Appendix P2. High Voltage Direct Current Electric and Magnetic Field Assessment

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Memorandum

To: Paul Pansing, Burns & McDonnell **Date:** July 23, 2021

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Subject: Scientific Considerations Related to the Potential Effects of Static Electric and Magnetic Fields (EMFs) Associated with High-Voltage Direct Current (HVDC) Transmission Lines to Human Health and Marine Species

Introduction and Summary

Although offshore wind development in the US has relied primarily on 60 hertz (Hz) high-voltage alternating current (HVAC) power transmission to date, high-voltage direct current (HVDC) transmission has been utilized for a number of European offshore wind projects and is expected to gain usage for US projects in the near future. Similar to 60 Hz AC power transmission, electric and magnetic fields (EMFs) are generated by HVDC transmission; however, rather than rapidly varying in direction, EMFs associated with HVDC transmission are static (*i.e.*, have a frequency of 0 Hz) and thus have significant differences from AC EMFs.

Below, we review scientific considerations related to HVDC EMFs, providing some background on static EMFs in Section 1, reviewing scientific evidence on potential adverse health effects to humans in Section 2, addressing the evolving science on the response of marine species to DC EMFs in Section 3, and summarizing DC EMF exposure guidelines in Section 4. Section 5 provides the reference list. We conducted literature searches using the US National Library of Medicine's PubMed biomedical literature database[1] and Elsevier's Scopus database[2] in order to identify published research studies and review articles relevant to the weak[3] static magnetic fields (MFs) that would be associated with submarine and onshore underground HVDC transmission from offshore wind projects. We focused primarily on static MFs rather than static electric fields (EFs) because both submarine export cables and onshore underground cables always include a metal sheath that shields the EFs generated by the cable voltage when grounded, and no external EFs are thus generated directly by DC submarine export cables or onshore underground cables. Moreover, Petri *et al*. (2017) conducted a systematic review of the biological effects to humans and other vertebrates of static EFs from overhead HVDC transmission, concluding: "The weight of the evidence from the literature reviewed did not indicate that static EF have adverse biological effects in humans or animals." Similarly, for marine organisms, Gill and Desender (2020) discussed how research efforts are focused on MFs for understanding potential impacts to marine species from EMFs associated with offshore power transmission.

Key findings from our review include the following:

[1] http://www.ncbi.nlm.nih.gov/pubmed/
[2] http://www.scopus.com/
[3] As discussed by Driessen *et al*. (2020), researchers have classified static MFs as either weak (<10,000 mG), moderate (10,000 to 10,000,000 mG), high (10,000,000 to 200,000,000 mG), and ultra-high (>200,000,000 mG).

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- Overall, it is well established that there are differences in how DC EMFs interact with both humans and marine species as compared to AC EMFs, and that the potential for biological responses cannot be directly compared between DC and AC EMFs (CSA Ocean Sciences Inc. and Exponent, 2019).
- There are a number of common natural and anthropogenic sources of static EMFs, including, most notably, the earth's cloud-generated EFs and geomagnetic field.
- For human health risks posed by DC EMFs, there is not as extensive a body of health effects literature as exists for human health risks posed by AC EMFs, but scientists have not found any confirmed health risks for the weak static EMFs associated with HVDC power transmission.
- For marine species, some studies have reported behavioral responses for certain marine species that suggest that EMFs from HVDC cables are perceptible to electromagnetic (EM)-sensitive marine species. However, as discussed below, there remains only inconsistent evidence of behavioral responses in some marine species and an absence of conclusive evidence supporting the observed behavioral responses as being indicative of potential population-level detrimental impacts.
- There are no US federal standards limiting general public or occupational exposure, or exposure of marine species, to EMF from HVDC transmission lines. As summarized below, international health and safety organizations have established health-based exposure guidelines for DC EMFs for both the general public and occupational populations. In particular, the International Commission on Non-ionizing Radiation Protection (ICNIRP) has established guidelines for continuous exposure of the general public to static MFs that are well above typical static MF exposures associated with HVDC transmission.

1 Background on Static Electric and Magnetic Fields (EMFs)

In contrast to the time-varying EMFs generated by 60 Hz AC power frequency transmission, steady (*i.e.*, static) EMFs with a frequency of 0 Hz are produced by HVDC transmission. While AC circuits typically have three conductors and are often called "three-phase circuits," DC circuits have just two conductors, namely one positive (+) and one negative (–) conductor. This memo is focused on DC MFs because both submarine export cables and onshore underground cables always include a metal sheath that shields the EFs generated by the cable voltage when grounded, and no external EFs are thus generated directly by DC submarine export cables and onshore underground cables.[4]

MFs from both DC and AC currents are similarly expressed as magnetic flux density (referred to as the "magnetic field") in units of gauss (G) or milligauss (mG) (1 G = 1,000 mG).[5] For a given configuration of current-carrying conductors, the size of MFs produced in both cases are directly proportional to the size of the current in the cables in exactly the same way, and both DC and AC MFs similarly decrease with distance from the conductors. Normandeau *et al*. (2011) reported DC MF modeling results for eight submarine cable projects where peak MFs at the seabed directly above the cables ranged from about 100 mG to more than 1,500 mG. Importantly, the Normandeau *et al*. (2011) modeling demonstrated the rapid decline in MFs with distance, *i.e.*, decreasing proportional to the square of the distance from the cables, as illustrated by average MFs at the sea floor being 783 mG directly above a cable, 60 mG at a horizontal distance of 4 meters from a cable, and 10 mG at a horizontal distance of 10 meters from a cable. The Normandeau *et al*. (2011) modeling results also illustrate the large heterogeneity in DC MF levels for

[4] Although the AC MFs produced by 60 Hz AC submarine cables will induce a weak EF in the surrounding marine environment near the buried cables, the load currents on DC submarine cables, because they are steady in time, will not induce EFs outside the cables (CSA Ocean Sciences Inc. and Exponent, 2019). However, similar to the induced EFs associated with water movement and marine animal movement through the earth's geomagnetic field, very weak static EFs will be induced by water flow or marine animal movement through the static MFs associated with DC submarine cables.

[5] Another unit for MF levels is the microtesla (μT) (1 μT = 10 mG).

submarine DC cables depending on the electric current flow, cable specifications (*e.g.*, conductor arrangement), and installation conditions (*e.g.*, burial depth).

A key difference between DC and AC MFs involves the fact that DC MFs, such as those associated with a submarine cable, can combine with the earth's static geomagnetic field to somewhat alter the direction and/or magnitude of the total MF nearby the cable. The earth's static geomagnetic field, which is associated with DC flow in the earth's liquid core as well as metallic crustal elements, is the largest source of DC MFs for both marine and terrestrial environments (Normandeau *et al*., 2011). The intensity of the background geomagnetic field at the earth's surface varies between about 300 mG near the equator to the highest values of ~700 mG near the south and north poles. Along the southern New England coast, the earth's MF has a magnitude of about 516 mG (CSA Ocean Sciences Inc. and Exponent, 2019). Whether the static MF from an HVDC submarine cable will either add to or subtract from the earth's geomagnetic field will depend on the direction/orientation of the cable relative to the direction of the earth's geomagnetic field at the location of interest.

Naturally occurring static EMFs are ubiquitous in coastal environments due to other sources besides earth's MF. Other natural static EMFs are associated with the movement of ocean currents and marine organisms through earth's MF and those directly produced by marine organisms. The movement of ocean currents and marine organisms through earth's MF produces weak DC EFs (CSA Ocean Sciences Inc. and Exponent, 2019). Marine organisms produce bioelectric fields, such as from heartbeats and gill movement, close to their body surfaces; in addition, electric fish species such as the electric eel can generate strong EFs for defense purposes. These bioelectric fields, which include both AC and DC EFs, can be as high as 0.5 volts per meter (V/m), but typically diminish to negligible levels within 4-8 inches, or 10-20 centimeters, from the source organism (CSA Ocean Sciences Inc. and Exponent, 2019). While these bioelectric fields can include AC fields that change direction several times per second, they are generally for frequencies of less than 10 Hz (*e.g.*, EFs from a heartbeat of 120 beats per minute would have a frequency of 2 Hz) and thus are considerably below the frequencies of the 60 Hz AC EFs that are characteristic of US power generation and transmission (CSA Ocean Sciences Inc. and Exponent, 2019).

Besides DC submarine cables, perturbations to earth's geomagnetic field in coastal environments can also be caused by various types of ferromagnetic sources, including shore-based structures such as docks, jetties, and bridges; sunken ships; pipelines; and ferromagnetic mineral deposits (Normandeau *et al*., 2011; CSA Ocean Sciences Inc. and Exponent, 2019). Normandeau *et al*. (2011) reported that MF impacts nearby to these sources can be on the order of tens of mG, while CSA Ocean Sciences Inc. and Exponent (2019) observed that undersea sources of DC MFs including steel ships and bridges can create DC MFs up to 100 times greater than MFs from DC submarine cables.

Anthropogenic sources of static MFs are also common in everyday life, including consumer products that use DC transmission or permanent magnets (*e.g.*, electric cars, trains for DC rail systems, loudspeakers, microphones, and toy magnets) as well as medical devices (*e.g.*, magnetic resonance imaging [MRI]) (Driessen *et al*., 2020). Driessen *et al*. (2020) reported the measurement of weak static MFs up to about 10,000 mG inside both hybrid technology cars and the driver's cabins of DC trains. Driessen *et al*. (2020) also discussed how MRI workers are commonly exposed to static MFs on the order of several million mG, with even higher potential exposures in research environments (*e.g.*, 20,890,000 mG for a 7 Tesla scanner). ICNIRP (2009) observed that scanned patients and MRI operators can have static MF exposures between 1,500,000 and 30,000,000 mG for systems encountered in MRI clinics. Other workers who may be exposed to elevated levels of static MFs include welders, aluminum production workers, and workers at chloralkali plants. Typical small permanent magnets, such as those used in magnet clips and magnetic attachments in bags, buttons, magnetic necklaces and bracelets, magnetic belts, and magnetic toys, can generate local static MFs that exceed 5,000 mG (ICNIRP, 2009).

2 Potential Adverse Health Effects to Humans

A greater amount of research has focused on potential human health risks posed by 60 Hz AC EMFs than DC EMFs. This is in part due to the failure of researchers to date to document any public health impacts for low-level exposures to DC EMF associated with HVDC transmission. As concluded by the U.S. Environmental Protection Agency (US EPA, 1992), "Direct current (DC) magnetic fields have not raised as many questions about potential health concerns as have the time-varying fields created by alternating current (AC)." It is well established that DC and AC EMFs interact in different ways with living organisms and their potential for eliciting biological responses cannot be directly compared (CSA Ocean Sciences Inc. and Exponent, 2019). Importantly, health effect research findings reported for 60 Hz AC EMFs have no direct relevance to DC EMFs, given the differences in their properties and characteristics (http://www.emfs.info).

There is some evidence for acute health effects of highly elevated static MFs in excess of 1 Tesla (10,000,000 mG) (WHO, 2006; ICNIRP, 2009), which is equal to 10,000,000 mG, *i.e.*, far larger than the MF present even in the immediate vicinity of HVDC submarine cables (<1,000 mG). For example, a person moving within static MFs in excess of about 2 Tesla (20,000,000 mG) may experience sensations of vertigo and nausea, and possibly a metallic taste in the mouth and perceptions of light flashes. Interactions between static MFs with strengths in excess of about 8 Tesla (80,000,000 mG) and moving charges in the blood can result in slight changes to blood flow and possible consequences ranging from minor changes in heartbeat to increased risk of abnormal heart rhythms (arrhythmia). As concluded by ICNIRP (2009), "In conclusion, current information does not indicate any serious health effects resulting from the acute exposure of stationary humans to static magnetic fields up to 8 T [8 Tesla= 80,000,000 mG]." Moreover, it should be noted that not only do HVDC submarine cables produce much smaller DC MF than this, but also, human exposure to DC MF in the vicinity of HVDC submarine cables is highly unlikely.

Several reviews have been conducted to assess whether lower-level (*e.g.*, <10,000 mG) static MFs may pose potential health risks to humans. Most recently, Driessen *et al*. (2020) conducted a systematic review focused on biological and health-related effects of weak static MFs (≤10,000 mG) in humans and vertebrates. They identified just 11 studies that met their eligibility criteria, all of which were experimental animal studies. Studies of worker populations with potential exposures to elevated levels of static MFs, including MRI workers and workers in aluminum reduction plants, were excluded due to co-exposures (*e.g.*, in the case of MRI workers, exposures to radiofrequency EMF and gradient MFs; in the case of workers in aluminum reduction plants, exposures to chemicals and heat) that did not allow for the characterization of potential health risks specific to static MFs *per se*. For the experimental animal studies, Driessen *et al*. (2020) reported that 8 of 11 studies reported biological responses for exposure to weak static MFs, but they highlighted a number of factors that affected the credibility of the study findings, including heterogeneity in the health endpoints and animal species that were studied, a lack of scientific rigor and quality for most of the available studies, and inconsistencies in the reported findings that have not been confirmed in replication studies conducted by other researchers. Driessen *et al*. (2020) observed, "It should be noted that it remained largely unclear from the interpretation of the results whether the reported effects in the evaluated studies are beneficial or detrimental for health. However, it is unlikely that the reported effects of exposure to weak SMF [static magnetic fields] pose a serious risk for health." Overall, Driessen *et al*. (2020) concluded based on their review, "The available evidence from the literature reviewed is not sufficient to draw a conclusion for biological and health-related effects of exposure to weak SMF."

The Driessen *et al*. (2020) conclusions are similar to those reached by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the World Health Organization (WHO) based on their prior reviews of the health effects evidence for static MFs:

- From the ICNIRP "Guidelines on Limits of Exposure to Static Magnetic Fields" (ICNIRP, 2009): "Overall, the few available epidemiological studies have methodological limitations and leave a number of issues unresolved concerning the possibility of risk of cancer or other outcomes from long-term exposure to static magnetic fields. These studies do not indicate strong effects of static magnetic field exposure of the level of tens of mT [hundreds of thousands of mG] on the various health outcomes studied, but they would not be able to detect small to moderate effects. Other occupations with a potential for higher magnetic field exposures have not been adequately evaluated, *e.g*., MRI operators."
- From Environmental Health Criteria 232, "Static Fields," prepared as part of the WHO International EMF Project (WHO, 2006): "The available evidence from epidemiological and laboratory studies is not sufficient to draw any conclusions with regard to chronic and delayed effects."

In addition, the Feychting (2005) review paper focused on the human epidemiological evidence specific to the potential long-term health effects of static MFs. Feychting (2005) identified a small number of epidemiological studies, most of which were focused on cancer risk. While observing that most of the available studies had "severe methodological limitations," Feychting (2005) highlighted their inconsistent results and the lack of any discernible patterns suggestive of potential cancer risks. Important methodological limitations included limited control of confounding in all studies, including inadequate control of smoking in analyses of lung cancer; as well as crude MF-exposure assessments. Overall, Feychting (2005) concluded, "In conclusion, the available evidence from epidemiological studies is not sufficient to draw any conclusions about potential health effects of static magnetic field exposure."

The International Agency for Research on Cancer (IARC), the specialized cancer agency of the WHO that conducts evaluations of the carcinogenicity of chemicals and other agents to humans, published its monograph on the carcinogenicity of static and extremely-low-frequency EMFs in 2002 (IARC, 2002). While IARC concluded that power-frequency MFs were a Group 2B possible human carcinogen, it classified both static EMFs as Group 3, unclassifiable as to human carcinogenicity, due to the absence of evidence in humans that they are carcinogens. Following up on the IARC hazard assessment of the carcinogenicity of static fields, WHO published its Environmental Health Criteria monograph for static EMFs in 2006 (WHO, 2006). This report, which expanded upon the hazard identification in the IARC monograph and discussed findings from a comprehensive health risk assessment conducted by WHO for static EMFs, similarly determined that the carcinogenicity of static fields to humans is not classifiable, and more broadly highlighted the insufficient evidence for drawing any conclusions regarding chronic and delayed health effects posed by static fields (WHO, 2006).

In conclusion, it bears mentioning that humans have lived for thousands of years in the presence of the earth's geomagnetic field, which is not known to adversely interact with biological processes or directly affect human health. It can thus be inferred that anthropogenic static MFs of a similar or lesser magnitude are unlikely to have significant public health impacts.

3 Biological Responses of Electromagnetic-Sensitive (EM) Marine Species

EMFs from both DC and AC submarine cables are hypothesized to have potential impacts to marine organisms given the body of science supporting marine organisms as using naturally occurring EMFs (*e.g.*, the earth's DC MF and fish-generated EFs in seawater) for certain specific purposes, such as orientation, navigation, prey location, and long-distance migration. Magnetosensitivity, which refers to an organism's ability to detect and respond to the earth's DC MF, is reasonably well established in some marine organisms and some avian species. Together with other senses, it is understood that magnetosensitive species use MFs to help find food, habitat, and spawning locations. Magnetosensitive marine species are known to include salmon, American eel, sturgeon, yellowfin tuna, sharks, skates, rays, lobsters, and sea turtles (CSA Ocean Sciences Inc. and Exponent, 2019).

Neither the DC geomagnetic field, nor DC cables, produce EFs directly in saltwater, but motion of the water, or motion of marine species in the water, can cause an EF to be generated by either of these DC MF sources. Thus, the potential effects of DC MFs should also consider an organism's electrosensory capabilities. A considerable amount of research has been targeted at elucidating the mechanism of electrosensory ability in aquatic organisms and the potential utility of this sensory modality for navigation and prey detection. This research has, to date, identified a smaller number of marine species that are known to be electrosensitive as compared to magnetosensitive species. Among the marine species documented to show electrosensitivity are sharks, rays, skates, and sturgeon (CSA Ocean Sciences Inc. and Exponent, 2019). Electrosensitivity appears developed enough to allow for detection and orientation toward prey-organism bioelectric fields, such as heartbeats at very low frequencies from about 1 to 20 Hz (CSA Ocean Sciences Inc. and Exponent, 2019). Occurring over distances of tens of centimeters, and not meters, the detection of bioelectric fields is used by electrosensitive fish species as part of their overall environmental sensory system to help them survive and navigate (CSA Ocean Sciences Inc. and Exponent, 2019).

The knowledge base on the potential impacts of DC fields on marine species is rapidly evolving, as a number of robust field and laboratory studies on sources of DC MFs, including from buried submarine HVDC cables, have been conducted in the last five years. Researchers have interpreted findings from these studies, including subtle behavioral responses of certain marine species, as suggesting that EMFs from HVDC cables are perceptible to some EM-sensitive marine species. However, as discussed below, there remains only inconsistent evidence of behavioral responses in some marine species and an absence of evidence supporting the observed behavioral responses as being indicative of potential population-level detrimental impacts. As Hutchison *et al*. (2020a) recently concluded, "For receptor species, it is difficult to translate the patchwork of knowledge about individual-level EMF effects into assessments of biologically or ecologically significant impacts on populations."

The recent Hutchison *et al*. (2020b) publication reported the findings from one of the more innovative field studies to investigate the interaction between bottom-dwelling marine species and EMFs from buried submarine HVDC cables. This study, which was funded by the Bureau of Ocean Energy Management (BOEM), investigated behavioral responses of both Little skates (*Leucoraja erinacea*) and American lobsters (*Homarus americanus*) for *in situ* enclosure experiments conducted on top of the Cross Sound Cable (CSC), a buried submarine HVDC cable (330 MW, 300 kV) that runs between Connecticut and Long Island. These two bottom-dwelling marine species were chosen for study since they are benthic species of ecological and commercial importance, and as bottom-dwelling species, they are expected to have greater encounter rates with EMFs from buried submarine cables than other species, such as pelagic fish species. The Little skate is recognized as a model organism for electro-sensitive elasmobranches, while the American lobster is believed to have magneto-sensory abilities (Hutchison *et al*., 2020b). In addition to conducting the *in situ* enclosure experiments, the researchers also directly measured both MF and EF components of the EMFs from the CSC as well as the Neptune Cable, a buried HVDC cable (660 MW, 500 kV) that connects New Jersey and Long Island. They measured DC MFs for both cables that typically extended 5-10 meters on either side of the cables, as well as unexpected AC EMFs of unknown origin.

Hutchison *et al*. (2020b) observed that both the Little skate and American lobster were able to move freely through the EMFs associated with the HVDC CSC, but they reported findings demonstrating "a striking increase in exploratory/foraging behaviour in skates in response to EMF and a more subtle exploratory response in lobsters." For the Little skate, Hutchison *et al*. (2020b) reported statistically significant differences for test animals in the treatment enclosure *versus* the control enclosure for multiple biologically relevant behavioral parameters considered to be indicative of increased exploratory/foraging behavior. The investigators classified the strongest observed behavioral responses to DC MF for the Little skate to include distance traveled per day, speed of movement, height from seabed, and proportion of large turns; moreover, for analyses that considered the gradient of DC MF within the treatment enclosure, they further reported that the zone of high DC MF (defined as >526 mG, with the corresponding zone of low DC MF defined as <497 mG) was associated with the different patterns of spatial distribution, distance traveled, and proportion of larger turns. Hutchison *et al*. (2020b) hypothesized that these findings are indicative of increased exploration/foraging with no return and thus may suggest detrimental energetic loss, unless the skate learn from the experience and can distinguish natural from anthropogenic DC MFs. During these experiments, the electric current on the CSC varied between 16 and 1,175 amps, with corresponding maximal MFs at the seabed of the treatment enclosure varying between 516 and 653 mG.

For the American lobster, fewer statistically significant differences in behavioral parameters were observed, with only the proportion of large turns and their height from seabed achieving statistical significance between the treatment and control enclosures. The researchers described these findings as supporting an "overall response" rather than an EMF response, given that there was "no indication that either of these parameters were associated with zones of high or low EMF." During the experiments for the American lobster, the CSC had a constant current of 1,175 amps, which corresponded to a maximal MF of 653 mG on the seabed of the treatment enclosure. Due to the lack of understanding of the component, intensity, and frequency of EMFs to which the Little skate or American lobster were responding, Hutchison *et al*. (2020b) concluded, "Further research must further define the EM [electromagnetic] environment together with sensitivity thresholds and likely encounter rate of EM sensitive species in order to establish if a behavioural effect may become a population level impact."

In contrast to the Hutchison *et al*. (2020b) findings, other studies have observed an absence of behavioral responses and/or adverse effects for bottom-dwelling species. For example, Taormina *et al*. (2020) conducted two different behavioral assays, one focusing on the avoidance/attraction effect of MF and another examining the effect of extended MF exposure on exploratory behavior and the ability to find shelter, as part of an aquarium study of juvenile European lobsters (*Homarus gammarus*). Novel design components of this study included its use of an early developmental phase of European lobsters, given hypotheses that early life stages may be more susceptible to EMF than adults, as well as treatment groups with exposure to AC or static MFs. For the first bioassay, they observed no changes in sheltering behavior in lobsters exposed to either artificial AC or static MF gradients (maximum intensity of 2,000 mG), as compared to non-exposed lobsters exposed to only the ambient MF. For the second bioassay, they observed no changes to the lobsters' ability to find shelter or their exploratory behavior following one week of exposure to artificial AC or static MFs (2,250 ± 50 mG), as compared to control lobsters. Based on their findings, Taormina *et al*. (2020) concluded, "It appears that static and time-varying anthropogenic magnetic fields, at these intensities, do not significantly impact the behavior of juvenile European lobsters in daylight conditions." In addition, in a laboratory study where several different types of marine benthic species were exposed to highly elevated static MFs (37,000 mG) over several week time periods, Bochert and Zettler (2004) observed no differences in survival between exposed and control test organisms that included North Sea prawn (*Crangon crangon*), round crab (*Rhithropanopeus harrisii*), glacial relict isopod (*Saduria entomon*), blue mussel (*Mytilus edulis*), and young flounder (*Plathichthys flesus*). Moreover, they observed no significant differences for either the gonad index or a condition index for blue mussels that received three months of static MF exposure during their springtime reproductive period.

Another notable field study involving buried HVDC submarine cables was conducted in San Francisco Bay by a collaborative team led by researchers at the University of California, Davis (EPRI, 2016; Klimley *et al*., 2017; Wyman *et al*., 2018). San Francisco Bay is home to the Trans Bay Cable (TBC), which is a ±200 kV, 400 MW, 85 km long HVDC buried submarine cable beneath the San Francisco Estuary that links Pittsburg, CA, with San Francisco, CA (Kavet *et al*., 2016). As part of this study, these researchers found that, due to ferromagnetic steel being present in their construction, bridges crossing the estuary produced much greater distortions in the earth's geomagnetic field than the TBC, with MF anomalies from the bridges exceeding anomalies from the TBC by an order of magnitude or more. Overall, these researchers did not observe strong evidence that DC MFs from either the TBC or from bridges affected the probability of successful natural migration of either Chinook salmon smolts (*Oncorhynchus tshawytscha*) or adult green sturgeon (*Acipenser medirostris*) (Klimley *et al*., 2017; Wyman *et al*., 2018). Wyman *et al*. (2018) reported some "mixed, but limited effects" on movements of Chinook salmon smolts from the TBC-related DC EMF (*e.g*., no significant impacts on the proportion of fish successfully migrating through the bay and on the probability of successful migration; after cable energization, higher proportions of fish crossing the cable location and being found south of their normal migration route), although they acknowledged the uncertainty in the potential long-term consequences of their findings.

BOEM recently commissioned a report aimed at summarizing what is currently known about potential EMF impacts in coastal marine environments, with a specific focus on fish species of commercial or recreational importance in southern New England (CSA Ocean Sciences Inc. and Exponent, 2019). This report includes an 8-page executive summary, a 36-page technical discussion, and a 7-page reference list with 92 specific citations. It addresses potential risks to marine species posed by both AC and DC fields. Overall, based on its review of the state of the knowledge regarding potential EMF-related impacts on marine life, the authors concluded, "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" (CSA Ocean Sciences Inc. and Exponent, 2019). This conclusion is based on the growing number of recent research studies published by US and European researchers, as well as information available from fish surveys conducted in Europe where both AC and DC submarine export cables have been operated in coastal environments for more than a decade. With respect to findings from fish surveys in Europe, the study authors concluded, "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."

More recently, as part of the Ocean Energy Systems (OES)- Environmental 2020 State of the Science Report, Gill and Desender (2020) published a review of the current knowledge relevant to "risk of animals from electromagnetic fields emitted by electric cables and marine renewable energy devices." Gill and Desender (2020) discussed how a number of targeted studies have contributed to an increase in the knowledge base since the analogous publication in the 2016 State of the Science Report, which highlighted significant gaps in the knowledge base. Gill and Desender (2020) observed that new research, including both field and laboratory studies, has included some measurable EMF-related effects and responses (*e.g*., behavioral, physiological, development, and genetic) on a limited number of individual species, but emphasized that these findings are not generally for EMF strengths associated with marine renewable energy (MRE) projects. Overall, based on their updated review of the available science, Gill and Desender (2020) concluded, "Based on the knowledge to date, biological or ecological impacts associated with MRE subsea power cables may be weak or moderate at the scale that is currently being considered or planned. It is important, however, to acknowledge that this assessment comes from a handful of studies and that data about impacts are scarce, so significant uncertainties concerning electromagnetic effects remain." While this conclusion is not specific to DC, many of the recent studies discussed by Gill and Desender (2020) were of DC transmission, including the Hutchison *et al*. (2020b), Taormina *et al*. (2020), and Wyman *et al*. (2018) studies. Gill and Desender (2020) highlighted the continued lack of conclusive evidence and the need for additional research targeting other receptor species, sensitive life stages, and different EMF exposures (sources, intensities).

4 DC EMF Exposure Guidelines

There are no US federal standards limiting general public or occupational exposure, or exposure of marine species, to EMFs from HVDC transmission lines. As summarized in Table 1, international health and safety organizations have established health-based exposure guidelines for both the general public and occupational populations. Importantly, health-protective MF guidelines are far above the typical MF present associated with HVDC submarine cables, even in the immediate vicinity of the cables (*e.g.*, as discussed previously, <2,000 mG). In particular, ICNIRP has established a general public exposure guideline of 4,000,000 mG for static MFs (ICNIRP, 2009). This exposure guideline encompasses safety factors in order to be sufficiently protective of the general public. Given potential harms to individuals with implantable medical devices containing ferromagnetic materials (*e.g.*, pacemakers and cardiac defibrillators), ICNIRP recommends that such individuals not be exposed to static MFs above 5,000 mG (ICNIRP, 2009). More recently, the International Committee on Electromagnetic Safety (ICES) within the Institute of Electrical and Electronics Engineers (IEEE) conducted an updated review of the scientific and medical research literature, and retained its safety guidelines for general public exposure to static MFs of 1,180,000 mG and 3,530,000 mG for head and trunk exposure and limb exposure, respectively (IEEE, 2019).

Table 1 DC EMF Guidelines Established by Health and Safety Organizations

Organization	Magnetic Field (MF)	Electric Field (EF)
General Public		
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (exposure to any part of the body)	4,000,000 mG[a]	See note b
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.6	1,180,000 mG[c] 3,530,000 mG[d]	5.0 kV/m[e,f]
Occupational		
International Commission on Non-Ionizing Radiation Protection (ICNIRP)	20,000,000 mG[g] 80,000,000 mG[h]	See note i
American Conference of Governmental and Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs)	20,000,000 mG[j] 200,000,000 mG[k] 5,000 mG[l]	25 kV/m[m]

Notes:
EMF = Electric and Magnetic Field; kV/m = Kilovolts Per Meter; mG = Milligauss.
(a) Applies to exposures to any part of the body (ICNIRP, 2009).
(b) For 1 Hz, 5 kV/m exposure limit (ICNIRP, 2010).
(c) Applies to head and of trunk exposure (IEEE, 2019).
(d) Applies to exposure of limbs (IEEE, 2019).
(e) Applies to whole body exposure (IEEE, 2019).
(f) Limit of 10 kV/m for within areas designated as power line right-of-way (or similarly designated area – *e.g.*, an easement or a corridor) (IEEE, 2019).
(g) Applies to head and of trunk exposure (ICNIRP, 2009).
(h) Applies to exposure of limbs (ICNIRP, 2009).
(i) For 1 Hz, 20 kV/m exposure limit (ICNIRP, 2010).
(j) ACGIH TLV for general workplace whole body exposure (ACGIH, 2020).
(k) ACGIH TLV for general workplace limb exposure (ACGIH, 2020).
(l) ACGIH TLV for workers with implanted ferromagnetic or electronic medical devices (ACGIH, 2020).
(m) ACGIH TLV for general workplace exposure to electric fields at frequencies of 0-220 Hz (ACGIH, 2020).

5 Conclusions

In summary, key findings from our review include the following:

- Overall, it is well established that there are differences in how DC EMFs interact with both humans and marine species as compared to AC EMFs, and that the potential for biological responses cannot be directly compared between DC and AC EMFs (CSA Ocean Sciences Inc. and Exponent, 2019).
- There are a number of common natural and anthropogenic sources of static EMFs, including, most notably, the earth's cloud-generated EFs and geomagnetic field.
- For human health risks posed by DC EMFs, there is not as extensive a body of health effects literature as exists for human health risks posed by AC EMFs, but scientists have not found any confirmed health risks for the weak static EMFs associated with HVDC power transmission.
- For marine species, some studies have reported behavioral responses for certain marine species that suggest that EMFs from HVDC cables are perceptible to electromagnetic (EM)-sensitive marine species. However, as discussed below, there remains only inconsistent evidence of behavioral responses in some marine species and an absence of conclusive evidence supporting the observed behavioral responses as being indicative of potential population-level detrimental impacts.
- There are no US federal standards limiting general public or occupational exposure, or exposure of marine species, to EMF from HVDC transmission lines. As summarized below, international health and safety organizations have established health-based exposure guidelines for DC EMFs for both the general public and occupational populations. In particular, the International Commission on Non-ionizing Radiation Protection (ICNIRP) has established guidelines for continuous exposure of the general public to static MFs that are well above typical static MF exposures associated with HVDC transmission.

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