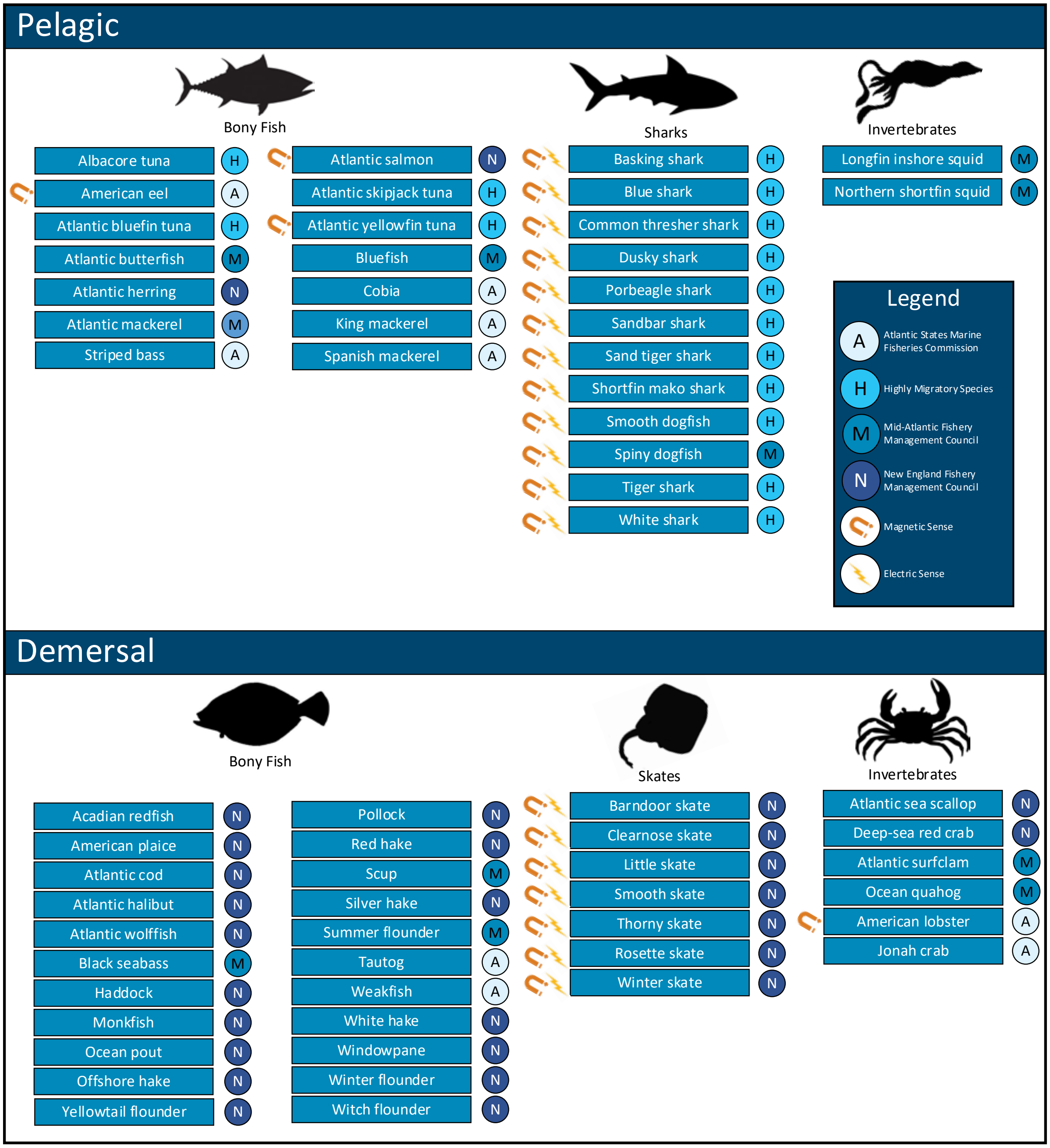

Figure ES-1. Species important to commercial and recreational anglers in southern New England area

Ⓐ = Managed by Atlantic States Marine Fisheries Commission, Ⓗ = Highly Migratory Species, Ⓜ = Managed by Mid-Atlantic Fishery Management Council, Ⓝ = Managed by New England Fishery Management Council, [magnet] = Magnetic Sense, [lightning] = Electric Sense.

Relative EMF Exposure of Various Fish Groups

Demersal fish species that inhabit coastal seafloor habitats are the most likely to encounter the EMF produced by undersea power cables. Pelagic fish that swim in the open ocean and high above the seafloor will be less likely to encounter EMF produced by undersea power cables. Fish species that migrate between the ocean and freshwater may be more likely to swim over power cables installed in coastal environments. Exposure to EMF can be momentary or longer term. Most exposures are expected to be very short, on the order of minutes, not hours, occurring only when mobile fish swim through the cable route area. Because the area around undersea power cables where EMF levels are elevated is small (less than approximately 10 m [33 ft] around the cable), it represents only a tiny portion of the available habitat for fish species, many of which travel multiple kilometers in a day.

Overall Evaluation of Potential Electric and Magnetic Field Effects

EMF levels discussed in this white paper are well below the recommended limits for human exposure, which are 12 to 100 times higher than the EMF levels from cables measured at the seafloor. Common household items, including television sets, hair dryers, and electric drills, can emit EMF levels similar to or higher than those emitted by undersea power cables associated with offshore wind energy projects.

Method for Evaluation of Effects on Fish

To determine overall initial impact significance, two factors were considered: impact consequence and impact likelihood. The duration (short or long term) of the EMF exposure, and the relative location of the animal in the water column also were assessed. These analyses combined all parameters and applied professional judgment and a risk matrix. Negative impacts were rated 4 (High overall impact significance), 3 (Medium overall impact significance), 2 (Low overall impact significance), or 1 (Negligible overall impact significance).

Analysis

Species summary

Table ES-1 presents a summary of the potential impacts to fishes and invertebrates in the southern New England area from EMF associated with undersea AC undersea power cables. Pelagic species generally swim well above the seafloor and can be expected to rarely be exposed to the EMF at the lowest levels from AC undersea power cables buried in the seafloor. Within the water column, impacts would be localized and transient, with no adverse effects on any pelagic species. Effects on demersal (bottom dwellers) species are not expected due to lack of sensitivity of species to 60-Hz EMF.

Demersal species (e.g., skates), that dwell on the bottom, will be closer to the undersea power cables and thus encounter higher EMF levels when near the cable. Demersal species also are likely to be exposed for longer periods of time and may be largely constrained in terms of location. However, the rapid decay of the EMF minimizes potential impacts.

Table ES-1. Significance of potential impacts to fishes and invertebrates in the southern New England area from offshore wind energy projects' AC EMF

Species	Potential Impact	Criteria	Consequence	Likelihood of Exposure	Significance
Pelagic Habitat – Magnetic Fields					
American eel, Atlantic salmon	Impairment of navigation or homing	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible
Pelagic Habitat – Electric Fields					
Bony fishes: bluefish, striped bass, bluefish and others; Pelagic sharks	Changes in feeding success, mate finding, and evading predators	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Rare	1 – Negligible
Demersal Habitat – Magnetic Fields					
Clearnose skate, little skate, winter skate, barndoor skate, thorny skate, rosette skate, and smooth skate	Impairment of navigation or homing	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible
Demersal Habitat – Electric Fields					
Clearnose skate, little skate, winter skate, barndoor skate, thorny skate, rosette skate, and smooth skate	Changes in feeding success, mate finding, and evading predators	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible

Conclusions

The operation of offshore wind energy projects is not expected to negatively affect commercial and recreational fishes within the southern New England area. Negligible effects, if any, on bottom-dwelling species are anticipated. No negative effects on pelagic species are expected due to their distance from the power cables buried in the seafloor.

Specific conclusions:

- AC undersea power cables associated with offshore wind energy projects within the southern New England area will generate weak EMF at frequencies outside the known range of detection by electrosensitive and magnetosensitive fishes;
- Most fishery species in the southern New England area are bony fishes, which have not evolved to detect EMF at 60 Hz;
- Pelagic fishes have habitat preferences away from the seafloor;
- Bottom-dwelling fishes are most likely to encounter EMF from undersea power cables; however, EMF decays very quickly with distance from the cable which minimizes potential exposure;

- Skates are the species with the greatest potential for exposure to EMF from undersea power cables; however, EMF decays very quickly with distance from the cable which minimizes potential exposure; and.
- Review of the evidence to date does not indicate that EMF from undersea power cables negatively affects commercially and recreationally important fish species within the southern New England area.

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List of Abbreviations and Acronyms

µT	microtesla
AC	alternating current
BIWF	Block Island Wind Farm
BOEM	Bureau of Ocean Energy Management
DC	direct current
EIS	Environmental Impact Statement
EMF	electric and magnetic fields
ft	foot
GW	gigawatt
HDD	horizontal directional drill
Hz	hertz
HVDC	high voltage direct current
IPFs	Impact producing factors
in.	inch
km	kilometer
kV	kilovolt
m	meter
mG	milligauss
MRE	marine renewable energy
mi	mile
mm	millimeter
mV	millivolt
MW	megawatt
NEPA	National Environmental Policy Act
U.S.	United States

1 Introduction

With the future development of offshore wind technology as a source of energy along the Atlantic coast of the United States (U.S.), members of the public, particularly some commercial and recreational anglers along the New England and the mid-Atlantic coast, are expressing concerns about the potential impacts of electric and magnetic fields (EMF) from undersea power cables on commercially and recreationally important fish species. To address these concerns, the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM) has completed multiple studies examining the issue. Normandeau et al. [1] provided a literature synthesis of the available information regarding the effect of EMF on elasmobranchs, but also discussed impacts on other fishes, marine mammals, sea turtles, and invertebrates. This literature synthesis was updated by Hutchinson et al. [2], including a review of more than 60 additional papers. In addition, BOEM has funded several field studies on the effects of EMF on marine species [3,4]. BOEM also has funded several ongoing studies, including *Potential Impacts of Submarine Power Cables on Crab Harvest* and *Electromagnetic Field Impacts on American Eel Movement and Migration* (https://www.boem.gov/studies/). Several other agencies and organizations have funded additional studies and held workshops to determine current knowledge and obtain additional data [5,6,7,8].

The National Environmental Policy Act (NEPA) of 1969 requires use of the natural and social sciences in any planning and decision making that may have an effect on the human environment. To this end, BOEM conducts environmental impact assessments that inform the decision about offshore wind energy projects such as Environmental Impact Statements (EISs) and Environmental Assessments. A key component of NEPA is public involvement to ensure that all interested and affected parties are aware of the proposed action and provided opportunities to comment.

Therefore, to implement Secretarial Order 3355, the issues need to be summarized in supporting documents such as this white paper, thus providing sufficient information on EMF and associated potential impacts to commercially and recreationally important fish species to support future NEPA analyses. This white paper also serves as a source of information to ocean users and the general public.

1.1 Stakeholder Concerns, Perceptions, and Misconceptions of EMF

During BOEM's outreach to stakeholders during the permitting of existing and future offshore wind energy projects, NEPA process concerns have been raised by the public, in particular by some commercial and recreational anglers, regarding the impacts on fish from EMF associated with the undersea power cables of these projects. Concerns include identifying species that are most likely to be affected by EMF; identifying the potential for cumulative or long-term impacts; understanding the effectiveness of mitigation measures (e.g., cable burial) to reduce impacts to humans and fish species; understanding potential impacts of EMF on species groups (e.g., demersal species, pelagic species); summarizing what has been learned from Europe regarding EMF from offshore wind energy projects; identifying potential impacts of EMF to fisheries stocks during different life stages and behavioral activities (e.g., predation, mating, navigation); and providing a better understanding of the existing ocean habitat regarding EMF levels. This white paper addresses these as well as other concerns and clarify perceptions and misconceptions regarding EMF and the potential impacts to fish species.

1.2 NEPA and the White Paper

NEPA established the Council on Environmental Quality to advise federal agencies on the environmental decision-making process and to oversee and coordinate the development of federal environmental policy. Department of the Interior Secretarial Order 3355 calls for the streamlining of the NEPA process, which includes limiting an EIS to 150 pages. The order encourages incorporation of information and data from sources by reference to provide discussions and evaluations of issues in detail.

The other goal of this white paper is to provide information that addresses potential effects of EMF from undersea power cables (inter-array and export) associated with offshore wind energy projects on commercial and recreational fish species. The report is intended to be incorporated by reference in future NEPA documents. The white paper 1) summarizes what is currently known about EMF issues in a form readily accessible to the public but is not a literature synthesis or summary of all information and studies performed to date; 2) addresses the most common stakeholder concerns and misconceptions; and 3) provides substantive background information about EMF in the environment and relevance to fish species of commercial and recreational fishing importance in the southern New England area (**Figure 1**). This area encompasses the continental shelf off southern Massachusetts, Rhode Island, New York, and New Jersey, and extends from the shoreline to the 37-m (120-ft) water depth contour. This outer depth limit was chosen because no current or planned offshore wind energy projects are in water depths greater than 37 m (120 ft). This white paper also provides graphics and other means of communication that can be incorporated into the NEPA process and for stakeholder outreach.

The information included in this document reflects currently available science; however, this science is continually advancing. Therefore, BOEM will update the materials periodically as new information becomes available and ongoing studies are completed. BOEM is required to use the best available science in all its documents and evaluations of activities authorized by the agency.

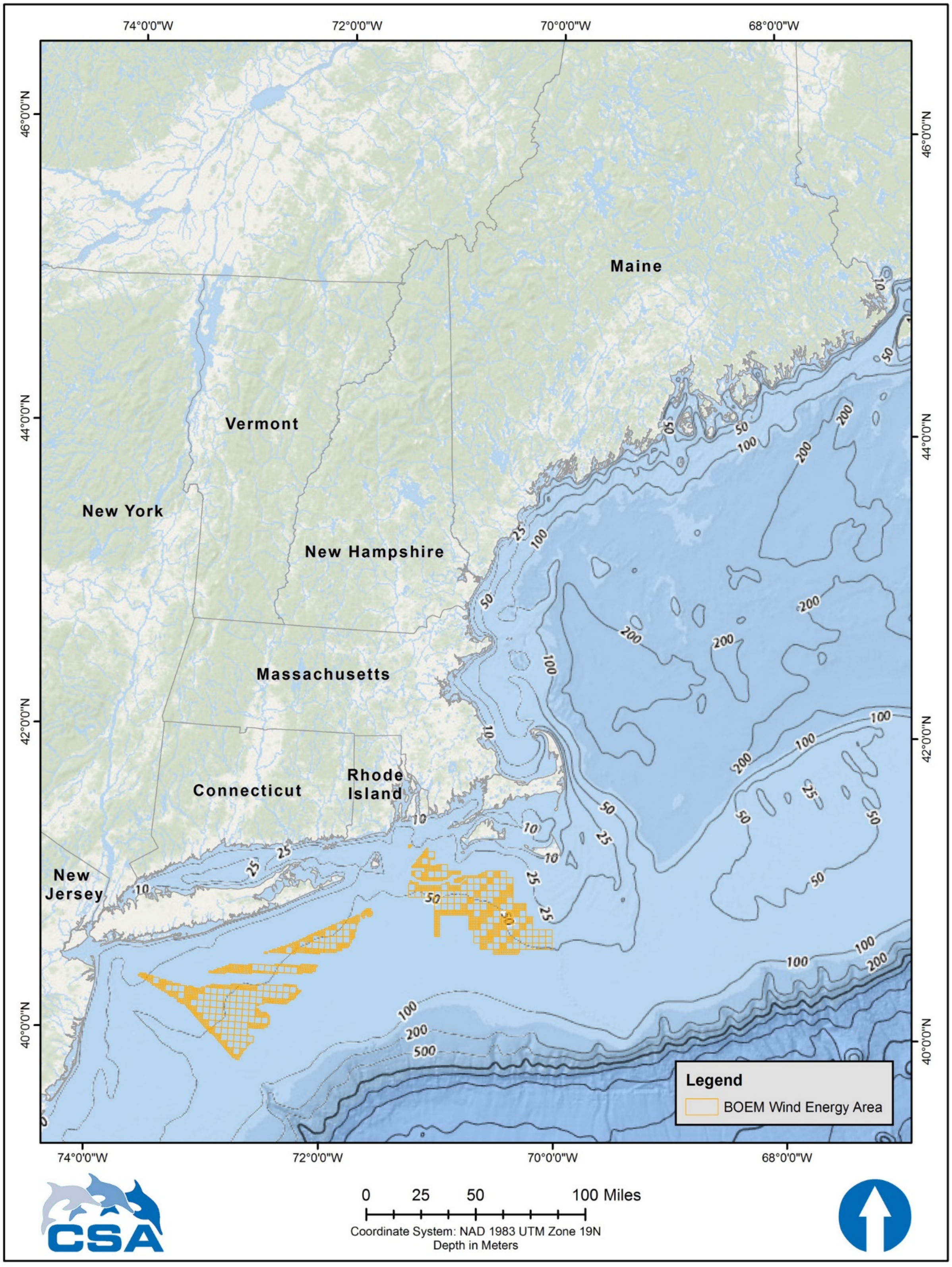


Figure 1. Southern New England area of interest
Identified by BOEM as potential Wind Energy Areas as of July 2019.

2 Description of a U.S. Offshore Wind Energy Projects

2.1 Wind Energy Project Layout, Components, and Undersea Power Cable Routes – Block Island Wind Farm

The Block Island Wind Farm (BIWF) is the first commercial offshore wind project installed in the U.S. It is located 4.8 km (3 mi) offshore Block Island, Rhode Island, in approximately 26 m (85 ft) water depth. The BIWF consists of 5 turbines in a single row, each with an output capacity of 6 megawatts (MW) for a maximum total of 30 MW. The turbines are connected by 34.5-kilovolt (kV) inter-array cables, which connect to the 34.5-kV undersea export cable that goes to Block Island. The buried cable comes ashore via horizontal directional drilling (HDD) to a manhole located in a beach parking lot, then traverses underground to an interconnection facility, and finally connects to a power substation for distribution to homes and businesses. From Block Island, a separate 34.5-kV undersea export cable (sea2shore) carries electricity not needed locally to the mainland. The burial depth of the inter-array and export cables typically ranges from 1.2 to 2.4 m (4 to 8 ft) below the seafloor, depending on the substrate encountered. In areas where less than 1.2 m (4 ft) of burial was anticipated, the cable was covered with concrete mattresses or rock placement for additional protection.

2.2 Comparison of BIWF with Future Regional Offshore Wind Energy Projects

The BIWF is representative of offshore wind energy projects currently in the various planning phases, albeit on a smaller scale. New projects have wind turbines with greater generating capacity and many more turbines. As with BIWF, the design of planned offshore wind energy projects includes the wind generator turbines to be connected with undersea inter-array cables and the export cable(s) to shore (**Figure 2**). Another difference between the BIWF and planned offshore wind energy projects is that the currently proposed projects plan for the inter-array cables and export cables to be connected at one or more offshore substations. The future planned offshore wind energy project turbines also are expected to have a greater maximum output capacity of up to 17 MW per turbine with a maximum planned total capacity of up to 1,700 MW.

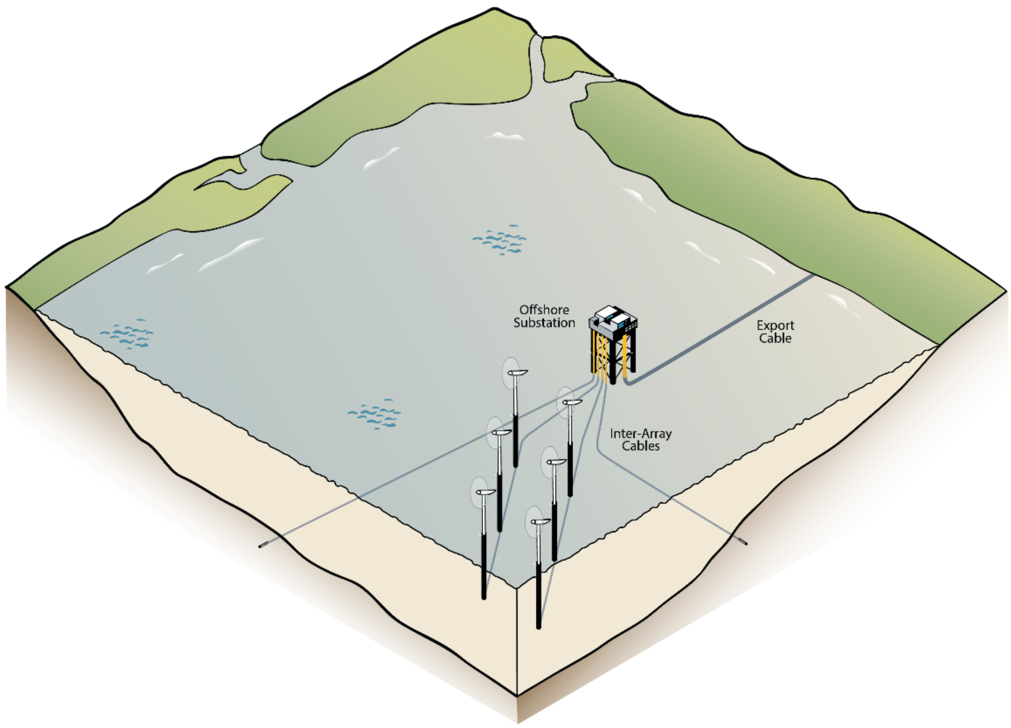


Figure 2. Diagram of the components of a typical offshore wind energy project

2.3 Discussion of Wind Energy Projects

In the U.S., only one offshore wind energy project (BIWF) with five turbines has been completed and is operational. Proposed offshore wind energy projects with more turbines are planned for installation offshore Massachusetts, Rhode Island, and New York and are under permitting review. There currently are seven offshore wind energy projects under permitting review located off Massachusetts/Rhode Island: Bay State Wind (>1,000 MW), Vineyard Wind I (800 MW) and II, Equinor Wind, Mayflower Wind, Revolution Wind (700 MW), and South Fork Wind Farm (130 MW). In addition, there is currently one offshore wind energy project, Empire Wind (816 MW), located off New York that currently is in the permitting process. There are several other planned projects beyond the southern New England area of interest, including Skipjack Wind Farm (120 MW), Garden State Wind, and Maryland Offshore Wind (750 MW) off Delaware; Ocean Wind (1,000 MW), Atlantic Shores Wind, Nautilus Wind (24 MW), and Boardwalk Wind (816 MW) offshore New Jersey; and Kitty Hawk Wind offshore North Carolina. **Figure 3** shows the undersea alternating current (AC) export cables of existing offshore wind energy projects as well as those in the advanced planning stages, as of July 2019, and direct current (DC) utility undersea power cables.

As discussed earlier and illustrated in **Figure 2**, the wind turbines within existing and currently planned offshore wind energy projects are connected with inter-array cables that typically are 34.5- or 66-kV cables approximately 155 to 165 mm (6.1 to 6.5 in.) in diameter. The export cables that connect the inter-array cables to shore in existing and currently planned projects typically are 138- to 230-kV cables approximately 200 to 300 mm (7.9 to 11 in.) in diameter. To date, all U.S. offshore wind energy projects use AC cables for power transmission. However, there are three DC power cables installed along the U.S. Atlantic coast (Cross Sound Cable, Neptune Regional Transmission System, and Hudson Cable), but these cables are used to transfer electricity between states or to supply power to offshore islands and are often labeled as high voltage direct current (HVDC) cables.

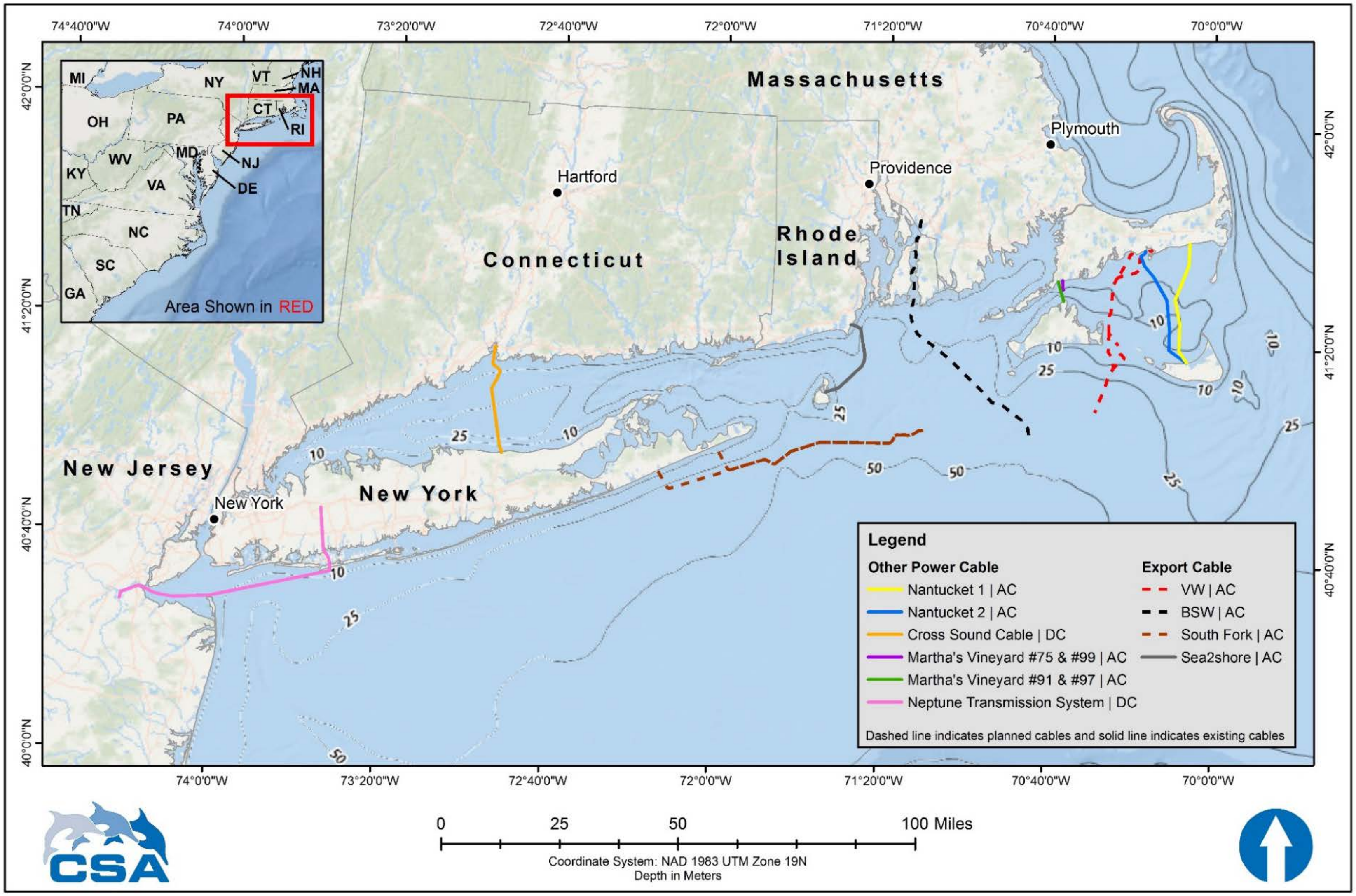


Figure 3. Undersea AC cables associated with existing and future wind energy projects and DC cables connecting utility power systems with the southern New England area of interest
As of July 2019.

In Europe, more than 100 offshore wind farms have been installed with 4 to 175 turbines per installation, and together, they produce 19 gigawatts (GW) of electricity [9], equivalent to the output of 38 500-MW coal or gas generation plants. As of July 2019, over the next 4 years, onshore and offshore wind energy in Europe is projected to increase on average by 16.5 GW per year [10,11]. In 2018, countries of the European Union installed more wind energy capacity than any other form of electric generation, with varying maximum power outputs and types of wind turbines among countries. From 2017 to 2018, the average rated capacity of turbines ranged between 5.9 and 6.8 MW. An example of larger turbines installed in the European Offshore Wind Development Centre wind farms are two 8.8 MW turbines with a rotor diameter of 164 m (538 ft) [11]. The largest project in Europe is the London Array in the United Kingdom, with a total project capacity of 630 MW and 175 turbines.

The European offshore wind farms typically use 22- to 33-kV inter-array cables to an offshore substation and 132- to 155-kV export cables to shore. The export cables typically range from 11 to 125 km (6.8 to 78 mi) in length [12].

3 Electric and Magnetic Fields in the Sea

3.1 Characteristics of Natural EMF Sources

Naturally occurring EMF are present everywhere in the world's seas and oceans. These fields are identified by their oscillation frequency (i.e., the number of times the strength and direction of the field alternates each second). The frequency of EMF is given in cycles per second or hertz (Hz).

Static (or DC) fields have a constant direction (i.e., no oscillations); thus, their frequency is 0 Hz. DC fields are closely linked to Earth's magnetic field as well as in the ocean linked to the movement of charges in ocean currents. In contrast, AC fields change direction many times per second (**Figure 4**). Natural AC fields relevant to marine organisms mostly occur at frequencies less than 10 Hz and are produced by marine organisms, including fish.

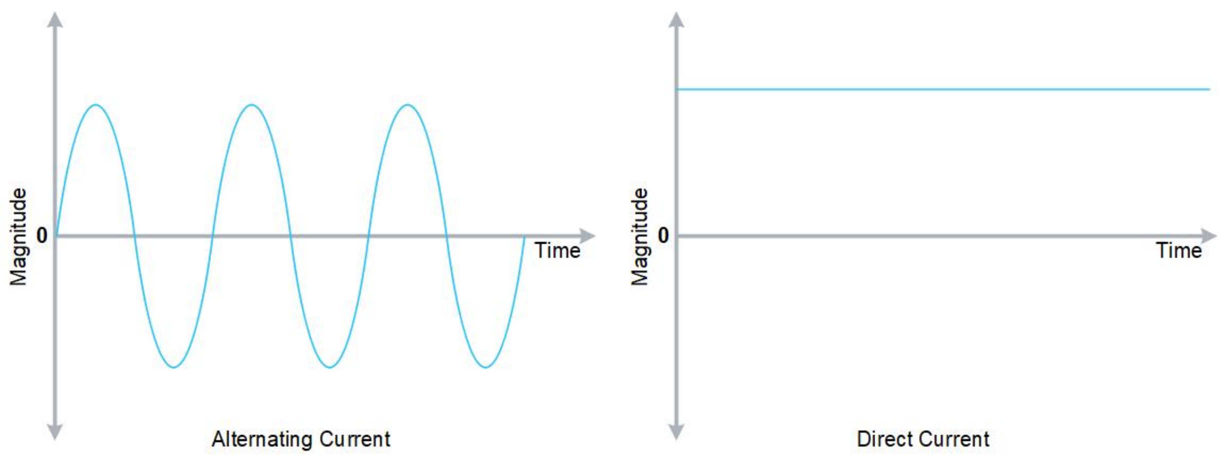


Figure 4. AC versus DC fields

EMF in marine environments are low intensity, so electric fields typically are measured in units of: millivolts per meter (mV/m), and magnetic fields in units of milligauss (mG). However, magnetic fields also can be measured in units of microtesla (µT); 1 µT equals 10 mG.

> **EMF Units**
>
> **Magnetic Fields**
> - Milligauss (mG) or microtesla (µT)
> - 1 µT = 10 mG
>
> **Electric Fields**
> - Millivolts per meter (mV/m)
> - 1 mV = 0.001 V

The Earth's DC magnetic field has a magnitude of approximately 516 mG (51.6 µT) along the southern New England coast [13]. This field originates from the flow of liquid metal in the Earth's core and local anomalies in the Earth's crust and results in a magnetic field much like a massive bar magnet with a north and south pole. This DC magnetic field causes a compass needle to align in a magnetic north-south direction.

As ocean currents and organisms move through this static magnetic field, a weak static electric field is produced. For example, the electric field generated by the movement of the ocean currents through Earth's magnetic field is reported to be approximately 0.075 mV/m or less [14,15,16].

Electric fields are produced by all marine organisms. The beating of a heart, gill movement, nerve impulses within an organism, and uneven distribution of electric charge on the body are sources of AC and DC electric fields of biological origin; these are known collectively as bioelectric fields. Such fields close to fish may reach values as high at 500 mV/m, but they quickly drop to much lower levels within 10 to 20 cm (4 to 8 in.) of the source animal [17,18]. Some marine organisms use these fields to find each other or to locate prey.

3.2 EMF Characteristics of Offshore Wind Energy Projects

There are many EMF sources introduced by human activity in the ocean, including components of offshore wind energy projects. Undersea cables used for power transfer can be notable sources of EMF [19], but corrosion of metals, telecommunication cables, and undersea communication cables also generate AC and DC EMF. Some less obvious sources of DC magnetic fields are steel ships and bridges. For example, Kavet et al. [20] measured DC magnetic fields in San Francisco Bay from a 400 MW DC undersea cable, under steel bridges, and near other sources of anomalous magnetic fields in the water. The researchers reported measured fields from the latter sources "could be up to 100 times greater than those from the [DC undersea] cable". They did not find that the magnetic field from the DC power cables or the other sources affected the natural migration of tagged salmonid smolts and adult green sturgeon [21,22].

For offshore wind energy projects, the sources of EMF are 1) the <u>inter-array cables</u> that carry electricity generated by individual wind turbines, and 2) the <u>export cables</u> that carry electricity from the inter-array cables to shore. For offshore wind energy projects with many turbines, the inter-array and export cables are connected at an offshore substation mounted on a platform (**Figure 2**). The generators atop wind turbine structures and the transformers and other power equipment on substation platforms are too far above the ocean to be sources of EMF exposure to fish.

To date, the electricity generated by proposed U.S. offshore wind energy projects is AC electricity with a frequency of 60 Hz, the same frequency as the electricity distributed by onshore electrical systems. <u>Thus, the research incorporated in this white paper focuses on exposure of marine organisms to AC EMF produced by undersea power cables associated with offshore wind energy projects</u>.

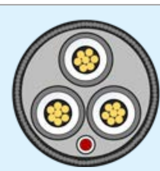
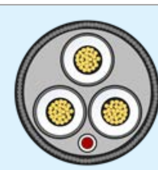
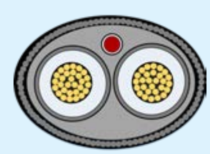
While aboveground power lines produce electric fields (proportional to the voltage of the lines) and magnetic fields (proportional to flow of electric current) in the air around the power line, the EMF from undersea power cables are somewhat different. For undersea power cables, the <u>voltage on the wire conductors within the cable does not produce an electric field in the seafloor or ocean</u> because it is locked (shielded) by the outer grounded metallic sheath encircling the conductors. However, the metal sheath magnetic around the undersea power cable do not shield the environment from the magnetic field; therefore, a 60-Hz magnetic field surrounds each cable. This oscillating AC magnetic field, in turn, induces a weak electric field in the surrounding ocean that is unrelated to the voltage of the cable. This means when the current flow on the undersea power cable increases or decreases, both the magnetic field and the induced electric field increase or decrease.

Although there are undersea DC power cables in the U.S. (not associated with offshore wind), this type of cable has not yet been used to connect proposed offshore wind energy projects to shore. In the future, the electricity generated by offshore wind energy projects in the U.S. may be converted from AC to DC for connecting multiple offshore wind energy projects or for transmitting power over export cables where the offshore wind energy projects are so far from shore that the power losses for an AC cable would be very great. Other advantages of DC power cables are that only two conductors are needed, and the conductors are smaller and lighter. Thus far, these advantages have been offset by very high costs of converting AC to DC offshore and then DC back to AC where the cable connects to onshore AC power systems. In the Baltic Sea off the coast of Germany, the factors favoring DC undersea power cables associated with offshore wind outweigh the AC to DC conversion costs. As such, 3 projects have been completed with DC undersea power cables linking offshore facilities and 10 DC connections from wind farms to shore are operating or under construction [23].

3.2.1 Characteristics of Undersea Power Cables Associated with Offshore Wind Energy Project

The voltage, size, operational characteristics, and magnetic fields of inter-array and export cables differ from one another and among different offshore wind energy project designs. **Table 1** compares some of the characteristics of undersea power cables from offshore wind energy projects. While the size and voltage of AC inter-array cables are smaller than AC export cables, the magnetic fields are quite similar. This is because magnetic fields depend on the current, and although the AC export cable carries all the power generated from the entire offshore wind energy project, the current flow is not much greater than on the AC inter-array cables because it operates at a higher voltage and less current is required to supply power. Less current means lower magnetic fields.

Table 1. Comparison of offshore undersea power cables. Magnetic fields are calculated between seafloor and 1 m above seafloor for cables buried ~1 - 2 m below seafloor[1]

Power Cable Characteristic	 AC Inter-Array Cable	 AC Export Cable	 DC Export Cables
Cable Voltage (kV)	34.5 to 161	138 to 400	±75 to ±500[2]
Cable Size (mm)	125 to 170	210 to 265	130[4]
Cable Current (A)	700 to 760	700 to 1265	625 to 1330[2]
AC Magnetic Field at seafloor (mG)	20 to 65	30 to 165	0[3]
DC Magnetic Field at seafloor (mG)	0[3]	0[3]	590 to 1250[2]

[1] Figure 5 provides a detailed cable cross section with the components.
[2] DC cable voltages, currents, and magnetic fields from Normandeau et al. [1], Appendix B, Tables B-1 and B-7.
[3] AC power cables are sources of AC magnetic fields but may be sources of very weak DC fields if ground currents flow on the cables or shields. DC power cables are sources of DC magnetic fields, and depending upon the technology, sometimes very weak harmonic AC fields.
[4] per cable rated at ±320 kV; AC cable at similar load lists bundle diameter as 220 mm [24].

Table 1 also includes DC power cables for comparison to AC power cables; however, to date, only one developer in the U.S. has proposed to deliver electricity generated offshore to land over DC power cables. Such DC power cables would be sources of DC magnetic fields, and depending on the technology, very weak harmonic AC fields. Although measured in the same units as AC fields, DC EMF are quite different in the way they interact with organisms and cannot be compared directly. Also, the magnetic field from DC power cables can add to or reduce the static magnetic field of the Earth based on the placement of the cables (i.e., side by side or next to one another) as well as the geographic alignment of the cables (i.e., running north-south or east-west, etc.).

3.2.2 Factors that Affect EMF Levels from Undersea Power Cables Associated with Offshore Wind Energy Projects

Three major factors determine levels of the magnetic and induced electric fields from offshore wind energy projects: 1) the amount of electrical current being carried by the cable, 2) the design of the cable, and 3) the distance of marine organisms from the cable.

Cable Current

Every cable has a maximum current capacity, which is determined by the cable design and operating voltage. Power is the primary design criterion, which is determined by voltage and current. Higher voltage will decrease the needed current for the same power but will increase cable size (and expense) because insulation layers etc. will need to be larger. Once voltage is set, current is the limiting factor (thermal heating). If greater power is needed, then the conductors must be larger to accommodate the higher current demand (also increasing cable size and cost).

Magnetic fields, and thus induced electric fields from power cables are directly proportional to the amount of current being on the cable, which depends on project design and operational factors (**Table 2**).

Table 2. Factors affecting AC cable currents and EMF levels from undersea power cables associated with offshore wind energy projects

Design Factors	Effect on EMF
Generating capacity of turbines	As turbines generate more power, there is a proportional increase in cable current and EMF.
Number of turbines in the wind energy project	More turbines increase cable current levels and EMF.
Number of turbines connected to each inter-array cable	More turbines connected to an inter-array cable will increase current levels and EMF.
Number of export cables	Dividing the total power output among multiple export cables reduces the current on each individual export cable and reduces EMF per cable.
Voltage at which power is transmitted	Higher voltages require less current to deliver the same amount of power and so reduce EMF.
Operational Factors	**Effect on EMF**
Speed of wind turning the rotor blades attached to the generators	Greater wind speed will spin the rotor blades faster and will generate more power, thus increasing cable currents and EMF.

Cable Design

Offshore wind energy projects AC undersea power cables are made with three copper conductor bundles separated by layers of insulation and sheathing and bundled together in a single armored (metallic-covered) cable. A cross-section of an example cable is shown in **Figure 5**. The current on each of the three conductors produces a magnetic field that will partially cancel out the magnetic field from the other two conductors, away from the cable.

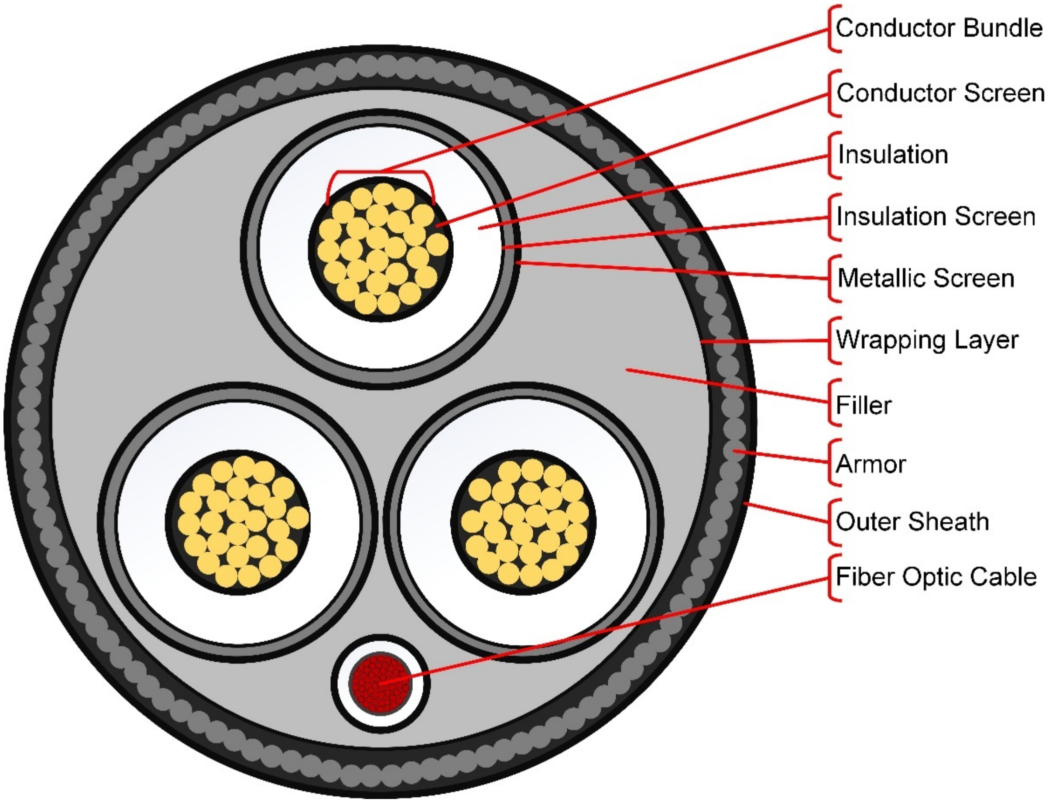


Figure 5. Example of offshore power cable cross-section

The closer the conductor bundles are to each other, the greater the magnetic field cancellation. Because the conductors of an AC undersea cable are very close together, there is an appreciable amount of cancellation. This causes the EMF from undersea cables to be weaker and decrease more rapidly with distance than onshore overhead transmission lines where the conductors are widely spread.

Higher voltage undersea power cables, like export cables, have more insulation between conductors, which slightly increases the distance between conductors and, in turn, slightly increases the magnetic fields. However, for a given power, higher voltage cables require less current to deliver that power (**Figure 6**), so the current and EMF are lower compared to a cable operating at a lower voltage. In selecting the cables for offshore wind energy projects, designers balance the lower cost of lower-voltage cables against the greater losses that occur when power is transported over longer distances at lower voltages. That is why higher-voltage cables with lower losses are used to transport power generated from offshore wind energy projects to shore.

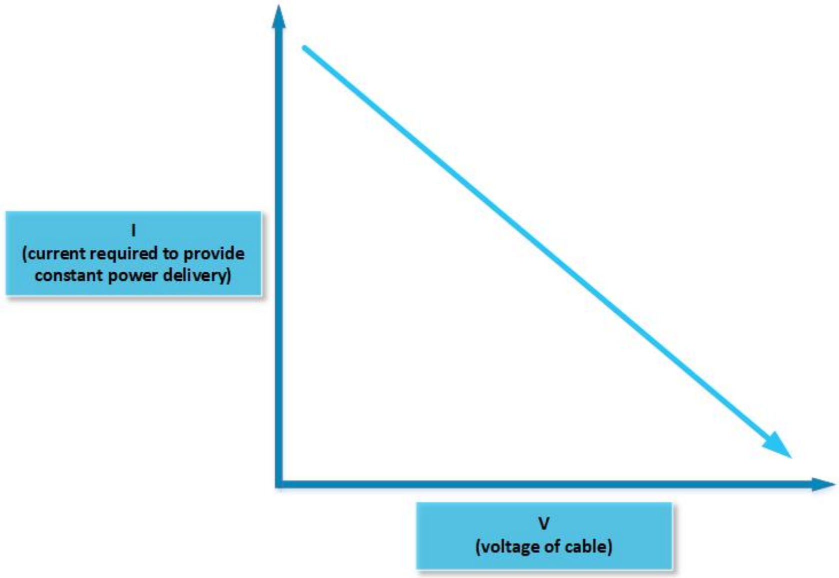


Figure 6. Voltage versus current relationship for constant power delivery

3.2.3 Factors that Reduce EMF Levels

Distance

Undersea power cables from offshore wind energy projects typically are buried under the seafloor to avoid damage from anchors or interference with fishing. Most materials, including seafloor sediments, do not shield magnetic fields. However, EMF from undersea power cables decrease rapidly with distance from the cable, so burying undersea power cables substantially reduces the levels of magnetic and induced electric fields in the marine environment. Most inter-array and export cables are buried to a target depth between 0.9 and 1.8 m (3 and 6 ft), depending on local conditions. The magnetic field at the seafloor is reduced about four-fold by increasing the burial depth from 1 to 2 m (3.3 to 6.6 ft). The target burial depth of undersea power cables reflects what is possible based on any existing infrastructure (e.g., existing pipelines or cables); the characteristics of the seafloor such as hard rock, minimizing the potential impacts to the seafloor by deeper cable burial; the additional cost of burying the cable deeper than necessary to provide physical protection; and the difficulty and increased cost of retrieving the cable for repair should it be damaged.

The burial depth of undersea power cables from offshore wind energy projects varies and depends on several factors, including installation method (e.g., jet plow, placed in conduits by HDD, open-cut trenching), seafloor conditions, presence of other existing infrastructure (e.g., power cables, fiber optic cables, pipelines), threats from other marine uses (e.g., dredging, anchoring, commercial fishing), and permit conditions. Where hardbottom seafloor conditions or existing infrastructure is encountered, the undersea power cables are laid on the seafloor and often covered with concrete mattresses, rock berms, or other coverings to protect the cable. These protective measures range from 15 to 30 cm (6 to 12 in.) thick, which substantially reduces the potential exposure to EMF by fish swimming near the undersea power cable as compared to the EMF exposure to an uncovered cable. However, the 15 to 30 cm (6 to 12 in.) of separation does not achieve the same level of EMF reduction compared to when the cable is buried to the target depth between 0.9 and 1.8 m (3 and 6 ft). **Figure 7** depicts qualitatively the EMF decay with distance from the undersea power cable.

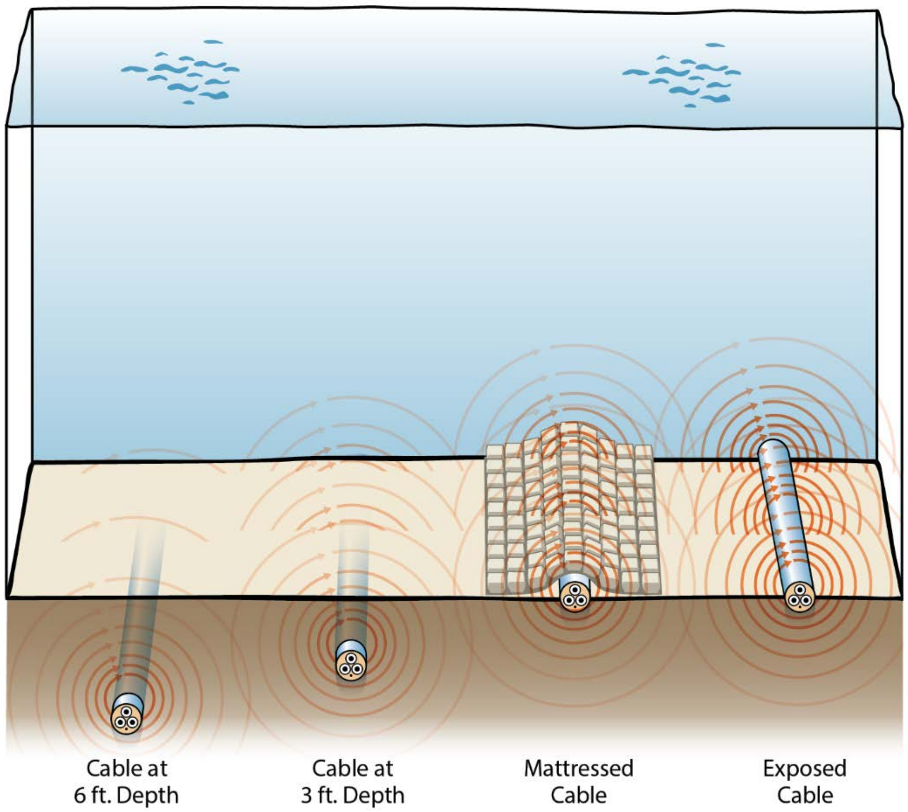


Figure 7. EMF decay with distance from four undersea power cable placement scenarios

In addition to the factors already discussed (i.e., compact conductor bundling within the cable, burial depth, and increased separation by covering cable on the seafloor), there are other cable design features that keep EMF levels from AC undersea power cables very low. However, when modeling EMF levels, these design features often are not included in the modeling predictions, which results in conservative upper-bound (highest) calculated EMF levels.

Twisting of Conductors

The magnetic field from the three conductor bundles within an AC undersea power cable often are modeled as being straight and parallel to one another for simplicity and because these assumptions cause the calculated fields from the cable to overestimate the actual field levels. However, during cable manufacturing, the three individual copper conductor bundles in the AC undersea power cable are helically twisted around one another. In this configuration, the magnetic field from each twisted conductor will more effectively cancel out the field from each of the other two conductors, resulting in a lower magnetic field near the cable. In addition, the magnetic field from the twisted conductors will decrease more rapidly with distance than a cable with straight conductors. Previous research has shown the magnetic field at approximately 0.9 m (3 ft) from a helically twisted three-phase cable is more than 10 times lower than that from an untwisted three-phase cable [25].

The field reduction from the helical twist of the cables can be calculated analytically or numerically. However, it is not always done in practice because the modeling is more difficult and time consuming and because modeling the conductors of an AC undersea power cable as untwisted yields higher field levels (i.e., conservative upper-bound of EMF levels).

Metal Armor

The outer layer of undersea power cables is made of small steel wires (**Figure 5**). In addition to providing physical protection for the cable, these steel wires partially shield the magnetic field from the outside environment due to opposing eddy currents induced in the armor and ferromagnetic shielding (**Figure 8**). It is difficult to calculate the precise factor by which the metal armoring reduces magnetic field levels because it depends on very specific characteristics of the undersea power cable construction and materials that are not known until the cable has been produced and tested. An estimate of the reduction, however, can be made from previous research, which showed a two-fold reduction in the magnetic field, with a much smaller reduction attributable to eddy currents [26].

In summary, the combination of the twisting of the conductors and the metal armor will lead to considerably lower magnetic fields than calculated for bare straight cables. As reported in a recent BOEM study of EMF measurement over AC undersea power cables "[t]he magnetic field produced by the AC sea2shore cable was ~10 times lower than modeled values commissioned by the grid operator…" [2]. This indicates the combination of cable twist and metal armor can result in a 10-fold reduction in the calculated magnetic field.

The metal sheath around the cable shields the electric field produced by the voltage on the conductors with the electric field confined to the cable's interior (**Figure 8**, left panel). There is an AC electric field outside the cable; however; it is caused by the AC magnetic field. The right panel in **Figure 8** shows that the AC magnetic field produced by the current flowing on the conductors, while not appreciably shielded by the metal sheath of the cable, produces a magnetic field <u>outside</u> the cable. This <u>time-varying magnetic field in turn induces a time-varying electric field outside the cable. In the case of DC cables, their load currents do not induce electric fields in the medium outside the cable</u>.

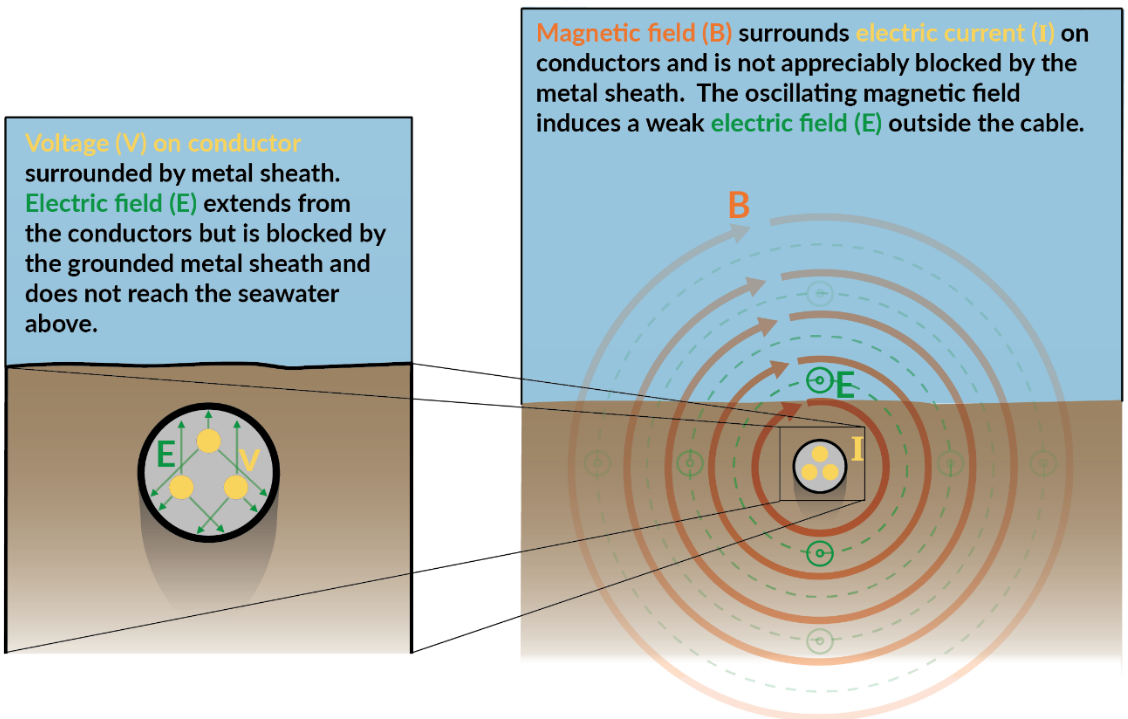


Figure 8. **Source of AC electric field outside an undersea cable**

3.3 Typical Levels of EMF from Undersea Power Cables Associated with Offshore Wind Energy Projects

As described earlier, EMF levels depend on the voltage, current, burial depth, and cable design. **Table 3** shows the magnetic and induced electric field levels expected directly over the undersea power cables and at distance from the cable for varying cable types. Directly above the cable, EMF levels decrease substantially as you move away from the seafloor to 1 m (3.3 ft) above the cable, while at distances greater than 3 m (10 ft), the magnetic fields at the seafloor and at 1 m (3.3 ft) above the seafloor are more similar (**Figure 9**).

Table 3. Typical EMF levels over AC undersea power cables from offshore wind energy projects

Power Cable Type	**Magnetic Field Levels (mG)**			
	Directly Above Cable		**3 to 7.5 m laterally away from cable**	
	1 m above seafloor	At seafloor	1 m above seafloor	At seafloor
Inter-Array	5 to 15	20 to 65	<0.1 to 7	<0.1 to 10
Export Cable	10 to 40	20 to 165	<0.1 to 12	1 to 15
Power Cable Type	**Induced Electric Field Levels (mV/m)**			
	Directly Above Cable		**3 to 7.5 m laterally away from cable**	
	1 m above seafloor	At seafloor	1 m above seafloor	At seafloor
Inter-Array	0.1 to 1.2	1.0 to 1.7	0.01 to 0.9	0.01 to 1.1
Export Cable	0.2 to 2.0	1.9 to 3.7	0.02 to 1.1	0.04 to 1.3

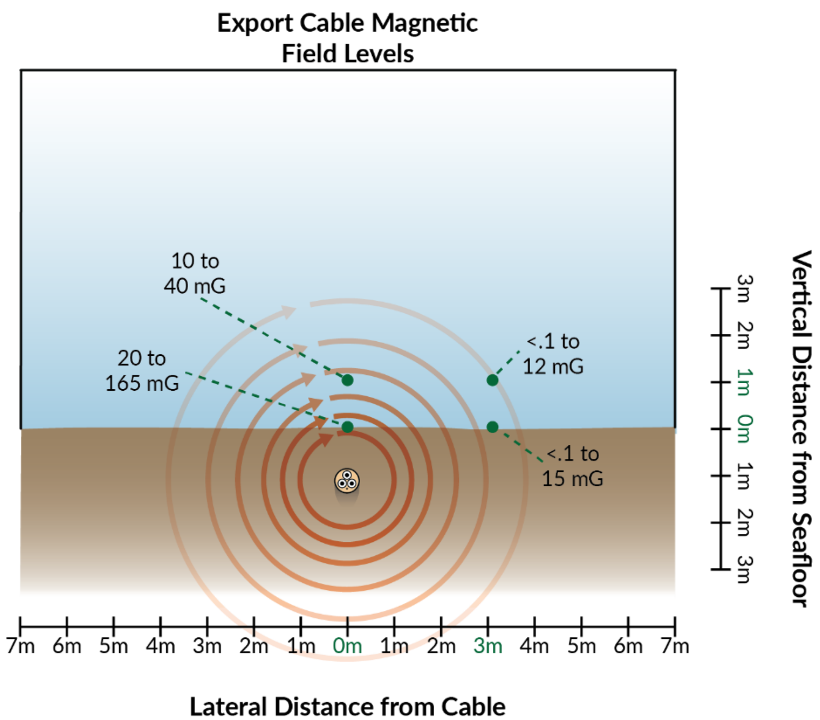


Figure 9. Illustration of magnetic field reduction with distance, both laterally and vertically, from undersea inter-array power cable

Note: The magnetic field around the cable is depicted by concentric 'rings'. High color density of the rings and close proximity to the cable depict zones where the magnetic field is higher. At greater distances from the cable the magnetic field weakens as shown by lower color density and more widely spaced 'rings'.

3.4 Circumstances in which Higher EMF Levels Might Exist at an Offshore Wind Energy Project

EMF levels will be higher than in **Table 3** where the distance from the undersea power cable to fish is reduced at specific locations, as discussed below.

Unburied Cables: As described in **Section 3.2**, at locations (typically a few short locations along the route) where it is not possible to bury undersea power cables to the target burial depth (e.g., over hard bottom, at existing cable/pipeline crossings), the cable is covered by protective concrete mattresses or rock berms (**Figure 7**). Because the distance between the cable and the water column is smaller, only 15 to 30 cm (6 to 12 in.) cover from the protective mattresses or rock, the EMF levels directly above the cable may be as much as 10 times greater than over the portions of the cable buried to the target depth. However, beyond approximately 3 m (10 ft) from the cable, the field levels for buried and mattress-covered cables are quite similar.

Cables at Substations: At a substation where the cables (inside a steel tube) travel up through the water column to connect with the substation (above the water line), the distance between the undersea power cable and swimming fish will be less, so EMF levels will be higher. The area over which these higher field levels might occur is vertical throughout the water column, but the surrounding area around the undersea power cable where EMF is higher is quite limited because the EMF from undersea power cables generally will be substantially shielded by steel tubes around the cables that protect them from damage.

4 Regional Fish Species of Concern

4.1 General Sensitivity of Fishes to EMF Exposure

The discussion of sensitivity of fishes to EMF is based on the basic functions of their sensory organs. All animals have nervous systems and the basic components are the same: sense organs that receive signals from the surrounding environment; nerves that transmit these signals to the brain, spinal cord, or ganglia for processing; and other nerves that deliver the processed response to the appropriate muscles. It is important to realize that fishes perceive their watery world very differently than humans do. Where humans have five senses—vision, smell, hearing, taste, and touch—fishes have the additional ability to detect water motion with their lateral lines) and some fish species can detect magnetic and sometimes electric fields with specialized sensory organs. Stevens [27] provided an apt reminder for anyone forgetting that fish differ greatly in their perception of their surroundings:

> "*Animals often do not perceive the world in the same way that humans do, and we need to be aware of this in studying sensory and behavioural ecology. First, there are entire sensory modalities that humans lack. For example, various animals have a magnetic sense, which they use to navigate over both relatively shorter and longer distances. Likewise, many fish (and some mammals and amphibians) have an electric sense. This can be both passive, involving detecting electric information from the environment (e.g., prey) or active, where the fish emits electricity to the environment and detects the changes in the returning signal. Electric senses are used in many ways, including detecting food, navigation, object detection, and aggressive and courtship interactions*."

Sharks, rays, and skates use their electric sense to complement vision, sound, smell, taste, and lateral line when finding and securing food [28]. Particular senses may switch on or off depending on distance to a food target; sound and smell can detect signals from the greatest distances, or closer in murky water. At closer range, or in clear water, vision will come into play, and at a very close distance, touch and the electric senses will assist with homing in on the target (**Figure 10**).

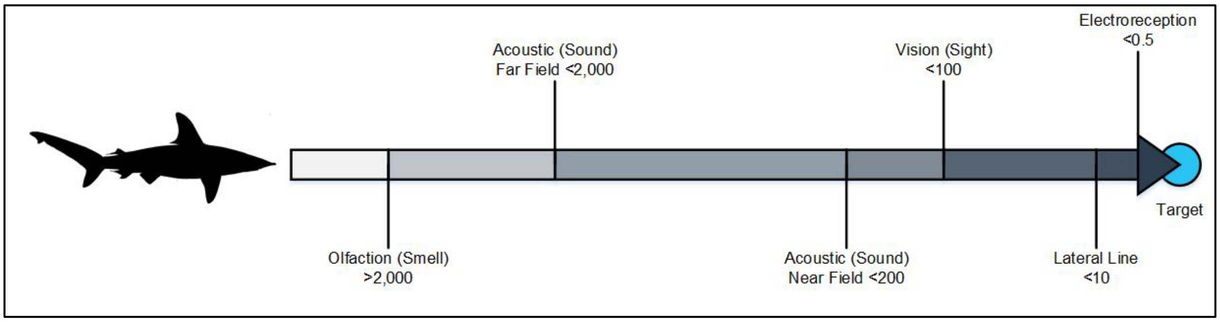


Figure 10. Relative importance of senses to target (prey) for a shark or skate as a function of distance
Distances are in feet. Figure modified from [29].

4.1.1 Magnetosensitivity in Fish

An organism's ability to detect and respond to the Earth's magnetic fields is called magnetosensitivity. Many fish species use the Earth's natural static magnetic field for guidance during migration. Like other environmental cues (e.g., temperature, light, salinity), the geomagnetic field varies across the environment. The ability to detect the natural magnetic field is valuable in guiding fish movements over long distances through aquatic environments. Fish that are capable of detecting these changes have additional environmental information that can make long-distance migrations more successful.

Magnetosensitivity and Use of Environmental Cues

The Earth acts like a large magnet with magnetic field lines traveling from one pole to the other. These lines dip downward or upward as one moves north or south toward the poles, potentially providing information on latitude. In recent decades, the ability of animals to align with or otherwise sense magnetic fields has been documented for bacteria, mollusks, bees, lobsters, fishes, birds, sea turtles, and mammals [30,31,32,33].

Researchers have studied how fish could transmit signals from a magnetic field into electric signals used by the nervous system [34,35]. Walker et al. [35,36] suggested fish can detect the Earth's magnetic field because their bodies contain tiny particles of a natural magnetic compound, magnetite. As a fish swims through the water, these particles are thought to respond to the natural fluctuations in the Earth's magnetic field, alerting the fish to these changes. Another theory suggests the magnetic fields can cause changes in light receptors in the eye, which are transmitted as signals to the brain [37]. The magnetite theory is popular but other theories involving magnetic-field-dependent chemical reactions and interaction with light-dependent cryptochrome are under study [38]. More sophisticated analytical methods and tools may be needed to ultimately resolve the debate [34]. Studies on migratory fish (e.g., salmon, American eels [*Anguilla rostrata*]) suggest changes in the Earth's magnetic field are combined with other environmental cues (e.g., water temperature, light, salinity) to guide migration routes in open ocean environments and in rivers [39].

Bony fishes and sharks can use magnetic senses to navigate in the ocean. Laboratory tests have shown that fish larvae may use magnetic senses to maintain direction at night. During daylight hours, these same larvae used sun-compass orientation to provide direction [40]. Adult and juvenile stages of American eels have demonstrated the ability to sense magnetic fields [41,42].

BOEM has commissioned an ongoing study to assess the potential effects of undersea cable EMF on the American eel using the same methodology used by Hutchinson et al. [2]. Concerns have been voiced that magnetic fields generated by undersea power cables would affect migrating individuals of magnetosensitive species; however, it is important to remember that magnetic senses work with other senses to help fish find food, habitat, and spawning locations. Of greater importance, these magnetic senses of fish are "tuned" to the frequency of Earth's static (0 Hz) magnetic field, not to the 60-Hz magnetic fields produced by undersea power cables from offshore wind energy projects.

How Common is Magnetosensitivity in Fish?

Observations of magnetosensitive organs in fish and laboratory studies on fish behaviors in response to magnetic fields suggest magnetosensitivity to static (0 Hz) magnetic fields is common in many types of fish. Species reported to be magnetosensitive include salmon, American eel, sturgeon, yellowfin tuna, sharks, skates, and rays. **Figure 11** lists grouped fish species important to commercial and recreational anglers in and around the southern New England area that are sensitive to EMF and provides their general location within the water column (closer to the surface [pelagic] or closer to the bottom [demersal]).

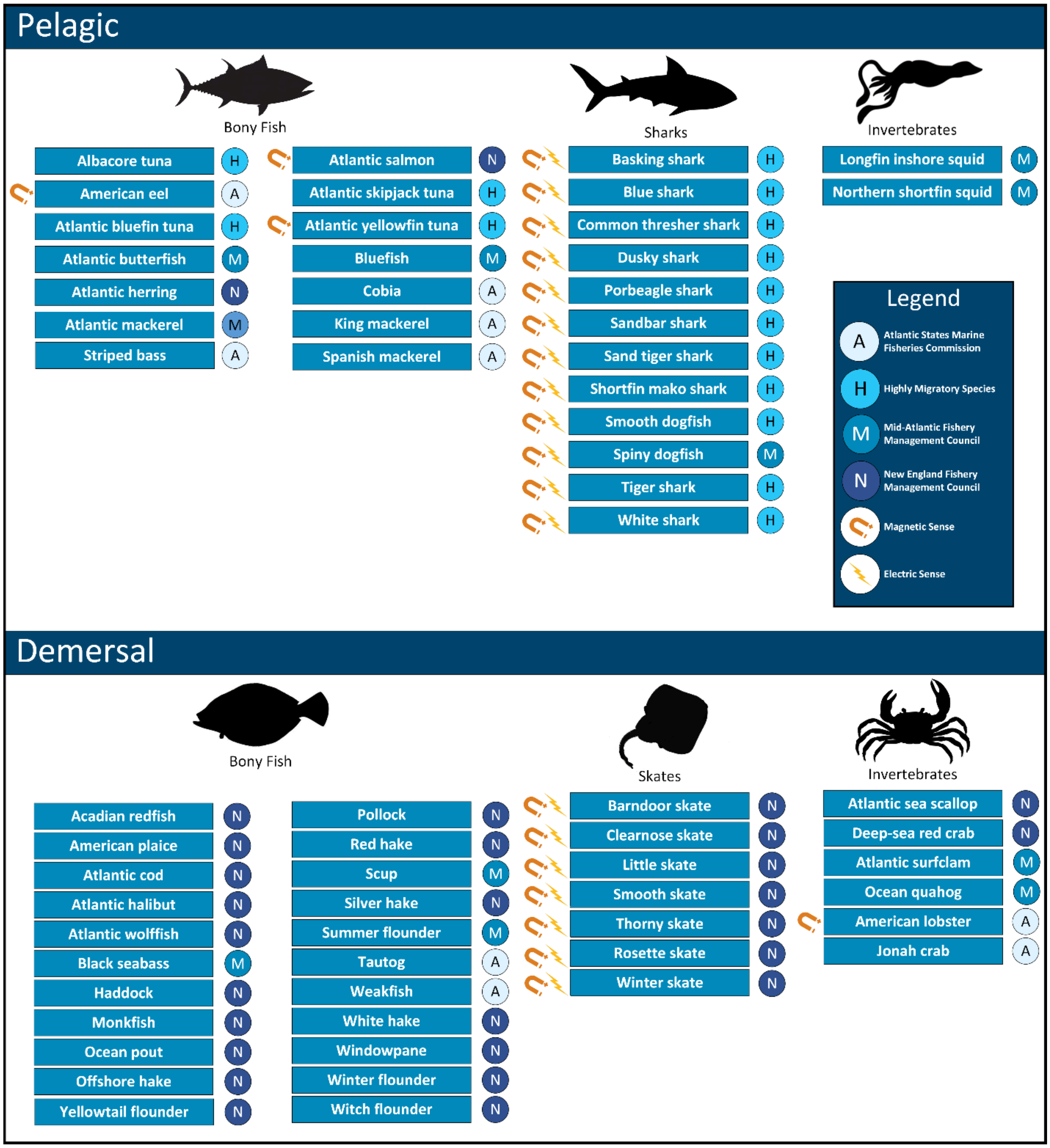


Figure 11. Species important to commercial and recreational anglers in the southern New England area and reported abilities to detect EMF

(A) = Managed by Atlantic States Marine Fisheries Commission, (H) = Highly Migratory Species, (M) = Managed by Mid-Atlantic Fishery Management Council, (N) = Managed by New England Fishery Management Council, [magnet icon] = Magnetic Sense, [lightning icon] = Electric Sense.

4.1.2 Electrosensitivity in Fish

A small number of fish species can detect weak electric fields from natural sources (**Figure 11**). These electric fields are produced by biological activity (i.e., bioelectric fields) or by movement of an animal through a magnetic field. Similar to the Earth's magnetic field, these naturally occurring weak electric fields are environmental cues that some fish have evolved to detect and use.

Electrosensitivity and Use of Environmental Cues

Electrosensitive fish perceive naturally occurring electric fields and use them to locate prey or detect the presence of predators. 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]. The capability of these organs to detect an electric field is limited to a small area around the fish. Some scientific publications have noted the detection of electric fields by sensitive species is limited to tens of centimeters, not meters, around these species [45].

Sharks and rays possess a special sensory organ that can read and process electric signals. The system consists of external openings in the skin called ampullae of Lorenzini. These ampullae are tiny pits (ampules) the size of a pinhead arranged in clusters and connected beneath the skin by canals filled with a conductive mucous-like material. The canals are insulated by the skin and conduct signals to central clusters of ampullae where nerve receptors transmit them to the brain. In rays (and skates), ampullae tend to be clustered around the mouth and on the ventral side of the broad, flat body and along the wing (pectoral fin) margin on the dorsal side. In sharks, ampullae are distributed along the flanks and around the dorsal and ventral portions of the head. Average bioelectric fields produced by invertebrates and bony fish can differ by a factor of 10; however, these all are produced at frequencies 10 Hz or less [45]. This electric-sensing system allows individuals to detect local fields produced by small prey, predators, or potential mates as well as uniform electric fields of inanimate origins for possible use in orientation and navigation [46, 47]. Because ampullae of Lorenzini are found throughout the sharks and rays (elasmobranchs), available information from studied species is used to infer expected responses of related but unstudied species.

Because of their bottom-dwelling habitat preference and their pedigree (electrosensitive elasmobranchs), skates would be the most likely of the regional fishery species to come in contact with the higher levels of electric fields that are closest to the cables. Skates feed on bottom-dwelling invertebrates and some fishes [48]. Skates likely rely on their electric senses to find mates more than larger, mobile sharks [49]. Field tests off Rhode Island on the little skate (*Leucoraja erinacea*) suggest some influence on behavioral movements when in proximity to DC power cables [2]. This study also found weaker AC fields associated with this DC cable, which was not expected and may be due to stray currents from utility systems located at each end on the outside of the cable. Little skates were placed in large cages in the ocean (known as mesocosms) that straddled undersea power cables. Individuals were tagged with small electronic transmitters that could track their movements relative to the cable. The tests showed individual skates moved about the cage more often when the cable was powered on. Such behavioral responses may have been related "to the DC magnetic field, the AC (electric and magnetic) field or the induced electric field from either water movement, or their own movement through the magnetic field." The investigators reported their tests overall showed only "minor" effects on behavior.

How Common is Electrosensitivity in Fish?

As with magnetic senses, some fish use electric fields as part of their overall environmental sensory system. Sight, sound, smell, and touch work with electric senses to help individuals survive and navigate. The number of fish species known to be electrosensitive is much smaller than the number of magnetosensitive species (**Figure 11**). Electrosensitivity has been documented in sharks, rays, skates, and other related species as well as in primitive fish like sturgeons.

4.2 EMF Sensitivity of Various Fish Groups

Exposure to EMF associated with undersea power cables is influenced by numerous factors. Fish species that inhabit coastal seafloor habitats (**Figure 12**) are the most likely to encounter the EMF produced by undersea power cables. In contrast, fish that swim in the open ocean high above the seafloor (**Figure 12**) will be less likely to encounter EMF produced by undersea power cables. In addition, fish species that migrate between ocean and freshwater (e.g., salmon, eel) may be more likely to swim above power cables installed in coastal environments.

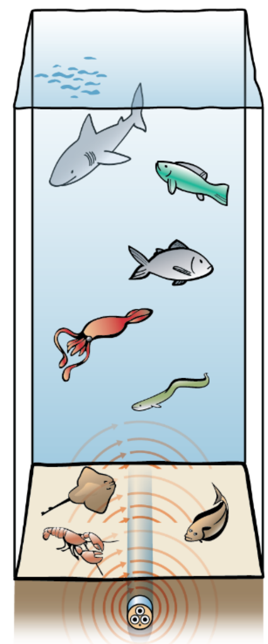


Figure 12. Exposure of fish to EMF varies with their preferred space in the water column

The time that fish are exposed to EMF can be momentary or longer term. Most exposures are expected to be very short (minutes, not hours), occurring only when mobile fish swim through the undersea power cable route area. Because the volume around undersea power cables where EMF levels are elevated is small (less than approximately 10 m [33 ft] around the cable), it represents only a tiny portion of the available habitat for fish species, many of which travel multiple kilometers in a day. Close to shore, the area where EMF is present is even smaller because the undersea power cables often are installed deeper by HDD or open-cut burial. These conditions have focused questions and concerns about potential effects of EMF focus on the behavior of fish that swim across the cable route, rather than their physiology or health.

A list of 62 species important to commercial and recreational anglers that reside in or around the southern New England area serve as focal species for analyses of potential effects (**Figure 11**). This list was analyzed based on fishery importance, genealogical relatedness (sharks and rays or bony fishes), and habitat preference (demersal or pelagic).

Species sought by recreational anglers working from shore, using kayaks or small boats, include striped bass (*Morone saxatilis*), weakfish (*Cynoscion regalis*), bluefish (*Pomatomus saltatrix*), winter flounder (*Paralichthys dentatus*), and Atlantic mackerel (*Scomber scombrus*). Blue water species sought by offshore anglers traveling to the shelf break and various undersea canyons include albacore (*Thunnus alalunga*), bluefin tuna (*T. thynnus*), yellowfin tuna (*T. albacares*), skipjack (*Katsuwonus pelamis*), shortfin mako (*Isurus oxyrinchus*), and common thresher shark (*Alopias vulpinus*). Most of these species are found beyond the study area boundaries, but they are included because individuals could enter one of the offshore wind energy project areas. **Figure 13** illustrates where in the water column the species groups inhabit and those that could encounter EMF.

Commercial species are represented by numerous invertebrates such as American lobster (*Homarus americanus*), surf clam (*Spisula solidissimus*), ocean scallop (*Placopecten megallanicus*), Jonah crab (*Cancer borealis*), and ocean quahog (*Arctica icelandia*). Yellowtail flounder, winter flounder, pollock, haddock, and other bottom-dwelling species are important to commercial bottom trawlers (draggers). A subset of less valuable but common species caught mostly by trawlers are termed "secondary" species [48]. Members of the secondary fish assemblage are quintessential demersal (bottom dwellers) species that eat small crabs, snails, worms, and shrimps. Secondary species contributing to the list include searobins (*Prionotus carolinus*, *P. evolans*), ocean pout (*Zoarces americanus*), longhorn sculpin (*Myoxocephalus octodecemspinosus*), Acadian redfish (*Sebastes fasciatus*), and goosefish (*Lophius americanus*) (more commonly known as monkfish).

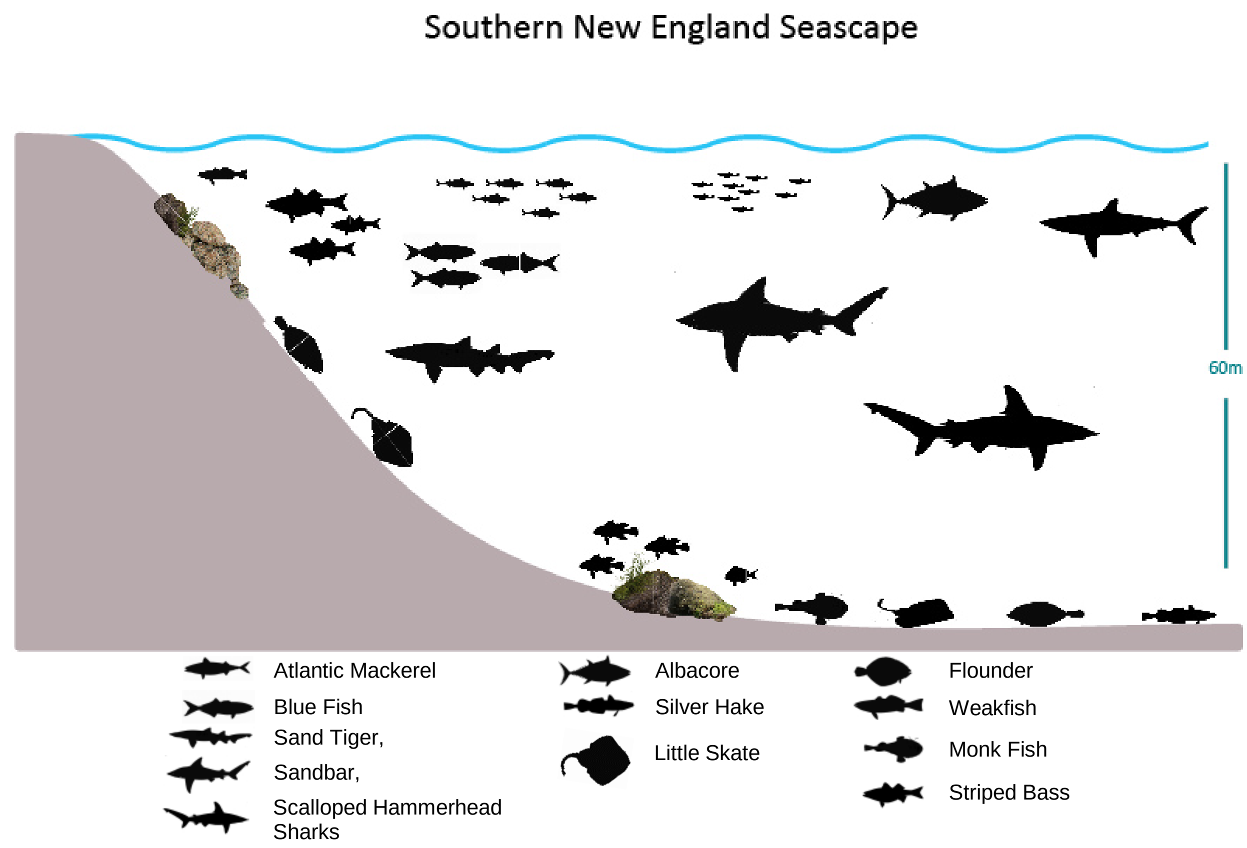


Figure 13. Southern New England seascape

Skates also are part of the secondary species group [48]. Seven skate species: little skate, rosette skate (*L. garmani*), winter skate (*L. ocellata*), thorny skate (*Amblyraja radiata*), clearnose skate (*Raja eglanteria*), barndoor skate (*Dipturus laevis*), and smooth skate (*Malacoraja senta*), are targeted by commercial anglers and collectively managed by the New England Fishery Management Council [50]. Little skate, clearnose skate, rosette skate, and winter skate are most common south of Cape Cod, whereas barndoor, smooth, and thorny skates are most common in the Gulf of Maine [50].

Relatedness

Genealogical relationships among species often are linked by common traits such as hair in mammals, feathers in birds, or skeletal composition in fishes. Fish biologists classify fishes into two broad groups based on their skeletons: members of the class Chondrichthyes (*Chondros* = cartilage and *ichthos* = fish) have skeletons made of cartilage and members of the class Osteichthyes (*osteos* = bone and *ichthos* = fish) have bone skeletons. The cartilaginous group is composed of sharks, rays, and chimaeras whereas the bony fishes include basses, flounders, catfishes, eels, tunas, and others. For this white paper, the cartilaginous species are combined into a large group containing all sharks and rays known as elasmobranchs (*elasmo* = plates, *branch* = gills). The chimaeras (also known as ratfishes) were dropped because these unusual fishes live in deeper waters than found in the study area.

An important trait that binds the sharks and rays as a related group is the ability to sense electric fields. The total numbers of shark and ray species in the world's oceans are approximately 633 and 570, respectively, and all have the ability to sense electric fields [51,52]. By contrast, only four groups of bony fishes are electrosensitive, and they mostly are restricted to the dark freshwater rivers and swamps of South America and Africa: elephantfishes, catfishes, electric eels (which are more closely related to catfishes than to true eels), and sturgeons. The only bony fishes found in the southern New England area known to be electrosensitive are Atlantic sturgeon (*Acipenser oxyrhynchus*) and shortnose sturgeon (*A. brevirostrum*). These are included here because of their endangered status, but neither currently is a managed fishery species. Another electrosensitive fish might be the northern stargazer (*Astroscopus guttatus*), which can generate electric charges, but its ability to detect electric fields has not been documented [53]. The area-specific species list (**Figure 11**) includes 19 sharks and rays; therefore, slightly less than one-third of the total list of species important to commercial and recreational anglers that reside in or around the southern New England area are electrosensitive.

Habitat Preference

After separating sharks and rays from bony fishes, the species list (**Figure 11**) was further divided into broad ecological groups reflecting what is known about individual species habitat preferences: demersal (bottom dwellers) and pelagic (water column dwellers). Regional fishery management councils use similar habitat-based schemes to group ecologically similar species into management units (e.g., highly migratory species, coastal pelagic species, groundfish species).

The pelagic group in the southern New England area consists of 28 species: 12 sharks and rays, 14 bony fishes, and 2 invertebrates (squids) (**Figure 11**). The most common bony fishes of the group include bluefish, striped bass, yellowfin tuna, and Atlantic mackerel. Most of these species are predators that migrate in response to seasonal water temperature changes and presence of prey. Striped bass spend less time than the others roaming widely over the seascape but will make predictable movements within their home ranges. Most notably, each spring, individuals will leave their preferred habitats around shoals, rock outcrops, and channels to journey upriver to spawn in freshwater. Upstream spawning migrations begin as early as March and peak in late April and early May. During summer months when downstream, most individuals associate with docks, rocks, wrecks, sand shoals, or channels.

Smaller members of the pelagic group such as butterfishes (*Peprilus triacanthus*), Atlantic mackerel, Atlantic herring (*Clupea harengus*), Atlantic menhaden (*Brevoortia tyrannus*), silversides (*Menidia* spp.), and American shad (*Alosa sapidissima*) often form large schools preyed on by the aforementioned predators. These species tend to be abundant but short-lived, exhibiting boom or bust population fluctuations. American shad also is anadromous and swims up freshwater rivers to spawn after spending several years growing at sea.

In contrast to American shad and striped bass, the American eel moves downstream to spawn in the ocean, not just in coastal waters but in the Sargasso Sea 1,609 km (1,000 mi) from the U.S. coast. They spawn with European eel (*A. anguilla*) stocks before reassembling and returning to their respective home shores [54,55] .

The pelagic group includes 12 sharks: basking shark (*Cetorhinus maximus*), blue shark (*Prionace glauca*), smooth dogfish (*Mustelus canis*), spiny dogfish (*Squalus acanthias*), common thresher shark

(*Alopias vulpinus*), dusky shark (*Carcharhinus obscurus*), sandbar shark (*C. plumbeus*), tiger shark (*Galeocerdo cuvier*), sand tiger shark (*Carcharias taurus*), porbeagle (*Lamna nasus*), shortfin mako (*Isurus oxyrinchus*), and white shark (*Carcharodon carcharias*). With the exception of the smooth and spiny dogfishes, these species are large and migrate extensively within and outside of the southern New England area [56]. Some species, including sand tiger shark, tiger shark, smooth dogfish, and spiny dogfish, will forage over the seafloor but generally swim well above it.

Two squid species are common in southern New England waters: the longfin squid (*Doryteuthis amerigo pealei*) and the northern shortfin, or *Illex*, squid (*Illex illecebrosus*). Adult longfin squids generally stay near the seafloor by day and enter the water column at night to feed on zooplankton. They lay their eggs in clusters on the seafloor. These clusters usually are attached to hard bottom, submerged vegetation, other natural or artificial structure, and sediments [57]. The northern shortfin squid is primarily found in the water column over the shelf edge. This species does not attach eggs to the seafloor but spawns in open water from December to June [58,59].

The demersal group is represented by 35 species: 29 fishes and 6 invertebrates (**Figure 11**). Of the fishes, 22 are bony fishes and 7 are skates. All the listed invertebrates, including Jonah crab, American lobster, and ocean scallop, live on or buried in (e.g., surf and ocean quahogs, sand lances [*Ammodytes* spp.]) the sediments. Bony fishes such as black seabass (*Centropristis striatus*) and weakfish (*Cynoscion regalis*) generally remain close to the seafloor but only occasionally rest on it. Bony fishes that rest or lie on the seafloor include yellowtail flounder (*Limanda ferruginea*), winter flounder (*Paralichthys dentatus*), witch flounder (*Glyptocephalus cynoglossus*), hakes (*Urophycis* spp.), silver hake (*Merluccius* spp.), goosefish, ocean pout, and longhorn sculpin. All these species feed on invertebrates (crabs, shrimps, worms, snails) and small fishes found on or within the sediments. Although not on the species list, Atlantic and shortnose sturgeons would be included in the demersal group.

To summarize, the list of 63 commercially and recreationally important fish species from the southern New England area (**Figure 11**) includes 8 bottom-dwelling species that are electrosensitive or magnetosensitive. Due to their preferred habitat, these species would have a high potential for exposure to EMF produced by undersea power cables associated with offshore wind energy projects. Twenty-eight species are pelagic (water column dwellers) and not likely to come close to buried undersea power cables during normal migratory or foraging activities. This group includes 12 shark species that are electrosensitive and magnetosensitive but are highly unlikely to detect weak electric fields emanating from undersea power cables because of their normal habits. The remaining 35 species are demersal (bottom dwellers) species capable of very close proximity to undersea power cables. The eight bottom-dwelling electrosensitive or magnetosensitive species (seven skate species and the American lobster) in this group likely would encounter electric fields induced by the magnetic field from undersea power cables. This group of skates is part of the commercial fishery managed by the New England Fishery Management Council [50].

4.3 Summary of Effects of EMF from Undersea Power Cables on Fishes

Studies have addressed effects of EMF on physiology and behavior in experiments conducted under controlled laboratory conditions. In such studies the frequency of the field is an important factor to consider, in some cases, even more important than the species tested.

Fishes have evolved sensory organs attuned to the Earth's magnetic field and fields generated by DC undersea power cables more closely resemble the Earth's natural static magnetic field. In contrast, fish species are not likely to be "tuned" to detect higher frequency (60 Hz) fields that are produced by AC power cables associated with offshore wind energy projects along the U.S. Atlantic coast.

4.3.1 Laboratory Studies Summary on Effects of EMF from AC Undersea Power Cables on Fishes

Studies examining the effects of EMF from AC undersea power cables on fish behaviors have been conducted to determine the thresholds for detection and response to EMF stimuli, although there are important commercial and recreational fish that have not been formally assessed for their ability to detect EMF from AC undersea power cables. Some of these fish, while not tested for sensitivity to AC fields, do not appear to respond to static magnetic fields, like the Earth's magnetic field, including striped bass, black sea bass, Atlantic croaker, and bluefish [60]. This suggests these fish might lack a sensory system for any magnetic field cues. Moreover, even for fish that can detect the Earth's magnetic field, research suggests EMF at frequencies outside the natural range of frequencies to which they have evolved are not easily detectable at levels produced by undersea power cables. **Table 4** shows that for several marine species, a documented sensitivity to the geomagnetic field is not indicative of the ability for the 50/60-Hz EMF to be detected or alter the distribution of these species at AC cable sites in the field. The weight of evidence presented here shows that EMF produced by 50/60-Hz AC power cables are not detectable even by magnetosensitive species and, therefore, are unlikely to affect these species in the field. Although numerous species of interest have not been tested, most are unlikely to be affected because these species are not expected to have any geomagnetic sensitivity or electrosensitivity.

Table 4. Relationship between static geomagnetic field detection, electrosensitivity, and the ability to detect 50/60-Hz AC fields in common marine species

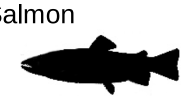
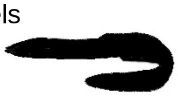
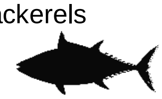
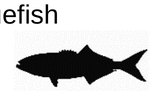
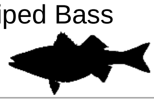
Species Group	Detect Static (DC) Geomagnetic Field?	Detect Bioelectric Fields or Electric Fields at <20 Hz?	Evidence from Laboratory Studies of 50/60-Hz EMF from AC Power Cables	Evidence from Field Studies of AC Power Cables
Lobsters and crabs 	Yes, for some lobster species [61,2]	Not tested [1]	No effect 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/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]

Table 4. Relationship between static geomagnetic field detection, electrosensitivity, and the ability to detect 50/60-Hz AC fields in common marine species (Continued)

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
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]

Research conducted at Oak Ridge National Laboratory demonstrated that even a 60-Hz magnetic field between 18,000 and 25,000 mG did not affect the behavior of sturgeon or largemouth bass [75]. In other studies, the magnetic field had to be increased to more than 1.5 million mG in order to alter fish behavior [74,75]. This finding led the Oak Ridge scientists to conclude that EMF produced by undersea AC power cables at this frequency would be of too low an intensity to affect fish behavior [75]. Similarly, exposure of Atlantic salmon and eel to a 950 mG magnetic field from a 50-Hz AC power source did not alter swimming behavior [66,67]. Both species are known to detect the Earth's magnetic field but were not sensitive to 50/60-Hz AC EMF.

In terms of magnetosensitive and electrosensitive sharks, EMF from 50/60-Hz AC sources appears undetectable. Laboratory research conducted with skates indicated that as the frequency of EMF increases above 1 Hz, skates become less sensitive. Kempster et al. [44] reported that small sharks could not detect EMF produced at 20 Hz and above, and a magnetic field of 14,300 mG produced by a 50-Hz source had no effect on bamboo shark (Scyliorhinidae, a group that includes catsharks and dogfish) behavior (**Table 4**).

Summary of Laboratory Studies

Laboratory studies of a wide variety of fish species indicate that when they can detect EMF, it is generally at frequencies less than 10 Hz. Therefore, at the low levels of the 50/60-Hz EMF from undersea power cables, fish typically would not respond to the levels associated with offshore wind energy projects. It is difficult to predict the effect of environmental cues like EMF on free-roaming populations of fish species based on the few studies available. Because the natural environment is so complex, many of the responses that can be observed and quantified in controlled studies may have no ecological meaning for wild populations. For this reason, information collected on studies of wild populations in the ocean are extremely valuable in understanding potential ecological effects of EMF from undersea power cables.

4.3.2 Field Studies Summary on Effects of EMF from AC Undersea Power Cables on Fishes

Telemetry Studies

Telemetry studies can reveal patterns of fish movement within urbanized waterways with ambient man-made sounds, electric fields, and water temperature modifications. For example, researchers in Florida discovered that tagged immature bull sharks (*Carcharhinus leucas*) favored an area of a lagoon where warm water was being discharged from a power plant, providing a refuge from cooler ambient waters [76]. Although not designed to examine effects of EMF, several telemetric studies are under way or recently were completed in or around the southern New England area where man-made alterations are widespread. Tagged species include electrosensitive species such sand tiger sharks [77] and Atlantic sturgeons [78] as well as non-electrosensitive striped bass [79]. To date, no unexpected deviations in movement patterns of tagged individuals in these studies have been observed, but that does not indicate there is no effect of man-made alterations within a small portion of the study areas.

Migration and Behavioral Response to the Presence of EMF from AC Undersea Power Cables

A number of field studies have observed behaviors of fish and other species around AC submarine cables in the U.S. Observations at three energized 35-kV AC undersea power cable sites off the coast of California that run from three offshore platforms to shore and are exposed (i.e., not submerged beneath the seafloor) along much of the route did not show that fish were repelled by or attracted to the cables [4]. This BOEM-funded study was conducted over a period of 3 years and assessed 44 different species of fish in nearshore and offshore communities. The BOEM-study report concluded that “EMFs generated by these energized undersea power cables are either unimportant to these organisms or that at least other environmental factors take precedence” [4]. A separate study reported that crab movement and location inside large cages was unaffected by proximity to energized AC undersea power cables off southern California and in Puget Sound, indicating crabs also were not attracted to or repelled by energized AC undersea power cables that were either buried or unburied [4].

The Hutchison et al. [2] field study described earlier in this report observed the behavior of American lobster (a magnetosensitive species) and little skate (a magnetosensitive and electrosensitive species) in large enclosures surrounding a buried DC undersea power cable. The researchers found that the DC and AC fields from the cable did not act as a barrier to movement or migration, as both species were able to freely cross the cable route. However, lobsters and skates were observed to swim closer to the seafloor and make more turns when near the energized cable.

Research conducted at the Trans Bay cable, a DC undersea cable near San Francisco, California, found that migration success and survival of chinook salmon (*Oncorhynchus tshawytscha*) and green sturgeon (*Acipenser medirostris*) was not impacted by the cable. However, as with the Hutchison et al [2] study, behavioral changes were noted when these fish were near the cable [20]. Salmon appeared to linger at the activated cable, while migration time for sturgeon increased in the seaward direction and decreased during inbound migration. Taken together, these studies demonstrate that while DC undersea power cables can result in altered patterns of fish mobility, these changes are temporary and do not interfere with migration success or population health. In addition, Kavet et al. [20] found the magnetic fields produced by the bridges in the project areas produced much larger distortions in the Earth's magnetic field than those produced by the DC power cables.

In a study conducted at a 130-kV AC undersea power cable in the Baltic Sea, the swimming behaviors of migrating eels were observed using acoustic tags. Only a brief and small reduction in swim speed at the cable site was observed but whether this was related to cable EMF or other aspects of the unburied cable was not determined [68]. Regardless, the paper's conclusion indicated that any delay in migration due to cable presence would be on the order of a few minutes, indicating no adverse effects on eel migrations or populations.

As field studies show, DC magnetic fields from undersea power cables can be detected by fish species with magnetosensitive sense organs, but they are not appreciably affected by those fields. The EMF from 60-Hz AC power cables in the U.S, fall outside the range of sensory capabilities of fish and will have little or no effect on fish behavior.

4.3.3 Interpretation of European Studies on the Effect of EMF from Power Cables Associated with Offshore Wind Energy Projects

Offshore wind energy projects, along with associated undersea power cables, have operated in coastal environments of Europe for more than a decade. During this time, many surveys have been conducted to determine if fish populations have declined following offshore wind energy project installation. The surveys have overwhelmingly shown that offshore wind energy projects and undersea power cables have no effect on fish populations [72,80,81,82]. Fish assessed as part of these surveys include flounder and other flatfish, herring, cod, and mackerel. These are similar to species harvested along the U.S. Atlantic coast.

A 2016 review of the ecological impacts of marine renewable energy (MRE) projects agrees with these findings. The authors concluded "there has been no evidence to show that EMFs at the levels expected from MRE devices will cause an effect (whether negative or positive) on any species" [83].

5 Analysis of Effects

Development of an offshore wind energy project involves three phases: construction, operations, and decommissioning. In standard EISs, environmental scientists evaluate potential effects of projects separately for each phase. This white paper only addresses the operations phase because EMF will be present only during that phase.

As described in **Sections 2** and **3**, the relevant EMF frequencies for this assessment are the 50/60Hz AC fields surrounding the offshore wind energy project inter-array cables (connecting the individual turbines) and the export cables (main power cables to shore). It is important to reiterate the statement from **Section 3.1**: *electricity generated by proposed U.S. offshore wind energy projects is AC electricity with a frequency of 60 Hz, the same frequency as the electricity distributed by onshore electrical systems*. This is an important aspect of EMF associated with offshore wind energy projects as they relate to potential impacts on commercially and recreationally important fish species.

Significance and Impacts of EMF from Undersea Power Cables Associated with Offshore Wind Energy Projects

The following assessment summarizes the characteristics and implications of exposure to EMF from AC cables for fish species of commercial and recreational importance. The impact assessment methodology considers potential interactions between EMF from undersea cables associated with offshore wind energy project power cables and fish species or species groups.

Two factors were used to determine potential impact significance: impact consequence and impact likelihood (**Figure 14**).

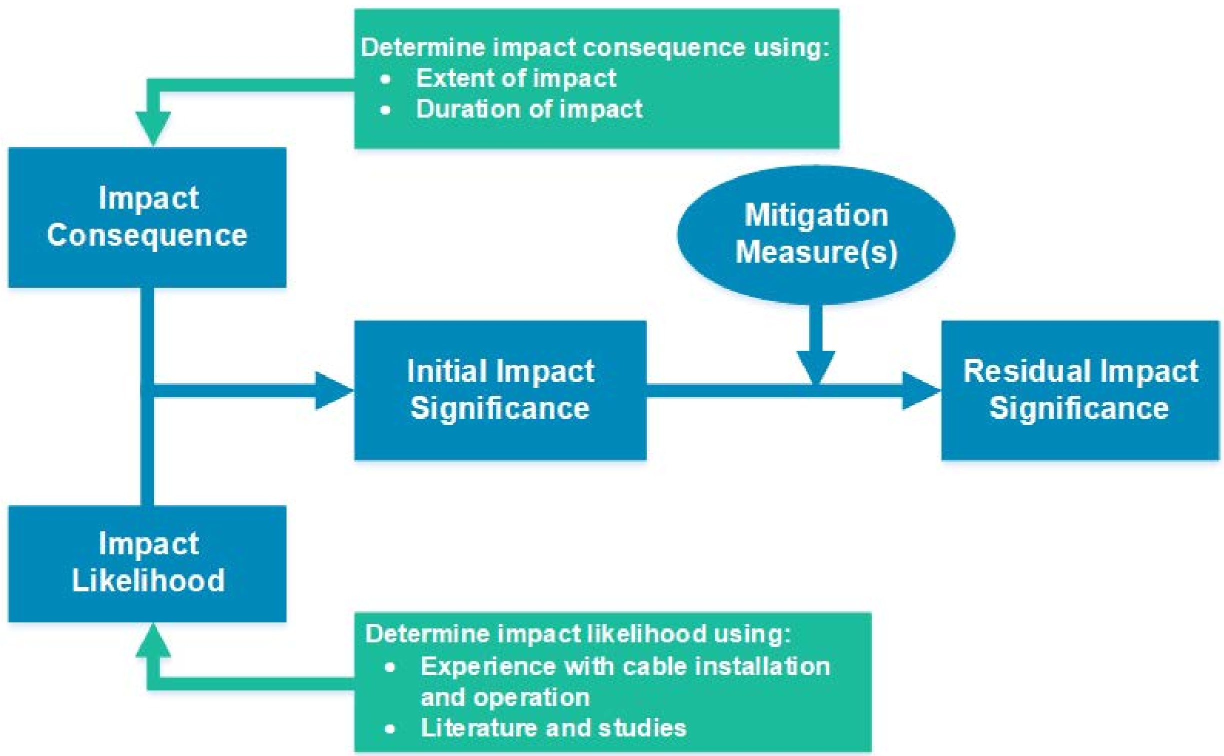


Figure 14. Impact assessment flowchart
Adapted from [84].

Impact consequence reflects an assessment of EMF characteristics on a specific marine resource (e.g., fish) arising from impact-producing factors (IPFs). The only IPFs addressed in this white paper are EMF associated with the operation of AC undersea power cables. Impact consequence was first determined regardless of impact likelihood. There are five impact consequence classifications: positive (beneficial), negligible, minor, moderate, and major (**Table 5**).

For negative impacts[a], the determination of impact consequence was based on consideration of two criteria: extent and duration of the impact. Positive impacts[b] are noted, but their consequence is not quantified.

[a] A negative impact is an impact where the change to the current situation of the resource generally is considered adverse or undesirable.

[b] A positive impact is an impact where the change to the current situation of the resource generally is considered better or desirable.

The spatial extent of an impact was rated using the following categories:

- **Immediate vicinity**: Limited to a confined space within the project area (i.e., cable footprint and corridor or where project activities are conducted);
- **Localized**: Influence goes beyond the cable footprint and corridor, but stays within a relatively small geographic area, generally within 10 km (6.2 mi) of the impact source; or
- **Regional**: Impact affects a large geographical area, generally more than 20 km (12.4 mi) from the impact source.

Duration of an impact describes the length of time over which the effects of an impact occur. It is not necessarily the same length of time as a specific activity or IPF as an impact may continue after the source has stopped or the impact may be shorter if there is an adaptation. Duration of the impact was classified as:

- **Short term**: Impacts occur only with respect to a particular activity or for a finite period of time; or
- **Long term**: Impacts are more likely to be persistent and chronic or even longer than the life of the project (e.g., irreversible impacts).

Impact consequence definitions are provided in **Table 5**.

Table 5. Definitions of impact consequence

Consequence Category	Resource Category
	Definition of Impact Consequence on Fish Species of Commercial or Recreational Fishing Importance
Beneficial	Likely to cause some enhancement to a species or species groups of commercial or recreational importance.
Negligible	No changes, or small adverse changes unlikely to be noticed or measurable against background activities.
Minor	Adverse changes that can be monitored and/or noticed but are within the scope of existing variability and do not meet any of the “major” or “moderate” impact definitions (below).
Moderate	Likely to result in one or more of the following: A few deaths or injuries of protected species; occasional, temporary disruption of critical activities (e.g., feeding, navigation during migration or homing, predator or conspecific detection, reproduction); and/or localized damage to critical habitat.
Major	Likely to result in one or more of the following: Numerous deaths or injuries of a protected species and/or continual disruption of critical activities (e.g., feeding, navigation during migration or homing, predator or conspecific detection, reproduction), and/or destruction of critical habitat.

Determinations also were made as to the likelihood of potential impacts. There were four likelihood categories, based on the following criteria:

- Likely (>50% likelihood; may happen a few times per year or more);
- Occasional (10% to 49% likelihood; may happen a few times during the lifetime of the project);
- Rare (1% to 9% likelihood; may happen once during the lifetime of the project); or
- Remote (<1% likelihood; unlikely to happen at all during the lifetime of the project).

Impact consequence and impact likelihood were combined to determine overall initial impact significance based on the following relationship (per **Figure 14**):

Impact Consequence × Impact Likelihood → Overall Initial Impact Significance

To summarize the overall significance of each impact, impact consequence and impact likelihood were combined using professional judgment and a risk matrix. According to the matrix, the overall impact significance for negative environmental impacts using a numeric, descriptive, and color-coded approach was rated as follows and summarized in **Table 6**:

- 1 – Negligible (gray);
- 2 – Low (yellow);
- 3 – Medium (orange); and
- 4 – High (red).

Table 6. Matrix combining impact consequence and impact likelihood to determine overall impact significance. Based on professional judgment, each combination of consequence and likelihood was assigned a significance value ranging from 1 to 4 (lowest to highest) for negative impacts

Likelihood vs. Consequence		← Decreasing Impact Consequence				
		Positive	Negative			
		Beneficial	Negligible	Minor	Moderate	Major
Decreasing Impact Likelihood ↓	Likely	Positive (No numeric rating applied)	1 – Negligible	2 – Low	3 – Medium	4 – High
	Occasional		1 – Negligible	2 – Low	3 – Medium	4 – High
	Rare		1 – Negligible	1 – Negligible	2 – Low	4 – High
	Remote		1 – Negligible	1 – Negligible	2 – Low	3 – Medium

5.1 Demersal Species

As discussed in **Section 4.2**, two species groups were included in this analysis: demersal (bottom dwellers) and pelagic (water column dwellers). Effects within each species group are examined separately for magnetosensitive and electrosensitive species.

5.1.1 Magnetosensitive Species

Bottom-dwelling fishes experience stronger and more frequent magnetic stimuli than pelagic fishes. Bottom-dwellers (e.g., skates) search for buried shrimps, crabs, worms, and clams using multiple senses. By proximity, EMF from undersea power cables have a higher potential to affect bottom-dwelling organisms near the cable, and those species likely are exposed for longer periods of time and may be largely constrained, in terms of location, by habit conditions over mattress-covered power cables. The maximum magnetic field expected for an offshore wind energy project's export cable EMF is about 165 mG, dropping to 40 mG 1 m above the cable, a decrease in field strength of 76% (**Table 3**). Although power cables are relatively narrow (15.5 to 30 cm [6.1 to 11.8 in.]), they traverse extended paths over the seafloor to shore. There has been speculation that longer or multiple adjacent cables might pose a barrier to migration by electrosensitive or magnetosensitive species, but there is no evidence supporting this speculation.

The American lobster is a demersal species reported to respond to static DC magnetic fields. Hutchison et al. [2] examined potential effects of a DC undersea power cable on American lobster behavioral activity (**Section 4**). Their analysis suggested magnetic fields from undersea power cables likely would not be detected by lobster (assuming a magnetite-based detection mechanism) beyond several meters at typical power levels of a 60-Hz magnetic field. The magnetic field from a HVDC undersea power cable could be detected more easily by American lobster, but effects still would be limited to areas close to the cable. In experimental cages straddling a DC undersea power cable producing both DC and AC magnetic fields, lobster activity was altered slightly with changes in field strength, but individuals readily crossed the cable.

American lobsters will likely encounter undersea power cables associated with offshore wind energy projects. However, only temporary behavioral effects on their migration or local movements, if any, are likely to occur due to EMF exposure. Effects would be in the small area surrounding the undersea power cables and would consist of small changes in behavior; thus, as defined in **Table 5**, the impact consequence is **negligible**.

5.1.2 Electrosensitive Species

Studies have shown the fish most likely to react to electric fields induced by magnetic fields from undersea power cables associated with offshore wind energy projects are those with electrosensitive capabilities and possessing ampullae of Lorenzini (**Section 4**). Ampullae are electrosensing organs in sharks, skates, rays, sturgeons, and paddlefishes. These species use the electrosensory system to locate prey (food), mates, and predators. Effects of EMF may include disruption or masking of electroreception in electrosensitive species. The group of demersal (bottom dwellers) species with greater exposure to EMF is the skates (Family Rajidae), including the common species: clearnose skate, little skate, rosette skate (, winter skate, barndoor skate, and thorny skate. Skates would be most likely to respond to 60-Hz fields if they are capable of such detection at low EMF levels. These species are electroreceptive, live in constant contact with the seafloor, and are an important fishery species in the southern New England area. Although skates are electrosensitive, their frequency range for AC electric field detection (2 to 3 Hz, for clearnose skate) is far lower than the 60-Hz EMF frequency produced by offshore wind energy project AC power cables [85,45].

The maximum electric field strength from an AC undersea power cable from an offshore wind energy project 1 m (3.3 ft) directly above the seafloor is 2 mV/m at 60 Hz, which is not expected to be detected by individuals unless the field intensity was higher and they were in very close range (<0.3 m [<1 ft]) (**Sections 3** and **4**). This value represents 46% lower field strength expected at the seafloor than directly above the cable (3.7 mV/m). The rapid attenuation of the field strength with distance from the cable restricts any potential effects to organisms that are very close to the cable.

In addition, there are multiple collateral sources of EMF in the regional environment that create considerable background levels in which electrosensitive species function. As presented in **Section 3.1**, the EMF associated with ocean currents can be 0.075 mV/m or less [14,15,16]. The fact that electrosensitive species can still use natural bioelectric fields in this environment clearly indicates that they are able to distinguish between different types of naturally occurring EMF.

The question has been raised whether skates could mistake the 60-Hz EMF for the <10-Hz frequency associated with potential prey items such as shrimps, crabs, or clams. It seems unlikely that this would occur given the sensory limitation imposed by these species' inherent inability to respond to 60-Hz EMF. Furthermore, if some individuals expend valuable energy mistaking EMF as potential food or mates, no long-term detriment is likely to occur to the individual or the species population. Studies have demonstrated that dogfish sharks can learn to avoid signals that do not yield food rewards. However, ultimately, the general nature of the emitted EMF from AC cables differs appreciably from the fields given off by prey [86,45]. Such effects on feeding behavior are not expected to affect catchability of skates (or dogfish sharks) by the commercial fishery. Individual skates from at least seven species likely would encounter EMF within the small area around the undersea power cables; however, effects would be small changes; therefore, as defined in **Table 5**, the overall impact consequence is **negligible** even when accounting for the potential duration of the encountered EMF.

5.2 Pelagic Species

5.2.1 Electrosensitive Species

Pelagic species generally swim well above the seafloor and only rarely will be exposed to the EMF from AC undersea power cables buried in the seafloor. As the undersea power cable routes extend into shallower water, there will be a greater chance for some individuals, including young stages, to encounter or cross a buried cable. Many species found in the southern New England area were grouped as pelagic (**Section 4**), including herring, Atlantic mackerel, shad, striped bass, weakfish, bluefish, and several sharks. Except for the sharks, most of these species are not known to be sensitive to electric fields and are unlikely to be exposed to EMF except for brief periods as they pass near the undersea power cables or turbine fields.

Pelagic sharks are electrosensitive but may possibly encounter EMF emitted from the buried power cables. However, some species such as sand tiger, bull, sandbar, hammerhead, and spiny dogfish sharks feed at the seafloor and occasionally could be influenced by the presence of EMF from an offshore wind energy project. These occasional behavioral responses are not expected to affect catchability for any of the pelagic species targeted by recreational or commercial anglers.

Electrosensitive species (sharks, skates, rays, and sturgeon) are known to avoid electric fields; this is the motivation for developing electric deterrents for divers, surfers, and swimmers [87]. But the electric field strengths that cause avoidance or deterrent response in white sharks (*Carcharodon carcharias*) in the upper water column are 30,000 times higher (approximately 105 V/m) than the highest fields emitted from undersea power cables associated with offshore wind energy projects. Fields from these latter sources appear to have little or no deterrent or repulsive effect on sharks, rays, skates, or sturgeon studied to date.

Substation platforms will act as artificial reefs and attract some pelagic (and demersal) species [88]. Substations also will support cables emerging from the seafloor for a distance similar to the water depth of the platform. However, even with this source of EMF in the water column near the platforms from the AC undersea power cables, due to the documented lack of response from fish with sensory organs to 60-Hz AC fields and the rapid decay of the EMF with distance, there would be no or few effects on these species or the fisheries targeting them, resulting in a **negligible** expected impact consequence, if any, as defined in **Table 5**.

5.2.2 Magnetosensitive Species

Magnetosensitive species include electrosensitive sharks and rays, some of which have been shown to use DC magnetic field cues to navigate (in the compass sense) to and from particular locations (e.g., seamounts) [89,90]. Other species such as salmon and American eels and their larval stages have demonstrated a magnetic sense. The magnetic environment is subject to considerable background noise, particularly from geomagnetic storms and other anomalies [91].

While the pelagic habitat (water column) is large and inhabited by many species, only a few species (i.e., pelagic sharks, American eels, Atlantic salmon) are magnetosensitive. In addition, the electric field from buried undersea power cables dissipates rapidly with distance, affecting very little of the water column. The operational life of offshore wind energy projects will be 20 to 25 years. Considering this duration for potential exposure to EMF by magnetosensitive pelagic sharks, American eels, or Atlantic salmon along with the small portion of the pelagic habitat that would experience detectable EMF, exposure to these species would rarely occur. In addition, effects to these species would not be detectable or would be small changes [44,68,66]; therefore, as defined in **Table 5**, the impact consequence to these species would be **negligible**.

Table 7 presents a summary of the potential impacts to fishes and invertebrates in the southern New England area from EMF associated with AC undersea power cables.

Table 7. Significance of potential impacts to fishes and invertebrates in the southern New England area from offshore wind energy projects' AC EMF

Species	Potential Impact	Criteria	Consequence	Likelihood of Exposure	Significance
Pelagic Habitat – Magnetic Fields					
American eel, Atlantic salmon	Impairment of navigation or homing	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible
Pelagic Habitat – Electric Fields					
Bony fishes: bluefish, striped bass, bluefish and others; Pelagic sharks	Changes in feeding success, mate finding, and evading predators	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Rare	1 – Negligible
Demersal Habitat – Magnetic Fields					
Clearnose skate, little skate, winter skate, barndoor skate, thorny skate, rosette skate, and smooth skate	Impairment of navigation or homing	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible

Table 7. Significance of potential Impacts to fishes and invertebrates in the southern New England area from offshore wind energy projects' AC EMF (Continued)

Species	Potential Impact	Criteria	Consequence	Likelihood of Exposure	Significance
Demersal Habitat – Electric Fields					
Clearnose skate, little skate, winter skate, barndoor skate, thorny skate, rosette skate, and smooth skate	Changes in feeding success, mate finding, and evading predators	Nature: Negative Intensity: Low Spatial Extent: Immediate vicinity Duration: Long term	Negligible	Likely	1 – Negligible

5.3 Cumulative Effects

Cumulative effects are those that result from incremental effects of additional sources of EMF considered together with other past, future, and reasonably foreseeable future actions (that also produce EMF). As discussed in **Sections 5.1** and **5.2**, direct effects of EMF produced by undersea power cables associated with offshore wind energy projects on recreationally and commercially important fish species in the southern New England area are expected to be negligible. As described in **Section 4**, exposure to the EMF from offshore wind energy project AC power cables may be more likely for some species, such as electrosensitive fish near the buried undersea power cables or cables emerging and extending on substation platforms. In general, the levels of the EMF will be strongest in the immediate vicinity of the undersea power cables. Although the frequency of the EMF is outside the sensitivity range of most electrosensitive species, detection of the 60-Hz field may be possible if the field strength is sufficiently large. Because EMF strength decreases rapidly with distance from the source cables, even sensitive species such as sharks or skates would have to pass very close to the undersea power cables to detect the fields. Also, cables from offshore wind energy projects are intentionally separated to minimize damage to multiple cables from local accidents. Species that normally inhabit the water column, including species that detect EMF (e.g., sharks, Atlantic salmon, American eels), only rarely would come in contact with EMF during forays near the seafloor; therefore, effects on pelagic species are expected to be negligible.

As more undersea power cables are added in the future, the potential for cumulative (incremental) effects could increase. Other actions that could affect recreationally and commercially important fish species in the southern New England area include marine mining/dredging, military activities, geophysical surveys, commercial fishing, and shipping. However, none of these actions are expected to contribute EMF, only other undersea power cables from offshore wind energy projects or for communications or power would be considered in the evaluation of incremental effects. The undersea power cables currently installed or planned for the southern New England region are depicted in **Figure 3**.

To fully understand the effects of additional undersea power cables being deployed in the future, one would need to account for how the physiology (energy expenditure) of sensitive species varies with each EMF encounter and whether many such encounters could lead to altered growth and reproduction rates of individuals. At present, detailed information on the life history and ecology of sensitive species is lacking. Hutchison et al. [2] suggested that for a wide-ranging species like the American lobster, encountering a single undersea power cable while migrating over the seafloor would represent a minor energy expenditure. However, if less active skates were consistently attracted to EMF from active power cables sufficient to markedly alter their behavior for each encounter and no habituation occurs, an incremental effect is possible. These are just two examples of potential cumulative effects. Individual projects will need to be evaluated in combination with other past, present, and reasonably foreseeable future actions (undersea power cables or other sources of EMF).

6 Conclusions

Based on the analysis in the preceding sections and the information presented in the white paper as a whole, offshore wind energy development as currently proposed is not expected to negatively affect commercially and recreationally important fish species within the southern New England area. Negligible effects, if any, on bottom-dwelling species are anticipated. No negative effects on pelagic species are expected due to their distance from the undersea power cables buried in the seafloor. Specific conclusions are as follows:

- AC undersea power cables associated with offshore wind energy projects within the southern New England area will generate weak EMF at frequencies outside the known range of detection by electrosensitive and magnetosensitive fishes;
- Most fishery species in the southern New England area are bony fishes, which have not evolved to detect EMF at 60 Hz;
- Pelagic fishes such as striped bass, bluefish, weakfish, and Atlantic mackerel have habitat preferences away from the seafloor where EMF levels are highest;
- Bottom-dwelling fishes are most likely to encounter EMF from undersea power cables associated with offshore wind energy projects; and
- The group of fishes with the greatest potential for exposure to EMF from undersea power cables are the skates (Family Rajidae), which combine electrosensitivity with a bottom-dwelling life history.

When considering effects of EMF, it may be helpful to understand the weak field strengths discussed in this white paper are well below the recommended threshold values for human exposure. For example, the guidelines set forth by the International Commission on Non-Ionizing Radiation Protection [92] for human exposure to time-varying electric fields are 12 to 100 times higher than the fields measured at the seafloor and presented in **Table 3**. Common household items, including television sets, hair dryers, and electric drills, can emit magnetic fields similar to or higher in intensity than those emitted by undersea project power cables.

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