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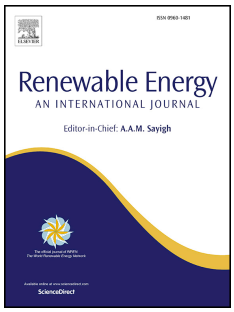

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PII: S0960-1481(21)00717-5

DOI: https://doi.org/10.1016/j.renene.2021.05.041

Reference: RENE 15398

To appear in: *Renewable Energy*

Received Date: 21 December 2020

Revised Date: 4 May 2021

Accepted Date: 6 May 2021

Please cite this article as: Hutchison ZL, Gill AB, Sigray P, He H, King JW, A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development, *Renewable Energy*, https://doi.org/10.1016/j.renene.2021.05.041.

A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development

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Abstract

The expanding marine renewable energy industry will increase the prevalence of electromagnetic fields (EMFs) from power cables in coastal waters. Assessments of environmental impacts are required within licensing/permitting processes and increased prevalence of cables will increase questions concerning EMF emissions and potential cumulative impacts. It is presumed that protecting a cable by burial, may also mitigate EMF emissions and potential impacts on species. Focussing on a bundled high voltage direct current (HVDC) transmission cable, we use computational and interpretive models to explore the influence of cable properties and burial depth on the DC magnetic field (DC-MF) potentially encountered by receptive species. Greater cable pair separation increased the deviations from the geomagnetic field and while deeper burial reduced the deviations, the DC-MF was present at intensities perceivable by receptive species. An animal moving along a cable route may be exposed to variable EMFs due to varied burial depth and that combined with an animal's position in the water column determines the distance from source and EMF exposure. Modelling contextually realistic scenarios would improve assessments of potential effects. We suggest developers and cable industries make cable properties and energy transmission data available, enabling realistic modelling and environmental assessment supporting future developments.

Keywords (6 max): Cumulative impacts, mitigation, buried cable, EMF propagation, receptor species, species perception

1. Introduction

The Earth's electromagnetic field (EMF) environment consists of both natural and anthropogenic sources. These EMFs may constitute environmental cues that many organisms detect and respond to throughout their lives [1]. Anthropogenic changes or additions to the EMF environment could alter cues with consequences for receptive animals; changes which will need to be considered by marine management groups and may require mitigation to reduce potential negative effects.

A major source of EMFs are subsea power cables (hereafter 'cables'). With the planned expansion in marine renewable energy (MRE; wind, wave, tidal stream) across the world as well as regional, national and international energy transfer, the prevalence of cables in coastal and offshore waters will increase greatly, resulting in EMF emissions becoming more frequent and therefore cumulatively more likely to be encountered by receptive animals. For example, there was 13% growth in ocean energy in 2019, with ambitious targets of 23% annual growth until 2030 [2], while offshore wind energy is expected to quadruple by 2030 [3]. Of particular relevance to the expanding MRE industries, is the permitting and consenting process which has a specific requirement for considering the potential impacts of EMFs on receptive species. Additionally, the formal process requires public and stakeholder consultation often raising concerns regarding EMF effects. The present lack of evidence and poor understanding of the effects, can cause delays as the concerns need to be addressed by reviewing literature, modelling and possibly collecting data. These processes are time consuming and mitigation measures to overcome perceived impacts may be costly. Despite this, EMF emissions from cables within the range of detection of receptive animals remains an understudied topic with regard to the environmental effects of energy transmission [4,5]. A more robust evidence base regarding EMFs and their effects on species is required to better inform the permitting and consenting process and remove barriers to present and future large-scale developments.

MRE industries use either alternating current (AC), or direct current (DC) cables, or a combination with transformer stations. The cables are either lower capacity inter-array, or higher capacity export cables. For exports, medium voltage AC cables are only used in small capacity developments close to shore (e.g. <20 km), whereas high voltage AC (HVAC) cables are commonly used for distances 15-50 km from shore, and high voltage DC cables (HVDC) are preferable for longer distances [6]. Presently, HVAC cables are most common in offshore wind farms (OWFs) however HVDC cable have

been used more in the past decade, due to better electrical performance over longer distances [6,7]. It is projected that HVDC will become more common as the MRE sector progresses [6]. An assessment of 57 European OWFs (>150 MW) demonstrated that between 2008 and 2019, the turbine power and installation depth as well as the OWF power and distance from shore had increased [6]. Preliminary designs of 20 MW wind turbine generators [8], further suggest increasing demands for higher capacity cables. Together with the increased number of MRE devices it is expected there will be higher intensity cable EMFs over wider spatial scales added to the existing EMF environment. As a result, questions have arisen concerning the spatial extent and intensity of cable EMFs encountered by receptive species and the potential consequences regarding natural EMF cues.

Natural EMFs provide ecologically important cues to marine species. The dominant source of natural EMF in the sea is the Earth's geomagnetic field which varies between 25 and 65 μTesla[1] from the equator to the poles [1]. In conductive water bodies, the combination of motion and the geomagnetic field creates motionally induced electric fields, arising from the movement of water bodies or animals through the geomagnetic field. Further biological sources are the bioelectric fields produced by organisms themselves [9]. Receptive species may be either electro-receptive, magneto-receptive, or both. Magneto-sensitive animals are able to detect and respond to very small changes in the intensity (i.e. nT-μT), the angle of inclination, direction of a magnetic field (polarity) and use these geomagnetic cues to aid navigation, using a 'magnetic compass' and/or 'magnetic map' sense [10–13]. These senses may facilitate homing, and short/long-distance migrations, to find ecologically important resources such as shelter, and feeding or reproductive grounds [10,14]. Electro-receptive species may be indirectly responsive to geomagnetic cues for the same ecological reasons however they may also be responsive to bioelectric cues important in predator-prey relationships, communication and in finding mates [15]. Such bioelectric fields may be AC or DC, typically low frequency (<1-20 Hz, up to 500Hz), and low intensity fields (nV/cm – μV/cm) [9,15]. Overall, natural electromagnetic cues are ecologically important to receptive animals throughout their life-cycle, contributing to the successful acquisition of food, survival and reproduction [12,15]. For this reason, it is important to understand both the anthropogenic changes to the EMF environment and the perception of EMFs from the vantage point of the receptive species (*sensu* [5]). Understanding EMFs encountered by receptive species, requires knowledge of cable characteristics and their influence on EMF emissions.

[1] 1T is equal to $1 kg \cdot s^{-2} \cdot A^{-1}$ (SI Base unit) or 1×10^4 G (Gaussian units)

Subsea cables are comprised of layers of materials around a conductive copper or aluminium core. Cables may occur in different arrangements, with varied layers of insulation depending on the type and manufacturer (Table 1) [16,17]. The cable shielding with mechanical resistance is typically comprised of lead and steel [16]. Depending on the cable type and properties, cables can weigh 30-80 kg/m, with conductor cross-sections from 300 up to 3000 mm^2, and external diameters of 70-210 mm [16,18]. Modern applications of subsea cables for floating renewable energy devices have further dynamic design considerations regarding mechanical loading and the hydrodynamic environment, particularly with upscaling to HV cables [17,19,20].

Table 1. Overview of the different types of cables and properties deployed in the marine environment [16,21]. Modern subsea HVDC cables are typically bipolar, paper insulated or extruded cables. Note that HVAC cables often use three conductors and that power cables may incorporate fibre optic cables in the bundle.

Cable arrangements:	
DC Monopolar	Single-core cable with metallic or sea return Two single core cable with metallic or sea return Concentric cable
DC Bipolar	Two separate single core cables Two single-core cables bundled
AC separate cables	Three single core cables
AC single cables	Three conductors embedded in one cable
Cable types:	**Insulation options:**
Self-contained fluid filled cables	Self-contained fluid/oil filled (SCFF/SCOF) High pressure fluid/oil filled (HPFF/HPOF) High-pressure gas filled (HFGF)/Gas compression (GC)
Paper insulated (lapped)	Mass impregnated (MI)/Paper insulated lead covered (PILC) Paper polypropylene laminate (PPL)
Extruded cables	Ethylene propylene rubber (EPR) Polyethylene (PE) Cross-linked Polyethylene (XPLE)

Generally, in a perfectly grounded cable the shielding contains the emitted electric field component of the EMF, however the magnetic field is emitted into the environment [22]. HVDC cables emit a static magnetic field (Figure 1), whereas HVAC cables emit a time varying magnetic field, from which an induced electric field is generated [1]. For both AC and DC cables, an animal or water body passing through the emitted magnetic field (regardless of AC or DC), creates a motionally induced electric field (shown for a DC cable in Figure 1) [1]. The intensity of EMF from a cable (DC bipolar, bundled and AC single cable) decreases approximately as an inverse square of the distance from source; this attenuation is the same for a cable buried in the seabed, lying uncovered on the seabed or suspended in the water column (dynamic cables). Furthermore, the properties of the cable

shielding, the internal cable arrangement and the power transmitted (voltage applied) all influence the EMF emitted into the surrounding environment [23,24].

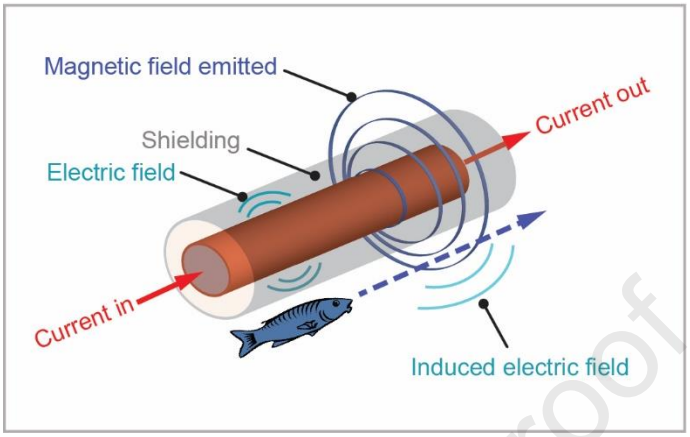


Figure 1. A simple representation of a subsea HVDC cable and emitted EMF. The electrical current passes through the cable conductor. The electric field is contained within the cable shielding, but the magnetic field is emitted into the surrounding environment. The motionally induced electric field arising from a fish passing through the emitted magnetic field is also shown. Single-core DC cables can be paired or bundled with another cable. Note that if the cable were HVAC, an induced electric field would also be emitted by the transmission of the electrical current. Adapted from [22].

The majority of subsea cables are bottom mounted. They may be laid on the seabed with hard protection (rock placement, concrete mattressing, tubular protections) or buried in the seabed, as a protective measure (e.g. from abrasion or third party damage) [25–27]. Regardless of the external cable protection, the cable will emit EMFs into the adjacent environment (Figure 1), within sensitivity ranges known to be perceptible by some animals [12,15]. While the primary function of burying a cable is to physically protect it [1], there are suggestions of added benefits as a mitigation measure for potential impacts on animals encountering the cable EMF. This may be stated within the documentation for environmental impact assessments. However, to be considered in the context of a potential environmental impact it is necessary to determine how the EMF emitted is influenced by the cable properties, the burial depth, and the distance of the receptive animal from the source.

Using previously defined and verified EMF models [28], we modelled the emissions from a HVDC transmission cable under different scenarios to explore the EMF environment likely to be encountered by receptive species. The HVDC cable studied offers (i) a real-world scenario for energy transmission between regions, (ii) a surrogate for high-capacity cables presently used to export energy from OWFs, and (iii) a future outlook for emerging MRE industries. To consider the influence of the cable arrangement, we assessed the degree of cable core separation within a bundled cable, on the level of EMF emitted. Then, with a constant cable separation, we modelled the influence of varying the burial depth on the EMF intensity emitted at the level of the seabed. Building contextual relevance applicable to environmental assessment of EMF effects and the management of MRE and power transmission industries, we provide conceptual interpretations of how EMF emissions may vary for the receptive species with regard to their distance from the cable and the variation in EMF along a cable route.

2. Methods

A model previously developed and verified was employed here using the commercially available COMSOL Multiphysics® software (hereafter, 'COMSOL model') [28]. The model and parameters used are described in brief, and readers are referred to Hutchison et al., (2020) for full details of the model and its empirical verification. Hereafter, we refer to the modelled DC magnetic field emitted from the HVDC cable as the 'DC-MF', deliberately differentiating from the EMF which is a broader reflection of electromagnetic field components in both the anthropogenic and natural context.

The model was built based on the properties of the subsea Cross Sound Cable (CSC) which is a 40 km HVDC domestic supply cable buried in Long Island Sound, USA (41.223563, -72.900229). The CSC is a bipolar cable which has two single-core cables bundled together. The highest nominal current was 1175 A (330 MW, 300 kV). This is comparable to the power transmission characteristics of a HVDC OWF export cable. The model was previously verified using *in situ* measurements of the EMF emitted from the CSC and the application of the model to a higher capacity cable was also verified (1320 A, 600 MW, 500 kV, Neptune Cable, New Jersey, USA). The COMSOL software modelled the DC-MF emitted from the CSC based on the physical details of the real-world environment, including the structural, morphological components, and material properties of the cable and the local geomagnetic field specific to the CSCs location (Table 2). This model was used to provide a detailed

and accurate prediction of the DC-MF at the level of the seabed and in the water column above the cable.

Within COMSOL, a Free Tetrahedral mesh was applied to the whole domain. The quadrilateral mesh consisted of 17952 domain elements and 1499 boundary elements with increased density close to the cables to accommodate the close-range variation in intensity. The permittivity Ɛ (F/m) and permeability μ (H/m) for each of the cable materials were derived by $\varepsilon=\varepsilon_r \cdot \varepsilon_0$ and $\mu=\mu_r \cdot \mu_0$ where ε_0 and μ_0 are the permittivity (8.8542×10^{-7} F/m) and the permeability ($4\pi\times10^{-7}$ H/m) of vacuum. For each cable material the relatively permittivity (ε_r) and relative permeability (μ_r) are reported in Table 2. Using the Cartesian coordinate system, the model was built where the x-axis orients to the northeast, the y-axis to the vertical direction of the earth and the cable lay on the z-axis. Within this local coordinate system, the geomagnetic field components, y corresponds to -47μT, and as calculated from vector decomposition, x corresponds to 10.6μT and z to -17.7μT. Therefore, the corresponding local geomagnetic flux density is $(B_x^b,B_y^b,B_z^b)=(10.6,-47,-17.7)\mu T$, and the background magnetic field is approximately 51.3μT. The magnitude of the total magnetic field was calculated by; $\|B_{tot}\|=\sqrt{(B_x^b+B_x)^2+(B_y^b+B_y)^2+(B_z^b)^2}$.

Using the 2D AC/DC module, the cable EMF was simulated using three equations. The magnetic field intensity (H) was used to derive the current density (J); $\nabla \times H = J$. The magnetic flux density (B) was derived from the magnetic vector potential (A); $B = \nabla \times A$. The current density (J) and magnetic flux density (B) could then be used to solve; $J = \sigma E + \sigma v \times B + J_e$, where σ is the electrical conductivity (Table 2), E is the electric field intensity, v is the velocity of the conductor and J_e is the externally generated current density. The equations were solved with a numerical iteration algorithm using a flexible generalised minimal residual method with a relative error tolerance of 0.001 and initial value of A = 0. The model converged and was used to produce baseline models of the EMF emitted from the CSC (Supplementary Figures 1 and 2).

Table 2. An overview of the layers of information incorporated in the COMSOL model. This includes the CSC properties and environmental characteristics for the base model as well as the electrical conductivity, relative permittivity, and relative permeability for each material. *Note that the standard distance between the bundled cables and the burial depth are provided as initially developed but were varied for the application in this paper.

Layers	Details	Electrical conductivity σ (s/m)	Relative permittivity ε_r	Relative permeability ε_0
HVDC cable*	Bipolar (bundled cable pair, separation distance 0.106 m)	-	-	-

Conductor	Copper, radius 0.053 m	5.8e7	1.0	1.0
Sheath	Lead, radius 0.041 m	1e6	1.0	1.0
Insulator	XLPE	0	2.3	1.0
Armour	Steel wire, thickness 0.01 m	1.1e6	1.0	1000
Water	Ocean, 35 ppt	1.0	81.0	1.0
Seabed*	Sediment, 1.5 m burial depth	0.24	25.0	1.0
Geomagnetic field	Vertical (47 μT), North (20 μT), East (-5 μT)	-	-	-

The COMSOL model was used to predict the DC-MF emitted, and how it varies due to (i) the separation distance between the two bundled cables and (ii) variable burial depth. Firstly, with a constant burial depth of 1.5 m, the DC-MF emitted at the level of the seabed-water interface was modelled with a cable separation distance varying between 0.106 and 0.689 m (centre to centre). Secondly, with a constant cable separation of 0.106 m, the DC-MF emitted at the level of the seabed-water interface was modelled for the CSC buried at depths varying from 0.6 to 1.8 m, in 0.2 m increments. In both cases, the DC-MF emitted at the level of the seabed-water interface is reported in terms of the corresponding maximal positive and maximal negative deviation from the local geomagnetic field of 51.3 μT (Supplementary Figure 1).

Lastly, to demonstrate the cable DC-MF emissions as they would be presented to a receptive species in the marine environment, two conceptual models were built. The first, demonstrates the fluctuation in the cable DC-MF intensity that an animal may experience moving along a cable route, at the level of the seabed-water interface. The second demonstrates the change in DC-MF exposure that a receptive animal would experience with increasing distance from the seabed using the computed model (Supplementary Figure 1 and 2).

3. Results

An asymmetry in the DC-MF on either side of the cable occurred (Supplementary Figure 1) due to the asymmetrical convolution with Earth's magnetic field, and for this reason, the maximal positive and negative deviations from the local geomagnetic field for each scenario are reported as the magnetic flux density.

3.1. Cable Separation Distance

In the baseline model the two bundled cables were placed in the horizontal plane and as a result the positive deviation in the DC-MF on one side of the cable was larger than the negative deviation on

the other side of the cable (i.e. asymmetrical, see Supplementary Figure 1). In subsequent models under the different scenarios, this relationship is maintained. The positive and negative deviations in the DC-MF are proportional to the separation distance between the two bundled cables (Figure 2a & b). The magnitude of the DC-MF increased for both the positive and negative deviation, as the distance between the bundled cables increased. However, the magnitude of change is different. For example, comparing a cable separation of 0.106 and 0.160 m, the positive deviation (Figure 2a) changes from 22.7 to 29.5 µT which is a 6.8 µT difference, whereas the negative deviation (Figure 2b) changes from -3.0 to -3.8 µT which is a 0.8 µT difference.

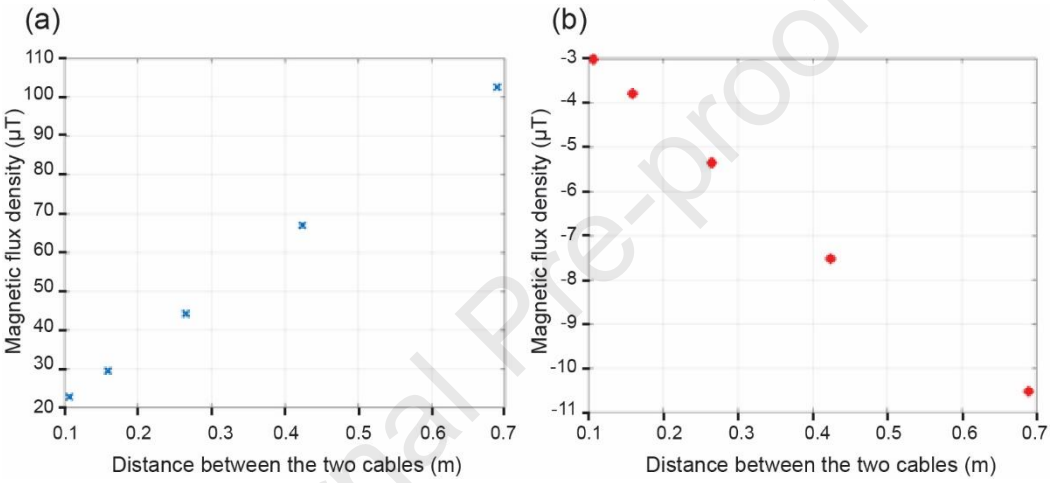


Figure 2. Influence of the separation distance between bundled cables on the DC magnetic field. The positive (a) and negative (b) deviation from the local geomagnetic field, as influenced by the degree of separation between bundled cables (centre to centre). The emitted DC-MF is reported as the magnetic flux density.

3.2. Variation in Burial Depth

The model of the DC-MF at the level of the seabed-water interface, with constant cable parameters but variable burial depth, demonstrates a decreasing magnitude of DC-MF emission as the burial depth increases (Figure 3a & b). The relationship is similar for both the positive and negative deviation from the geomagnetic field; an increase in burial depth reduces the maximum intensity of the distortion but again, the magnitude of change is different. For example, comparing a burial depth of 0.6 and 0.8 m, the positive deviation (Figure 3a) changes from 93.2 to 52.0 µT which is a 41.2 µT difference, whereas the negative deviation (Figure 3b) changes from -9.4 to -6.1 µT which is

a 3.3 µT difference. The DC-MF is undisturbed by the sediment properties, in both the water column and in the sediments, since the sediment is non-magnetic.

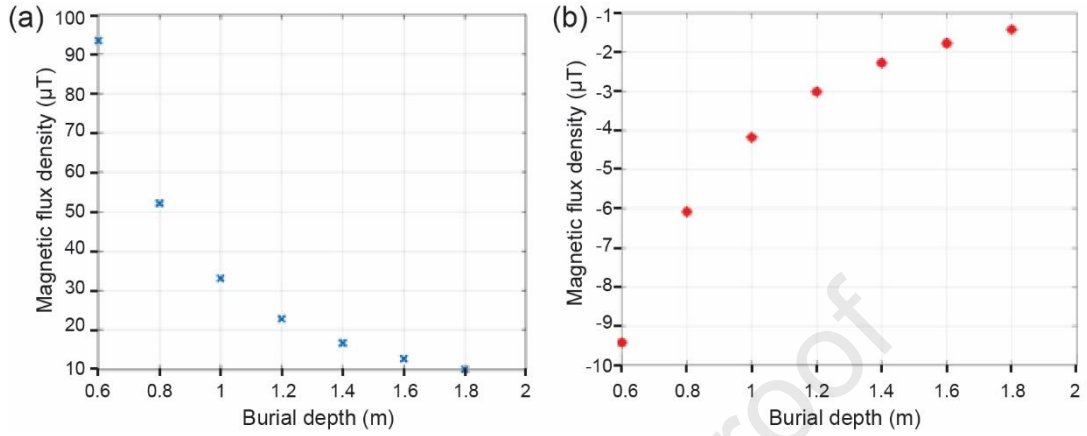


Figure 3. The influence of burial depth on the DC magnetic field. The positive (a) and negative (b) deviation from the geomagnetic field, as influenced by the burial depth of the cable. The emitted DC-MF is reported as the magnetic flux density.

3.3. Interpretive Models of the DC-MF Presentation to a Receptive Species

Many receptive species are mobile entities, and their movement plays a role in the EMF intensity they will be exposed to. To demonstrate the cable DC-MF emissions as they would be presented to a receptive species in the marine environment, the baseline models (Supplementary Figure 1 and 2) with a constant bundled cable separation of 0.106 m and burial depth of 1.5 m, were used to build interpretive models. These models report the total magnetic field (geomagnetic field plus the maximal positive distortion).

The first scenario incorporates the third dimension and demonstrates the emitted DC-MF intensity that an animal may experience moving along a cable route. Figure 4 demonstrates the fluctuation in the emitted DC-MF intensity at the level of the seabed-water interface. The emitted DC-MF is depicted as the total magnetic field with the assumption of a stable geomagnetic field (51.3 µT).

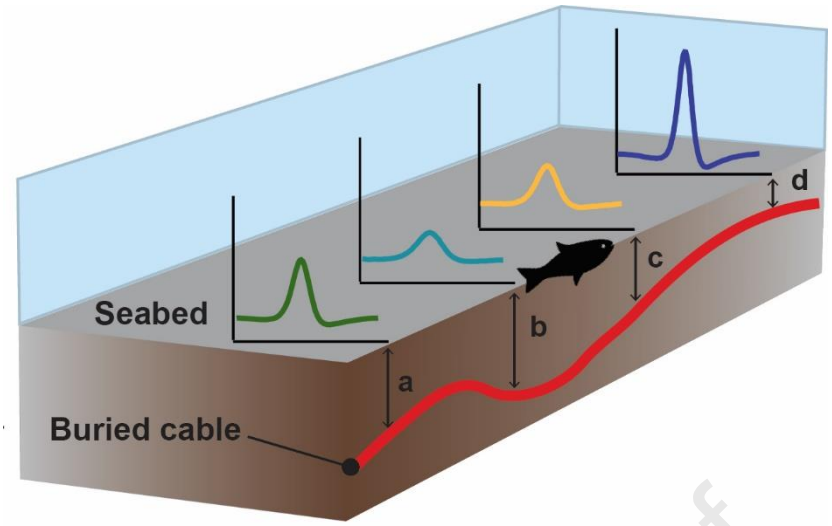
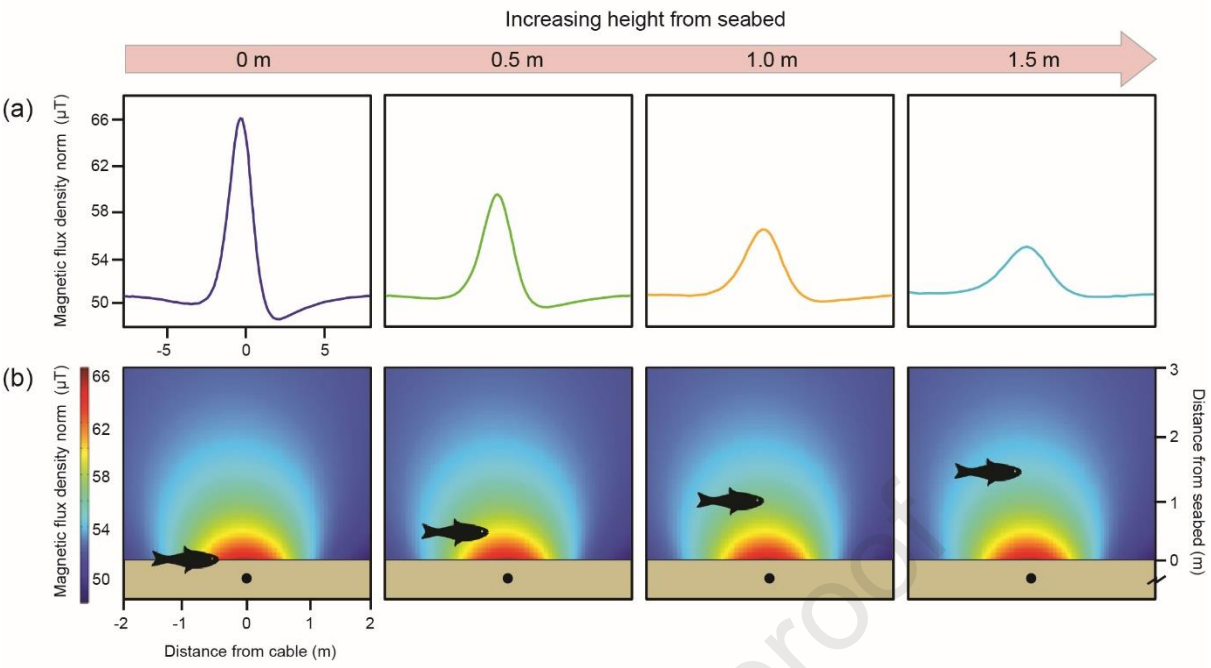


Figure 4. **Exposure of a receptive species to the emitted DC magnetic field, relative to the animal's movement along a cable route.** The cable burial depth may vary along a cable route due to different burial depths. For a species moving along the seabed, the variable burial depth of the cable, changes the distance from source and exposes the animal to variable DC-MF intensities. Burial depths depicted are approximations and not to scale; (a) 2.0 m, (b) 3.0 m, (c) 2.5 m, (d) 1.5 m.

The second interpretative model considers the vertical movement of the receptive species in the water column directly above the buried cable. Figure 5 demonstrates an animal positioned at the seabed-water interface and then at increasing distances above the seabed, in 0.5 m steps. Where the animal is positioned at the seabed-water interface, the animal would experience the maximum emitted DC-MF intensity possible in this scenario, which is 14.7 µT, a total field of 66 µT (Figure 5, first panel). The animal cannot get closer to the cable due to the physical barrier provided by the seafloor and is a total of 1.5 m from the cable. As the animals moves further into the water column, the animal is still exposed to the DC-MF. Even at 1.5 m above the seabed, which is a total of 3 m from the cable, the animal is exposed to a DC-MF within the sensitivity range known to be perceptible by some animals. The change in the horizontal spatial extent of the emitted DC-magnetic field can also be observed in Figure 5.



278

279 **Figure 5**. **Exposure of a receptive species to the emitted DC magnetic field, relative to the animal's**
280 **position in the water column.** The total magnetic flux density norm (cable DC-MF plus geomagnetic
281 field) is shown as a line graph (a) and as a density distribution (b), with increasing distance from the
282 seabed moving from left to right. The cable was buried at 1.5 m in the seabed and the local
283 geomagnetic field was 51.3 μT. The fish is representative of any receptive species and is not to scale.

284

285 ## 4. Discussion

286 The planned expansion of the marine renewable energy (MRE) industries and the need for energy
287 transfer between regions will increase the prevalence of electromagnetic fields (EMFs) emitted by
288 subsea cabling in coastal and offshore waters [2,3,6]. Presently, high voltage alternating current
289 (HVAC) cables are the most prevalent MRE cable type, with fewer high voltage direct current (HVDC)
290 cables in use for OWF energy exports [6]. With technological advancements, greater power
291 production and increasing distances from shore, a move towards the increased use of HVDC is
292 expected [6,29]. While this is a present scenario for OWFs, it is a future outlook for emerging
293 industries such as wave and tidal stream energy conversion. With greater cable deployment the
294 potential for marine species to encounter cable emitted EMFs rises. Although the potential
295 consequences of EMF encounters remain poorly understood for the subsea cables [4,5], there is
296 growing evidence that marine species can respond to cable EMFs [28,30,31]. There have been
297 suggestions that burying a cable will negate potential effects in animals encountering cable EMFs. In
298 response to this knowledge gap we modelled the EMF using data from an existing bundled HVDC

transmission cable (the Cross Sound Cable, CSC, Long Island Sound, USA) to investigate the influence of cable separation distances and the relationship between cable burial and a receptive species.

An asymmetrical total field resulted from the superimposition of the three-dimensional cable emitted DC-MF field on the three-dimensional geomagnetic field [28]. The modelling demonstrated that the change in magnitude of the asymmetrical DC magnetic field (DC-MF) was proportional to the separation distance between the bundled cables. At the maximum burial depth modelled (1.8 m), the DC-MF remained present at the level of the seabed. With increasing burial depth, the magnitude of the DC-MF was shown to decrease, with both positive and negative deviations from the local geomagnetic field. To contextualise the modelling regarding a receptive species encounter with cable EMFs, we demonstrated the change in EMF intensity that an animal on the seabed may experience when moving along a cable route with varying cable burial depths. We further demonstrated that the EMF encountered by a receptive species, varies with the animal's proximity to the cable, which is determined by both an animal's position in the water column and the cable burial depth. Our results highlight the importance of understanding how the cable characteristics influence the EMF emitted as well as the context of how an animal may encounter a cable EMF.

4.1. Cable Properties Influence the Emitted EMF

The separation distance between cables bundled together is one example of how cable properties will influence the emitted EMF. Each cable current generates a stationary magnetic field and if perfectly overlapped, the magnetic fields will cancel each other. For the CSC, bundling the cables did not result in DC-MF cancellation. However, cables bundled closer to each other reduced the magnitude of the DC-MF for both the positive and negative deviation from the geomagnetic field indicating a degree of cancellation (Figure 2). For bipolar cables in general, spatial arrangements of cables may vary due to the way that cables are bundled together, or due to different cable external diameters [16]. Closer spatial arrangements may reduce the deviation from the geomagnetic field, but the variable shielding would need to be considered in models of other cables (Table 1). The properties of shielding used in a cable may further influence the emitted DC-MF (permittivity, conductivity and permeability [23,24]) or additional armour where the cable is required to withstand mechanical stress [27]. The extent of cable separation modelled in this paper (0.689 m maximum, Figure 2) exceeds what is likely for bundled cables. In scenarios where bipolar cables are deployed as two individual cables, the degree of separation is broader owing to water depth and allowing cables to be safely accessed in the event of cable fault or maintenance [26,32]. Other cable properties which influence the EMF emitted from a bundled cable is the rotation of the cable pair as they are deployed into or onto the seabed and the orientation of the emitted EMF to the

geomagnetic field [28]. Additionally, three-core AC cables have magnetic fields that are 120^{o} out of phase and emit a rotating induced electric field into the environment [24]. Furthermore, helically twisted AC cables, reduces the magnetic field generated and therefore the induced electric field, compared to three straight concentric conductors [33].

4.2. Cable Burial Does Not Eliminate the Emitted EMF

The model of the CSC showed an increasing intensity of DC-MF at the seabed surface with shallower burial depth (i.e. closer proximity to the source) (Figure 3). Bottom fixed cables are buried for their protection from abrasion, fishing activities and other maritime use of the area [27]. The techniques used for burial (e.g. jetting, ploughing, cutting) and depths of burial obtained are dependent on the seabed type and the type of fishing activity in the area [34]. A Burial Protection Index takes account of these factors and guides the most suitable burial depth [27,34,35]. However, a balance of mitigating risk to the cable and achieving economical burial may result in variable target burial depths [27](e.g. deeper burial in a shipping lane). The realised burial depths may also vary owing to the seabed properties (e.g. geological deposits unknown at the planning stage) in which case the installation process adopts the principles of reasonable endeavour, distinguishing between minimum and target burial depths [27]. Once buried, natural erosion may reduce the burial depth or may expose portions of the cable [35], leading to further variation in burial depths along a cable route.

Variable burial depth along a cable route results in a changing intensity of EMF experienced by a receptive animal on the seabed (Figure 4). Species may encounter cable EMFs each time they cross over the cable route or they may follow the cable route. The change in EMF intensity is a function of distance from source. Therefore, while we explain the EMF variation due to different burial depths, a change in proximity to the cable may also result from other cable protections used, even along the same cable [5,27]. For example, the Wave Hub (UK) 25 km export cable is buried in soft sediment within 7 km of shore, and beyond that has rock armouring (0.3 m deep) with concrete mattressing at 120 m intervals [36]. The Paimpol-Brehat tidal test site (France) similarly has 4 km of buried cable close to shore and 11 km of unburied cable protected with concrete mattressing (0.3 m deep blocks) at approximately 50 m intervals [37]. In both cases, the maximum increase in distance from the EMF source due to the unburied cable protection is 0.3 m. Furthermore, the protection provides hard substrate to be colonised by species and structural heterogeneity offering crevices for animals to live in [36,37], which may increase the likely encounter of EMF and allow animals to get closer than 0.3 m from the cable. This highlights that the animal's proximity to the cable, regardless of protection is a key factor in their exposure to EMFs (Figure 5). The frequency of an encounter, i.e. the encounter rate, is also important in the context of cumulative effects. Laboratory studies of

exposure to electric fields have shown the capacity of a receptive species to learn, habituate and retain only short-term memory of experiences [38]. This observation implies that reinforcement is required for an experience to be memorised for a longer period and if MFs are variable due to variable protection and an animal's proximity to the cable, longer term memory of an encounter may not be supported.

Spatial configurations of cables are also important in the context of an animal's encounter. The movement of animals within an array of MRE devices may provide further variation in the encountered EMF due to varied cable size and increasing power generation between interconnected devices [39]. In the case of offshore wind arrays, inter-array cable configurations (topology) may be radial, star or loop designs and future optimization, required due to growing capacity arrays, may consider the topology as well as cable size and number of substations to minimise power losses and installation expenses [40,41]. Furthermore, arrays of floating wind or suspended wave and tidal devices introduce unprotected dynamic cables into the water column [17,19,29], presenting EMFs to pelagic species. Such EMF scenarios experienced by benthic and pelagic species, may become more complex with the advancement of co-location and multi-use platforms [42]. Furthermore, multiple arrays in a region may have export cables which cross paths, share a common cable corridor, or energy collection platforms/systems may be used facilitating connection to the grid through a common higher capacity cable [5].

4.3. Understanding Animal Interactions with EMFs

When considering cable EMFs it is important to take account of movement ecology for both benthic and pelagic species as the likely encounter of a cable EMF may change during the lifecycle of the receptive species [5]. For buried cables, the proximity of an animal to the seabed is a contributing factor to the distance from source and will influence the intensity of EMF the animal is exposed to (Figure 5). For example, demersal species often swim in the water column and pelagic species may come into contact with the EMF owing to their use of seabed habitats [5]. Important use of benthic habitats by pelagic species are exemplified by herring spawning on coastal gravel beds [43] and cod using benthic feeding grounds [44]. The movements between pelagic and benthic zones may change by the hour, day or over the longer term, such as seasonally. Use of benthic habitats varies throughout a species lifecycle as can the perception and/or ecological relevance of natural EMF cues which are in the same range as cable EMFs [12,15]. For example embryonic skates and rays can detect bioelectric cues from predators facilitating survival and later, as mature adults bioelectric cues are used to forage and find mates [45,46]. In the Caribbean spiny lobster (*Panulirus argus*), demonstrated to use the geomagnetic field in homing [14], a similar developmental shift in

responses to magnetic fields has been proposed [47]. Salmonids and anguillids also use the geomagnetic field to orientate during early life-history and adult migrations [48–50]. Since species obtain cues from natural EMFs differently at different stages of their life, it is reasonable to expect that their responses to cable EMFs may also differ.

Cable EMFs may interact with important natural cues obtained from small-scale changes in the local geomagnetic field. For example, local geomagnetic imprinting has been shown in sockeye salmon (*Oncorhynchus nerka*) and it is proposed that they use the small differences in geomagnetic intensity as an environmental cue during homing to their natal rivers for spawning [50]. Gradual drift of the geomagnetic field with annual differences ranging from 138 to >200 nT influenced the diversion rate of migrating salmon [50]. Similarly small-scale changes in the geomagnetic field intensity (4.9%) and inclination angle (3.0%) have been demonstrated to influence the orientation of juvenile European eels (*Anguilla anguilla*) [51], and elasmobranchs were able to detect and respond to artificial field gradients ranging from 25 to 100 µT, relative to an ambient field of 36 µT [52]. These studies highlight that very low intensity changes in the geomagnetic field used by animals, can be both positive and negative. For the CSC modelled here, the EMF was an asymmetrical field with variable positive and negative deviations from the geomagnetic field. The relationships between burial depth and the positive and negative deviation of the DC-MF were not linear and furthermore the total intensities experienced by an animal, differ with their proximity to the cable. Despite a lower intensity EMF at greater distance from the cable, the change from the ambient geomagnetic field, which may be a higher or lower total field, may still present distortions of the local geomagnetic field that species respond to. For example, in Figure 5, at 1.5 m above the seabed (3 m from source) the magnetic field changes by approximately 3 µT (3000 nT) and is within the expected perceptive range of a receptive species. Aside from the change in EMF intensity, orientation of the cable to the geomagnetic field and potential distortion of the inclination should be a further consideration. There is growing evidence that species may be responsive to the angle of inclination of the geomagnetic field (e.g. turtles [53,54], salmon [50,55], eels [56], elasmobranchs [13]) and feasibly may be responsive to the angle of declination [11]. It is important that we take the vantage point of the receptive species to understand how species perceive the EMF environment and how cable EMFs may change the cues ecologically important in the acquisition of food, survival and reproductive success [5].

4.4. The Need to Consider EMF Cumulative Effects

Energy transmission is a major component of MRE developments [57], applicable to fixed and floating devices and multi-platform or co-location designs (e.g. [42]). Presently, EMF emissions are

considered in the planning and licensing/permitting process as a potential operational environmental impact. Cumulative impacts, where combined incremental effects (which may be considered minor alone) pose a greater likelihood of impact on marine life are also considered [58]. Concerns regarding cumulative EMF impacts will increase with the growth of MRE industries and a greater prevalence of energy generation and power transmission in the sea. Action now, in the form of data availability, EMF model verification with empirical measurements and targeted research on species effects and impacts, will support the development of these industries at larger scales in future.

Concerns regarding EMF impacts are typically scoped out at an early stage, often stating that the cable will be buried (inferred as mitigation), and the emitted EMF is modelled to be below the geomagnetic field (25 to 65 μT) or nearly cancelled due to cable properties. However, the models demonstrate that EMF emissions are not eliminated by cable burial (Section 4.2). Furthermore, our knowledge has advanced to determine that species respond to very low intensity changes (i.e. nT-μT) and inclination of the geomagnetic field (Section 4.3). We now have empirical measurements of EMFs in similar ranges from buried cables [28,59], including those that are considered to have a degree of self-cancellation [60]. Empirical evidence of species responding to cable EMFs also exists [28,30,31]. Based on such modern evidence, it is not appropriate to dismiss the EMF emissions as being below background levels, the interaction of the cable emitted EMF and local geomagnetic field must be considered, together with physical variations along cable routes and temporal variability in energy transmission. The present knowledge base available to determine if there is an impact on species is lacking both in terms of the characterisation of EMFs (physical) and how species respond to them (biological/ecological) [5]. The evidence indicates that EMF should be explored further, and be a cumulative impact consideration for future large-scale developments, particularly where multiple cables occur in a given region [61].

Modelling is a standard approach for determining the EMF emissions from AC and DC cables [62]. However, models are 2D idealised scenarios which are rarely supported by empirical in situ measurements. The model used in this study is also a 2D scenario of the DC-MF emitted from the CSC and while demonstrated to be representative of the DC-MF, it is known to be an underestimate and oversimplification of the full EMF emissions. Empirical measurements of the CSC revealed different shape signatures of the emitted DC-MF along the cable route due to the interaction with the geomagnetic field, and unexpected AC fields (magnetic and electric) were associated with the DC CSC and other DC cables [28]. Yet, the application of the model in this study was suitable for analysing the emitted DC-MF under the different scenarios selected. While empirical measurements of deployed subsea cables are essential to improve the knowledge base, they would likely be

considered an excessive burden on developers [63], particularly where there is no standardised methodology for measuring and reporting EMFs [4,5]. Laboratory measurements may provide verifications for some aspects relating to operational cable properties in the absence of environmental influences. To reduce uncertainty about the environmental impact of EMFs and to validate the knowledge from modelling, a combined approach is needed and is reliant on data availability. Models can be applied to more contextually relevant, realistic scenarios which better inform on the likely EMFs emitted and verified through empirical measurements of EMFs from different cable types, orientations and configurations. Relevant cable property information and temporal energy transfer data being readily available and accessible would facilitate these goals. Subsequently, a fuller understanding of the EMFs presented to species will follow enabling improved assessments of environmental effects and impacts. This approach will either inform us that the risk can be retired (*sensu* [61]) with a degree of confidence for cable scenarios or that appropriate mitigations are necessary, ultimately reducing future barriers to development.

5. Conclusions and Recommendations

This study demonstrates the need to consider cable properties and the position of the cable in the environment (including burial) with respect to how the emitted DC-MF is presented and encountered by receptive species. We focused on a bipolar bundled HVDC cable since they are representative of modern installations and are expected to become more common in future [6,21,29]. However, the model presented only addressed the DC component of the emitted EMF and through empirical measurements of the CSC cable and others, it is known that AC fields may be associated with HVDC cables, extending greater spatial ranges than the DC magnetic field [28]. Going forward, models should be expanded to include all aspects of the EMF (DC and AC, magnetic and electric fields) which would be better informed by empirical characterizations [1]. Greater contextual relevance of the EMF presented to receptive species could also be obtained by incorporating temporal changes in the power transmission [28] and variability of the cables position in the marine environment. This approach is of particular importance as fixed and dynamic cables become more frequent and present EMFs at different orientations within the water column and/or as more advanced configurations in the marine environment [17,40]. Incorporation of these recommendations into future EMF models would improve their contextual relevance, further supporting assessments of the potential effects of receptive species however, this must be coupled with a better understanding of how a receptive species may encounter and respond to cable EMFs [5].

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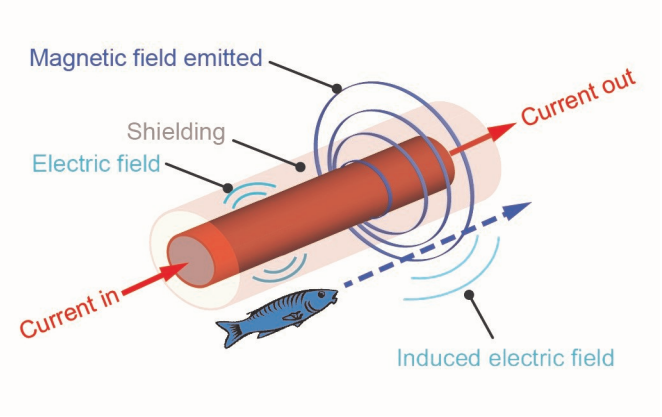
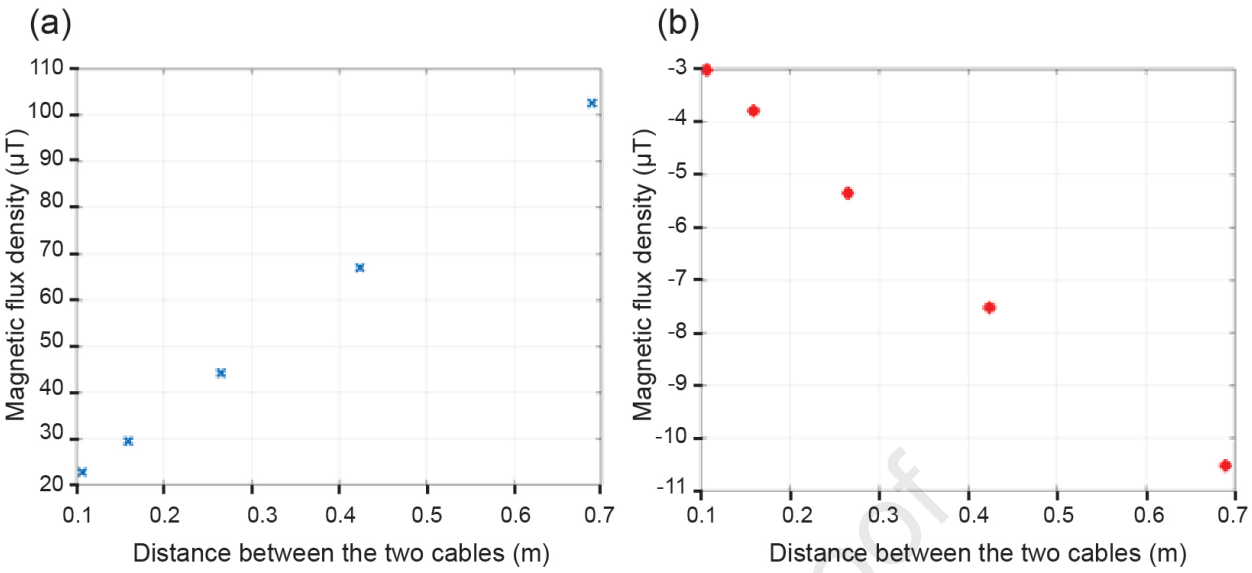
Acknowledgements

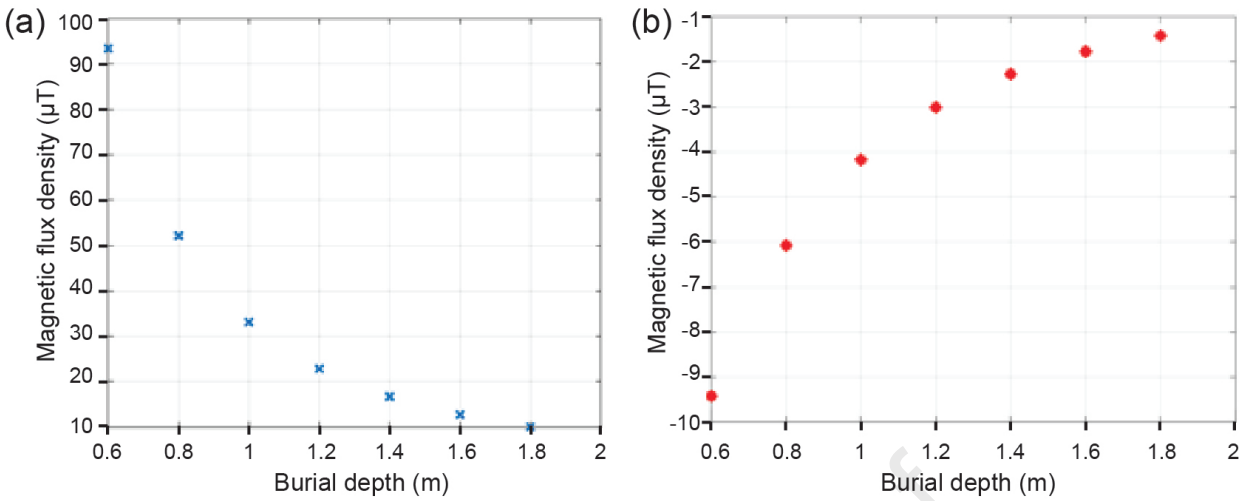
Part of this work was supported by the Bureau of Ocean Energy Management (contract number M14PC00009). We thank He Jiang and Yufei Tang (URI) for assistance with modelling and Carol Gibson (URI) for assistance with graphics. We thank the Guest Editors for the invitation to submit an article to this Special Issue.

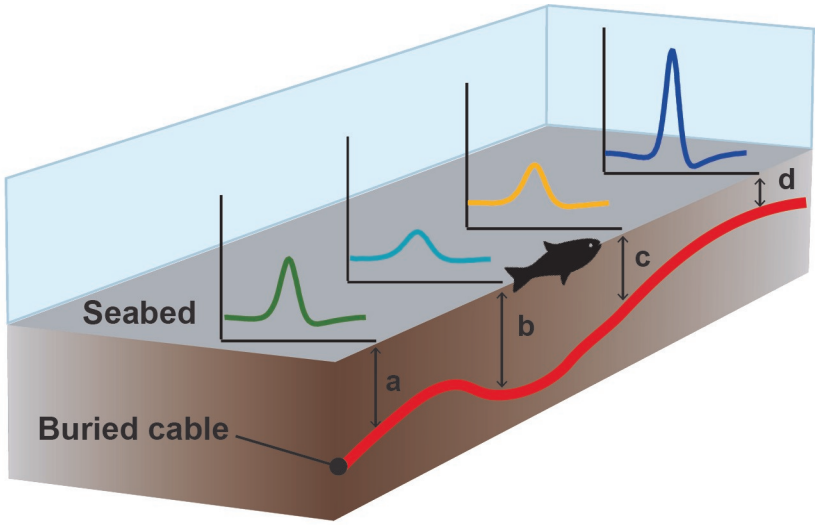
CREDIT statement

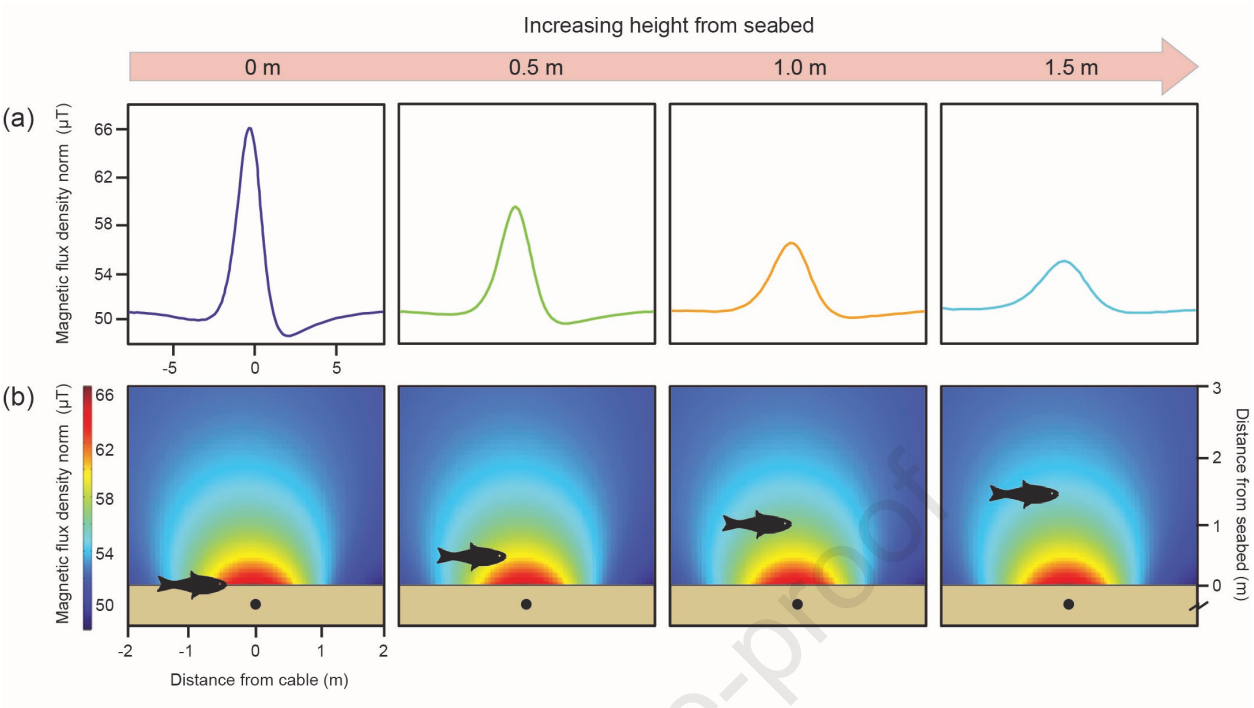
ZLH: Conceptualisation, writing - original draft, interpretive modelling. ABG: Conceptualisation, interpretative modelling, writing - review & editing. PS: Interpretative modelling, writing - review & editing. HH: Computational modelling, writing - review & editing. JWK: Supervision, funding acquisition, project administration, writing - review & editing.











Highlights

1. In a bundled DC cable, closer cable cores reduced the emitted DC magnetic field (DC-MF) intensity
2. As a cable's burial depth increased, the intensity of DC-MF at the seabed surface decreased
3. Buried cables still present a DC-MF at intensities perceivable to some receptive species
4. Variable burial depth along a cable route will present a variable EMF to receptive species
5. An animal's proximity to a cable (buried or not) influences their exposure to the EMF

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: