Review of the Impacts to Marine Fauna from Electromagnetic Frequencies (EMF) Generated by Energy Transmitted through Undersea Electric Transmission Cables

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Executive Summary

As part of New Jersey's overall renewable energy goals, Governor Murphy announced on November 19th, 2019 the State's plan to produce 7,500 MW of electricity from offshore wind (OSW) turbines by 2035 (Executive Order No. 92). As a result, high-efficiency transmission cables will be required to connect each turbine in series, whereas each OSW farm would afterwards be connected to a larger common conduit, or export cable travelling to a mainland connection point and electrical substation. The installation and operation of submarine transmission cables can affect marine benthic organisms and habitats in a variety of ways, some of which can include sediment disturbance, reef effects, thermal emission, and notably the distortion of the natural geomagnetic field via emission of electromagnetic frequencies. Electromagnetic Frequencies, or EMFs are generated by electric current flowing through undersea transmission cables that can be associated with onshore or offshore renewable energy projects (wind or hydrokinetic resources) or other power-generating sources (traditional power plants). Based on empirical evidence and laboratory investigations, the observed impacts to marine biota and ecosystems are considered to be minor or short-term. Electrosensitive species such as elasmobranchs and benthic species have been shown to sense EMFs more acutely than marine mammals and pelagic fishes, although only minor responses such as lingering near or attraction to cabled areas have been noted. However, uncertainties do remain as to whether physiological impacts occur and what life stage is most affected, and or if any long-term impacts will develop. Herein, a review of the current scientific literature is provided summarizing the observed, *in situ* effects of EMF on marine fauna from interactions with and proximity to undersea transmission cables.

Introduction

Submarine transmission cables are present in many locations worldwide, including operational cables deployed along both US coasts and within coastal embayments. The decision for installation in these environments usually depends on the distance from the electric generating source (e.g. onshore power station, offshore windfarm) to the service distribution point, as well as the physical nature of the location itself, such as whether the location is an island, bound or blocked by a geographical barrier, or subject to other restrictions which necessitate the need for an undersea route (Taormina et al. 2018). Terrestrial considerations that may guide a transmission cable installer to an undersea route could also include the presence of sensitive habitats, open space, infrastructure restrictions, or other anthropogenic barriers. The following examples illustrate where the use of coastal waters provides the most cost-effective and efficient transit route for high voltage electric cables:

- Trans Bay Cable (TBC): a 400 MW bundled-high voltage direct current (HVDC) electric/fiber optic cable (53 mi. in length) which transmits power from Pittsburg, CA to San Francisco, CA through San Francisco Bay.
- Cross Sound Cable (CSC): a 330 MW bipolar-HVDC cable (24 mi. in length) that passes through Long Island Sound from New Haven, CT to Shoreham on Long Island, NY.
- Neptune HVDC cable: a 660 MW HVDC cable (65 mi. in length), stretching from Sayreville, NJ to Levittown on Long Island, NY.

A consequence of electric current transmission through a conduit is the generation and emission of electromagnetic frequencies. Electromagnetic Frequencies (EMF) are comprised of two main components and their resultant interaction: the electric field ("E" field – created by electrons in the cable) and the magnetic field ("M" field – "B" or "H" in the literature – generated by the movement of electric current). The intensity of EMF or an EM field generated and emitted by a cable is a direct function of the voltage level passing through it, as well as the depth to which the cable is buried and the distance between cables (if multiple cables are running adjacently in close proximity). Modelling of EMF from submarine cables with contrasting conductor sizes and current loads has shown that there is a direct proportional relationship between the electric current and the resultant E- and M-fields (Gill et al. 2012). Thus, if the current load is reduced by half, the size of the resultant fields would correspondingly be halved. With regard to mitigating EMF, cable spacing is an important issue for both alternating current (AC) and direct current (DC) cables. If multiple cables are required, installing AC cables near one another can ensure that induced currents are reduced; for DC cables, proximal placement can reduce the generation of magnetic fields (Wright et al. 2002). Although armoring applied to a transmission cable can effectively dampen much of the EMF emitted, E- and M-fields will still be generated above and at a short distance from the cable. Additionally, EMF dissipation rapidly occurs with increasing distance from the generating source. For example, an electric transmission cable with a 1600 A load (3200 µT M-field) would experience an order of magnitude reduction in the M-field at 1 m away (320 µT); at 6 m, the magnitude of the generated M-field would further be reduced to approximately 50 µT (Taormina et al. 2018). Export cables proposed for New Jersey OSW applications will likely carry loads of about 250 kV AC, which is in the range of approximately ± 600 A (although this depends on other factors such phase and power factor). An EMF modeling study performed by Tricas and Gill (2011) suggests that EM fields are strongest directly above a high voltage cable, but decrease rapidly as horizontal and vertical distances from it increase. For the purpose of protection, current industrial standards require that transmission cables be buried between 0.6 m to 3 m in water depths down to 1500 m, which subsequently aids in the dampening of EMF intensity (Wright et al. 2002, BOEM 2011, Szyrowski et al. 2013).

Electric current moving through undersea cables can be either AC or DC, preference for which is usually determined by distance, cost, and other engineering considerations (Green et al. 2007, Wright et al. 2012, Parol et al. 2015). New Jersey OSW installations will be designed to employ HVAC cables, which has been determined to be appropriate for these applications. Cables carrying AC tend to produce lower EMF intensities, whereas those transmitting DC can exert greater influence on the intensity, inclination and declination of the local geomagnetic field, especially if they run perpendicular to magnetic north. For longer transmitting distances and higher voltages, DC cables (HVDC) are preferable and specialized cable designs are available for minimizing loss of capacitance and so on (Wright et al. 2002). Notably, some marine organisms possess sensory organs that can detect naturally occurring electric and/or magnetic fields and use them to navigate, orientate, and sense prey, mates and predators. These animals include elasmobranchs – sharks and rays, decapod crustaceans, eels, marine mammals, sea turtles, and many groups of fishes – yellowfin tuna, Atlantic cod, etc. These faunae may also be potentially impacted when encountering anthropogenically induced sources of EMF (Tricas and Gill 2011, Gill et al. 2012, Claisse et al. 2015, Hutchinson et al. 2018). Sensitive species, such as elasmobranchs, can detect very low E-fields (≥ 0.005 μV/cm) and M-fields (20 - 75 μT), for which much of the concern regarding EMF has been derived (Taormina et al. 2018).

Over the last decade, there have been multiple reviews and studies evaluating the potential vulnerability of marine species to EMF from undersea cables. Researchers from Europe as well as those in the United States (e.g. California, Rhode Island, New Jersey – NJ Offshore Wind Ecological Baseline Studies, New York – NYSERDA Offshore Wind Studies, US DOI - Bureau of Ocean Energy Management: https://www.boem.gov/Renewable-Energy-Completed-Studies/, etc.) have conducted studies and literature reviews that document the most recent findings, although the potential negative impacts proposed remain largely speculative. Most documented effects involve subtle, albeit sub-lethal behavioral responses of individual species when in close proximity to sources of EMF (e.g., fish being repelled by or attracted to fields), although it is uncertain as to whether the observed responses have produced negative or positive consequences for any group or species (Tricas and Gill 2011, Claisse et al 2015). Despite this, the subtle observations still demonstrate that there are some potential EMF effects that influence how marine organisms use electro- and magneto-sensory organs (i.e. for navigation, orientation, feeding, or reproductive purposes). Since offshore wind farms are likely to create habitat and colonization opportunities for a number of species, it is also likely that those in direct contact with or close to EMF sources (directly over a buried cable or on an exposed cable) may be affected (Gill et al 2012). Overall, more focused *in situ* research on this topic is needed to accurately determine the potential positive or negative impacts associated with EMF and ally the uncertainties.

Research and Observed Organismal Responses to EMF

Marine fauna that possess the ability to respond to magnetic fields are generally categorized into two groups: (1) those that have a response based on chemical-mediated detection (magnetite) and (2) those that respond to an induced electric field (Gill et al 2012). Certain species that migrate great distances or rely on navigation in harsh environments, such as the European eel (*Anguilla anguilla*) and other fish species, along with some groups/species of insects, birds, sea turtles and marine mammals have significant amounts of magnetite within their skeletal structure to accomplish this (biomagnetism). This mechanism is thought to allow these organisms to sense or 'feel' the Earth's geomagnetic field and orientate accordingly. Active and passive detection are also possible, either by the organism generating its own EMF by interaction with the earth's magnetic field horizontal component (active) or through interaction with tide/wind driven currents and the vertical magnetic field component (passive) (Gill et al. 2012, Kavet et al. 2016). Table 1 below summarizes the observed organismal responses to EMF exposure from marine cables. More detailed information gleaned from the literature is provided in the sections that follow.

Table 1. Summary of the observed impacts to marine species groups from EMF emissions.

Species Group*	Observed Effect	Impact Severity
Elasmobranchs (sharks, skates, rays)	Behavioral (e.g. alterations in swimming patterns, lingering over cables, slight attraction to cabled areas)	Minimal (innocuous, non lethal)
Fish (pelagic and demersal, eels)	Behavioral (e.g. slight alterations of migration pathways in smolts, lingering over cables)	Minimal (innocuous, non lethal)
Benthics (molluscs, crustaceans, corals, sponges, polychaetes)	Behavioral (e.g. attraction to cabled areas); Physiological (e.g. reduced ammonia excretion in the polycheate *H. diversicolor*).	Minimal (non lethal)
Marine Mammals	None – undetermined	Negligible (Undetermined)
Sea Turtles	None – undetermined	Negligible (Undetermined)

*Note: the information provided is a summary of observed and theoretical effects based on species-specific laboratory investigations and empirical observations, and may not be representative of the species group as a whole.

Elasmobranchs (Sharks, skates and rays)

Elasmobranchs detect magnetic fields via the mechanism of induction, a process by which an electric field is created when a marine organism swims through a magnetic field (the strength is dependent on the speed and orientation of the organism relative to the M-field). These faunae are believed to be the most sensitive to both natural and artificial sources of EMF, based on having anatomical structures (i.e. ampullae of Lorenzini) designed for electromagnetic field detection (Claisse et al. 2015). The elasmobranchs utilize natural EMFs for navigation and for migratory behavior (Gill et al. 2011; Geo-Marine, Inc. 2010, Hutchinson et al. 2018), as well as for detecting prey, predators and mates (Claisse et al. 2015). Studies indicate that these faunae can detect artificial EMFs, with some species having remarkable sensitivity to electric fields in seawater (5 – 48 mV/cm). Avoidance thresholds may be species-specific, however Gill et al. (2012) reported that avoidance can occur when encountering EMFs in the range of 400-1,000 μV/m (the average amplitudes of the CSC magnetic and electric fields are 0.14 μT and 0.7 mV/m, respectively). Some elasmobranchs with known sensitivity to EMFs and found in or near NJ waters include several species of sharks (smooth dogfish [*Mustelus canis*], blue shark [*Prionace glauca*], scalloped hammerhead [*Sphyrna lewini*], sandbar shark [*Carcharhinus plumbeus*]), skates, and eels (*Anguilla* sp.), (Geo-Marine, Inc. 2010). Most recently, Hutchinson et al (2018) conducted a behavioral study looking at the effects of little skates (*Leucoraja erinacea*) within an enclosure perched above the CSC in Long Island Sound. The results from the test group exhibited a strong behavioral response to the EMF from the cable (i.e. traveled further but slower, closer to the seabed, with elevated exploratory activity/area-restricted foraging behavior) as compared to control animals. However, the conclusion of the study was that EMF associated with the CSC did not constitute a significant barrier to movements across the cable for the skates. It is important to note that there are still many inconsistencies in the literature, with some studies suggesting that EMFs cause behavioral effects in marine organisms, and others suggesting that they are negligible (Gill et al. 2011).

Fish and Benthic Organisms

Several studies have been conducted to investigate EMF responses related to fish behavior and catchability. Research supports that some teleost fishes have magnetic receptors and can orientate to natural magnetic fields, in contrast to elasmobranch’s use of induction. Gill et al. (2011) found that fish may be able to detect a magnetic field generated by a DC cable at distances of up to 20 m, however the range of detection can be dependent on factors such as the depth of the cable and its orientation relative to the earth's magnetic field. When a marine organism swims parallel to a cable's magnetic field, it will not generate an induced electric field (Gill et al 2011).

There have been multiple laboratory studies performed on fish to investigate the potential effects of EMF, however only a few of the most recent laboratory and *in situ* studies will be discussed given that these are more relevant to OSW development. In these studies, although some deviations from migration routes or brief lingering activity near undersea cables have been observed, the data do not currently support a finding that overall navigational capabilities in fish are impaired. One example is from Kavet et al. (2016), who conducted acoustic tracking studies on Chinook salmon (*Oncorhynchus tshawytscha*) and green sturgeon (*Acipenser medirostris*) migrating through the San Francisco Bay, where there are several EMF-emitting sources. Bridges were shown to distort the local magnetic field to a greater extent than the undersea transmission cables (notably, the Trans Bay Cable – TBC and High Voltage Direct Current cable - HVDC) running through San Francisco Bay. They suggested that the reasoning for this effect is likely due to magnetic orientation of the EMF emitters, being that the bridges are oriented across the Bay (and consequently perpendicular to the geomagnetic field) and the TBC and HVDC run parallel to the local geomagnetic field. Even in combination, the study found that the bridges, TBC, and HVDC do not appear to have created a barrier to the seasonal migrations of these species of fish. Kilfoyle et al. (2018) assessed whether EMF from undersea transmission cables from the South Florida Ocean Measurement Facility (SFOMF; 60 Hz) affected coral reef fish assemblages using diver surveys of fish species occurrence and abundance associated with different cables and noted any fish reaction when EMF changed (i.e. power on vs. off). Electric field (10 Hz) and M-field (210 μV/m) levels were measured 4 m above the energized cables (2.4A DC current; 1.9A AC 60 Hz current). No significant difference was apparent between power states, however there were indications of higher fish abundance at sites when the power was switched off. Based on their findings, further study was suggested.

Westerberg and Lagenfelt (2008) examined migration patterns and behavior of European eels (*A. anguilla*) near an AC electric cable in the Baltic Sea. Tagged eels were monitored during migration and their swimming speeds measured. Although eel swimming speeds appeared slower in close proximity to the cable compared to locations north and south, behavior and other physiological effects were not noted. Dunlop et al. (2016) investigated whether the presence of a HVAC (3-core XLPE – Cross-linked polyethylene: extruded insulation), 245 kV cable in Lake Ontario (Wolfe Island Wind Power Project) affected the spatial pattern and composition of nearshore and offshore fishes (numerous species, including the EM-sensitive American eel, *A. rostrata*). Following a two-year study, no detectable effects on the fish community from the cable were discovered. Accordingly, the investigators concluded that local habitat variables, including substrate or depth, seemed to better justify variation in fish density than proximity to the cable.

Hutchinson et al. (2018) conducted a study looking at behavioral responses of American lobster (*Homarus americanus*) when exposed to EMF from the HVDC transmission cable connecting New Jersey to Long Island, NY. Lobsters exhibited a statistically significant but subtle change in behavior in the treatment enclosure (i.e. closer to the seabed, exhibited a higher proportion of changes in the travel direction, and made more use of the central space of the enclosure near the cable) compared to the control. However, the EMF associated with the HVDC cable did not constitute a barrier to movements across the cable for this species. Catchability of Dungeness crabs (*Metacarcinus magister*) and rock crabs (*Cancer productus*) was investigated by Love et al. (2017), specifically to determine whether these animals would cross an energized, buried cable to reach baited traps. The results demonstrated no observed difference in crab response or catchability.

The effects of submarine cable installation and operation on benthic biota are more enigmatic and have been the focus of recent study in the Baltic Sea and in the Northwestern Atlantic (e.g. Block Island Sound). A study performed by Dunham et al. (2015) investigated changes in the condition of glass sponge reef and the responses of associated megafauna following transmission cable installation. Although live sponge cover and megafauna coverage was lower on the direct cable footprint, the effect of the cable (presumably emitting EMF) directly on species presence could not be determined. It was postulated that initial disturbance associated with the installation of the cable appeared to be the major contributor to the delayed recovery of the reef, although rates of reestablishment and presence of megafauna were not significantly different. Andrulewicz et al. (2003, as cited by Taormina et al. 2018) reported that for soft substrates in the Baltic Sea, cable burial following one-year post-installation did not result in significant changes to the abundance, diversity, or biomass of benthic organisms along the cable route. However, recovery and resilience of fauna depends on several factors which are species-dependent, such as its ability to return post-disturbance, the duration of the impact (in this case physical disturbance of the habitat rather than EMF), and the species' life history requirements. A new study by Jakubowska et al. (2019) examined the behavior and bioenergetics of the polychaete *Hediste diversicolor* when exposed to EMF values typically recorded in the vicinity of submarine cables (i.e. 50 Hz, 1 mT). In this experiment, polychaetes were placed in aquaria (reference vs. exposure) and exposed to the prescribed EMF value above. No avoidance or attraction behavior was observed, however burrowing activity was enhanced in the EMF treatment. Further, *H. diversicolor* maintained a positive energy balance and growth rates in the exposure treatments. An unexpected result from the study was that ammonia excretion rate was significantly reduced in the EMF treatment as compared to reference conditions. Many marine aquatic and marine fish, and almost all marine invertebrates excrete ammonia as a toxic waste product from protein metabolism (Theil et al. 2017). The effect of the EMF exposure on the animal's waste removal mechanism could be the upregulation of several genes on ammonia transport processes, however further investigation is needed to confirm this finding.

Marine Mammals and Sea Turtles

Although information on the impacts from transmission cable EMF to these groups is lacking, there may be some potential effects related to the proximity of an animal to the undersea cables. Specifically, species feeding near or in the benthos (i.e. benthopelagic feeding dolphins, or beluga whales - *Delphinapterus leucas* and gray whales - *Eschrichtius robustus*) may have a greater potential for exposure than those species foraging elsewhere in the water column (Tricas and Gill 2011, Hutchinson et al. 2018). Thus, animals feeding near or above transmission cables may be exposed to magnetic fields above their sensitivity threshold. However, little evidence is available as to what the response would be to these types of exposure. Information is available showing that sea turtles rely on the earth's magnetic field for migration and navigation, and can respond to subtle changes in the field's intensity. Putman et al. (2015) studied the magnetic navigation of the oceanic life stages of loggerhead turtles (*Caretta caretta*) using a combination of field and laboratory studies, concluding that the navigation behavior of sea turtles is closely tied to interactions between ocean circulation and dynamics in the geomagnetic field. Other studies suggest that the geomagnetic environment during incubation can influence sea turtle magnetic orientation behavior during hatching and potentially into maturity (Hutchinson et al. 2018).

Summary of the Impacts and Effects of EMF

Although current studies and literature on EMF-species interactions are increasing, there are still significant data gaps in the knowledge base. In a recent review on the effects EMF on marine species for BOEM (CSA Ocean Sciences Inc. and Exponent 2019), the report concluded that "the operation of OSW 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". Many marine organisms can act as potential receptors, but few, if any studies have demonstrated negative impacts of biological significance. In addition, little is known as to what the long-term effects (and for many the short-term effects) of EMF on individual species or groups of species. At most, species responses that have been observed are behavioral and non-lethal in nature (e.g. lingering near cables, slowed swimming speed, avoidance, etc.). Species possessing electro- and magneto-sensory organs sensitive to variations in the natural magnetic field have been shown to elicit some response to artificial sources of EMF. Some studies indicate developmental (laboratory/experimental) and or physiological responses to EMF, however these effects could be species dependent or do not adequately factor in the multiple stressors acting on the organism as they would in a natural setting (Hutchinson et al. 2018). Benthic and demersal species are more likely to be exposed to higher field strengths from buried cables than pelagic species based on their habitat preferences and life history requirements. However, negative effects on pelagic species are not expected due to their distance from the cables buried in the seafloor (CSA Ocean Sciences Inc. and Exponent 2019).

Many researchers and literature suggest that improved methods are needed to measure the intensity of the EMFs generated by a high voltage transmission cables for better site characterization of effects (Taormina et al. 2018, BOEM, In progress). The most accurate measure of EMF intensity, at present can only be made within 10 m of a subsea cable, whereas beyond 60 m water depth EMF detection and intensity measures are significantly more challenging (Szyrowski 2013). The strength of EMF, time exposure, range, and targeted species all need to be considered and studied prior to making further conclusions on impacts, or mitigation measures if applicable. The key points that summarize the mechanism by which EMFs influence and or affect the marine environment, habitats and fauna are as follows:

- Electromagnetic fields generated by transmission cables carrying electricity from offshore energy sources (e.g. OSW turbines, tidal energy systems) to shore may produce local distortions in the earth's main geomagnetic field.

- Marine animals that migrate along the continental shelves may orient to the EMF generated from high voltage submarine cables, potentially altering their swimming behavior or deviating from their normal migration routes.

- Empirical and experimental evidence supports that marine organisms sensitive to E and B fields do exhibit minor behavioral responses to EMF from undersea cables, although not all species are affected.

- Research suggests that EMFs associated with DC cables (as compared to AC cables with similar voltage) are more likely to be detected by marine organisms and have a greater potential to alter behavior.

- Research to-date has not shown significant evidence that EMF from undersea electric cables causes (physiological) impacts to individual species and populations or impacts to habitat.

Overall, ecological impacts associated with submarine cables and associated EMFs range from benign to moderate (Taormina et al. 2018). As to whether these impacts to marine organisms are positive or negative (though in some cases this can be subjective), the results to-date remain inconclusive and warrant further study (Hutchinson et al. 2018, Wright 2018).

Abbreviations and Units of Measurement

A	Amperes (or amps)
AC	Alternating current
BOEM	Bureau of Ocean Energy Management (US DOI)
CSC	Cross-sound Cable
DC	Direct current
US-DOI	United States - Department of Interior
E-field	Electric-field
EM	Electromagnetic
EMF	Electromagnetic frequency
HVAC	High voltage alternating current
HVDC	High voltage direct current
Hz	Hertz
km	Kilometers
kV	Kilovolts
m	Meters
M-field	Magnetic-field
mi.	Miles
mT	Milli-Tesla
µT	Micro-Tesla
mV/cm	Millivolts per centimeter
µV/m	Microvolts per meter
MW	Megawatts
NYSERDA	New York State Energy Research & Development Authority

OSW	Offshore wind
SFOMF	South Florida Ocean Measurement Facility
TBC	Trans Bay Cable

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