VINEYARD NORTHEAST

CONSTRUCTION AND OPERATIONS PLAN
VOLUME II APPENDIX

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Appendix II-O Magnetic Field (MF) Modeling Analysis

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Magnetic Field (MF) Modeling Analysis – Proposed Vineyard Northeast Development

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Abbreviations

A	Amperes
AC	Alternating Current
ACGIH	American Conference of Governmental and Industrial Hygienists
BOEM	Bureau of Ocean Energy Management
CPUE	Catch Per Unit Effort
CSC	Cross Sound Cable
DC	Direct Current
EM	Electromagnetic
EF	Electric Field
EFSB	Energy Facilities Siting Board
EMF	Electric and Magnetic Fields
ESP	Electrical Service Platform
ft	Feet
G	Gauss
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
Hz	Hertz
ICES	International Committee on Electromagnetic Safety
IEEE	Institute of Electrical and Electronics Engineers
IGRF	International Geomagnetic Reference Field
ICNIRP	International Commission on Non-Ionizing Radiation Protection
kV	Kilovolts
kV/m	Kilovolts Per Meter
m	Meters
MF	Magnetic Field
mG	Milligauss
MRI	Magnetic Resonance Imaging
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
nT	Nanotesla
OECCs	Offshore Export Cable Corridors
OSW	Offshore Wind
RMS	Root Mean Square
ROW	Right-of-Way
TLV	Threshold Limit Value
V/m	Volts Per Meter
WHO	World Health Organization
WTG	Wind Turbine Generator

1 Introduction and Summary

Vineyard Northeast LLC (the "Proponent") proposes to develop, construct, and operate offshore renewable wind energy facilities in Bureau of Ocean Energy Management (BOEM) Lease Area OCS-A 0522 (the "Lease Area") along with associated offshore and onshore transmission systems. This proposed development is referred to as "Vineyard Northeast." Vineyard Northeast includes wind turbine generator (WTG) and electrical service platform (ESP) positions within the Lease Area. Two offshore export cable corridors (OECCs) – the Massachusetts OECC and the Connecticut OECC – will connect the renewable wind energy facilities to onshore transmission systems in Massachusetts and Connecticut. The Proponent may install a booster station along the Massachusetts OECC if high voltage alternating current (HVAC) offshore export cables are used.

Epsilon Associates, Inc. (Epsilon) requested that Gradient perform a modeling analysis of the magnetic field (MF) levels associated with high-voltage direct current (HVDC) and HVAC offshore export cables under consideration for use in the Vineyard Northeast OECCs. The modeling analysis examines the offshore export cables that will carry electricity from the ESP(s) to the landfall site(s), given that they are expected to be the largest MF source to the marine environment. The WTGs, as well as the transformers and other power equipment on the ESP(s) and booster station, are not expected to be significant sources of potential MF exposure to marine organisms, given their locations far above the ocean surface (CSA Ocean Sciences Inc. and Exponent, 2019). MF levels for the lower voltage inter-array cables that will carry electricity generated by WTGs to the ESP(s) and the inter-link cables that may be used to connect the ESPs together are expected to be lower than those associated with the high voltage offshore export cables, due to lesser current flows, lower voltages, and smaller diameter cables. This will consequently lead to greater MF cancellation due to the close spacing of the phase conductors.

This modeling analysis is focused on MFs because the electric fields produced by the voltage on the offshore export cables will be contained by the metallic sheathing and/or steel armoring of the cables – *i.e.*, the metallic sheathing and/or steel armoring will completely shield the electric fields arising from the voltage on the cables. Magnetic fields are not completely shielded by either metallic sheathing or steel armoring, although the usage of ferromagnetic steel (*e.g.*, galvanized) steel armoring can serve to partially attenuate the MFs found outside 3-phase 60-Hz AC cables (CSA Ocean Sciences Inc. and Exponent, 2019). As discussed in CSA Ocean Sciences Inc. and Exponent (2019), due to their time-varying nature, the MFs associated with submarine 60-Hz AC cables can induce weak electric fields in the immediate marine environment above the cables.[1] The steady MFs associated with direct current (DC) submarine cables do not induce electric fields, but similar to the induced electric fields associated with water movement and marine animal movement through the earth's geomagnetic field, very weak DC electric fields will be induced by water flow or marine animal movement through the DC MFs associated with DC submarine cables. These induced electric fields are not modeled by electric and magnetic field (EMF) modeling programs such as the FIELDS computer program used in this assessment. However, they are weak in nature and are considered to pose less of a potential risk to marine species than the MFs from offshore export cables, especially given that electrosensitive marine species do not appear to have significant problems distinguishing bioelectric fields from the induced electric fields associated with water movement and

[1] By Faraday's Law of Induction, a time-varying MF (*i.e.*, changing magnetic flux) will induce a time-varying electric field in a conducting medium, such as seawater. This is the same principle by which coils rotating in a steady MF generate a flow of electricity.

marine animal movement through the earth's geomagnetic field (Gill and Desender, 2020; CSA Ocean Sciences Inc. and Exponent, 2019).

The Massachusetts OECC will include up to two 320 to 525-kV HVDC cable bundles[2] or up to three 220 to 345-kV 3-phase HVAC offshore export cables, with a minimum of 50-meter (m; 164-feet [ft]) spacing between adjacent cable bundles/cables. The Connecticut OECC will include up to two 320 to 525-kV HVDC cable bundles,[3] with a minimum of 50-m (164-ft) spacing between adjacent cable bundles. As a result, our MF modeling analysis examined representative cross sections of either two HVDC offshore export cable bundles or three 3-phase HVAC offshore export cables for both a typical burial case (minimum target burial depth of 1.5 m, or approximately 5 ft, to the top of the cables), and for a worst-case surface-laid case (with cable protection). We conducted separate modeling analyses for the HVDC and HVAC offshore export cables since it is recognized that there are differences in how marine species detect and respond to DC MFs as compared to 60-Hz AC MFs. For the HVDC MF modeling, multiple cable route geographic orientations and current flow directions were assessed to determine the upper bound DC MF results, because the geographic orientation of the cables and the current flow direction affect how the DC MFs associated with the cables combine with the earth's DC geomagnetic field – *i.e.*, the total MF as well as the maximum deviation from the earth's geomagnetic field depend on both the cable geographic orientation and the current flow direction. Table 1.1 summarizes each of the HVDC and HVAC modeling scenarios.

Table 1.1 Magnetic Field (MF) Modeling Scenarios

Cable Type	Cable Voltage	Cable Installation Scenario	Number of HVDC Cable Bundles or HVAC Cables	HVDC Cable Bundle or HVAC Cable Separation Distance	Loading Level	Modeled Representative Cable Route Geographic Orientations (HVDC cables only)
HVDC	±320 kV	Buried 1.5 m (4.92 ft) below seabed	2	50 m (164 ft)	2,300 A	North-South, East-West
		Surface-laid with cable protection[a]	2	50 m (164 ft)	2,300 A	North-South, East-West
HVDC	±525 kV	Buried 1.5 m (4.92 ft) below seabed	2	50 m (164 ft)	2,300 A	North-South, East-West
		Surface-laid with cable protection[a]	2	50 m (164 ft)	2,300 A	North-South, East-West
HVAC	220 kV	Buried 1.5 m (4.92 ft) below seabed	3	50 m (164 ft)	1,700 A	—
		Surface-laid with cable protection[a]	3	50 m (164 ft)	1,700 A	—

[2] The positive- and negative-voltage cables are adjacent (side-by-side) and touching in the horizontal cable bundles, meaning that the separation of the ± conductor centerlines is equal to the outside diameter of the insulated cable (see Table 3.1).
[3] The positive- and negative-voltage cables are adjacent (side-by-side) and touching in the horizontal cable bundles, meaning that the separation of the ± conductor centerlines is equal to the outside diameter of the insulated cable (see Table 3.1).

Cable Type	Cable Voltage	Cable Installation Scenario	Number of HVDC Cable Bundles or HVAC Cables	HVDC Cable Bundle or HVAC Cable Separation Distance	Loading Level	Modeled Representative Cable Route Geographic Orientations (HVDC cables only)
HVAC	345 kV	Buried 1.5 m (4.92 ft) below seabed	3	50 m (164 ft)	1,700 A	—
		Surface-laid with cable protection[a]	3	50 m (164 ft)	1,700 A	—

Notes:
A = Ampere; ft = Feet; HVAC = High Voltage Alternating Current; HVDC = High Voltage Direct Current; kV = Kilovolts; m = Meters; MF = Magnetic Field; — = Not Applicable.
(a) Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering.

All MF modeling used maximum loadings for the offshore export cables provided by the Proponent that are conservative values assuming maximum WTG output corresponding to 100% capacity. Identical loadings of 2,300 amps were conservatively used for both the ±320-kV and ±525-kV HVDC cables, and loadings of 1,700 amps were used for both the 220-kV and 345-kV HVAC cables. Other conservatisms in our modeling analysis included the assumption of no shielding of MFs from the cable protection used for the surface-laid cable modeling scenarios; and for the HVAC cables, no attenuation of MF levels from either the metallic cable sheathing or armoring, from induced sheath currents, or from the expected helical twisting of the 3-phase cables.

For the HVDC offshore export cable modeling scenarios, DC MF impacts are reported using three metrics: (1) as cable-specific DC MF magnitudes (*i.e.*, sizes, and not directions) in units of milligauss (mG), (2) as DC MF magnitude deviations (in mG) from the earth's geomagnetic field that factor in the directions of the vector components of the cable MFs relative to the vector components of the earth's geomagnetic field, and (3) as total DC MFs (in mG) that reflect the combined DC fields from the cables and the earth's geomagnetic field. DC MF deviations caused by the HVDC offshore export cables and total DC fields are reported because the earth's DC geomagnetic field and the DC MFs from the offshore export cables will combine with each other as vectors with both magnitude and direction. In the vicinity of the cables, the combination of the fields can result in either increases in MF magnitude above the ambient geomagnetic field (*i.e.*, positive MF deviations) or decreases in MF magnitude relative to the ambient geomagnetic field (*i.e.*, negative MF deviations), depending on the orientations and sizes of the MF vectors from the cable pairs.

Table 1.2 summarizes the cable-specific DC MF magnitudes, while Table 1.3 summarizes maximum DC MF deviations in mG from the earth's geomagnetic field of 508 mG, which was selected as being representative of the OECCs (graphs for each modeled scenario showing total DC MFs that reflect the combined DC fields from the cables and the earth's geomagnetic field are provided in Appendix B). Ranges in Table 1.3 represent the maximum positive and negative MF deviations across the modeling cases for each installation scenario that include two representative cable route geographic orientations (north-south and east-west) and both possible current flow direction scenarios for each representative cable route geographic orientation. Magnetic field results are provided at the seabed for the scenarios with buried cables. For the surface-laid cable scenarios which are assumed to have 0.5-m (1.6-ft) thick cable protection covering, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) above the ±320-kV cables, and 0.67 m (2.20 ft) above the ±525-kV cables.

Table 1.2 Summary of Modeled Cable-specific Magnetic Fields for HVDC Offshore Export Cables

Cable Voltage	Installation Scenario[a]	Maximum DC MF (Above Cables) (mG)	DC MF at ± 10 ft[b] (mG)	DC MF at ± 25 ft[b] (mG)	DC MF at ± 50 ft[b] (mG)
±320 kV	Buried	282	59.6	11.6	3.0
	Surface-laid	2,076	72.9	12.0	3.0
±525 kV	Buried	312	66.5	13.0	3.3
	Surface-laid	2,245	81.6	13.4	3.4

Notes:
DC = Direct Current; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables.
(b) Horizontal distance is measured from the centerline of the cable bundle.

Table 1.3 Summary of Modeled Magnetic Fields for HVDC Offshore Export Cables as Deviations from Earth's Steady DC Magnetic Field[a]

Cable Voltage	Installation Scenario[b]	Maximum MF Deviation (Above Cables) (mG)	DC MF Deviation at ± 10 ft[c] (mG)	DC MF Deviation at ± 25 ft[c] (mG)	DC MF Deviation at ± 50 ft[c] (mG)
±320 kV	Buried	-268 to 271	-49.9 to 51.8	-11.5 to 11.5	-2.9 to 2.9
	Surface-laid	-266 to 2,039	-72.4 to 72.5	-11.5 to 11.5	-2.8 to 2.8
±525 kV	Buried	-296 to 300	-55.4 to 57.8	-12.9 to 12.9	-3.3 to 3.3
	Surface-laid	-268 to 2,207	-81.0 to 81.2	-12.9 to 12.9	-3.2 to 3.2

Notes:
DC = Direct Current; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) Magnetic fields are presented as the deviation from the earth's steady DC magnetic field of 508 mG and are maximum positive and negative deviations across modeling cases that include two representative cable orientations (north-south and east-west) and both possible current flow direction scenarios for each representative cable orientation. Negative values are the maximum reductions below the earth's steady DC magnetic field of 508 mG.
(b) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables.
(c) Horizontal distance is measured from the centerline of the cable bundle.

As shown in Table 1.2, the peak magnitudes (*i.e.*, the size, not the direction) of the cable-specific DC MFs (directly above the cables) were 282 mG and 312 mG for the buried cable installation cases, and 2,076 mG and 2,245 mG for the surface-laid cable installation cases. Table 1.2 also shows the rapid drop-off in MF levels with increased lateral distance from the cable bundles for each of the modeling scenarios. More specifically, the analysis shows >95% to >99% reductions in MF levels at lateral distances of ±7.6 m (±25 ft) from the cable bundle centerlines as compared to the maximum MF levels directly above the cable bundles; and at lateral distances of ±7.6 m (±25 ft), there is a negligible difference in MF levels for the buried *versus* the surface-laid cables. At the minimum 50 m (164 ft) spacing between HVDC offshore export cable bundles, the modeled magnetic fields from the cables at the midpoint between adjacent cable bundles are essentially zero and there is no discernible additive or cumulative effect for MFs from adjacent cable bundles.

Table 1.3 shows that the DC cable bundles will contribute to highly localized DC MF deviations from the earth's geomagnetic field in the immediate vicinity of the cable bundles, including MF deviations at 3 m (10 ft) from the centerline of a cable bundle that range between -81.0 mG to +81.2 mG (-15.9% to +16.0% of the earth's geomagnetic field) across the buried cable and surface-laid cable modeling scenarios. At the slightly greater distance of 7.6 m (25 ft) from the centerline of a cable bundle, MF deviations have decreased to a range of -12.9 mG to +12.9 mG (-2.5% to +2.5% of the earth's geomagnetic field). In the water column above the cables, there will be even lower MF deviations than those modeled at the seabed surface.

Table 1.4 summarizes the modeled MF levels at the seabed for the 60-Hz AC offshore export cable cross sections. The modeling shows that the highest modeled AC MF levels occur directly above the offshore export cables, ranging from maximums of 191 mG to 214 mG for the buried cables and maximums of 1,243 mG to 1,354 mG for the surface-laid cables. Table 1.4 shows that MF levels also diminish very rapidly with lateral distance away from the cable centerlines for the 60-Hz AC offshore export cables. More specifically, the analysis shows >95 to >99% reductions in MF levels at lateral distances of ±7.6 m (±25 ft) from the cable centerlines. The MF levels will similarly drop off very rapidly moving vertically from the seabed into the water column. Table 1.4 also shows that at lateral distances of ±7.6 m (±25 ft) there is little difference in the MF levels for the buried *versus* the surface-laid cables. Similar to the HVDC cables, there is no evidence of an additive or cumulative effect from adjacent cables at the minimum 50 m (164 ft) spacing between HVAC offshore export cables.

Table 1.4 Summary of Modeled Magnetic Fields for HVAC Offshore Export Cables[a]

Cable Voltage	Installation Scenario[b]	Maximum AC MF (mG)	AC MF at ± 10 ft[c] (mG)	AC MF at ± 25 ft[c] (mG)	AC MF at ± 50 ft[c] (mG)
220 kV, 3-phase	Buried	191	43.6	9.0	2.8
	Surface-laid	1,243	54.0	9.3	2.8
345 kV, 3-phase	Buried	214	49.6	10.2	3.1
	Surface-laid	1,354	61.6	10.7	3.2

Notes:
AC = Alternating Current; ft = Feet; HVAC = High Voltage Alternating Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) The offshore export cable MF modeling assumes straight-laid phase-conductor cable cores rather than helical or "twisted" phase-conductor cores (the expected cable design). As discussed in Section 4.1, field measurements taken for the Block Island "sea2shore" cable show that a helical design achieves a considerable degree of magnetic field cancellation, hence the modeled MF levels are expected to be overestimates of actual MF levels.
(b) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported on top of the cable protection, specifically at 0.79 m (2.58 ft) for 220-kV cables, and 0.82 m (2.68 ft) for 345-kV cables.
(c) Horizontal distance is measured from the cable centerline.

No regulatory thresholds or guidelines for allowable EMF levels in marine environments have been established for either HVAC or HVDC submarine power transmission. For HVAC transmission, the weight of the evidence indicates that 60-Hz AC EMFs are considerably above the typical frequency range of EMFs to which magnetosensitive and electrosensitive marine species are known to detect and respond. In particular, magnetosensitive marine species such as salmon, whales, and sea turtles are specifically tuned to the earth's steady (*i.e.*, DC) geomagnetic field for navigation/migration purposes, while electrosensitive marine species such as sharks and rays primarily respond to electric field frequencies below 10 Hz for helping to locate prey and/or mates (CSA Ocean Sciences Inc. and Exponent, 2019). For HVDC transmission, there is a growing body of evidence suggesting that the steady MFs from HVDC cables may be perceptible to some electromagnetic (EM)-sensitive marine species that are tuned to detect the earth's steady geomagnetic field, but there remains a lack of evidence indicating potential harmful impacts at the population- or community-level for the various types of marine species which may experience brief exposure to DC MFs nearby offshore export cables (CSA Ocean Sciences Inc. and Exponent, 2019; Gill and Desender, 2020; NYSERDA, 2021; SEER, 2022; Taormina *et al.*, 2018). Based on the localized nature of the MF impacts of the offshore export cables as well as the lack of reported evidence of significant harms to EM-sensitive marine species from either HVDC or HVAC submarine transmission, there is no expectation that MFs associated with either the HVDC or HVAC offshore export cables will cause significant population-level harms to marine species in the OECCs.

Section 2 of this report describes the nature of EMFs and provides background on human and marine organism exposures to EMF. Section 3 outlines the EMF modeling procedures for calculating DC MFs and provides DC MF results for the modeled HVDC offshore export cable cross sections. Section 4 describes the modeling procedures and 60-Hz AC MF results for the modeled HVAC offshore export cable cross sections. Section 5 summarizes the conclusions, and the Reference list provides the scientific references cited in this report.

2 Nature of Electric and Magnetic Fields

All matter contains electrically charged particles. Most objects are electrically neutral because positive and negative charges are present in equal numbers. When the balance of electric charges is altered, we experience electrical effects. Common examples are the static electricity attraction between a comb and our hair, or a static electricity spark after walking on a synthetic rug in the wintertime. Electrical effects occur both in nature and through our society's use of electric power (generation, transmission, and consumption).

2.1 Units for EMFs Are Kilovolts Per Meter (kV/m) and Milligauss (mG)

The electrical tension on utility power lines is expressed in volts or kilovolts (1 kV = 1,000 V). Voltage is the "pressure" of the electricity and can be envisioned as analogous to the pressure of water in a plumbing system. The existence of a voltage difference between overhead power lines and ground results in an "electric field," usually expressed in units of kilovolts per meter (kV/m). The size of the electric field depends on the line voltage, the separation between lines and the ground surface, and other factors.

Power lines also carry an electric current that creates a "magnetic field." The units for electric current, which is a measure of the "flow" of electricity, are amperes (A). Electric current is analogous to the flow of water in a plumbing system. The magnetic field produced by an electric current is usually expressed in units of gauss (G) or milligauss (mG) (1 G = 1,000 mG).[4] The size of the magnetic field depends on the electric current in the line conductors, the distance to the current-carrying conductor, and other factors.

2.2 Human Exposure to EMF

2.2.1 There Are Many Natural and Man-made Sources of DC (Steady) and 60-Hz AC (Power-Frequency) EMFs

Everyone experiences a variety of natural and man-made EMFs. EMF levels can be steady or slowly varying (often called "direct current" or "DC fields"); or EMF levels can vary in time (often called "alternating current"[AC] or "AC fields"). When the time variation corresponds to that of standard North American power line currents (*i.e.*, 60 cycles per second), the fields are called "60-hertz (Hz) AC," or power-frequency, EMF.

Man-made magnetic fields are common in everyday life. For example, many childhood toys contain magnets. Such permanent magnets generate strong, steady (DC) magnetic fields. Typical toy magnets (*e.g.*, "refrigerator door" magnets) have fields of 100,000-500,000 mG. On a larger scale, earth's core also creates a steady DC magnetic field that can be easily demonstrated with a compass needle. Along the southern New England coast, the earth's DC geomagnetic field has a magnitude on the order of 500 mG (CSA Ocean Sciences Inc. and Exponent, 2019) (less than 1% of the levels generated by "refrigerator door" magnets).

[4] Another unit for magnetic field levels is the microtesla (μT) (1 μT = 10 mG; and 1 Tesla = 10,000 Gauss).

In North America, electric power transmission lines, distribution lines, and electric wiring in buildings carry AC currents and voltages that change size and direction at a frequency of 60 Hz. These 60-Hz currents and voltages create 60-Hz AC EMFs nearby. The size of the magnetic field is proportional to the line current, while the size of the electric field is proportional to the line voltage. The EMFs associated with electrical wires and electrical equipment decrease rapidly with increasing distance away from the electrical wires and/or equipment. Specifically, EMFs from three-phased, balanced conductors decrease in proportion to the square of the distance from the conductors (*i.e.*, $1/d^2$) (IEEE, 2014).

When EMFs derive from different wires or conductors that are in close proximity, or adjacent to one another, the level of the net EMFs produced will be somewhere in the range between the sum of the EMFs from the individual sources and the difference of the EMFs from the individual sources. EMFs may partially add, or partially cancel, but generally, because adjacent phase conductors are often carrying current in opposite directions for typical 3-phase lines, the EMFs produced tends to cancel.

EMFs in the home arise from electric appliances, indoor wiring, grounding currents on pipes and ground wires, and outdoor distribution or transmission circuits. Inside residences, typical baseline 60-Hz MF (away from appliances) range from 0.5-5.0 mG.

Higher 60-Hz MF levels are found near operating appliances. For example, electric can openers, mixers, blenders, refrigerators, fluorescent lamps, electric ranges, clothes washers, toasters, portable heaters, vacuum cleaners, electric tools, and many other appliances generate MF levels in the range of 40-300 mG at distances of 0.3 m (1 ft) (NIEHS, 2002). MF levels from personal care appliances (*e.g.*, shavers, hair dryers, massagers) held within 0.15 m (0.5 ft) can produce average fields of 600-700 mG. At school and in the workplace, lights, motors, copy machines, vending machines, video-display terminals, pencil sharpeners, electric tools, electric heaters, and building wiring are all sources of 60-Hz MF.

Magnetic resonance imaging (MRI) is a diagnostic procedure that puts humans in much larger, but steady, DC MFs (*e.g.*, levels of 20,000,000 mG). The scanning MF superimposed on the large steady DC field (which is the source of the characteristic audio noise of MRI scans) exposes the body to time-varying MF similar to time-varying power-frequency MF.

2.2.2 Exposure Guidelines for DC EMFs

There are no US federal standards limiting general public or occupational exposure to EMFs from DC transmission sources, and the states of Massachusetts, Connecticut, and New York also do not have guidelines specific to DC EMFs. As summarized in Table 2.1, international health and safety organizations have established health-based exposure guidelines for both the general public and occupational populations. In particular, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established a general public exposure guideline of 4,000,000 mG for DC 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 DC 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 DC MFs of 1,180,000 mG and 3,530,000 mG for head and trunk exposure and limb exposure, respectively (IEEE, 2019).

Table 2.1 DC EMF Guidelines Established by International Health and Safety Organizations

Organization	Magnetic Field	Electric Field
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:
DC = Direct Current; EMF = Electric and Magnetic Field; kV/m = Kilovolts Per Meter; mG = Milligauss. TLV = Threshold Limit Value.
(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, 2022).
(k) ACGIH TLV for general workplace limb exposure (ACGIH, 2022).
(l) ACGIH TLV for workers with implanted ferromagnetic or electronic medical devices (ACGIH, 2022).
(m) ACGIH TLV for general workplace exposure to electric fields at frequencies of 0-220 Hz (ACGIH, 2022).

2.2.3 Exposure Guidelines for 60-Hz AC EMFs

Table 2.2 shows exposure guidelines for 60-Hz AC fields from international health and safety organizations that are designed to protect workers and the general public against any adverse health effects. The limit values should not be viewed as demarcation lines between safe and dangerous levels of EMFs, but rather, levels that assure safety with an adequate margin to allow for uncertainties in the science. As part of its International EMF Project, the World Health Organization (WHO) has conducted comprehensive reviews of EMF health-effects research and existing standards and guidelines. The WHO website for the International EMF Project (WHO, 2023) notes, "*[T]he main conclusion from the WHO reviews is that EMF exposures below the limits recommended in the ICNIRP international guidelines do not appear to have any known consequence on health.*"

The US has no federal standards limiting either residential or occupational exposure to 60-Hz AC EMF. Table 2.3 lists guidelines that have been adopted by various states in the US, including by the Massachusetts Energy Facilities Siting Board (EFSB). The MA EFSB has adopted, and long used, edge-of right-of-way (ROW) guideline levels of 85 mG for magnetic fields and 1.8 kV/m for electric fields. State guidelines such as those of the EFSB are not health-effect based, and have typically been adopted to maintain the *status quo* for EMFs on and near transmission line ROWs.

Table 2.2 60-Hz AC EMF Guidelines Established by International Health and Safety Organizations

Organization	Electric Field	Magnetic Field
American Conference of Governmental and Industrial Hygienists (ACGIH) (occupational)	25 kV/m[a]	10,000 mG[a] 1,000 mG[b]
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (general public)	4.2 kV/m[c]	2,000 mG[c]
International Commission on Non-Ionizing Radiation Protection (ICNIRP) (occupational)	8.3 kV/m[c]	10,000 mG[c]
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.6 (general public)	5.0 kV/m[d]	9,040 mG[d]
Institute of Electrical and Electronics Engineers (IEEE) Standard C95.6 (occupational)	20.0 kV/m[d]	27,100 mG[d]

Notes:
AC = Alternating Current; EMF = Electric and Magnetic Field; Hz = Hertz; kV/m = Kilovolts Per Meter; mG = Milligauss.
(a) The ACGIH guidelines for whole-body exposure for the general worker (ACGIH, 2022).
(b) The ACGIH guidelines for workers with cardiac pacemakers (ACGIH, 2022).
(c) ICNIRP (2010).
(d) IEEE (2019).

Table 2.3 State 60-Hz AC EMF Standards and Guidelines for Transmission Lines

State	Line Voltage (kV)	Electric Field On ROW (kV/m)	Electric Field At Edge of ROW (kV/m)	Magnetic Field On ROW (mG)	Magnetic Field At Edge of ROW (mG)
Florida[a]	69-230 >230-500 >500	8.0 10.0 15.0	2.0[b] 2.0[b] 5.5[b]	- - -	150[b] 200[b] 250[b,c]
Massachusetts	-	-	1.8	-	85
Minnesota	-	8.0	-	-	-
Montana	-	7.0[d]	1.0[e]	-	-
New Jersey	-		3.0	-	-
New York[a]	-	11.8 11.0[f] 7.0[d]	1.6	-	200
Oregon	-	9.0	-	-	-

Notes:
AC = Alternating Current; EMF = Electric and Magnetic Field; Hz = Hertz; kV = Kilovolt; kV/m = Kilovolts Per Meter; mG = Milligauss; ROW = Right-of-Way; - = No Value Available.
(a) Magnetic fields for winter-normal (*i.e.*, at maximum current-carrying capability of the conductors).
(b) Includes the property boundary of a substation.
(c) Also applies to 500-kV double-circuit lines built on existing ROWs.
(d) Maximum for highway crossings.
(e) May be waived by the landowner.
(f) Maximum for private road crossings.
Sources: NIEHS (2002); FLDEP (2008); MA EFSB (2009).

2.3 Marine Organism Exposures to EMF

Naturally occurring EMFs are ubiquitous in coastal environments. Most prominently, the earth's steady 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 on the order of 500 mG (CSA Ocean Sciences Inc. and Exponent, 2019). As discussed later, the steady MFs from an HVDC offshore export cable will either add to or subtract from the earth's geomagnetic field depending on the direction/orientation of the cable relative to the direction of the earth's geomagnetic field at the location of interest.

Naturally occurring steady (DC) EMFs are also ubiquitous in coastal environments due to other sources besides earth's geomagnetic field. Other natural steady (DC) EMFs are associated with the movement of ocean currents and marine organisms through earth's geomagnetic field and those directly produced by marine organisms. The movement of ocean currents and marine organisms through earth's geomagnetic field 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 (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).

There are already present a variety of submarine transmission cables along the Eastern seaboard. Examples of AC cables include the Nantucket I and II electrical distribution cables and four electrical distribution cables feeding Martha's Vineyard, the 34.5-kV inter-array cables and 34.5-kV offshore export cable that were installed prior to 2016 as part of the Block Island Wind Farm, and the 34.5-kV sea2shore cable connecting Block Island to the mainland. Examples of DC cables include the 330-MW bipolar Cross Sound Cable (CSC) that transects Long Island Sound between New Haven, CT, and Shoreham, NY; and the 660-MW Neptune cable that runs between Sayreville, NJ, and Long Island, NY. It bears mentioning that more than 100 offshore wind farms have been constructed in Europe, with both HVAC and HVDC offshore export cables (CSA Ocean Sciences Inc. and Exponent, 2019).

Other manmade sources of perturbations to earth's steady DC geomagnetic field in coastal environments include 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.

No regulatory thresholds or guidelines for allowable EMF levels in marine environments have been established for either HVAC or HVDC submarine power transmission.

2.3.1 Marine Organism Sensitivity to 60-Hz AC EMFs

For HVAC transmission, the weight of the scientific evidence indicates that 60-Hz AC EMFs are considerably above the typical frequency range of EMFs to which magnetosensitive and electrosensitive marine species are known to detect and respond. In particular, magnetosensitive marine species such as salmon, whales, and sea turtles are specifically tuned to the earth's steady (DC) geomagnetic field for navigation/migration purposes, while electrosensitive marine species such as sharks and rays are primarily tuned to electric field frequencies below 10 Hz for helping to locate prey and/or mates (CSA Ocean Sciences Inc. and Exponent, 2019).

Importantly, a seven-year study reported the first findings in the United States of the response of demersal fish (*i.e.*, fish living close to the sea floor) and invertebrates to construction and operation of an offshore wind (OSW) project (Wilber *et al*., 2022). Published in March 2022, this study analyzed catch data from monthly demersal trawl surveys conducted by local fisherman and scientists during construction and operation of the Block Island Wind Farm, a pilot-scale 30 MW project that is North America's first offshore wind farm. This study did not identify harmful impacts of EMF from the project's 60-Hz AC submarine export cables or other offshore electrical infrastructure on local demersal fish and invertebrates, and instead reported evidence of increased populations of several fish species near the wind farm during the operation time period relative to the reference areas. Statistically significant interactions in catch per unit effort (CPUE) due to operation of the wind farm were not observed for any of the fish species that were frequently caught in the surveys in the project and reference areas, including black sea bass (*Centropristis striata*), little skate (*Leucoraja erinacea*), summer flounder (*Paralichthys dentatus*), windowpane (*Scophthalmus aquosus*), winter flounder (*Pseudopleuronectes americanus*), winter skate (*Leucoraja ocellata*), and longfin squid (*Loligo pealeii*). These findings are consistent with those for European offshore wind farm projects. In a report to BOEM, CSA Ocean Sciences Inc. and Exponent (2019) provided the following summary of findings from fish surveys conducted in Europe in areas with offshore wind development:

> 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.

As part of the US Offshore Wind Synthesis of Environmental Effects Research (SEER) effort, researchers at the US Department of Energy's Wind Energy Technologies Office, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory published a Brief titled "Electromagnetic Field Effects on Marine Life" (SEER, 2022). This Brief was reviewed by external subject matter experts (Dr. Andrew Gill of the Centre for Environment, Fisheries, and Aquaculture Science; and Dr. Zoe Hutchison of the University of St Andrews) and the SEER Science and Technical Advisory Committee. The Brief included the following summary of the overall state of the knowledge:

> Overall, there is no conclusive evidence that EMFs from a subsea cable creates any negative environmental effect on individuals or populations. To date, no impacts interpreted as substantially negative have been observed on electrosensitive or magnetosensitive species after exposure to EMFs from a subsea cable. Behavioral responses to subsea cables have been observed in some species, but a reaction to EMFs does not necessarily translate into negative impacts. Continued research and monitoring are required to understand the ecological context within which short-term effects are observed and if species experience long-term or cumulative effects resulting from underwater exposure to EMFs. (SEER, 2022)

The Brief further concluded, "Overall, the effects of EMFs have been considered minor-to-negligible and a less significant issue than other environmental effects at OSW farms" (SEER, 2022). It discussed how such factors as cable burial depth, cable shielding, and the limited range of EMFs result in "a highly localized environmental condition that does not affect the entire habitat range for an animal" (SEER, 2022).

2.3.2 Marine Organism Sensitivity to DC EMFs

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. Together with other senses, it is understood that magnetosensitive marine 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). To date, researchers have 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 for such purposes as prey detection and navigation 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 ranging 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).

For HVDC submarine transmission, there is a growing body of evidence suggesting that the steady MFs from HVDC cables may be perceptible to some electromagnetic (EM)-sensitive marine species that are known to detect the earth's steady (DC) geomagnetic field, but there remains a lack of evidence indicating potential harmful impacts at the population- or community-level for the various types of marine species which may experience brief exposure to DC MFs nearby offshore export cables (CSA Ocean Sciences Inc. and Exponent, 2019; Gill and Desender, 2020; NYSERDA, 2021; SEER, 2022; Taormina *et al*., 2018). Several different types of studies have been conducted in recent years, including experimental field studies, experimental laboratory studies, and field surveys, with a limited number of inconsistent findings of subtle behavioral responses and physiological changes from some studies. For example, Hutchison *et al*. (2020) observed minor behavioral responses of both little skates (*Leucoraja erinacea*) and American lobsters (*Homarus americanus*) for *in situ* enclosure experiments conducted on top of the CSC, a buried submarine HVDC cable (330 MW, 300 kV) that runs between Connecticut and Long Island. They did not report evidence of a barrier effect as both species were observed to freely cross over the cable, but their findings included several responses indicative of increased exploratory/foraging behavior for the little skate, and more limited evidence of a subtle behavioral exploratory response for the American lobster. Despite the usage of highly elevated DC MF levels, laboratory experimental studies have frequently reported an absence of evidence of adverse biological responses. For example, Taormina *et al*. (2020) conducted laboratory experiments of juvenile European lobsters (*Homarus gammarus*) for much higher DC MF gradients (as high as 2,250 mG), observing no changes in sheltering behavior or exploratory behavior. For a laboratory study where several different types of marine benthic (seafloor) species were exposed to highly elevated DC 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*).

It is important to distinguish the types of subtle behavioral responses and physiological changes that have been observed in some research studies from evidence of potential harmful impacts at the population- and community-level (Taormina *et al*., 2018). Moreover, since exposures to elevated MF levels from submarine cables will be limited to small areas along the seafloor surrounding the submarine export cables, it is important to consider the low exposure potential of most marine species. For example, because they breathe at the sea surface and have large migratory ranges, marine mammals such as sea turtles and whales would not be expected to spend significant amounts of time at the seafloor in the vicinity of specific submarine export cables. Overall, although knowledge gaps remain and there is a need for continued research, the weight of the currently available evidence does not provide support for significant population-level harms to marine species from EMFs associated with HVDC submarine transmission.

3 Magnetic Field Modeling for HVDC Offshore Export Cables

As discussed below, we performed a modeling analysis of the MF levels associated with the HVDC offshore export cables under consideration for use in the OECCs. This modeling analysis is focused on magnetic fields because the electric fields produced by the voltage on the offshore export cables will be contained by the metallic sheathing and/or steel armoring of the cables – *i.e.*, the metallic sheathing and/or steel armoring will completely shield the electric fields arising from the voltage on the cables. Magnetic fields are not completely shielded by either metallic sheathing or steel armoring. Similar to the induced DC electric fields associated with water movement and marine animal movement through the earth's geomagnetic field, very weak DC EFs will be induced by water flow or marine animal movement through the steady DC MFs associated with DC submarine cables. These induced electric fields are not modeled by EMF modeling programs such as the FIELDS computer program used in this assessment. However, they are weak in nature and are considered to pose less of a potential risk to marine species than the DC MFs from offshore export cables, especially given that electrosensitive marine species do not appear to have significant problems distinguishing bioelectric fields from the induced DC electric fields associated with water movement and marine animal movement through the earth's geomagnetic field (Gill and Desender, 2020; CSA Ocean Sciences Inc. and Exponent, 2019).

3.1 DC Cable Specifications and Representative Cross Sections

MFs were modeled for two DC circuits spaced a minimum of 50 m (164 ft) apart, each consisting of two single-core submarine cables – one positively charged and the other negatively charged – bundled together in a horizontal arrangement (*i.e.*, touching side-by-side during installation, with conductor separations of either 152 mm or 170 mm [approximately 6.0 or 6.7 inches]). Although the HVDC cable bundles may also include a neutral third power cable (Figure 3.1), the presence of the unenergized neutral power cable is not expected to change the MF modeling results. Modeling was conducted for two different voltage cables (±320 and ±525 kV) with the specifications and currents summarized in Table 3.1. All MF modeling used maximum loadings for the offshore export cables provided by the Proponent that are conservative values assuming maximum WTG output corresponding to 100% capacity. Identical loadings of 2,300 amps were conservatively used for both the ±320-kV and ±525-kV HVDC cables. Figure 3.1 provides an example schematic of the type of DC cable to be used, showing both the cable components and the conductor arrangement for the cable bundles.

Table 3.1 HVDC Offshore Export Cable Specifications and Currents

Parameter	±320-kV HVDC Cable	±525-kV HVDC Cable
Burial Depth (m)[a]	1.5, or surface-laid	1.5, or surface-laid
Cable Voltage (kV)	±320	±525
Conductor Diameter (mm)	73.0	73.0
Cable Diameter (mm)	151.8	170.2
Conductor Area (mm^2)	4,185	4,185
Current (A)	2,300	2,300

Notes:
A = Ampere; HVDC = High Voltage Direct Current; kV = Kilovolts; m = Meter; mm = Millimeter.
(a) For the buried cable bundles, to the top of the insulated ± conductors; for the surface-laid cable bundles, cable protection with a thickness of 0.5 m (1.6 ft) is assumed.

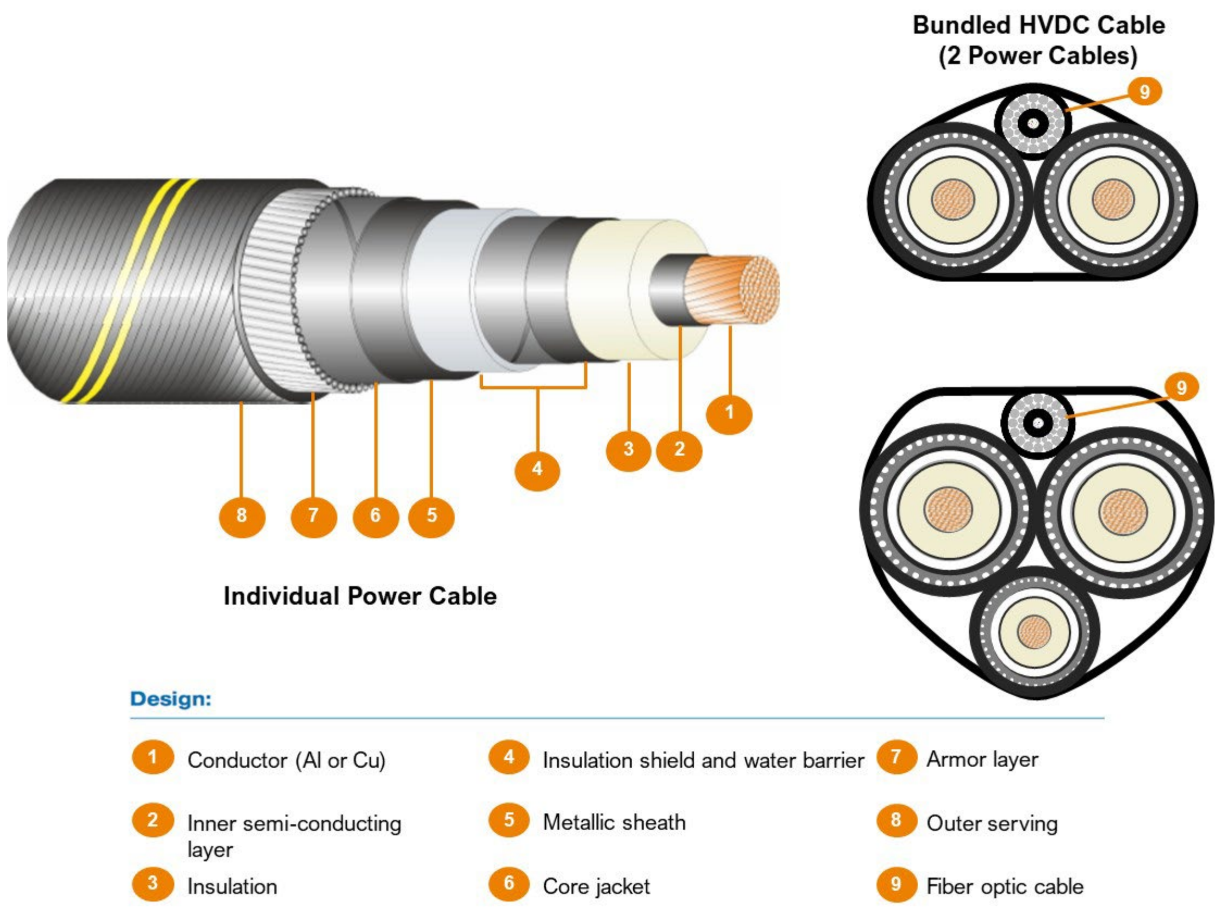

Figure 3.1 Example HVDC Cable Cross Section Illustration.

Two installation scenarios were modeled for the DC offshore export cables: (1) a buried cable installation case where the cable bundles were assumed to be buried to a minimum target depth of 1.5 m (4.92 ft)[5], and

[5] For the buried HVDC cable bundle modeling scenarios, we assumed a burial depth of 1.5 m (4.92 ft) to the top of the ± conductors. As shown in Figure 3.1, the cable bundles are expected to include a fiber optic cable bundled in between and on top of the ± conductors. The modeling, which assumed a burial depth of 1.5 m (4.92 ft) to the top of the ± conductors, is thus slightly conservative if the installed burial depth is to the top of the fiber optic cable – *i.e.*, in this case, the distance to the tops of the ± conductors would be slightly greater than 1.5 m (4.92 ft).

(2) a surface-laid cable installation case where the cable bundles were installed directly on the seabed surface and covered by cable protection with 0.5-m (1.6-ft) thickness. MFs associated with the buried offshore export cables were modeled directly on the seabed surface, while MFs associated with the surface-laid offshore export cables were modeled at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables. We assumed that there will be no attenuation of MFs by whatever type of cable protection is used.

To encompass the range of possible DC MF impacts associated with the HVDC offshore export cables, modeling was performed for two representative cable route geographic orientations (north-south and east-west) and both possible current flow direction scenarios for each of the cable route geographic orientations – *i.e.*, for the north-south cable route geographic orientation, northern current flow direction in the western cable and southern current flow direction in the eastern cable, as well as the case with the flow directions reversed (southern current flow direction in the western cable and northern current flow direction in the eastern cable); and for the east-west cable route geographic orientation, eastern current flow direction in the northern cable and western current flow direction in the southern cable, as well as the case with the flow directions reversed (western current flow direction in the northern cable and eastern current flow direction in the southern cable). Although for the same cable type and cable bundle arrangement the magnitudes of cable-specific MFs will be identical for the different cable route geographic orientations and current flow directions, differences in the directions of the vector components of the cable MFs between the cable route geographic orientation and current flow direction scenarios will result in differences in DC MF magnitude deviations caused from interaction with the earth's geomagnetic field and thus in total (*i.e.*, combined MFs from the cables and the earth's geomagnetic field) DC MFs in the proximity of the cables. In total, there were 16 HVDC offshore export cable MF modeling scenarios, which are summarized in Table 3.2.

Table 3.2 HVDC Offshore Export Cable Magnetic Field (MF) Modeling Scenarios

Cable Voltage	Installation Scenario	Number of HVDC Cable Bundles	Cable Bundle Separation Distance	Loading Level	Modeled Representative Cable Route Geographic Orientations	Modeled Current Flow Direction Cases
±320 kV	Buried 1.5 m (4.92 ft) below seabed	2	50 m (164 ft)	2,300 A	North-South	Northern flow in western cable and southern flow in eastern cable, and reverse case
					East-West	Eastern flow in northern cable and western flow in southern cable, and reverse case
	Surface-laid with cable protection	2	50 m (164 ft)	2,300 A	North-South	Northern flow in western cable and southern flow in eastern cable, and reverse case
					East-West	Eastern flow in northern cable and western flow in southern cable, and reverse case
±525 kV	Buried 1.5 m (4.92 ft) below seabed	2	50 m (164 ft)	2,300 A	North-South	Northern flow in western cable and southern flow in eastern cable, and reverse case
					East-West	Eastern flow in northern cable and western flow in southern cable, and reverse case
	Surface-laid with cable protection	2	50 m (164 ft)	2,300 A	North-South	Northern flow in western cable and southern flow in eastern cable, and reverse case
					East-West	Eastern flow in northern cable and western flow in southern cable, and reverse case

Notes:
A = Ampere; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; m = Meter; MF = Magnetic Field.

3.2 Software Program Used for Modeling Cable-specific DC Magnetic Fields

The FIELDS computer program, designed by Southern California Edison, was utilized to calculate DC MF levels from the proposed offshore export cables, as well as the vertical and horizontal components of the fields that are used for determining both the DC MF deviations from the earth's geomagnetic field and the total DC MFs for the cables and earth's geomagnetic field (see Section 3.3 below). This program operates using Maxwell's equations, which accurately apply the laws of physics as related to electricity and magnetism (EPRI, 1982, 1993). Modeled fields using this program are both precise and accurate for the input data utilized. Results of the model have been checked extensively against each other and against other software (*e.g.*, CORONA, from the Bonneville Power Administration, United States Department of Energy) to ensure that the implementation of the laws of physics are consistent. In these validation tests, program results for MF levels were found to be in very good agreement with each other (Mamishev and Russell, 1995).

3.3 Calculation of DC Magnetic Field Deviations and Total Combined (Cable + Earth) DC Magnetic Fields

DC MF deviations caused by the HVDC offshore export cables, as well as total DC magnetic fields that represent the combined fields from the cables and earth's geomagnetic field, were calculated because the earth's DC geomagnetic field and the DC MFs from the offshore export cables will combine with each other as vectors with both magnitude and direction. For calculating both DC MF deviations from the earth's geomagnetic field as well as total combined DC MFs (*i.e.*, combined fields from the cables and the earth's geomagnetic field), the DC MFs from the cable and the earth's geomagnetic field were separated into mutually orthogonal vectors in a Cartesian coordinate space, consisting of vectors pointing in easterly[6], northerly[7], and vertical directions (*i.e.*, into the earth, for the earth's geomagnetic field). The vector components of the earth's geomagnetic field ($B_{GeoNorth}$, $B_{GeoEast}$, $B_{GeoVertical}$), as well as the total geomagnetic field ($B_{GeoTotal}$), were calculated using an MF calculator available on the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) website.[8] We used the latitude and longitude for a location between the Massachusetts and Connecticut OECCs, noting that there is only minor variation in the earth's geomagnetic field in the region of each of the OECCs. The earth's geomagnetic field at this location was calculated using the International Geomagnetic Reference Field (IGRF) Model on the NCEI website. Table 3.3 summarizes the geomagnetic components ($B_{GeoNorth}$, $B_{GeoEast}$, $B_{GeoVertical}$) and the total geomagnetic field ($B_{GeoTotal}$) that were used in all calculations.

[6] For the east-west cable route geographic orientation modeling cases, geomagnetic field only, because for cables with a east-west orientation and east-west current flow directions, the east-west MF vector for the cables will be equal to zero.
[7] For the north-south cable route geographic orientation modeling cases, geomagnetic field only, because for cables with a north-south orientation and north-south current flow directions, the north-south MF vector for the cables will be equal to zero.
[8] https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml?#igrfwmm.

Table 3.3 Estimated Values for the Earth's Geomagnetic Field in the Region of the OECCs

Component	Earth's Geomagnetic Field[a] (nT)	Earth's Geomagnetic Field[a] (mG)
Northern Component ($B_{GeoNorth}$)	20,496	204.96
Eastern Component ($B_{GeoEast}$)	-5,169	-51.69
Vertical Component ($B_{GeoVertical}$)	46,242	462.42
Total Geomagnetic Field ($B_{GeoTotal}$):	**50,844**	508.44

Notes:
mG = Milligauss; nT = Nanotesla; OECCs = Offshore Export Cable Corridors.
(a) Calculated for a location between the Massachusetts and Connecticut OECCs using the International Geomagnetic Reference Field (IGRF) Model available on the NOAA National Centers for Environmental Information (NCEI) website: https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml?#igrfwmm.

The magnitude of the total field (B_{Total}) representing the combined fields from the cables and the earth was calculated using the formula:

$$B_{Total} = [(B_{CableNorth} + B_{GeoNorth})^2 + (B_{CableEast} + B_{GeoEast})^2 + (B_{CableVertical} + B_{GeoVertical})^2]^{0.5}$$

As noted above, for cables with a north-south geographic route orientation and north-south current flow directions, the $B_{CableNorth}$ term is equal to zero; analogously, for cables with an east-west geographic route orientation and east-west current flow directions, the $B_{CableEast}$ term is equal to zero.

The DC MF magnitude deviations ($B_{Deviation}$) from the earth's geomagnetic field were calculated as:

$$B_{Deviation} = B_{Total} - B_{GeoTotal}$$

The DC MF magnitude deviations can either be positive or negative, representing increases or decreases to the ambient geomagnetic field, depending on the geographic orientation of the cables and the cable flow directions.

3.4 DC Magnetic Field Modeling Results

Table 3.4 summarizes the cable-specific DC MF magnitudes (*i.e.*, sizes, and not directions), and Figures 3.2 through 3.5 show the cable-specific DC MF magnitudes as a function of distance from the centerline of the cable bundles. As shown in Table 3.4 and the figures, the peak magnitudes of the cable-specific DC MFs (directly above the cables) were 282 mG and 312 mG for the buried cable installation cases, and 2,076 mG and 2,245 mG for the surface-laid cable installation cases. The table and figures show the rapid drop-off in MF levels with increased lateral distance from the cable bundles for each of the modeling scenarios. More specifically, the analysis shows >95 to >99% reductions in MF levels at lateral distances of ±7.6 m (±25 ft) from the cable bundle centerlines as compared to the maximum MF levels directly above the cable bundles; and at lateral distances of ±7.6 m (±25 ft) and beyond, there is a negligible difference in MF levels for the buried *versus* the surface-laid cables. At the minimum 50-m (164-ft) spacing between HVDC offshore export cable bundles, the modeled magnetic fields from the cables at the midpoint between adjacent cable bundles are essentially zero and there is no evidence of an additive or cumulative effect for MFs from adjacent cable bundles.

Table 3.4 Summary of Modeled Cable-specific Magnetic Fields for HVDC Offshore Export Cables

Cable Voltage	Installation Scenario[a]	Maximum DC MF (Above Cables) (mG)	DC MF at ± 10 ft[b] (mG)	DC MF at ± 25 ft[b] (mG)	DC MF at ± 50 ft[b] (mG)
±320 kV	Buried	282	59.6	11.6	3.0
	Surface-laid	2,076	72.9	12.0	3.0
±525 kV	Buried	312	66.5	13.0	3.3
	Surface-laid	2,245	81.6	13.4	3.4

Notes:
DC = Direct Current; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables.
(b) Horizontal distance is measured from the centerline of the cable bundle.

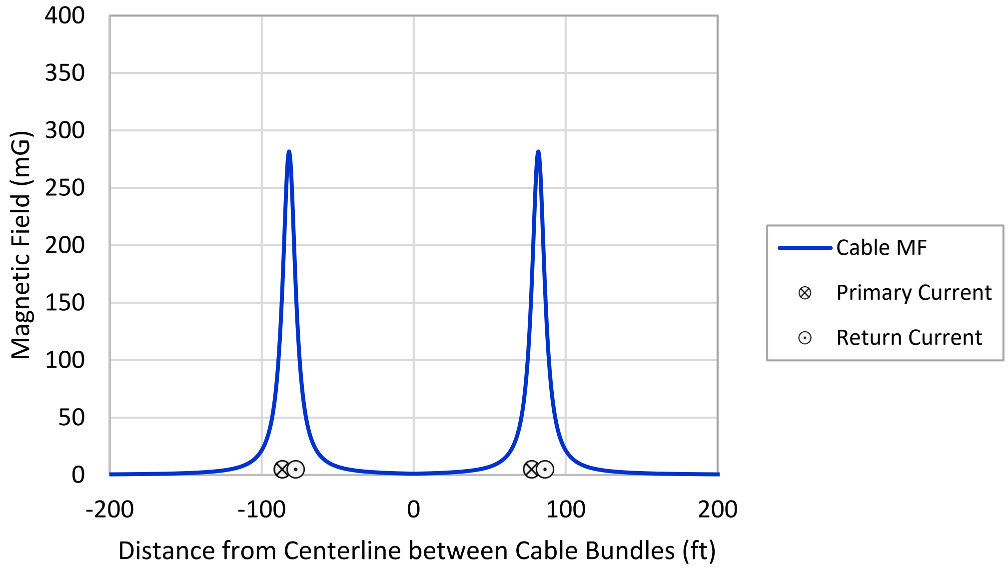

Figure 3.2 Cable-Specific DC Magnetic Field Modeling Results at the Seabed for Buried ±320-kV HVDC Offshore Export Cables. mg= Milligauss. Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Conductor locations on the graph are not to scale and are provided to show relative locations.

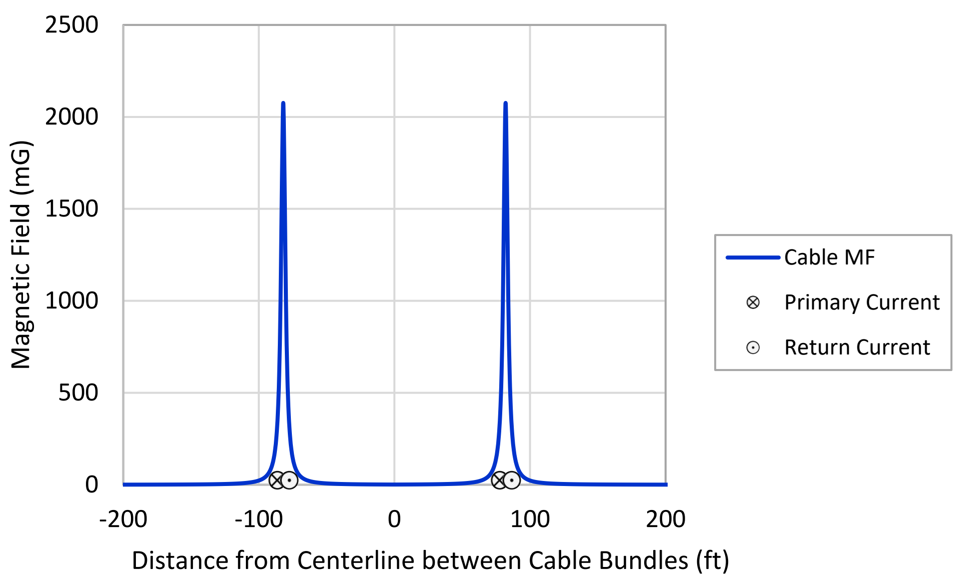

Figure 3.3 Cable-Specific DC Magnetic Field Modeling Results at 0.65 m (2.14 ft) Above the Seabed for Surface-Laid ±320-kV HVDC Offshore Export Cables. mg= Milligauss. It is assumed that cable bundles are installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness. Each cable bundle has a loading of 2,300 A and there is 50-m (164-ft) spacing between cable bundles. Conductor locations on the graph are not to scale and are provided to show relative locations.

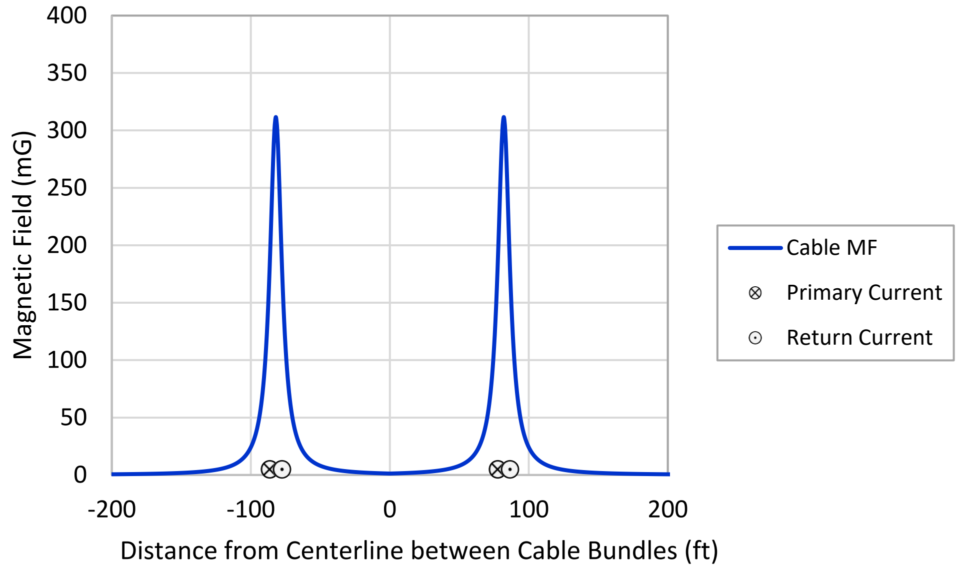

Figure 3.4 Cable-Specific DC Magnetic Field Modeling Results at the Seabed for Buried ±525-kV HVDC Offshore Export Cables. mg= Milligauss. Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Conductor locations on the graph are not to scale and are provided to show relative locations.

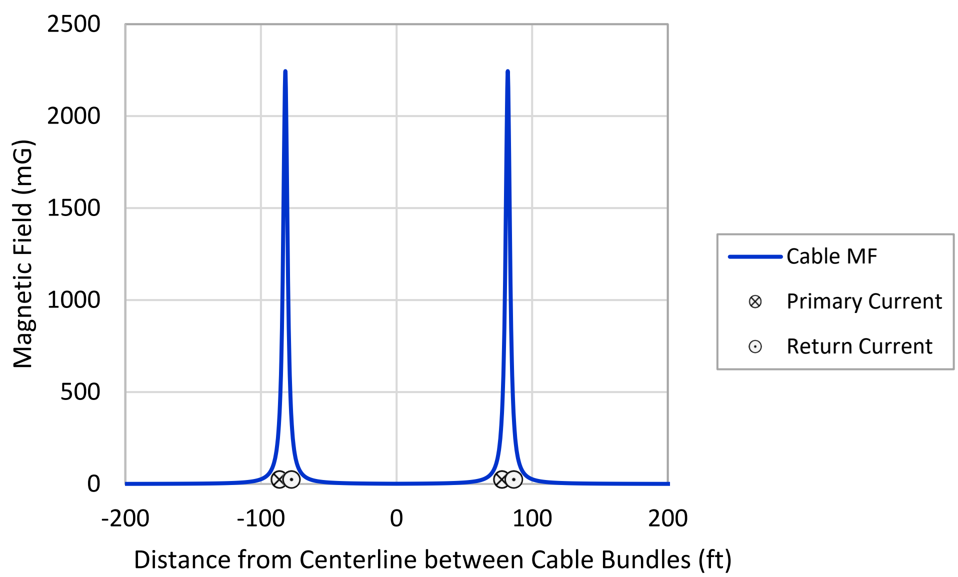

Figure 3.5 Cable-Specific DC Magnetic Field Modeling Results at 0.67 m (2.20 ft) Above the Seabed for Surface-Laid ±525-kV HVDC Offshore Export Cables. mg= Milligauss. It is assumed that cable bundles are installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness. Conductor locations on the graph are not to scale and are provided to show relative locations.

Table 3.5 summarizes maximum DC MF deviations in mG from the earth's geomagnetic field of 508 mG selected as being representative of the OECCs, while Appendix A contains the full set of maximum DC MF deviation results. Appendix B provides graphs for each modeling case that show total DC MFs that reflect the combined DC fields from the cables and the earth's geomagnetic field. In the vicinity of the cables, the combination of the fields can result in either increases in MF above the ambient geomagnetic field (*i.e.*, positive MF deviations) or decreases in MF relative to the ambient geomagnetic field (*i.e.*, negative MF deviations), depending on the orientations of the MF vector from the cable pair. Ranges in Table 3.5 represent the maximum positive and negative MF deviations across the modeling results for each cable bundle type and installation scenario that include two representative cable route geographic orientations (north-south and east-west) and both possible current flow direction scenarios for each cable route geographic orientation.

Table 3.5 Summary of Modeled Magnetic Fields for HVDC Offshore Export Cables as Deviations from Earth's Steady DC Magnetic Field[a]

Cable Voltage	Installation Scenario[b]	Maximum MF Deviation (Above Cables) (mG)	DC MF Deviation at ± 10 ft[c] (mG)	DC MF Deviation at ± 25 ft[c] (mG)	DC MF Deviation at ± 50 ft[c] (mG)
±320 kV	Buried	-268 to 271	-49.9 to 51.8	-11.5 to 11.5	-2.9 to 2.9
	Surface-laid	-266 to 2,039	-72.4 to 72.5	-11.5 to 11.5	-2.8 to 2.8
±525 kV	Buried	-296 to 300	-55.4 to 57.8	-12.9 to 12.9	-3.3 to 3.3
	Surface-laid	-268 to 2,207	-81.0 to 81.2	-12.9 to 12.9	-3.2 to 3.2

Notes:
DC = Direct Current; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) Magnetic fields are presented as the deviation from the earth's steady DC magnetic field of 508 mG and are maximum deviations across modeling cases that include two representative cable route geographic orientations (north-south and east-west) and both possible current flow direction scenarios for each representative cable route geographic orientation. Negative values are the maximum reductions below the earth's steady DC magnetic field of 508 mG.
(b) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 2.14 ft for the ±320-kV cables, and 2.20 ft for the ±525-kV cables.
(c) Horizontal distance is measured from the centerline of the cable bundle.

As shown in Table 3.5 and the Appendix A and B tables and figures, the MF modeling results indicate that the DC cable bundles will contribute to highly localized DC MF deviations from the earth's geomagnetic field magnitude of 508 mG in the immediate vicinity of the cable bundles. For the buried cables, the maximum MF deviations at the seabed surface directly above the cable bundles range from -296 mG to +300 mG (-58 to +59% of the earth's geomagnetic field), and the maximum MF deviations decrease very rapidly with increasing lateral distance from the cable bundle centerlines, dropping to -55.4 mG to +57.8 mG (-10.9 to +11.4% of the earth's geomagnetic field) and -12.9 mG to +12.9 mG (-2.5 to +2.5% of the earth's geomagnetic field) at distances of 3 m (10 ft) and 7.6 m (25 ft), respectively, from the cable bundle centerlines. Although the peak maximum MF deviations just above the cable protection exceed the earth's geomagnetic field by about 4 times for the surface-laid cables, the MF deviations from the earth's geomagnetic field drop to small values very rapidly moving away from the cable bundles, and the earth's geomagnetic field dominates DC MFs at short distances from the cable bundles. At a lateral distance of 3 m (10 ft) from the cable bundle centerlines, the maximum MF deviations caused by the DC MFs from the surface-laid cables are higher than for the buried cables, ranging from –81.0 mG to +81.2 mG (-15.9 to +16.0% of the earth's geomagnetic field); but at a lateral distance of 7.6 m (25 ft) from the cable bundle centerlines, they have dropped to similar values as the buried cables, ranging from -12.9 mG to +12.9 mG (-2.5 to +2.5% of the earth's geomagnetic field). In the water column above the cables, there will be even lower MF deviations than those modeled at the seabed surface for the buried cables and at the height of the top of the cable protection for the surface-laid cables.

The graphs in Appendix B (Figures B.1 through B.8) compare the total (cable + earth's geomagnetic field) MFs to the earth's geomagnetic field for each of the DC MF modeling scenarios. The two panels for each figure represent the two possible current flow direction cases for a particular cable bundle type (±320-kV or ±525-kV cables), installation scenario (buried or surface-laid), and cable route geographic orientations (north-south or east-west). For example, for Figure B.1 that shows total DC MF modeling results at the seabed for buried ±320-kV HVDC offshore export cables with a north-south route orientation, the top panel corresponds to the case of a northern current flow in the western cable and southern current flow in the eastern cable, and the bottom panel corresponds to the case of a southern current flow in the western cable and northern current flow in the eastern cable. For the buried cable modeling scenarios, the graphs show how the magnitudes of the deviations in the total MFs at the seabed surface associated with the cables are similar for the two power flow cases, but that the signs of the deviations (positive corresponding to an increase of the earth's geomagnetic field, or negative corresponding to a reduction of the earth's geomagnetic field) depend on the direction of current flow in the cables. For the surface-laid cable modeling cases, both power flow cases are associated with large positive MF deviations directly above the cable bundles, although the maximum deviations are larger for the power flow cases where the vertical field from the cable is aligned with the direction of the vertical component of the earth's geomagnetic field. Overall, the graphs show the localized nature of the DC MF deviations from the earth's geomagnetic field caused by the DC MFs from the offshore export cables, and further illustrate how the peak maximum positive and negative deviations from the earth's geomagnetic field occur directly above the cable bundles. As illustrated by the graphs, beyond distances of approximately 7.6 m (25 ft) from the conductor centerlines, there are only very small (*i.e.*, between approximately -2.5% and +2.5%) differences between the total (cable + earth's geomagnetic field) MFs and the earth's ambient geomagnetic field.

4 Magnetic Field Modeling for the HVAC Offshore Export Cables

We performed modeling of the magnetic field levels associated with the HVAC offshore export cables that are under consideration for use in the Massachusetts OECC. As with the HVDC MF analysis, this modeling analysis is focused on magnetic fields because electric fields produced by the voltage on the offshore export cables will be shielded by steel sheathing/armoring. It bears mentioning that the 60-Hz AC MFs produced by submarine cables will induce a weak electric field in the surrounding marine environment near the buried cables.[9] These induced electric fields differ from direct electric fields produced by power cables, as they are very low in strength and are unrelated to the voltage of the cable (CSA Ocean Sciences Inc. and Exponent, 2019). Because they are induced by the 60-Hz AC MFs surrounding a submarine cable, they are instead proportional to the current flow on the cable. These induced electric fields are not modeled by EMF modeling programs; however, CSA Ocean Sciences Inc. and Exponent (2019) provided information on the typical strengths of these induced electric field levels for AC submarine export cables from offshore wind energy projects, which ranged from 0.0019 to 0.0037 V/m (1.9-3.7 mV/m) at the seafloor directly above a cable to 0.00004 to 0.00013 V/m (0.04-0.13 mV/m) at the seafloor 3 to 7.5 m (about 10 to 25 ft) laterally away from a cable.

4.1 AC Cable Specifications and Representative Cross Sections

Modeling was performed for a representative cable installation scenario consisting of 3 three-core HVAC cables spaced a minimum of 50 m (164 ft) apart. Two different voltage cables (220 kV and 345 kV) were modeled with the specifications and currents presented in Table 4.1. Identical conductor loadings of 1,700 amps were conservatively assumed for both HVAC cables. All MF modeling used maximum loadings for the offshore export cables provided by the Proponent that are conservative values assuming maximum WTG output corresponding to 100% capacity. Figure 4.1 provides an example schematic of the type of cable to be used.

Table 4.1 HVAC Offshore Export Cable Specifications and Currents

Parameter	220-kV HVAC Cable	345-kV HVAC Cable
Burial Depth (m)[a]	1.5, or surface-laid	1.5, or surface-laid
Cable Voltage (kV)	220	345
Conductor Diameter (mm)	48.0	55.2
Cable Diameter (mm)	286.7	317.3
Conductor Area (mm^2)	1,810	2,393
Current (A)	1,700	1,700

Notes:
A = Ampere; HVAC = High Voltage Alternating Current; kV = kilovolts; m = meter; mm = millimeter.
(a) For the buried cables, to the top of the cables; for the surface-laid cables, cable protection with a thickness of 0.5 m (1.6 ft) is assumed.

[9] By Faraday's Law of Induction, a time-varying MF (*i.e.*, changing magnetic flux) will induce a time-varying electric field in a conducting medium, such as seawater. This is the same principle by which coils rotating in a steady MF generate a flow of electricity.

Design:

1 Conductor (Al or Cu)	5 Water barrier	9 Fillers
2 Inner semi-conducting layer	6 Metallic sheath	10 Armor bedding
3 Insulation	7 Inner sheath	11 Armor layer
4 Outer semi-conducting layer	8 Fiber optic cable	12 Outer serving

Figure 4.1 Example HVAC Cable Cross Section Illustration

While not shown in Figure 4.1, the three cores within the cable are expected to be helically wound, where the phase conductors would have a "twisted" design rather than being straight and parallel over long distances. This twisting of the conductors is expected to contribute to substantially greater self-cancellation of MF than for straight conductors, although less than the cancellation associated with the triangular geometry of the conductors (CSA Ocean Sciences Inc. and Exponent, 2019). This additional self-cancellation from the twisting of the phase conductors is not typically reflected in MF modeling analyses of submarine cables due to the complexity of modeling it. It has been estimated for the 30-MW 60-Hz AC "sea2shore" cable, which was commissioned in 2016 to connect the Block Island wind energy project with the Rhode Island mainland grid, that the helical twisting of the three-phase cable reduced MF levels by at least 10-fold as compared to an untwisted three-phase cable (CSA Ocean Sciences Inc. and Exponent, 2019; Hutchison *et al.*, 2018).[10]

Although steel armoring is more commonly used, the usage of ferromagnetic metal armoring such as galvanized steel armoring in the cables would also serve to partially attenuate the MFs reaching the outside environment as a result of both ferromagnetic shielding and opposing eddy currents that are induced in the

[10] As sponsored by the Bureau of Ocean Energy Management (BOEM), the Hutchison *et al.* (2018) research study compared modeled MF levels with field measurements of actual MF levels in the proximity of the 30-MW 60-Hz AC "sea2shore" cable. The authors found measured MF levels to be substantially lower than the modeled values, which did not take into account the three-conductor twisted design: "The magnetic field produced by the AC sea2shore cable (range of 0.05-0.3 µT) was ~10 times lower than modeled values commissioned by the grid operator, indicating that the three-conductor twisted design achieves significant self-cancellation" (Hutchison *et al.*, 2018).

armor (CSA Ocean Sciences Inc. and Exponent, 2019). This shielding factor is difficult to calculate due to the discontinuous nature of the wire armoring, although it will provide less shielding than a solid ferromagnetic pipe covering (for which a shielding factor of 10 is generally assumed; EPRI, 1993; EPRI and HVTRC, 1994). Studies provide support for a shielding factor of approximately two from ferromagnetic metal armoring of submarine cables (Lucca, 2013; CSA Ocean Sciences Inc. and Exponent, 2019).

Two installation scenarios were modeled for each type of HVAC offshore export cables: (1) a buried cable installation case where the cables were assumed to be buried to a minimum target depth of 1.5 m or 4.92 ft, and (2) a surface-laid cable installation case where the cables were installed directly on the seabed surface and covered by cable protection with 0.5-m (1.6-ft) thickness. MFs associated with the buried cables were modeled directly on the seabed surface, while MFs associated with the surface-laid cables were modeled at the top of the cable protection, specifically at 0.79 m (2.58 ft) for the 220-kV cables, and 0.82 m (2.68 ft) for the 345-kV cables. Balanced currents were assumed for the cables. We assumed that there will be no attenuation of MFs by whatever type of cable protection is used. Table 4.2 summarizes the four modeling scenarios for HVAC offshore export cables.

Table 4.2 HVAC Offshore Export Cable Magnetic Field Modeling Scenarios

Cable Voltage	Installation Scenario	Number of Cables	Cable Separation Distance	Loading Level
220 kV	Buried 1.5 m (4.92 ft) below seabed	3	50 m (164 ft)	1,700 A
	Surface-laid with cable protection	3	50 m (164 ft)	1,700 A
345 kV	Buried 1.5 m (4.92 ft) below seabed	3	50 m (164 ft)	1,700 A
	Surface-laid with cable protection	3	50 m (164 ft)	1,700 A

Notes:
A = Ampere; ft = Feet; HVAC = High Voltage Alternating Current; kV = Kilovolts; m = Meter.

4.2 Software Program Used for Modeling AC Magnetic Fields

MF levels from the HVAC offshore export cables were calculated using the FIELDS computer program, which was previously described in Section 3.2 of this report. Modeled fields using this program are both precise and accurate for the input data utilized; however, the model assumes that conductors have a continuously straight trefoil configuration and thus does not account for any reductions in MF levels associated with helical twisting of the offshore export cable conductors.

Modeled 60-Hz AC magnetic field levels from FIELDS are reported as root mean square (RMS) values of the resultant fields, generally referred to as $B_{Resultant}$ or B_{Res}, and sometimes as $B_{Product}$ or B_{Prod}. We have reported B_{Res} values to be consistent with the magnetic field levels that will be reported by instruments relying on three fixed orthogonal coils (*e.g.*, fixed-coil instruments like the EMDEX II), where the electronics calculate the sum of the squares of magnetic fields detected by each orthogonal coil separately. However, it is important to note that B_{Res} will always be larger than the real "maximum" rotating magnetic field (*i.e.*, the RMS value of the semi-major axis magnitude of the field ellipse; known as $B_{Maximum}$ or B_{Max}) when modeling (or measuring) elliptically or circularly polarized fields. In other words, B_{Res} is a conservative metric for modeled magnetic field values, in particular for elliptically or circularly polarized fields.

4.3 AC Magnetic Field Modeling Results

Table 4.3 summarizes the modeled 60-Hz AC MF levels for the offshore export cable cross sections, and Figures 4.2 through 4.5 show the AC MF magnitudes as a function of distance from the centerline of the cables. The modeling shows that the highest modeled AC MF levels occur directly above the offshore export cables, ranging from maximums of 191.3 mG to 214.4 mG for the buried cables and maximums of 1,243 mG to 1,354 mG for the surface-laid cables. Table 4.3 and the figures show that MF levels diminish very rapidly with lateral distance away from the cable centerlines for the 60-Hz AC offshore export cables, such that there are >95 to >99% reductions in MF levels at lateral distances of ±25 ft (±7.6 m) from the cable centerlines. MF levels in the water column will be less than the modeled MF levels at the seabed or above the cable protection, with the rate of decrease in MF levels as a function of height above the cables being similar to the rate of fall-off as a function of distance laterally from the cables. Table 4.3 also shows that at a lateral distance of 7.6 m (25 ft) there is negligible difference in the MF levels for the buried *versus* the surface-laid cables. Finally, as illustrated in the figures, at the assumed 50-m (164-ft) spacing between cables, the modeled magnetic fields at the midpoint between adjacent offshore export cables are essentially zero, indicating a lack of interaction for the MFs between adjacent cables.

Table 4.3 Summary of Modeled Magnetic Fields for HVAC Offshore Export Cables

Cable Voltage	Installation Scenario[a]	Maximum AC MF (mG)	AC MF at ± 10 ft[c] (mG)	AC MF at ± 25 ft[c] (mG)	AC MF at ± 50 ft[c] (mG)
220 kV, 3-phase	Buried	191	43.6	9.0	2.8
	Surface-laid	1,243	54.0	9.3	2.8
345 kV, 3-phase	Buried	214	49.6	10.2	3.1
	Surface-laid	1,354	61.6	10.7	3.2

Note:
AC = Alternating Current; ft = Feet; HVAC = High Voltage Alternating Current; kV = Kilovolts; MF = Magnetic Field; mG = Milligauss.
(a) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported on top of the cable protection, specifically at 0.79 m (2.58 ft) for 220-kV cables, and 0.82 m (2.68 ft) for 345-kV cables.
(b) Horizontal distance is measured from the cable centerline.
(c) The offshore export cable MF modeling assumes straight-laid phase-conductor cable cores rather than helical or "twisted" phase-conductor cores (the expected cable design). As discussed in Section 4.1, field measurements taken for the Block Island "sea2shore" cable show that a helical design achieves a considerable degree of magnetic field cancellation, hence the modeled MF levels are expected to be overestimates of actual MF levels.

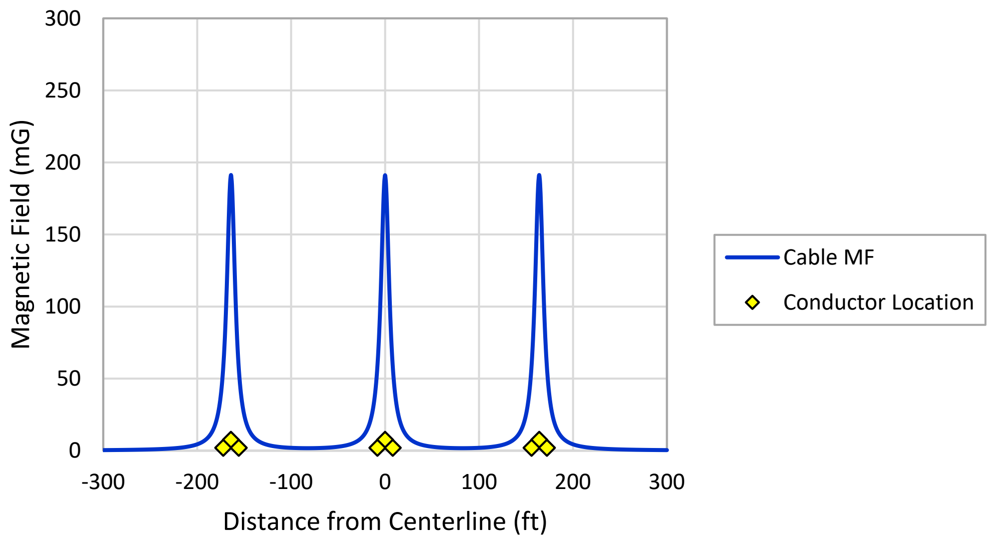

Figure 4.2 AC Magnetic Field Modeling Results at the Seabed for Buried 220-kV HVAC Offshore Export Cables. mG = Milligauss. Modeling results are based on three cables buried 1.5 m (4.9 ft) beneath the seabed, each carrying 1,700 A and with 50-m (164-ft) spacing between cables. Conductor locations on the graph are not to scale and are provided to show relative locations.

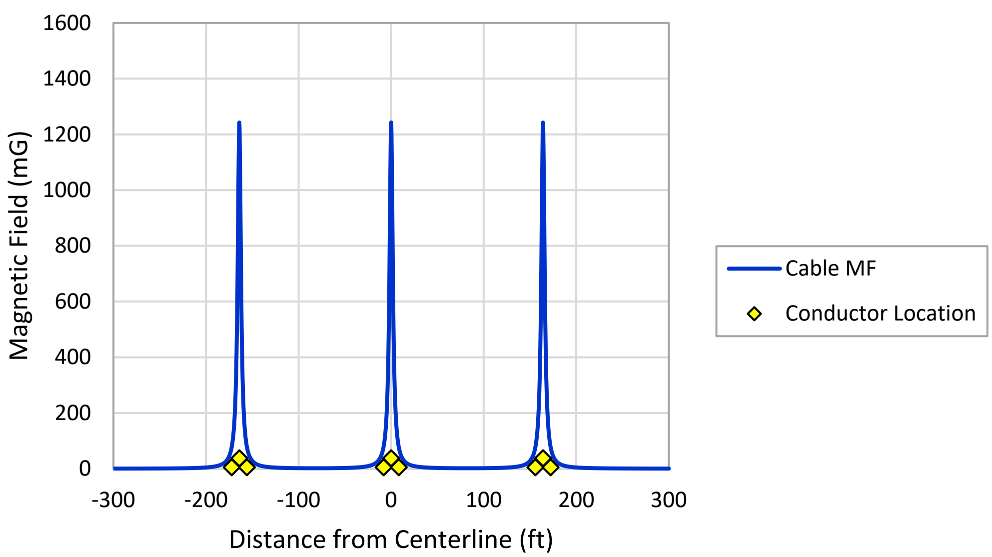

Figure 4.3 AC Magnetic Field Modeling Results at 0.79 m (2.58 ft) Above the Seabed for Surface-Laid 220-kV HVAC Offshore Export Cables. mG = Milligauss. Modeling results are based on three cables installed on the seabed covered by 0.5-m (1.6-ft) thick cable protection, each carrying 1,700 A and with 50-m (164-ft) spacing between cables. Conductor locations on the graph are not to scale and are provided to show relative locations.

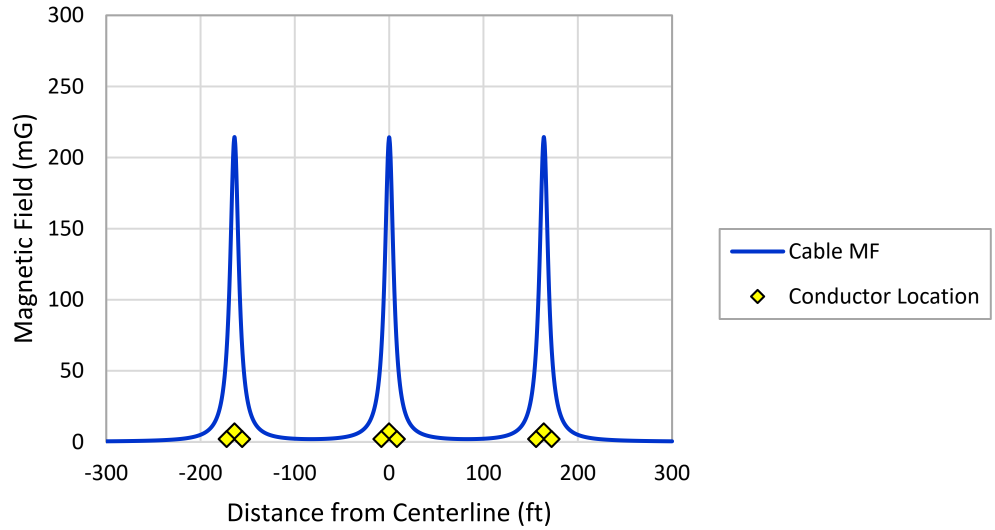

Figure 4.4 AC Magnetic Field Modeling Results at the Seabed for Buried 345-kV HVAC Offshore Export Cables. mG = Milligauss. Modeling results are based on three cables buried 1.5 m (4.9 ft) beneath the seabed, each carrying 1,700 A and with 50-m (164-ft) spacing between cables. Conductor locations on the graph are not to scale and are provided to show relative locations.

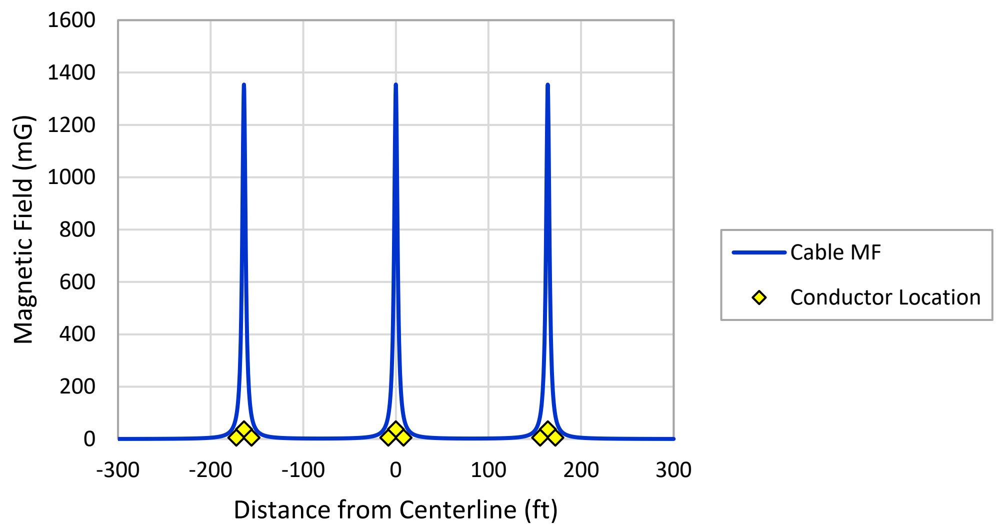

Figure 4.5 AC Magnetic Field Modeling Results at 0.82 m (2.68 ft) Above the Seabed for Surface-Laid 345-kV HVAC Offshore Export Cables. mG = Milligauss. Modeling results are based on three cables installed on the seabed covered by 0.5-m (1.6-ft) thick cable protection, each carrying 1,700 A and with 50-m (164-ft) spacing between cables. Conductor locations on the graph are not to scale and are provided to show relative locations.

5 Conclusions

Epsilon requested that Gradient perform a modeling analysis of the MF levels associated with HVDC and HVAC offshore export cables under consideration for use in the Vineyard Northeast OECCs. This modeling analysis is focused on MFs because the electric fields produced by the voltage on the offshore export cables will be contained by the metallic sheathing and/or steel armoring of the cables – *i.e.*, the metallic sheathing and/or steel armoring will completely shield the electric fields arising from the voltage on the cables. Magnetic fields are not completely shielded by either metallic sheathing or steel armoring, although the usage of ferromagnetic steel (*e.g.*, galvanized) steel armoring can serve to partially attenuate the MFs found outside 60-Hz AC cables (CSA Ocean Sciences Inc. and Exponent, 2019). As discussed in CSA Ocean Sciences Inc. and Exponent (2019), due to their time-varying nature, the MFs associated with 60-Hz AC cables can induce weak electric fields in the immediately surrounding marine environment near cables.[11] The steady MFs associated with DC cables do not induce electric fields, but similar to the induced electric fields associated with water movement and marine animal movement through the earth's geomagnetic field, very weak DC EFs will be induced by water flow or marine animal movement through the DC MFs associated with DC submarine cables. These induced electric fields are not modeled by EMF modeling programs such as the FIELDS computer program used in this assessment. However, they are weak in nature and are considered to pose less of a potential risk to marine species than the MFs from offshore export cables, especially given that electrosensitive marine species do not appear to have significant problems distinguishing bioelectric fields from the induced electric fields associated with water movement and marine animal movement through the earth's geomagnetic field (Gill and Desender, 2020; CSA Ocean Sciences Inc. and Exponent, 2019).

The Massachusetts OECC will include up to two 320 to 525-kV HVDC cable bundles[12] or up to three 220 to 345-kV 3-phase HVAC offshore export cables, with a minimum of 50-m (164-ft) spacing between adjacent cable bundles/cables. The Connecticut OECC will include up to two 320 to 525-kV HVDC cable bundles,[13] with a minimum of 50-m (164-ft) spacing between adjacent cable bundles. As a result, our MF modeling analysis examined representative cross sections of either two HVDC offshore export cable bundles or three 3-phase HVAC offshore export cables for both a typical burial case (minimum target burial depth of 1.5 m, or approximately 5 ft, to the top of the cables) and for a worst-case surface-laid case (with cable protection). For the HVDC MF modeling, multiple cable route geographic orientations and current flow directions were assessed to determine the upper bound DC MF results, because the geographic orientation of the cables and the current flow direction affect how the DC MFs associated with the cables combine with the earth's DC geomagnetic field – *i.e.*, the total MF as well as the maximum deviation from the earth's geomagnetic field depend on both the cable geographic orientation and the current flow direction.

For both the HVDC and HVAC offshore export cables, conservative modeling analyses[14] were conducted that predicted the highest MF levels directly above the cables, with the modeling demonstrating the rapid

[11] By Faraday's Law of Induction, a time-varying MF (*i.e.*, changing magnetic flux) will induce a time-varying electric field in a conducting medium, such as seawater. This is the same principle by which coils rotating in a steady MF generate a flow of electricity.

[12] The positive- and negative-voltage cables are adjacent (side-by-side) and touching in the horizontal cable bundles, meaning that the separation of the ± conductor centerlines is equal to the outside diameter of the insulated cable (see Table 3.1).

[13] The positive- and negative-voltage cables are adjacent (side-by-side) and touching in the horizontal cable bundles, meaning that the separation of the ± conductor centerlines is equal to the outside diameter of the insulated cable (see Table 3.1).

[14] Conservatisms in the modeling analysis include the use of maximum loadings for the offshore export cables provided by the Proponent that are conservative values assuming a maximum WTG output corresponding to 100% capacity; no shielding of MFs

fall-off of MF levels with increased lateral distance from the HVDC cable bundles or HVAC cables. For example, for the HVDC cable bundles, there was little difference in MF levels from the buried and surface-laid cables at a lateral distance of 7.6 m (25 ft) from either side of the cable bundle centerlines, where small MF deviations from the earth's DC geomagnetic field ranging from -12.9 mG to +12.9 mG (-2.5% to +2.5% of the earth's geomagnetic field) were calculated. For the HVAC cables, the modeling analysis showed >95 to >99% reductions in levels of 60-Hz AC MFs at lateral distances of ±7.6 m (±25 ft) from the cable centerlines. MF levels in the water column will be less than the model-predicted MF levels at the seabed or above the cable protection, with the rate of decrease in MF levels as a function of height above the cable bundles/cables being similar to the rate of fall-off as a function of distance laterally from the cable bundles/cables. For both the HVDC and HVAC offshore export cables, there was no evidence of interaction between MFs from adjacent cable bundles or cables for the assumed 50-m (164-ft) spacing between cable bundles/cables. Overall, the MF modeling analysis provides evidence of highly localized increases in either DC or 60-Hz AC MF levels directly above the cable bundles/cables at the seabed, which fall off rapidly both laterally and vertically moving away from the cable bundles/cables.

No regulatory thresholds or guidelines for allowable EMF levels in marine environments have been established for either HVDC or HVAC submarine power transmission. For HVAC transmission, the weight of the evidence indicates that 60-Hz AC EMFs are above the typical frequency range of EMFs to which magnetosensitive and electrosensitive marine species are known to detect and respond. In particular, magnetosensitive marine species such as salmon, whales, and sea turtles are specifically tuned to the earth's steady (DC) geomagnetic field for navigation/migration purposes, while electrosensitive marine species such as sharks and rays respond to electric field frequencies below 10 Hz for helping to locate prey and/or mates (CSA Ocean Sciences Inc. and Exponent, 2019). For HVDC transmission, there is a growing body of evidence suggesting that the steady MFs from HVDC cables may be perceptible to some EM-sensitive marine species that are known to detect the earth's steady (DC) geomagnetic field, but there remains a lack of evidence indicating potential harmful impacts at the population- or community-level for the various types of marine species which may experience brief exposure to DC MFs nearby offshore export cables (CSA Ocean Sciences Inc. and Exponent, 2019; Gill and Desender, 2020; NYSERDA, 2021; SEER, 2022; Taormina *et al*., 2018). Based on the localized nature of the MF impacts of the offshore export cables as well as the lack of reported evidence of significant harms to EM-sensitive marine species from either HVDC or HVDC submarine transmission, there is no expectation that MFs associated with either the HVDC or HVAC offshore export cables will cause significant population-level harms to marine species in the OECCs.

from the cable protection used for the surface-laid cable modeling scenarios; and for the HVAC cables, no attenuation of MF levels from either the metallic cable sheathing or armoring, from induced sheath currents, or from the expected helical twisting of the 3-phase cables.

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Appendix A

Summary Tables of DC Magnetic Field Deviations for the ±320-kV and ±525-kV HVDC Offshore Export Cable Modeling Scenarios

Table A.1 Summary of EMF Modeling Results for ±320-kV HVDC Offshore Export Cables, as Deviations from Earth's Steady DC Magnetic Field[a]

Installation Scenario[b]	Cable Route	Current Flow Direction in Western or Northern Cable	DC Magnetic Field Deviation (mG)[c]									
			-75 ft	-50 ft	-25 ft	-10 ft	Max -	Max +	+10 ft	+ 25 ft	+50 ft	+75 ft
±320 kV - Buried	North-South	North	-1.2	-2.7	-10.1	-33.9	-34.6	265	-23.4	-9.2	-2.6	-1.2
		South	1.2	2.7	10.2	38.3	-230	44.1	29.0	9.2	2.6	1.2
	East-West	East	-1.3	-2.9	-11.5	-49.9	-58.6	271	-8.3	-7.7	-2.4	-1.1
		West	1.3	2.9	11.5	51.8	-268	73.0	15.0	7.9	2.4	1.1
±320 kV - Surface-laid	North-South	North	-1.2	-2.8	-11.0	-63.1	-152	2,039	-57.0	-10.6	-2.7	-1.2
		South	1.2	2.8	11.0	65.4	0.08	1,119	60.6	10.6	2.7	1.2
	East-West	East	-1.2	-2.8	-11.5	-72.4	-266	2,039	-48.0	-10.0	-2.6	-1.2
		West	1.2	2.8	11.5	72.5	0.08	1,119	53.4	10.1	2.6	1.2

Notes:

DC = Direct Current; EMF = Electromagnetic Field; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; m = meters; mG = Milligauss.

a) Magnetic fields are presented as the deviation from the earth's steady DC magnetic field of 508 mG.

b) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables.

c) Horizontal distance is measured from the center of the cable bundle.

Table A.2 Summary of EMF Modeling Results for ±525-kV HVDC Offshore Export Cables, as Deviations from Earth's Steady DC Magnetic Field[a]

Installation Scenario[b]	Cable Route	Current Flow Direction in Western or Northern Cable	DC Magnetic Field Deviation (mG)[c]									
			-75 ft	-50 ft	-25 ft	-10 ft	Max -	Max +	+10 ft	+ 25 ft	+50 ft	+75 ft
±525 kV - Buried	North-South	North	-1.4	-3.0	-11.3	-37.3	-37.8	294	-25.5	-10.2	-2.9	-1.3
		South	1.4	3.0	11.4	42.8	-249	49.7	32.5	10.3	2.9	1.3
	East-West	East	-1.4	-3.3	-12.9	-55.4	-64.0	300	-8.5	-8.6	-2.7	-1.3
		West	1.4	3.3	12.9	57.8	-296	81.8	16.8	8.8	2.7	1.3
±525 kV - Surface-laid	North-South	North	-1.4	-3.1	-12.3	-70.3	-158	2,207	-63.2	-11.8	-3.0	-1.4
		South	1.4	3.1	12.3	73.2	0.09	1,286	67.8	11.9	3.0	1.4
	East-West	East	-1.4	-3.2	-12.9	-81.0	-268	2,207	-52.9	-11.2	-3.0	-1.3
		West	1.4	3.2	12.9	81.2	0.08	1,286	59.7	11.3	3.0	1.3

Notes:

DC = Direct Current; EMF = Electromagnetic Field; ft = Feet; HVDC = High Voltage Direct Current; kV = Kilovolts; m = meters; mG = Milligauss.

a) Magnetic fields are presented as the deviation from the earth's steady DC magnetic field of 508 mG.

b) Magnetic fields at the seabed are reported for buried cables. Surface-laid cables are assumed to have 0.5-m (1.6-ft) thick cable protection covering. For these scenarios, magnetic fields are reported at the top of the cable protection, specifically at 0.65 m (2.14 ft) for the ±320-kV cables, and 0.67 m (2.20 ft) for the ±525-kV cables.

c) Horizontal distance is measured from the center of the cable bundle.

Appendix B

Graphs of Total (Cable + Earth) DC Magnetic Field Modeling Results for the ±320-kV and ±525-kV HVDC Offshore Export Cable Modeling Scenarios

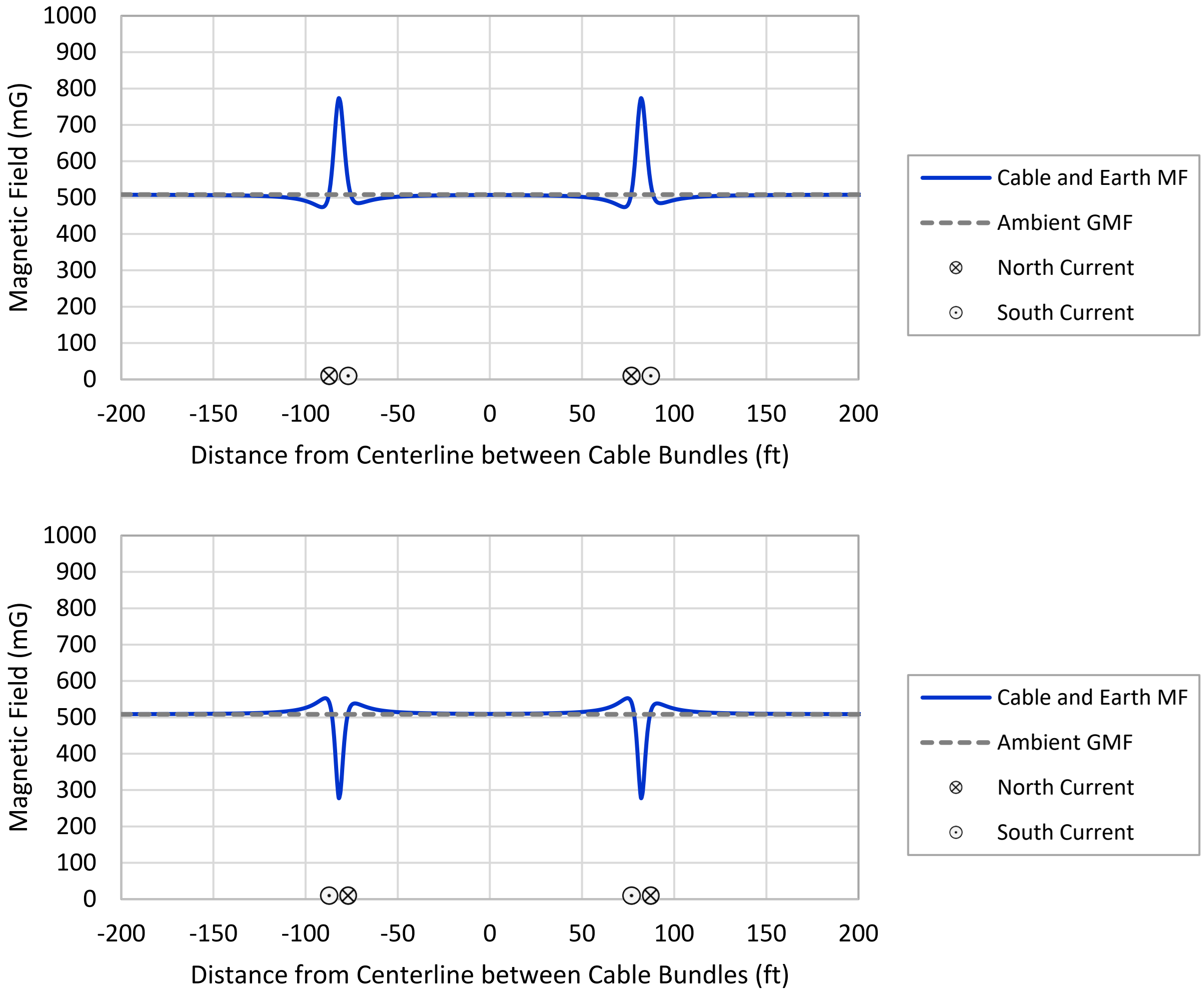
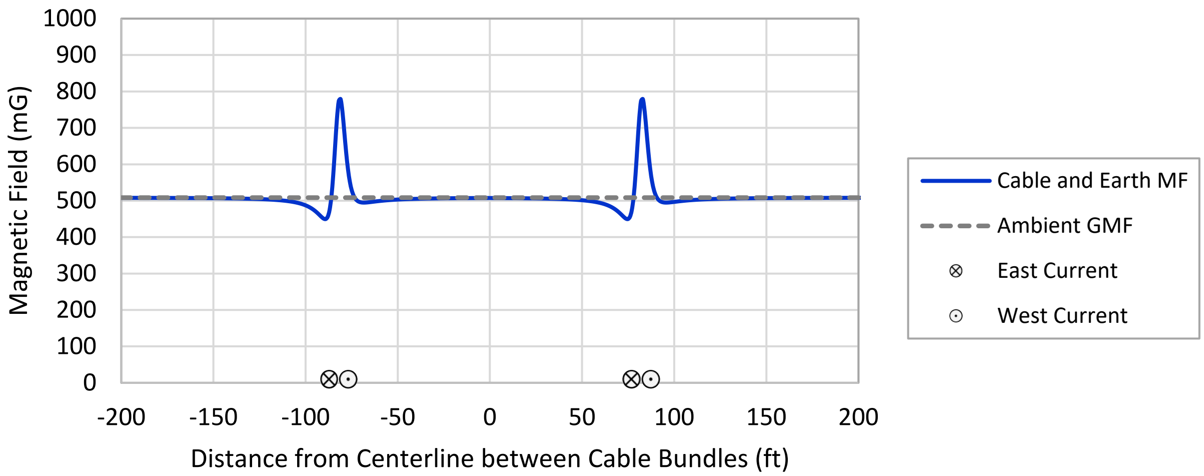


Figure B-1 Total DC Magnetic Field Modeling Results at the Seabed for Buried ±320-kV HVDC Offshore Export Cables with North-South Route Orientation. mG = Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Cables are oriented in a north-south direction and the view is facing north.



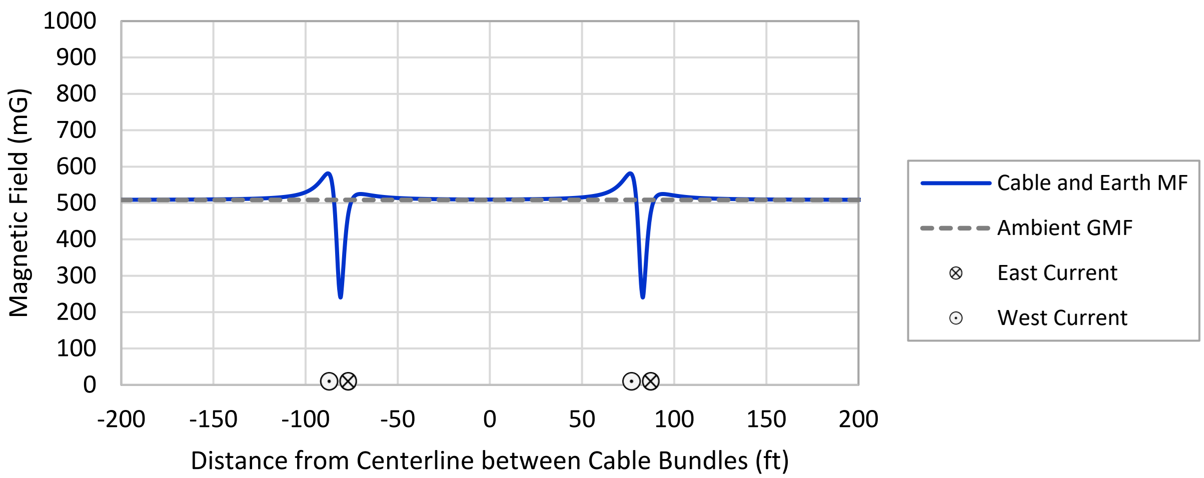
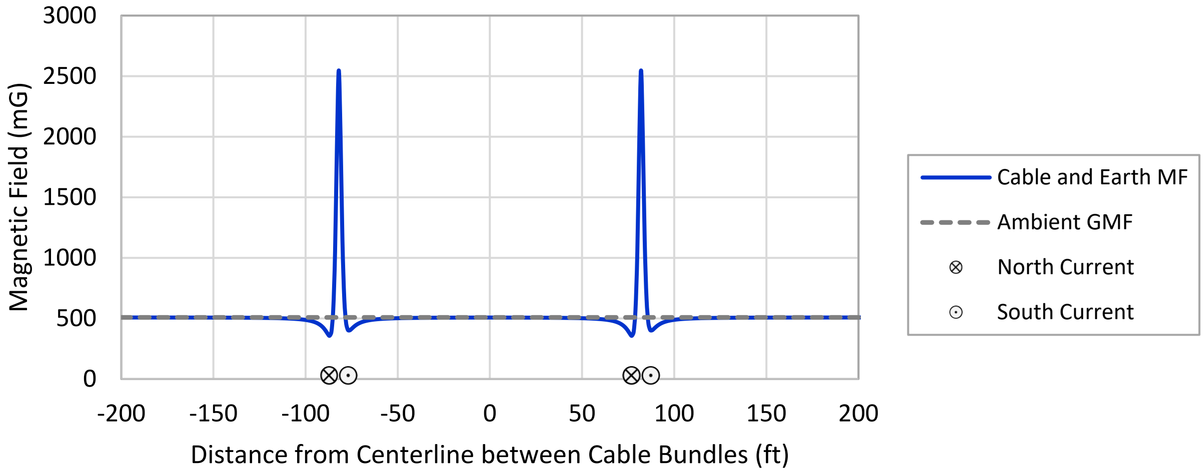


Figure B-2 Total DC Magnetic Field Modeling Results at the Seabed for Buried ±320-kV HVDC Offshore Export Cables with East-West Route Orientation. mG = Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Cables are oriented in an east-west direction and the view is facing east.



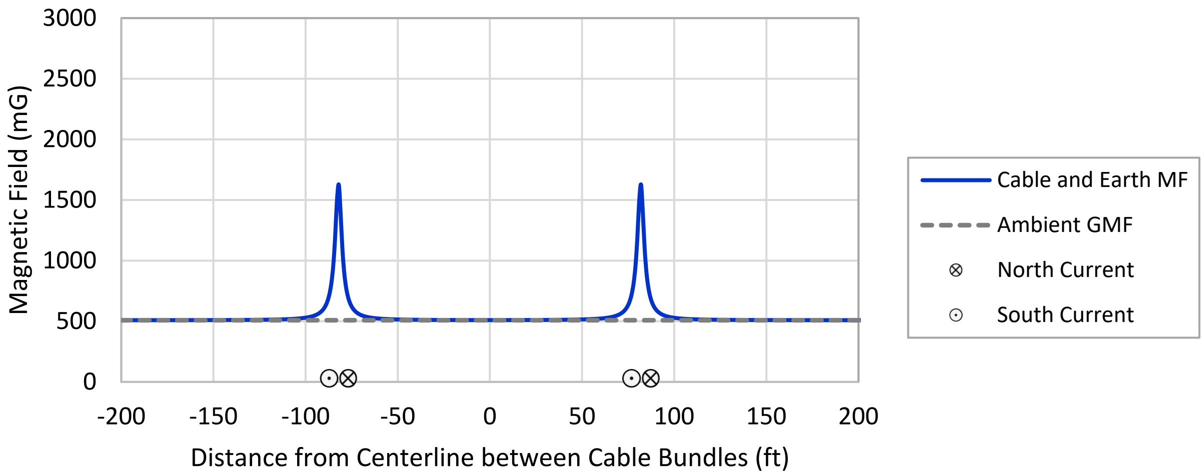


Figure B-3 Total DC Magnetic Field Modeling Results at 0.65 m (2.14 ft) Above the Seabed for Surface-Laid ±320-kV HVDC Offshore Export Cables with North-South Route Orientation. mg= Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness, each carrying 2,300 A and with 50-m (164-ft) spacing between cables. Cables are oriented in a north-south direction and the view is facing north.

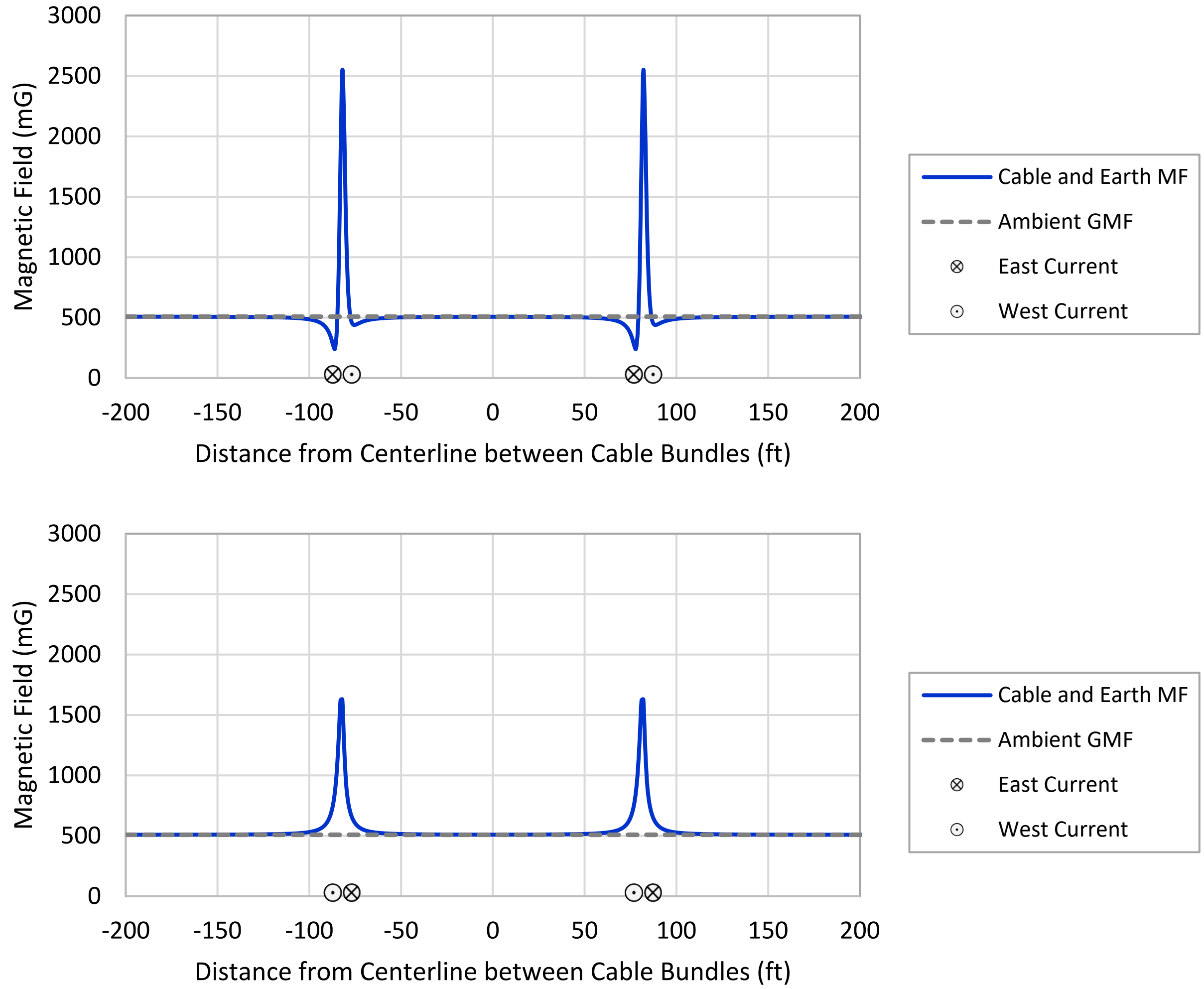


Figure B-4 Total DC Magnetic Field Modeling Results at 0.65 m (2.14 ft) Above the Seabed for Surface-Laid ±320-kV HVDC Offshore Export Cables with East-West Route Orientation. mg= Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness, each carrying 2,300 A and with 50-m (164-ft) spacing between cables. Cables are oriented in an east-west direction and the view is facing east.

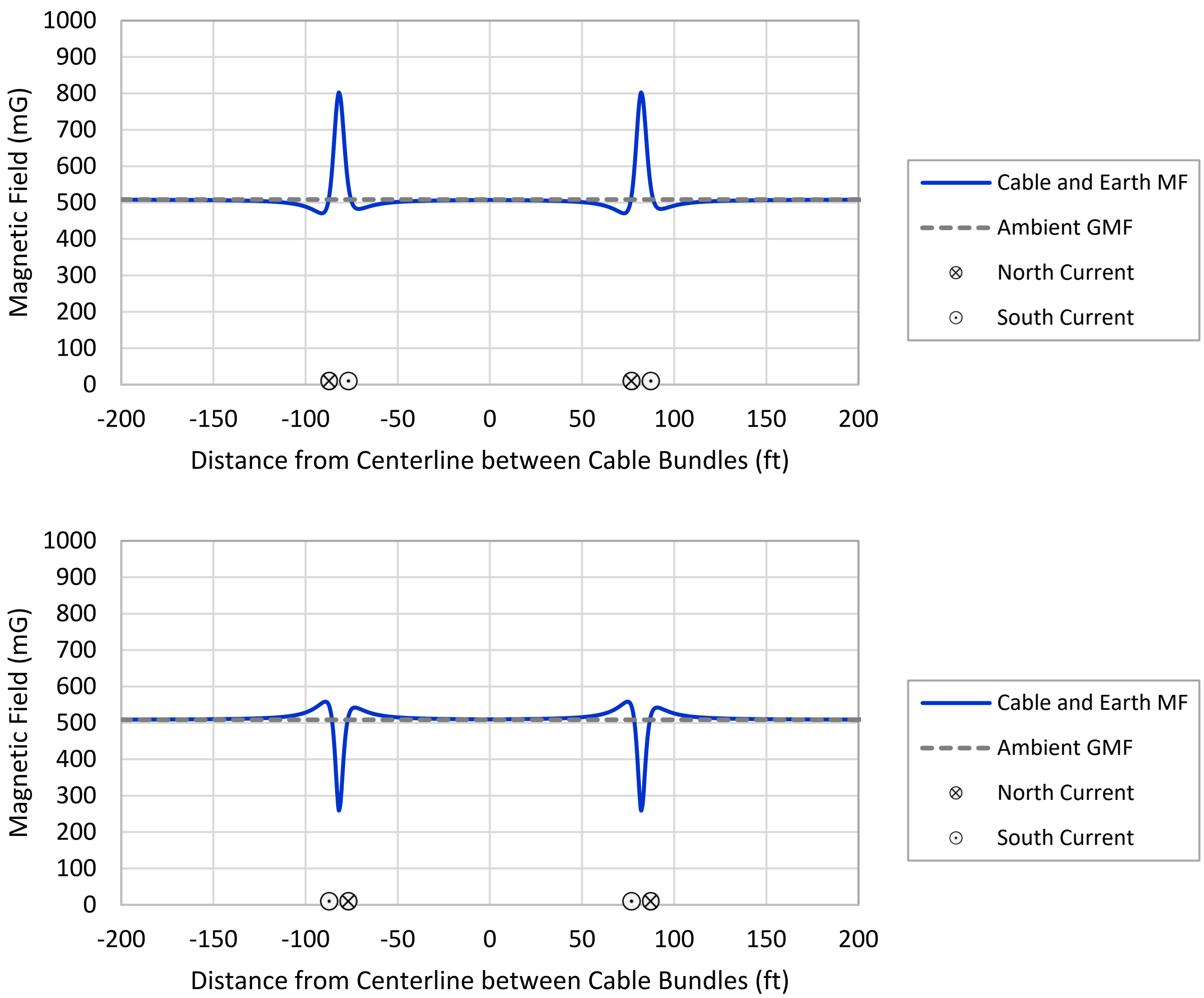
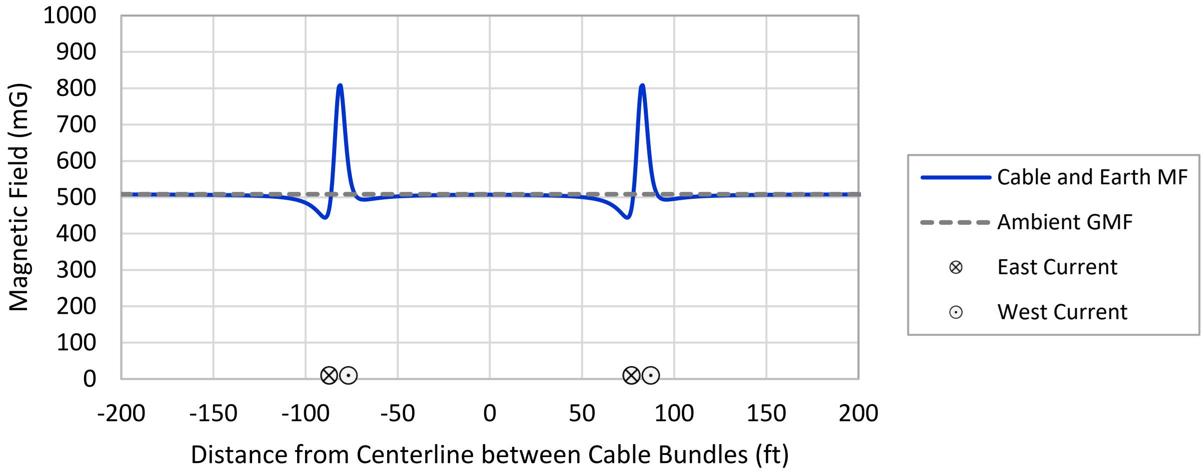


Figure B-5 Total DC Magnetic Field Modeling Results at the Seabed for Buried ±525-kV HVDC Offshore Export Cables with North-South Route Orientation. mG = Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Cables are oriented in a north-south direction and the view is facing north.



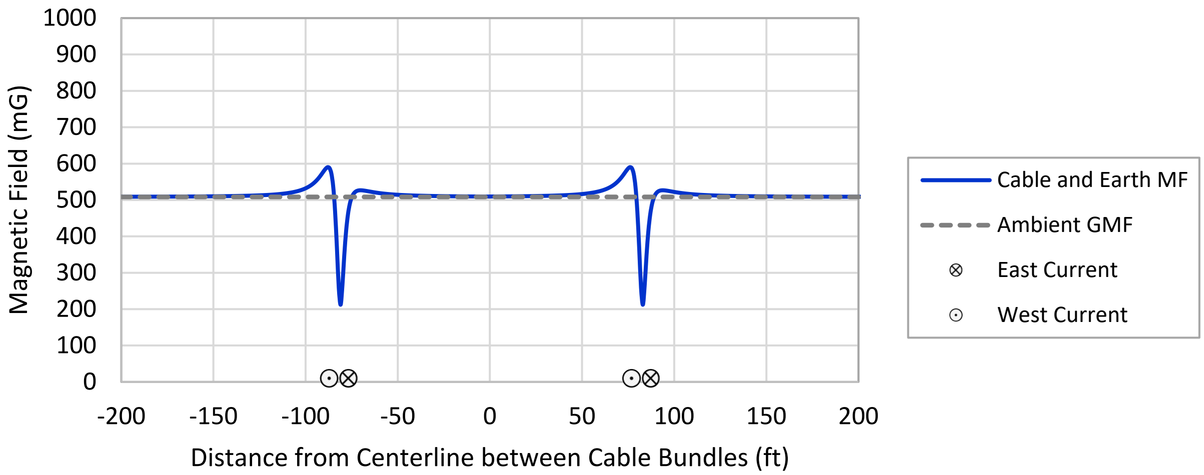


Figure B-6 Total DC Magnetic Field Modeling Results at the Seabed for Buried ±525-kV HVDC Offshore Export Cables with East-West Route Orientation. mG = Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles buried 1.5 m (4.9 ft) beneath the seabed, each carrying 2,300 A and with 50-m (164-ft) spacing between cable bundles. Cables are oriented in an east-west direction and the view is facing east.

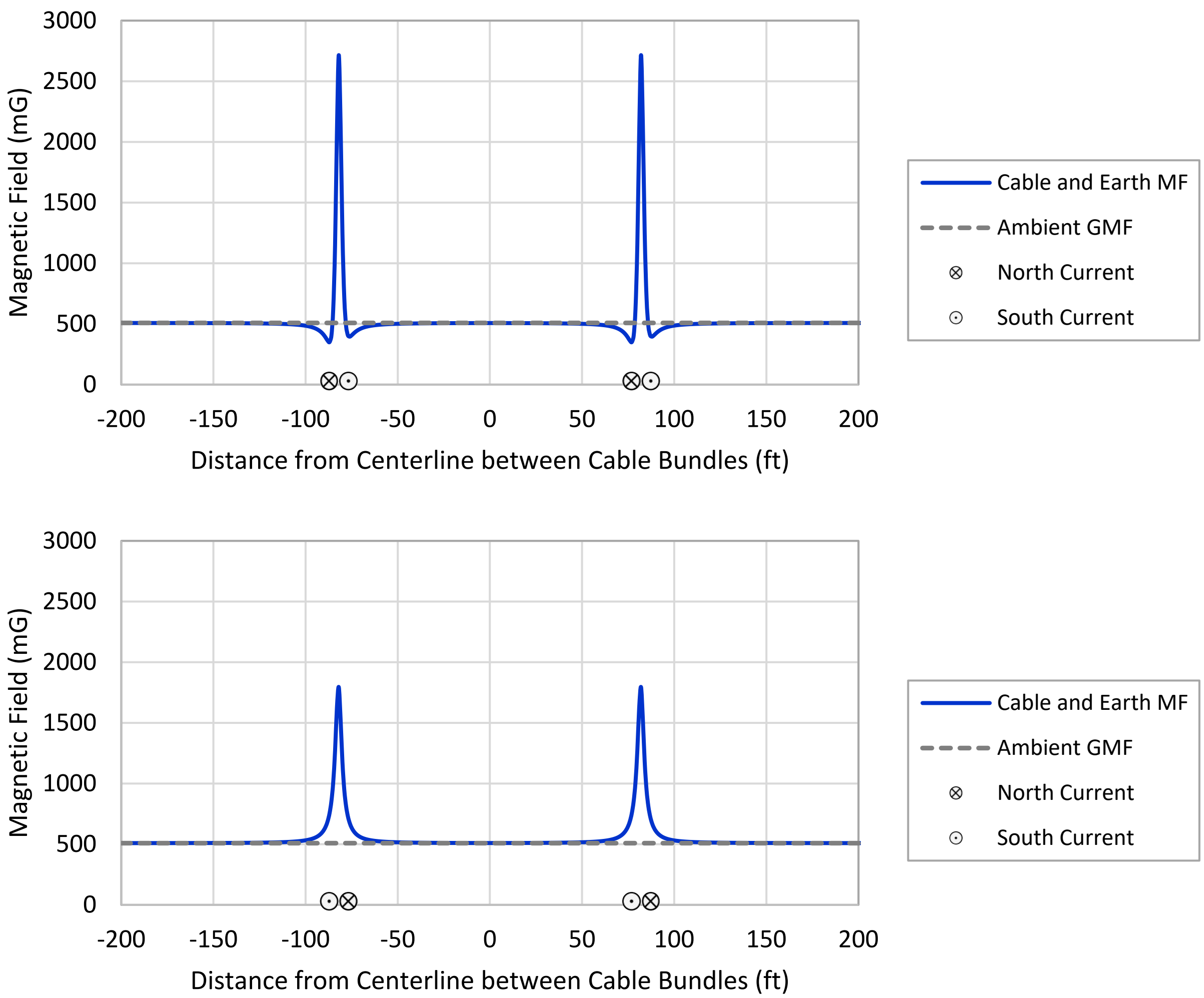
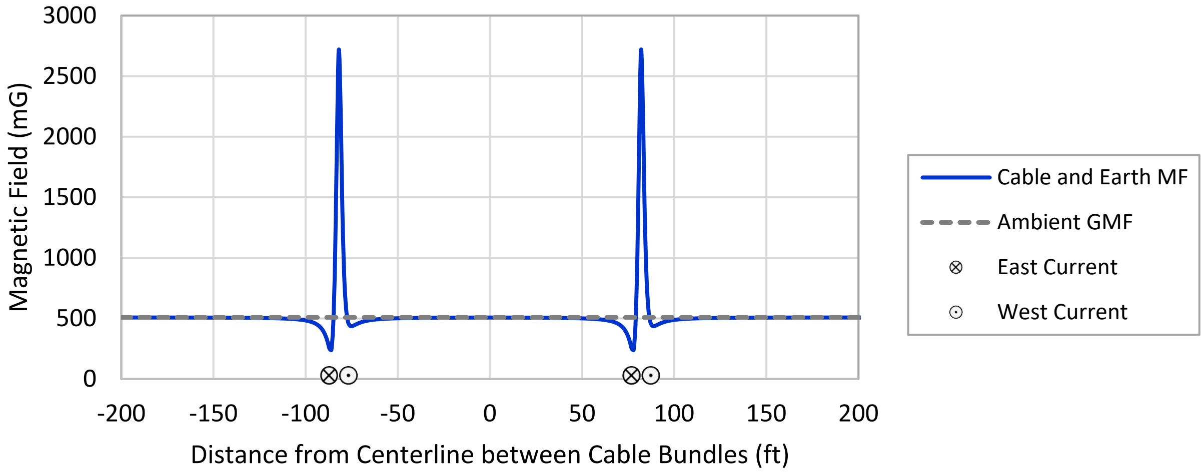


Figure B-7 Total DC Magnetic Field Modeling Results at 0.67 m (2.20 ft) Above the Seabed for Surface-Laid ±525-kV HVDC Offshore Export Cables with North-South Route Orientation. mg= Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness, each carrying 2,300 A and with 50-m (164-ft) spacing between cables. Cables are oriented in a north-south direction and the view is facing north.



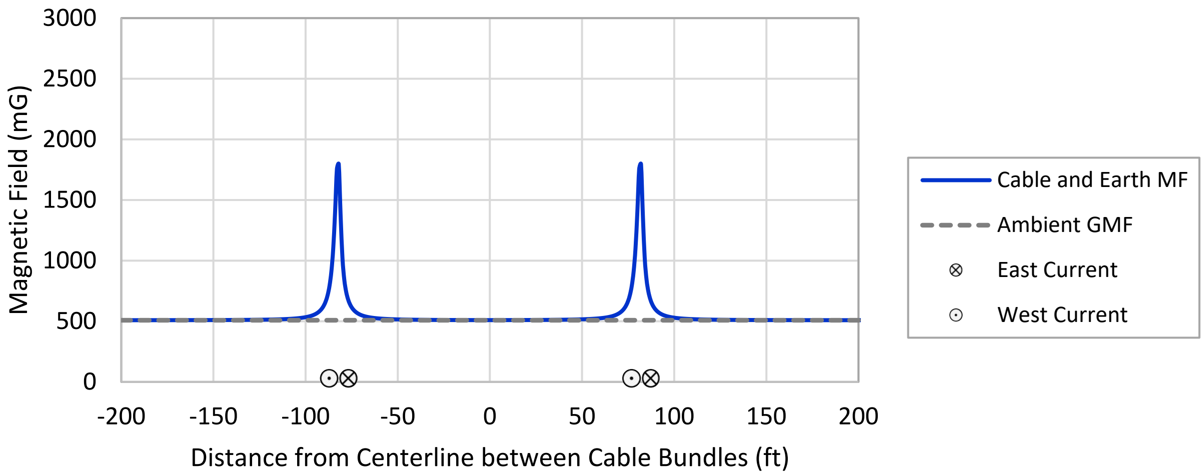


Figure B-8 Total DC Magnetic Field Modeling Results at 0.67 m (2.20 ft) Above the Seabed for Surface-Laid ±525-kV Submarine Cables with East-West Route Orientation. mg= Milligauss. Total DC magnetic field modeling results are the combined fields from the HVDC offshore export cables and the earth's geomagnetic field (GMF). Modeling results are based on two cable bundles installed on the seabed and covered by cable protection with 0.5-m (1.6-ft) thickness, each carrying 2,300 A and with 50-m (164-ft) spacing between cables. Cables are oriented in an east-west direction and the view is facing east.