East Anglia
Offshore Wind

VATTENFALL

SCOTTISHPOWER
RENEWABLES

East Anglia THREE

Appendix 9.2

Electromagnetic Field Environmental Appraisal

Environmental Statement
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1. This appendix contains a report written by CMACS providing a literature of expected electromagnetic fields (EMF) from sub-sea cabling associated with the East Anglia One Offshore Wind Farm.

APPENDIX 9.2 Electromagnetic Field Environmental Appraisal

Centre for Marine and Coastal Studies Ltd

EAST ANGLIA ONE OFFSHORE WIND FARM: ELECTROMAGNETIC FIELD ENVIRONMENTAL APPRAISAL

Assessment of EMF effects on sub tidal marine ecology

Client: Vattenfall and Scottish Power

Document: J3184 East Anglia EMF report v2

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1.0	02/12	Internal Draft	JAK	IGP	IGP
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Executive Summary

The following report relates information from research and literature review on expected electromagnetic fields (EMF) from sub-sea cabling associated with the planned East Anglia One Offshore Wind Farm with current understanding of the potential effects of such EMF upon marine organisms.

There are a number of cabling designs being considered, including both alternating current (AC) and direct current (DC) cables of different voltage ratings. Alternating current cables are most likely to consist of three-core technology, although there is a small possibility that single-core cables might be used (likely deployed in trefoil but possibly separately). Direct current cables will be bipole systems, whereby current is transmitted along two separate cables in opposite directions, with bundling of the two cables the most likely deployment method, although there is a small possibility that they may be separated. Tentative predictions of estimated EMF expected to be generated by each cable design and deployment are included.

The current flowing through the cables generates a magnetic (B) field, which constantly changes with AC cabling, but is static with DC cables. B fields are expected to attenuate rapidly with distance from cables. Bundling single-core AC and bipole DC cables reduces B field generation owing to cancellation effects of similar fields transmitted along adjacent cables in opposite directions. Electric fields generated by the cables directly will be shielded and not emitted to the environment. However, electric fields may be induced (iE fields) by the movement of B fields generated by AC cabling through seawater, and by tidal flow or marine fauna moving through the B field generated by DC cabling. Owing to their dependence on B fields, these iE fields are also expected to attenuate rapidly with distance from the cables.

Review of the literature reveals a large number and wide variety of organisms that are sensitive to electromagnetic fields (EMF). The main concerns relating to B field emanation are potential impairment of navigation and physiological effects. The main concerns relating to iE field emanation are potential repulsion, confusion with bioelectric fields and physiological effects. Research into electromagnetically sensitive species and their interactions with anthropogenic EMF is ongoing and at an early stage, but cautious assessment of potential effects of EAONE EMF upon marine fauna has been undertaken.

No effects are expected for either B or iE fields upon marine flora or micro fauna, nor marine mammals and chelonians. Marine invertebrates are expected to be unaffected by iE fields, but may potentially be affected by B fields (navigation and/or physiology). Teleost fish may potentially be affected by both B (navigation and/or physiology) and iE fields (navigation). Elasmobranchs are highlighted as potentially the most vulnerable taxa, owing to their acute sensitivity to EMF and their use of electro-sense for prey detection, predator avoidance, mate location, in addition to orientation and migration. B fields have potential to affect their navigation, while iE fields have potential to cause confusion (weaker fields) or avoidance (stronger fields). Most effects are, however, expected to be minor and temporary, occurring only within close proximity of the cables.

Burial of cables is proposed, where possible, to a depth of 0.5 to 5m, which will reduce potential effects of EMF upon marine fauna. Where burial is not possible (e.g. where cables cross pre-existing cables or over harder substratum), covering with rocks or mattresses will be undertaken.

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1. Introduction

Having been awarded a licence by the Crown Estate to develop a total of approximately 7,200MW of wind capacity under the Round 3 Offshore Wind Licensing Arrangements, Scottish Power Renewables (SPR) and Vattenfall Wind Power Limited (VWP) have formed a joint venture, East Anglia Offshore Wind Ltd (EAOW), to develop the East Anglia zone with six 1,200MW projects. The first of these projects will be the East Anglia ONE Offshore Wind Farm (EAONE).

Centre for Marine and Coastal Studies Ltd (CMACS) has been contracted by EAOW to provide advice on the likely environmental impacts of magnetic and electric fields generated by the subsea cable network associated with the proposed EAONE wind farm upon marine fauna. This work forms part of a wider Environmental Impact Assessment.

Anthropogenic (i.e. human produced) magnetic and electric fields are of interest in the marine environment since a relatively large number of marine species are sensitive to magnetic and/or electric fields and adapted to utilise naturally occurring fields as environmental cues. If artificial fields are present and detected by marine organisms there is potential for environmental effects.

Research into possible interactions between marine fauna and anthropogenic electromagnetic fields (EMF) is at an early stage and uncertainties remain. Hence, there are no specific limits imposed on subtidal EMF generation from a marine biological perspective (in contrast to emissions in the terrestrial environment). However, fields of the magnitude anticipated from submarine power cabling have been both modelled and, in limited situations, measured. They have also been demonstrated by experimental studies to lie within the sensitivity ranges of a variety of marine organisms (CMACS 2003; Gill *et al* 2009). In view of this overlap, and given the burgeoning UK offshore renewable energy industry and the related expansion in offshore grid connections, there is concern that potential effects should be considered (Gill 2005; Gill & Kimber 2005; Ohman *et al* 2007; Sutherland *et al* 2008); especially bearing in mind that many electromagnetically sensitive species are also commercially exploited (e.g. salmon, thornback rays), with some having suffered severe population declines in recent decades (e.g. skates and rays: Baum *et al* 2003; Myers & Worm 2003). Accordingly, regulators, key consultees and statutory advisers are keen to ensure EMF is considered, as far as possible, during the planning, construction and operation phases of offshore grid connection projects and offshore renewable energy developments.

To date, the majority of assessments of EMF generation in the marine environment have concerned 50 Hz alternating current (AC) cables used extensively in the relatively small, inshore, Round 1 wind farms. These assessments largely drew upon industry research supported by the Collaborative Offshore Wind Research into the Environment (COWRIE) charity. As demand upon the UK transmission network and associated supporting infrastructure increases, and as offshore wind farms become larger and are installed further offshore (Rounds 2 & 3), high voltage direct current (HVDC) cables are increasingly being proposed, especially given recent improvements in cabling technology increasing financial viability. The nature of EMF emissions generated by AC and HVDC cables, and resultant magnetic and electric fields in the marine environment, differ; hence environmental considerations including the potential responses of organisms to the resultant environmental fields cannot be assumed to be comparable according to current understanding. Key differences between EMF emissions associated with AC and HVDC cables are discussed in Section **4**.

2. Project description

2.1. Overview

The proposed EAONE site and offshore export cable corridor are shown in **Figure 1.** The array area lies between approximately 50 and 70km off the coast of East Anglia (in the region of Aldeburgh and Lowestoft). The export cable corridor runs in approximately a south-westerly direction from the array area to a landfall north of Felixstowe. Onshore cables will then be required to connect the offshore turbines to an onshore converter station adjacent to the existing substation at Bramford, Suffolk.

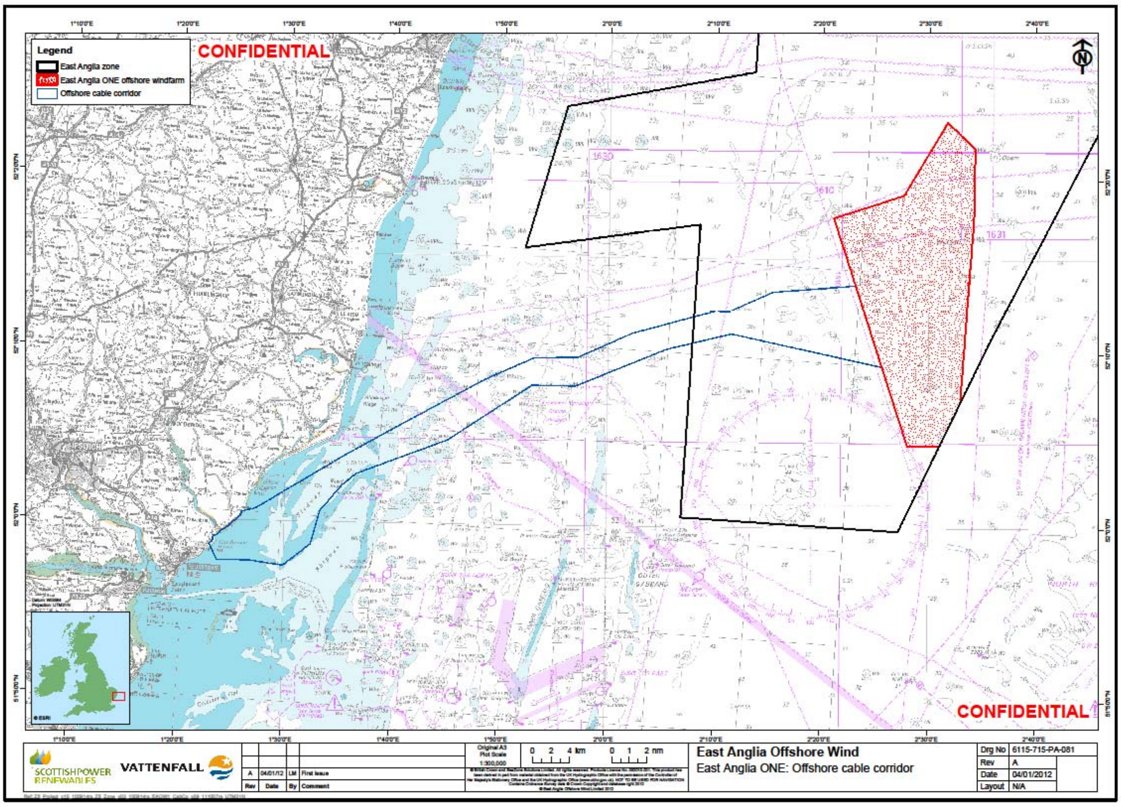

Figure 1. Proposed East Anglia ONE offshore wind farm site and offshore export cable corridor

In order to connect the wind turbines to the national grid network, a system of three different subsea cable types will be utilised: alternating current (AC) array cables to link up the turbines with offshore collector stations; high voltage alternating current (HVAC) export cables to feed power from the collector stations to an offshore converter station; and high voltage direct current (HVDC) export cables to transmit the power to shore. There are two main options currently being considered for EAONE):

Option 1 (minimum cabling; Figure 2):

- 2 x offshore collector station
- 1 x offshore converter station
- 4 x HVAC – each 15km long – total of 60km
- 2 x HVDC – each 100km long – total of 200km
- Array AC – total of 160km

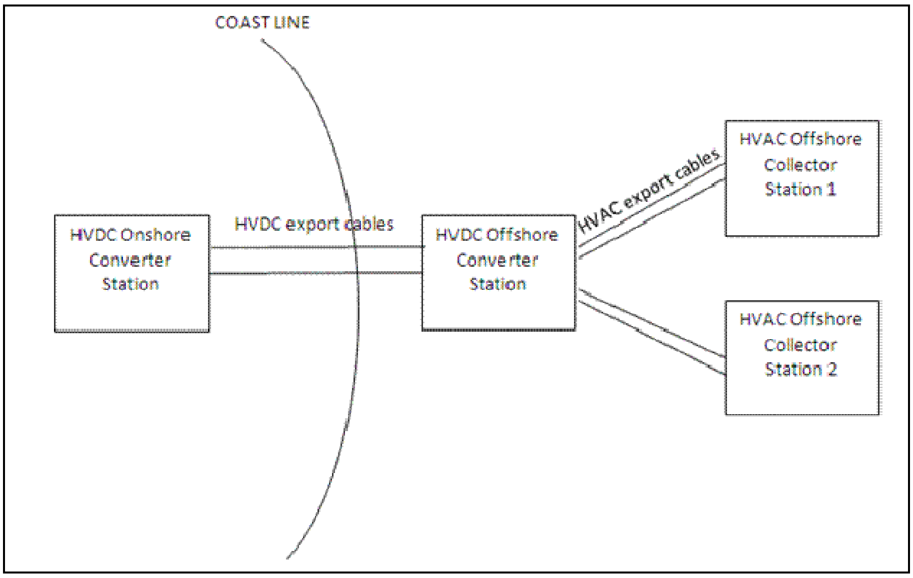

Figure 2. Development plan entailing least amount of cabling

Option 2 (maximum cabling; Figure 3):

- 3 x offshore collector stations
- 2 x offshore converter stations
- 13 x HVAC – each 15km long – total of 130km
- 4 x HVDC – each 100km long – total of 400km
- Array AC – total of 550km

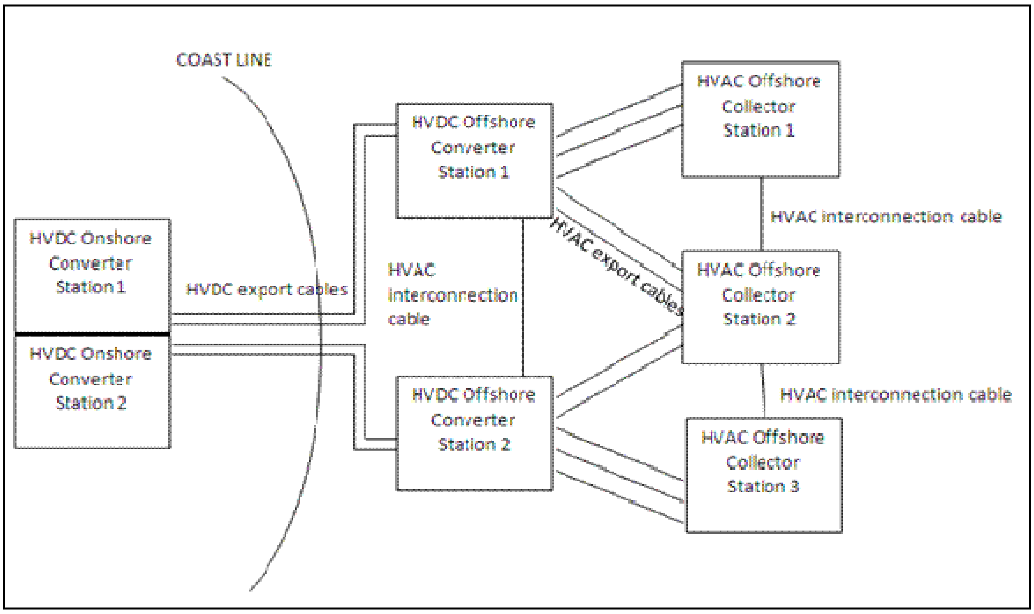

Figure 3. Development plan entailing most amount of cabling

2.2. Cable specifications

3. Array cabling is proposed to consist of 50Hz, dry or wet XLPE insulated, three-core alternating current designs, which have been used extensively at the majority of existing Round One and Two offshore wind farms. They will be rated between 33kV and 75kV, and measure between 104mm^2 and 154.4mm^2 cross-sectional area, depending on electrical load to be carried (see Appendices

Appendix 1 for typical design).

HVAC export cabling is also proposed to consist of 50Hz, dry or wet XLPE insulated, three-core alternating current designs. Cables will be rated between 132kV (825A current load and 1000mm^2 cross-sectional area) and 220kV (825A and 1000mm^2). Many existing wind farms utilise this design, but have generally been limited to 132kV; cables rated at 220kV have only recently been developed and are currently being applied for the Malta-Sicily Inter-connector (due in 2013). Alternatively, there is a small possibility that single-core cables, possibly laid separately but more likely close together in trefoil (a triangular formation), and rated at 275kV (also 825A and 1000mm^2) will be used to connect the converter stations. The latter variation depends on cable and installation technology being suitably developed in time.

HVDC export cabling is proposed to consist of bipole, XLPE insulated or mass impregnated non-draining (MIND) designs (see Appendix 2 for typical design), most likely deployed bundled together, but possibly separated by 50m. Cables will be rated between 320kV (1407A current load and 2400mm^2 cross sectional area) and 600kV (1667A and 3300mm^2). HVDC cables currently in use are restricted to 320kV and are most likely to be used at EAONE, but 500kV designs are planned for deployment in the near future, and, due to the rate of technological change in this field, it is thought there is a possibility that such cables or slightly larger may be available for the EAONE project. Bipole systems transmit current along two, separate cables in opposite directions (one with positive polarity and the other with negative polarity), thereby completing the circuit. This contrasts with a monopole system, whereby current is transmitted through a cable with a single conductor core and the return current is directed through the external environment (earth/sea) between two sea electrodes (an anode and a cathode). The latter have been associated with deleterious environmental effects due to strong electric fields and the generation of pollution products through electrolysis (Poleo *et al* 2001) and so will not be considered for EAONE. The temporary use of sea electrodes during cable maintenance cannot, however, be ruled out (see Section 4.5).

Optical fibre units will run alongside the power cables (composite design or separately), but their contribution to EMF is expected to be negligible in comparison to the power cables, and are therefore not considered further.

Whilst the development of a three-core, 420kV AC cable is thought to be possible in the near future, this design is not considered here, as it is considered unlikely to be available within the time frame of the EAONE project. The same applies to DC gas insulated line (GIL) cabling (thought to enable up to 6300A current load at 500kV) and super-conducting cables (thought to enable transmission of 5000MW across 10 to 15km), which are currently limited to onshore trials, and not likely to be commercially available for at least a decade.

4. Electromagnetic field generation

Submarine power cables generate magnetic fields owing to the electric current flowing along the cables. The magnitude of the magnetic fields produced is directly dependent upon the amount of current flow. The design of the cables, including lead sheathing and armoured cores, prevents the propagation of electric (E) fields into the surrounding environment; however, these materials are permeable to magnetic (B) fields, which therefore emanate into the surrounding environment, effectively unimpeded. The B field attenuates with both horizontal and vertical distance from the cable conductor.

Three-core AC cables transmit three current flows that fluctuate between positive and negative polarity. The B fields generated by these cables are therefore constantly changing. In turn, the motion of these B fields through the surrounding seawater continuously induces varying electric (iE) fields (CMACS 2003; Gill *et al*. 2009).

In contrast, the B field generated by bipole, DC cables is static and thus varying iE fields will not be induced in the same way as AC cables. However, localised, static iE fields may be induced as seawater (tidal flow) or other conductors such as marine organisms pass through the HVDC cable's B field.

Owing to the dependence of iE field magnitude upon B field magnitude, iE fields will attenuate with both horizontal and vertical distance from the cable conductor.

3.1. Cable deployment

In some instances, the deployment methodology (alignment arrangement, rather than installation technique) chosen for different cable types may affect EMF generation magnitude.

3.1.1. Alternating current cabling

B fields (and therefore iE fields) generated by AC designs vary with cable design. Three-core cables or three single-core cables arranged in trefoil (a similar, triangular arrangement) reduce B field generation in contrast with individual single-core cables laid separately. B and iE fields generated by the latter increase with increasing separation distance (to a certain point).

3.1.2. Direct current cabling

Assuming balanced loads, owing to the fact that effectively identical B fields are generated by each cable core, the opposite alignment of these cores in bipole DC systems results in significant cancellation effects on resultant fields should the cables be bundled in close proximity to each other. The further the cables are laid apart, the more they will behave as single cables, for which reduction through cancellation would be observed. The two cable cores will also act increasingly as single cables the more unbalanced the loads carried in each become (should, for example, some current flow through to the ground following damage to one or other of the cables).

3.2. Cable burial

Surface-laying of cables is planned to be avoided as far as possible. Instead, it is proposed that cables be buried between 0.5 and 5.0m within the substratum via ploughing, trenching/cutting or jetting (burial targets to be confirmed later). If the cable cannot be buried, such as at crossings with existing cables or pipelines, or over ground that cannot realistically be penetrated to sufficient depth, the cable will be surface laid, but protected as far as possible by rock dumping, concrete mattresses or frond mattresses.

Gill *et al* 2005 suggest that B field propagation will not be diminished through the sediment any more than through water (in the absence of magnetic rocks; see Section 4.4). However, burial may confer benefit in reducing the maximum magnitude of EMF at the sediment-seawater interface, as the further away from the seawater the cable lies, the more the field strengths will have attenuated. Therefore, from a marine biological perspective and taking a precautionary view, the deeper cables can be buried, the better, since many fauna will be prevented from approaching the strongest EMF (except burrowing infauna) but this may not result in ecologically significant reductions.

5. Predicted magnetic (B) and induced electric (iE) fields

Estimates of likely EMF emissions have been made based on review of available literature and previous work undertaken by CMACS.

4.1. Alternating current cables

4.1.1. Existing information

Three-core AC cables under consideration for use for the EAONE project, including array cables and HVAC export cables, range from 33kV to 220kV. 275kV single core cables are also being contemplated (see Section 2.2) but their use will depend on cable and installation technology being developed in time for EAONE. Data are available for similar, industry standard three-core cables ranging from 33kV to 132kV, and therefore certain well supported predictions can be made, whereas more general assumptions must be made for the higher powered and single core designs.

33kV cables were installed at Kentish Flats OWF and CMACS (2004; cited in Gill *et al*. 2005) reported that B fields of up to 0.015 μT and iE fields of up to 2.5 μV/m would be anticipated at the seabed-seawater boundary under full power generation conditions and burial to a depth of 1m.

Engineers predicted slightly higher B fields of 0.54 μT for similar 33kV cables at Burbo OWF (SeaScape Energy 2008), also at maximum power and buried to 1m. They also estimated that the B fields would attenuate by approximately ten times to 0.05 μT over a distance of 10m through seawater (SeaScape 2008). iE fields would attenuate at a similar rate, owing to their dependence on B field magnitude.

The University of Liverpool modelled EMF generation by industry standard, 132kV cables operating at maximum load and buried to 1m, and concluded that B fields of 1.6 μT might be expected at the seabed, inducing iE fields of 91 μV/m (CMACS 2003). They suggested the magnitudes would attenuate by approximately ten times through 8m of seawater, which matches, approximately, the attenuation rate estimated for Burbo OWF 33kV cables.

These figures have been used to inform many assessments using similar designs, and generally match similar trends reported by Tricas and Gill (2011), who averaged and plotted B field generation predicted from ten, buried, subsea AC cables of varying designs against distance from the cables (Figure 4 & Table 1). Projects incorporated in calculations included Naikun Wind Energy Project, San Juan Cable Project, Nysted OWF, Kentish Flats OWF, Horns Rev 2 OWF and North Hoyle OWF, among others.

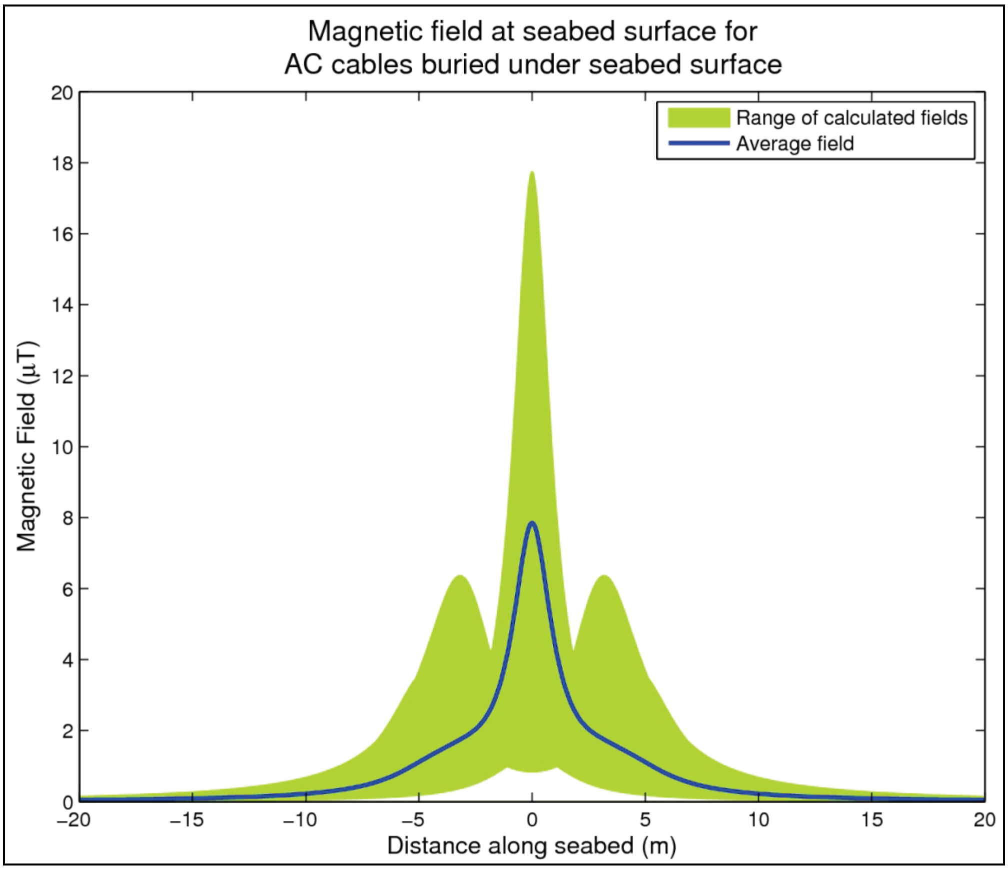

Figure 4. Average and range of AC magnetic fields calculated at seabed surface assuming 1m burial for various projects (from Tricas & Gill 2011). Note: bimodal peaks either side of the main peak can be ignored in this case, as they represent data from two-core, non-adjacent cable designs (Cape Wind and Replacement of 138kV cables in Long Island Sound).

Table 1. AC magnetic fields reflecting averaged values for various projects at intervals above and along the seabed assuming 1m burial (from Tricas & Gill 2011).

Vertical distance above seabed (m)	Field Strength (μT) Horizontal Distance from cable (m) 0	4	10
0	7.85	1.47	0.22
5	0.35	0.29	0.14
10	0.13	0.12	0.08

4.1.2. Predictions

Table 2 lists the magnitude of EMF that might be expected for the different AC cables under consideration for the EAONE project, both at the seabed immediately above the buried cable, and at a distance (horizontal or vertical) from the cable of 8 or 10m, assuming burial to 1m depth. Estimations have been based upon existing information available where possible (Section 4), but for cable designs for which no data currently exist (75kV, 220kV and 275 kV), more general approximations have been suggested.

In general, as would be expected, B fields vary with the voltage rating of the cable, with higher rated cables generating stronger fields (although the relationship is not linear). iE fields, induced by the three, constantly changing B fields' movements through the seawater, follow a similar pattern.

The table demonstrates the rapid attenuation of both B and iE fields with increasing distance from the cables, such that the strongest fields are limited to within close proximity of the seabed above where the cables are buried. The depth to which the cables are buried will affect how strong the fields at the seabed are with shallower depths resulting in stronger fields and *vice versa*. The depth to which the cables are buried will affect just how strong the fields at the seabed are. For example, should the cables be buried to the minimum depth proposed for the current project of 0.5m, markedly stronger fields are likely to be present at the seabed (owing to the geometric relationship between EMF generated and distance from the cable). Conversely, should the cables be buried to the maximum depth proposed of 5m, only markedly weaker fields are likely to be present at the seabed. Covering surface-laid cabling with rock-dumping or other methods (where burial is not possible) will have no practical dampening effect upon either B or iE field generation with respect to AC cables. It will, however, prevent certain organisms from approaching the strongest fields, although to what extent is uncertain (covering depth is likely to be less than burial).

It is assumed that EMF generated by 75kV AC cables will fall between those for similar 33kV and 132kV cables. 220kV AC cables represent the most likely worst-case scenario cable deployment in this case (as 275kV cables are unlikely to be available during the time-scale of this project). By extending trend lines on scatter plots of existing data for 33kV and 132kV, tentative extrapolations of approximate EMF have been included in Table 2, which suggest potential worst-case B fields of <10 at the seabed above the cable and <1μT at 10m away from the cable, and iE fields of a few hundred and a few tens of μV/m at the same relative positions. It must be stressed that these are approximate, albeit informed, estimates and that modelling would need to be undertaken to ascertain more accurate figures should such cable designs be implemented.

No estimated figures have been given for single core AC cables, considering the early development stage of such designs. However, it can be assumed that trefoil deployment (which resembles the 3-core design) might generate marginally stronger EMF than 220kV 3-core cables (owing to the slightly higher voltage). It can also be assumed that separated deployment of single cables is likely to generate significantly stronger EMF still, depending upon separation distance.

Table 2. Predicted EMF magnitude generated by EAONE OWF alternating current cables (assuming 1m burial)

	Three-core							Single-core trefoil 275kV*	Single-core separate 275kV*
	33kV		75kV*	132kV		220kV*			
Field	At seabed	At 10m	-	At seabed	At 8m	At seabed	At 10m	-	-
B field (µT)	0.015 – 0.54	0.0015 – 0.05	<Intermediate>	1.6	0.18	<10	<1	<Marginally stronger	< Significantly stronger
iE field (µV/m)	2.5	0.25	<Intermediate>	91	10	A few hundred	A few tens	<Marginally stronger	< Significantly stronger

***NB**: no data available for precise estimates of 75kV or 220 & 275kV cables, and therefore tentative assumptions and/or estimates made.

4.2. Direct current cables

4.2.1. Existing information

DC cables under consideration for use for the EAONE project, specifically bipole HVDC export cables, range from 320kV to 600kV designs, with current loads of 1407A and 1667A respectively, although it is most likely that 320kV will be utilised (see Section 2.2). Owing to relatively little data being available for similar, industry standard cables, informed predictions are made where possible, with more general assumptions made where data are lacking.

Poleo *et al* (2001) calculated a B field of 5500μT at the surface of a 1600A HVDC cable, attenuating to 50 μT at a distance of 10m. Modelling of EMF for Docking Shoal & Race Bank OWF export cabling, which consists of an HVDCLight 150kV design, predicted a B field of 1369μT at the seabed assuming 0.5m burial, reduced to 37μT assuming 1m burial (CMACS 2008). B fields were also predicted to attenuate almost completely at a distance of 10m from the cable.

Modelling undertaken by Swedpower for the BritNed Inteconnector HVDC cable, rated at 450kV with a maximum load of 1320A, predicted the following B and iE fields for different deployment methods and distances from the cables assuming 1m burial (Table 3; Voet 2005). Note that iE fields were assumed to be caused by tidal flow through the B field, and an estimated 0.85m/s tidal flow rate was used in calculations.

Table 3. Magnetic and electric fields generated by BritNed Interconnector assuming 1m burial (adapted from Voet 2005)

Cable deployment	B field (μT)		iE field (μV/m)	
	1m from cable	5m from cable	1m from cable	5m from cable
Bundled (0.2m)	72	2.2	61	1.9
2m separation	310	21	260	18

Another project CMACS has recently worked on[1] predicted EMF generated for similar 500kV HVDC cables (assuming no burial) with slightly higher maximum current loads than BritNed. B fields were estimated at approximately 5000 μT at the cable surface, with attenuation to approximately 800 μT at 0.5m distance (horizontal or vertical) and approximately 80 μT at 5m for cable separation of 50m. Attenuation for bundled cables was more rapid to approximately 250 μT at 0.5m distance and approximately 2 μT at 5m. iE fields at the cable surface were predicted to be approximately 6500 μV/m, with attenuation to approximately 1000 μV/m at 0.5m and approximately 100 μV/m by 5m for a cable separation distance of 50m. Again, attenuation for closely bundled cables was more rapid to approximately 500 μV/m at

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[1] Unpublished as yet, and therefore project details unavailable at time of writing

0.5m and approximately 1.5 μV/m at 5m. Tidal flow of the area of proposed development was estimated at up to 1.25m/s; 70% of maximum surface flow.

The data, above, generally match similar trends reported by Tricas and Gill (2011), who averaged and plotted B field generation predicted from nine, buried, subsea HVDC cables of varying designs against distance from the cables (Figure 5 & Table 4). Projects incorporated in calculations included Naikun Wind Energy Project, Juan de Fuca Transmission Project, Cross Sound Cable, EirGrid Irish Interconnector and Basslink Interconnector, among others.

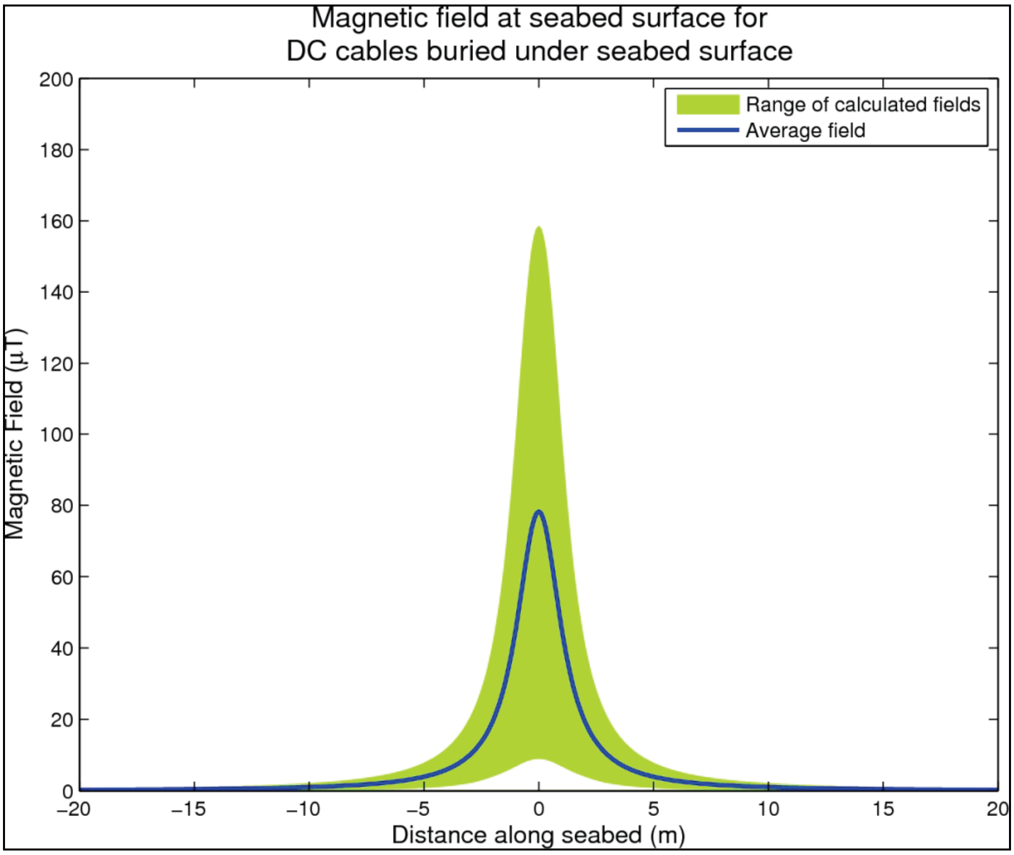

Figure 5. Average and range of DC magnetic fields calculated at seabed surface for various projects assuming 1m burial (from Tricas & Gill 2011).

Table 4. DC magnetic fields reflecting averaged values from various projects at intervals above and along the seabed assuming 1m burial (from Tricas & Gill 2011).

Vertical distance above seabed (m)	Field Strength (μT) Horizontal Distance from cable (m) 0	4	10
0	78.27	5.97	1.02
5	2.73	1.92	0.75
10	0.83	0.74	0.46

4.2.2. Predictions

Table 5 Table 6 list the magnitude of B and iE fields that might be expected for the different DC cables under consideration for the EAONE project, both at the cable surface, and at varying distances from the cable (assuming no burial). Estimations have been based upon existing information available where possible (Section 4.2), but for cable designs for which no data currently exist, more general approximations have been suggested. For estimations of iE field, a conservative estimate of the maximum tidal flow at the seabed (1.2m/s) has been used, based upon 50% of the maximum tidal flow at the surface depicted on the relevant Admiralty chart.

In general, as would be expected, B fields vary with the voltage of the cable design, with higher rated cables generating stronger fields (although the relationship is not linear). However, the table demonstrates the rapid attenuation of the fields with increasing distance from the cables. Attenuation occurs significantly more quickly around bundled cables compared to those separated by 50m, owing to the cancellation effect of two similar fields of opposite polarity aligned in opposite directions (see Section 3.1.2). B fields are therefore markedly stronger with increasing distance from separated cables when compared to bundled cable fields at similar distances. iE fields induced by seawater moving through the B field (tidal flow) follow similar patterns. iE fields induced by organisms passing through the B fields will be dependent upon both the magnitude of the B field and the organisms' speed of movement, and whether they are moving with or against the tide. A fast moving fish swimming with a strong tide, for example, will induce a stronger iE field than one swimming more slowly or against the tide. It is therefore possible that electric fields induced by fast-moving organisms could be stronger than those estimated for tidal flow in Table 6, but by how much is uncertain owing to difficulties in knowing swimming speed of marine fauna.

Again, the depth to which the cables are buried will affect how strong the fields at the seabed are with shallower depths resulting in stronger fields and *vice versa.* Where surface-laid cables are covered by rock-dumping or other methods, B field propagation will not be hindered. However iE field induction is likely to be dampened due to the reduction in tidal flow past the cable, and prevention of marine fauna from swimming through the strongest B fields. Equally, any organisms inhabiting interstitial spaces will not be able to move as rapidly, and the iE fields generated by their movement will also be dampened.

With relatively few data to base predictions upon, estimates of EMF magnitude in Table 5 & Table 6 are tentative. Figures for 500kV are the best supported (based upon the unpublished work CMACS has recently been involved with and BritNed calculations, the latter of which involved cables of slightly less voltage). Interpolations of EMF likely to be generated by 320kV cables have been included by comparing information from 450kV and 500kV cables with HVDCLight 150kV cables, but it must be stressed that the estimates are tentative, especially owing to uncertainty of similarity between HVDCLight and standard HVDC technology. Owing to this uncertainty, extrapolation of 600kV EMF was not possible, due to the unsuitability of using estimates for 300kV EMF on scatter plots. It has therefore simply been suggested that EMF likely to be generated by 600kV cables would be expected to be slightly stronger than those generated by 500kV cables. The worst-case DC cable deployment, when considering EMF, can therefore be assumed to be 600kV cables separated by 50m. Again, it must be stressed that these are approximate, albeit informed, estimates and that modelling would need to be undertaken to ascertain more accurate figures should such cable designs be implemented.

Table 5. Predicted B field magnitude (μT) generated by EAONE OWF direct current cables (assuming no burial)

	320kV*		500kV		600kV*
Distance from cable	Bundled	50m separation	Bundled	50m separation	
Cable surface	A few thousand	A few thousand	5000	5000	<Slightly stronger
0.5m	≈175	≈500-600	250	800	<Slightly stronger
1m	≈50	A few hundred	≈80*	≈500*	<Slightly stronger
5m	≈1	≈50	2	82	<Slightly stronger
10m	≈0.5	A few dozen	≈1*	50	<Slightly stronger

***N.B.** No data available therefore tentative assumptions and/or estimates made

Table 6. Predicted iE field magnitude (μV/m) generated by EAONE OWF direct current cables (assuming 1.2m/s tidal flow)

	320kV*		500kV		600kV*
Distance from cable	Bundled	50m separation	Bundled	50m separation	
Cable surface	≈3500	≈4500	6500	7000	<Slightly stronger
0.5m	≈200	≈700	300	1000	<Slightly stronger
1m	≈50	≈400	≈70*	≈500*	<Slightly stronger
5m	≈1.5	≈70	2	100	<Slightly stronger
10m	≈0.5	≈30	≈1*	60	<Slightly stronger

***N.B.** No data available therefore tentative assumptions and/or estimates made

4.3. Background fields

The background geomagnetic field off the East Anglia coast of the UK is approximately 48 to 49µT. From Table 2, it can be seen that B fields generated by any AC cable design will not reach the magnitude of the geomagnetic field at the seabed (assuming 1m burial). Table 7 lists predictions of approximate distances at which B fields generated by DC cables attenuate below geomagnetic field magnitude assuming different burial depths.

Table 7. Distances at which B fields generated by DC cables attenuate below Earth's background geomagnetic field

		Distance (m)		
Deployment	Burial depth (m)	320kV	500kV	600kV
Bundled	None	1	2 - 3	< Slightly further
	0.5	0.5	1.5 – 2.5	< Slightly further
	1	0	1 – 2	< Slightly further
Separated	None	5	10	< Slightly further
	0.5	4.5	9.5	< Slightly further
	1	4	9	< Slightly further

The background electric field in the area in question will depend upon the tidal flow moving through the local geomagnetic field. Tidal charts indicate the maximum tidal flow at the surface in the area is 2.4m/s. A conservative estimate of maximum seabed flow (50% surface flow) would be 1.2m/s. The background electric field could therefore be expected to reach a maximum of approximately 60µV/m.

Table 8 lists predictions of approximate distances at which iE fields generated by AC cabling attenuate below background (tidally induced) fields assuming 1m burial depth. Note that data used for AC predictions were all based upon 1m burial depth, and therefore it is not possible to be confident about precise strengths of EMF at cable surfaces or 0.5m distance (i.e. burial less than 1m).

Table 8. Distances at which iE fields generated by AC cables attenuate below Earth's background field induced by tidal flow (based upon 1m burial)

	3-core				1-core Trefoil	1-core separated
	33kV	75kV	132kV	220kV	275kV	275kV
Distance (m)	0	0	0.5 – 1	5 – 10	<Marginally further	< Significantly further

iE fields induced around DC cabling will attenuate to background levels at the same distances as B fields (see Table 7) when considering tidal flow, since both depend on the same tidal flow flowing through the B fields; i.e. when the B field drops to the same level as the geomagnetic field, the iE field will also drop to the same level as the background electric field. These distances might be increased when considering fast-moving organisms, should their velocity be greater than the tidal flow considered.

How, or whether, the fields generated by the EAONE project may interact with background fields, and how they may be perceived by electromagnetically sensitive organisms is not certain. The current understanding is that whichever magnetic field (B field or geomagnetic) is more intense is likely to be more easily detected and therefore of greater interest to an organism (Andrew Gill pers. com.). Assuming so, once B fields attenuate to below the geomagnetic field, they may be less relevant to the organisms in question. However, owing to differences in the fields' geometries and characteristics, and the fact that additive or subtractive interactions may occur, dependent upon their directions, the two fields may still be decipherable.

Similarly, once iE fields generated by AC cables attenuate to below the background (tidally induced) iE field, they may be less relevant to organisms, although owing to differences in geometries and interactions, the two fields may still be decipherable. Contrastingly, background iE fields and those generated by organisms' movements around DC cables are likely to be of increasingly different magnitude, and therefore more decipherable, with increasing disparity in velocities. Should tidal flow and organism movement be of comparable velocities, the iE fields are likely to be of similar magnitude, and therefore possibly less distinguishable. However, once more, possible additive or subtractive interactions or geometric differences may increase distinguishable characteristics.

4.4. Magnetic anomalies

Another factor which can complicate interpretation of anthropogenic electromagnetic fields is the presence of magnetic anomalies; namely iron-bearing magnetic rocks. If the EAONE project location (Figure 1) is compared with a map of seabed sediments in the relevant area (Figure 6), it appears the majority of sediment the cables are likely to be laid in/on will be medium sand, although there are patches of stony substrata. Site specific surveys of the East Anglia zone support the predominance of sandy gravel and gravelly sand with occasional areas of cobbles and boulders (MESL 2011). Whilst areas of medium sand would be unlikely to have significant relevance to interpretation of the effects of the EAONE project's cabling EMF, the possible presence of magnetic rocks may complicate potential interactions between marine organisms and cable EMF, although just how such anomalies would affect detection of cable EMF is uncertain.

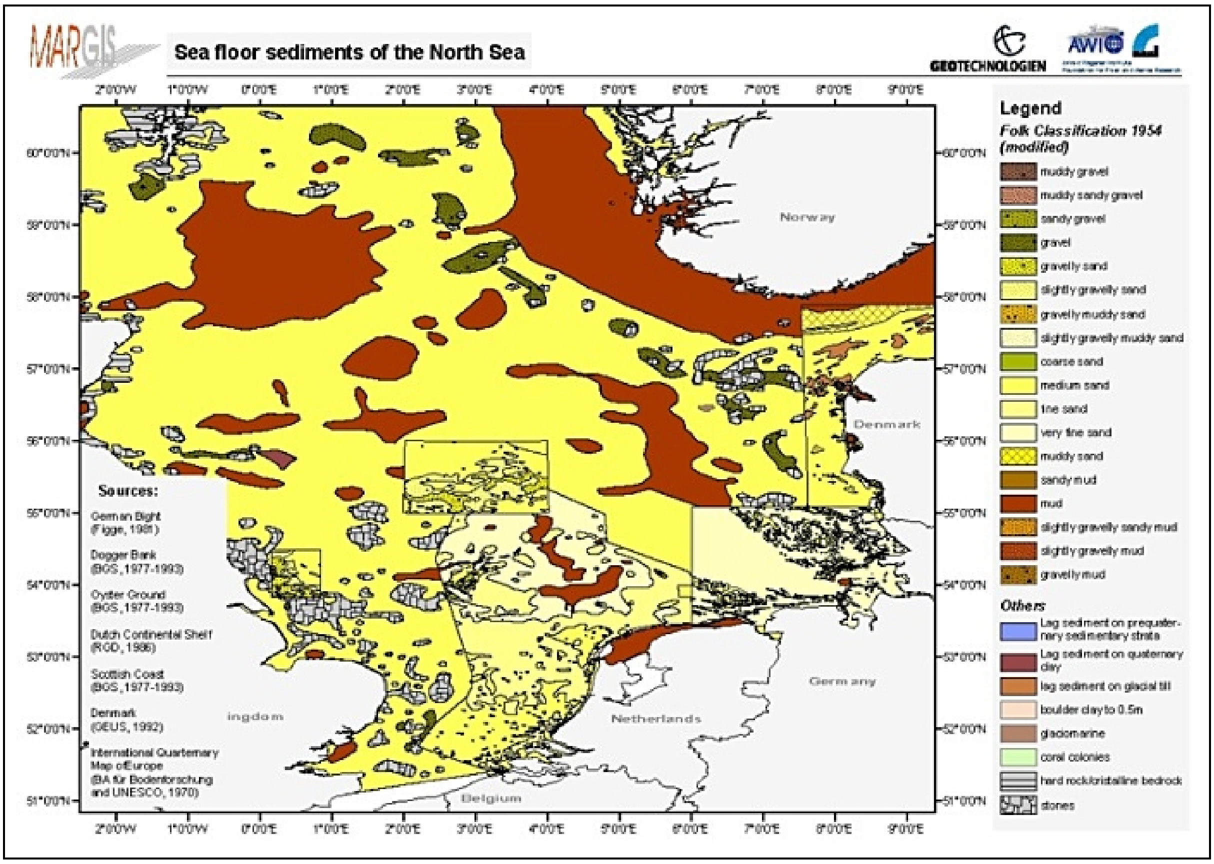

Figure 6. Seabed sediments in the North Sea
(from http://www.awi-bremerhaven.de/GEO/Marine_GIS/Margis%20homepage/index.html)

4.5. Sea electrodes

Whilst there is no mention of sea electrodes in the current project's planned methodology, sea electrodes are sometimes utilised temporarily during cable maintenance for similar developments. The magnitudes and propagation distances of expected EMF, in addition to likely duration of use, would need to be considered should the decision be made to use such a system, owing to the deleterious effects associated with them (Poleo *et al* 2001).

6. Electromagnetic field detection

A relatively large number of organisms in the marine environment are either known to be sensitive to electromagnetic fields or have the potential to detect them (Gill & Taylor 2001; Gill *et al* 2005). The following summary of magnetic and electric field detection (Sections 5 and 5.2 below respectively) is adapted from an account in Gill *et al* (2005).

5.1. Magnetic field detection

Magnetically sensitive organisms can be categorised into two groups based on their mode of magnetic field detection: induced electric field detection; and direct magnetic field detection.

The first group relates to species that are electroreceptive, the majority of which are elasmobranchs (cartilaginous fishes; sharks, skates and rays), though also includes holocephalans (chimaeras; e.g. ratfish), and agnathans (jawless fishes; e.g. lampreys). These animals detect the presence of a magnetic field indirectly by detection of the electrical field induced by the movement of water through a magnetic field or by their own movement through that field. The magnetic field could be the Earth’s own (geomagnetic) field or a magnetic field produced by a power cable. In natural scenarios induction of the electric field usually results from organisms positioning themselves in tidal currents and animals may time certain activities (e.g. foraging) by detecting diurnal cues resulting from varying tidal flows.

The second group is believed to use magnetic particles (magnetite) within their own tissues in magnetic field detection (Kirshvink 1997). Whilst the mechanism of how these organisms detect magnetic fields is still unknown it is generally acknowledged that they are able to use magnetic cues, such as the Earth’s geomagnetic field, to orient in their environment during migration. In UK waters, such organisms include cetaceans (whales, dolphins and porpoises), chelonians (turtles), teleosts (bony fishes; e.g. salmon and eel), crustaceans (lobsters, crabs, prawns and shrimps) and molluscs (snails, bivalves and cephalopods).

Table 9. List of magnetoreceptive species in UK coastal waters (adapted from Gill *et al* 2005)

Species	Common name	Relative occurrence in UK waters	Evidence of magnetite and/or response to magnetic fields
Cetacea	**Whales, dolphins & porpoises**		
Phocoena phocoena	Harbour porpoise	Common	✓
Tursiops truncatus	Bottlenose dolphin	Common	✓
Delphinus delphis	Short-beaked common dolphin	Common	✓
Balaenoptera acutorostrata	Minke whale	Occasional	
Globicephala melas	Long-finned pilot whale	Occasional	✓
Lagenorhynchus acutus	Atlantic white-sided dolphin	Occasional	✓
Orcinus orca	Killer whale	Occasional	
Lagenorhynchus albirostris	White-beaked dolphin	Occasional	
Grampus griseus	Risso's dolphin	Occasional	✓
Physeter macrocephalus	Sperm whale	Occasional	✓
Megaptera novaengliae	Humpback whale	Occasional	
Balaenoptera physalus	Fin whale	Occasional	✓
Stenella coeruleoalba	Striped dolphin	Rare	✓
Monodon monoceros	Narwhal	Rare	
Delphinapterus leucas	Beluga	Rare	
Pseudorca crassidens	False killer whale	Rare	
Hyperdoon ampullatus	Northern bottlenose whale	Rare	
Ziphius cavirostris	Cuvier's beaked whale	Rare	
Mesoplodon bidens	Sowerby's beaked whale	Rare	
Balaenoptera borealis	Sei whale	Rare	
Balaenoptera musculus	Blue whale	Rare	
Eubalaena glacialis	Northern right whale	Rare	
Kogia breviceps	Pygmy sperm whale	Rare	✓
Lagenodelphis hosei	Fraser’s dolphin	Rare	
Peponocephala electra	Melon-headed whale	Rare	

Species	Common name	Relative occurrence in UK waters	Evidence of magnetite and/or response to magnetic fields
Chelonia	**Turtles**		
Caretta caretta	Loggerhead	Occasional	✓
Dermochelys coriacea	Leatherback	Occasional	
Chelonia mydas	Green	Occasional	✓
Eretmochelys imbricata	Hawksbill	Rare	
Lepidochelys kempi	Kemp's Ridley	Rare	
Teleostei	**Bony fish**		
Anguilla anguilla	European eel	Common	✓
Salmo salar	Atlantic salmon	Common	✓
Scombridae †	Tunas & mackerels	Common	✓
Pleuronectes platessa	Plaice	Common	✓
Salmo trutta	Sea trout	Occasional	✓
Thunnus albacares	Yellowfin tuna	Occasional	✓
Elasmobranchii	**Sharks, skates & rays**	All Elasmobranchii, Holocephali and Agnathans possess the ability to detect magnetic fields (for species see Table 10. Electroreceptive species list)	
Holocephali	**Chimaeras**		
Agnatha	**Jawless fish**		
Crustacea †	**Lobsters, crabs, shrimps & prawns**	*Specific cases non-UK* Decapoda: *Crangon crangon* (ICES 2003) *Carcinus maenas* (Everitt 2008) Isopoda: *Idotea baltica* (Ugolini & Pezzani 1995) Amphipoda: *Talorchestia martensii* (Ugolini 1993); *Talitrus saltator* (Ugolini & Macchi 1988)	
Molluscs †	**Snails, bivalves & squid**	*Specific case non-UK* Nudibranch: *Tritonia diomedea* (Willows 1999)	

† = evidence of magnetic response in species outside UK waters

5.2. E field detection

As previously mentioned, the predominant electroreceptive marine organisms are elasmobranchs. These animals (and also holocephalans) have specialist electroreceptive organs, Ampullae of Lorenzini (AoL), which are relatively well studied and described (see Tricas & Sisneros 2004 for review). Upon encounter with a polar electric field, for example originating from the bioelectric field emitted by a prey organism buried in sediment, an elasmobranch can locate the source of emission based on differential voltage potential at the pores opening to the AoL with reference to the internal voltage potential of the body. In a uniform electric field, for example a field resultant from water movement through a magnetic field, the different length and orientation of the AoL canals allows an elasmobranch to compare voltage gradient change. Elasmobranchs are highly sensitive and can detect very weak voltage gradients, as low as 5 to 20nV/m (Kalmijn 1982; Tricas & New 1998). Species that have specialised electroreceptors naturally detect bioelectric emissions from prey, conspecifics and potential predators/competitors (the latter being more likely for early life history stages). The electrosense is primarily used in close proximity to the source and other senses (such as hearing or smell) are used at distances of more than approximately 30cm. This means that the electrosense is highly tuned for the final stages of feeding or detecting conspecifics and predators.

Other species that are electrosensitive (e.g. agnathans) do not possess specialized electroreceptors but are able to detect induced voltage gradients associated with water movement through the geomagnetic field. The actual sensory mechanism of detection is not yet properly understood. It is likely that the E fields that these species respond to are associated with peak tidal movements (Pals *et al* 1982).

Table 10. List of electrosensitive species in UK coastal waters (adapted from Gill *et al* 2005)

Species	Common name	Relative occurrence in UK waters	Evidence of response to E fields
Elasmobranchii	**Sharks**		
Cetorhinus maximus	Basking shark	Common	
Galeorhinus galeus	Tope	Common	
Lamna nasus	Porbeagle	Common	
Mustelus asterias	Starry smooth-hound	Common	
Scyliorhinus canicula	Small-spotted catshark	Common	✓
Squalus acanthias	Spurdog	Common	
Alopias vulpinus	Thintail thresher	Occasional	
Chlamydoselachus anguineus	Frilled shark	Occasional	
Dalatias licha	Kitefin shark	Occasional	
Isurus oxyrinchus	Shortfin mako	Occasional	
Mustelus mustelus	Smooth-hound	Occasional	
Prionace glauca	Blue shark	Occasional	✓
Scyliorhinus stellaris	Nursehound	Occasional	
Centrophorus squamosus	Leafscale gulper shark	Rare	
Centroscyllium fabricii	Black dogfish	Rare	
Deania calcea	Birdbeak dogfish	Rare	
Echinorhinus brucus	Bramble shark	Rare	
Etmopterus spinax	Velvet belly lantern shark	Rare	
Galeus melastomus	Blackmouth catshark	Rare	
Heptranchias perlo	Sharpnose sevengill	Rare	

Species	Common name	Relative occurrence in UK waters	Evidence of response to E fields
	shark		
Hexanchus griseus	Bluntnose sixgill shark	Rare	
Oxynotus centrina	Angular rough-shark	Rare	
Scymnodon obscurus	Smallmouth velvet dogfish	Rare	
Scymnodon squamulosus	Velvet dogfish	Rare	
Somniosus microcephalus	Greenland shark	Rare	
Sphyrna zygaena	Smooth hammerhead	Rare	
Squatina squatina	Angelshark	Rare	
Elasmobranchii	**Skates & Rays**		
Amblyraja radiata	Starry ray	Common	
Raja clavata	Thornback ray	Common	✓
Dipturus nidarosiensis	Norwegian skate	Occasional	
Leucoraja circularis	Sandy ray	Occasional	
Leucoraja fullonica	Shagreen ray	Occasional	
Leucoraja naevus	Cuckoo ray	Occasional	
Raja brachyura	Blonde ray	Occasional	
Raja microocellata	Small-eyed ray	Occasional	
Raja montagui	Spotted ray	Occasional	
Raja undulata	Undulate ray	Occasional	
Amblyraja hyperborea	Arctic skate	Rare	
Bathyraja spinicauda	Spinetail ray	Rare	
Dasyatis pastinaca	Common stingray	Rare	
Dipturus batis	Common skate	Rare	
Dipturus oxyrinchus	Long-nose skate	Rare	
Mobula mobular	Devil fish	Rare	
Myliobatis aquila	Common eagle ray	Rare	
Rajella fyllae	Round ray	Rare	✓
Rostroraja alba	White skate	Rare	
Torpedo marmorata	Spotted/marbled torpedo ray	Rare	
Torpedo nobiliana	Atlantic torpedo ray	Rare	
Holocephali	**Chimaeras**		
Chimaera monstrosa	Rabbit fish	Rare	✓
Agnatha	**Jawless fish**		

Species	Common name	Relative occurrence in UK waters	Evidence of response to E fields
Lampetra fluviatilis	European river lamprey	Common	✓
Petromyzon marinus	Sea lamprey	Occasional	✓
Teleostei	Bony fish		
Anguilla anguilla	European eel	Common	✓
Gadus morhua	Cod	Common	✓
Pleuronectes platessa	Plaice	Common	✓
Salmo salar	Atlantic salmon	Common	✓

7. Potential impacts of subsea power cables

Uncertainty remains as to how or whether potential effects of AC and DC electromagnetic fields upon marine organisms may differ. Therefore, while also considering that research in this area is relatively young, with reasonably few studies available to base assumptions on, potential effects of both AC and DC electromagnetic fields are considered together. However, it should be noted that the effects of these two types of electromagnetic fields may not necessarily be the same owing to differing geometric characteristics, and comparisons are therefore tentative.

6.1. B fields

Research into possible interactions between marine fauna and magnetic fields generated by sub-sea cables is still at an early stage and information therefore relatively limited. However, given the sensitivity of a wide range of marine organisms to magnetic fields there is potential for effects to occur. There are two main concerns:

- Impairment of navigation
- Physiological effects

6.1.1. Invertebrates

Compass orientation, demonstrated by migration in magnetic fields as weak as 50μT, is evident even among bacteria (Kirschvink 1980) and algae (Lins de Barros *et al* 1982). However, no effects upon their distribution or physiology of HVDC sub-sea cable B fields have been recorded (e.g. Poleo & Harboe Jr 1996).

Despite many marine invertebrates being magnetically sensitive, there is little and contradicting evidence of interactions with anthropogenic sources of magnetic fields. The brown shrimp (*Crangon crangon*) has been recorded as being attracted to AC B fields of the magnitude expected around wind farms (ICES 2003). Shore crabs (Carcinus maenas) have been demonstrated to be less aggressive in the presence of an AC B field generated to match the magnitude of wind farm cabling (Everitt 2008). Contrastingly, Bochert & Zettler (2004) found no effects of exposure to static

B fields upon the same species, nor upon the round crab (*Rhithropanopeus harrisii*), an isopod (*Saduria entomon*) or the mussel (*Mytilus edulis*). Equally, demonstrations of B fields ranging between 1-100µT delaying embryonic development in sea urchins (Zimmerman *et al* 1990), and of high frequency AC EMF causing cell damage to barnacle larvae and interfering with their settlement (Leya *et al* 1999), contrasts with anecdotal evidence of benthic invertebrates living directly upon DC electrodes (Nielsen 1986) with no apparent effects (Walker 2001; Swedpower 2003). No similar information exists for invertebrates living upon or over AC cables, as far as CMACS is aware, other than diver observations of some algae and anemones colonising an exposed J-tube[2] (Bunker 2004). The J-tube was otherwise bare, but this may have been due to scour. It would seem, therefore, that DC B fields cause fewer biological effects upon these taxa than AC B fields, although this assumption should be made tentatively owing to the sheer lack of relevant studies.

A number of marine invertebrate species that inhabit the southern North Sea are magnetically sensitive, including important commercial taxa (Parker-Humphreys 2004). Site specific surveys undertaken at the EAONE project area recorded lobster, edible crabs and squid (MESL 2010 & 2011), and International Beam Trawl Survey Data (IBTS) also recorded brown shrimp and cockles (DATRAS 2011) in the relevant ICES rectangles (33F1, 33F2 & 32F1). Surveys undertaken by CMACS at nearby wind farm sites (Gabbard and London Array) also recorded brown shrimp, many crabs (including some edible), queen scallops, common whelk, edible mussel, cuttlefish and squid (CMACS 2005; RPS 2005).

B fields expected to be generated by AC cables within the EAONE site (assumes array and HVAC export cables of 33kV to 220kV) will be below background geomagnetic field magnitude (assuming burial of greater than 0.5m). Should the cutting edge 275kV cables be used (which is unlikely), the B fields are more likely to reach background levels, especially if they are deployed separately, whereby markedly stronger fields are likely to be generated.

Background levels will be reached by B fields generated by all HVDC designs likely to be utilised at EAONE, but will attenuate below the geomagnetic field at distances of approximately 1m (bundled) and 5m (separated) for 320kV cables, a few meters (bundled) and 10m (separated) for 500kV cables and slightly further still for 600kV cables (bundled and separated). The deeper cables are buried, the weaker the B fields encountered by most marine fauna will be (except borrowing species such as polychaetes and bivalve molluscs). Bundling cables, rather than utilising separation deployment, will also markedly reduce the distance at which organisms are likely to encounter B fields stronger than the background field. Where cables are covered with rocks or mattresses, invertebrates are highly likely to colonise any interstitial spaces, and may therefore come into direct contact with the cables. They could therefore potentially be exposed to strong B fields of approximately 5000µT or more when considering HVDC cabling.

In summary, the potential for effects upon invertebrates' navigation and/or for physiological effects may therefore exist within tens of meters of separated HVDC

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[2] J-tubes convey AC cables away from wind turbines; they are normally buried, but had apparently been exposed by scour in this case.

cables and within close proximity (a few meters) of bundled HVDC cables or HVAC cables, depending upon burial depth. However, the extent and ecological significance of such potential effects is uncertain.

6.1.2. Fish

There is extensive evidence of teleost fish possessing magnetic receptors (see Kirschvink 1997 for review), often supported by demonstrations of orientation behaviour, for example in species such as eels (*Anguilla rostata*; Souza *et al* 1988), plaice (*Pleuronectes platessa*; Metcalfe *et al* 1993), salmon (*Salmo salar*; Rommel & McCleave 1973; *Oncorhynchus tshawaytscha*; Kirschvink *et al* 1985) and trout (*Salmo gairdneri*; Chew & Brown 1989). Equally, chondrichthyans' ability to detect magnetic fields by induction of electric fields (Kalmijn 1984), is supported by demonstrations of orientation behaviour towards magnetic fields, including species such as round stingray, *Urobatis halleri*, and leopard shark, *Triakis semifasciata* (Kalmijn 1978), and sandbar, *Carcharhinus plumbeus*, and scalloped hammerhead, *Sphyrna lewini*, sharks (Meyer *et al* 2004). Whether these fish would be affected by B fields from sub-sea cables, however, is unclear. Bochert & Zettler (2004) found no significant effects of static B fields upon flounder, *Platichthys flesus*. Swedpower (2003) found no measurable impact of subjecting salmon and trout to magnetic fields twice the magnitude of the geomagnetic field. The European eel (*Anguilla anguilla*) has been shown to deviate from its migration route in the presence of a 5µT HVDC field, however the effect was short term and over a short distance (Westerberg 2000; Ohman *et al* 2007), and such effects are therefore thought unlikely to affect key functions such as breeding or feeding success. Atlantic salmon migration in and out of the Baltic Sea, over a number of operating sub-sea HVDC cables, seems to continue unaffected (Walker 2001).

There are many relevant teleost fish taxa that inhabit the southern North Sea, including important commercial species (Parker-Humphreys 2004; Fishbase 2010). Site specific surveys for the EAONE OWF predominantly recorded benthic whiting, plaice, bib, dab, cod, raitts and greater sand eels, as well as pelagic herring, sprats, anchovies and pilchards (BBM 2011). Similar teleost assemblages were also recorded in IBTS data and during surveys at nearby OWF sites (CMACS 2005; RPS 2005; DATRAS 2011), which also mentioned Dover sole, turbot, brill and a number of goby species. Many of these species have undergone significant population declines, predominantly owing to overfishing, and some are therefore listed as Annex II species. Gobies are scheduled species under the Bern Convention, protected for their importance at the trophic level. Migrating species of teleost fish including salmon, trout and eels, and also lampreys (Agnathans or jawless fish) are also known to be present in the area, especially European eels, for which there used to be a strong fishery, and which are particularly numerous in ICES rectangle 32F1, along the proposed export cable route (DATRAS 2011). There are also a number of important elasmobranch species occurring in the area, some of which are fished, face population decline and are protected (Parker-Humphreys 2004; Compagno *et al* 2005). Those recorded during site specific and nearby OWF surveys and in IBTS data include small-spotted catshark, smoothhounds and spurdog (*Squalus acanthias*), and thornback (*Raja clavata*), spotted and blonde rays (CMACS 2005; RPS 2005; BBM 2001; DATRAS 2011). Others known to occur, albeit occasionally or seldomly, are nursehounds, tope (*Galeorhinus galeus*), thresher, porbeagle

(*Lamna nasus*), angel (*Squatina squatina*) and basking (*Cetorhinus maximus*) sharks, and skates (*Dipturus* spp.). A number of spawning grounds are known to occur off East Anglia (Coull *et al* 1998; Ellis *et al* 2012) including herring, cod, plaice, sand eels and sole (as well as the invertebrate, *Nephrops norvegicus* or Norway lobster), with associated nursery grounds, as well as thornback ray and tope nurseries.

With respect to the EAONE project, only 275kV HVAC and HVDC cabling are likely to generate B fields above background levels, and even worst-case scenarios (separated deployment of higher rated designs) result in attenuation below these levels over distances of approximately ten meters, with bundled deployment resulting in propagation to just a few meters. Pelagic species, such as herring, mackerel, salmon, porbeagle and basking sharks are therefore likely to be unaffected, unless venturing into very shallow waters. Benthic fish species are more likely to encounter the B fields, and are possibly even still able to detect them at distances at which they fall below the geomagnetic field (Westerberg 2000; Meyer *et al* 2004; see Section 4.3). However, it is thought that any effects upon teleost or elasmobranch orientation behaviour are likely to be small and temporary (akin to demonstrations of eel deviation; Westerberg 2000; Ohman *et al* 2007), with normal movement/migration expected to resume once beyond the few to ten distances mentioned above, or slightly further should fields below background levels still be detectable.

In areas where rock dumping or mattresses are used (at cable crossings or areas of hard substrate) there is potential for smaller species to encounter strong magnetic fields of up to approximately 5000μT or more in the case of separated deployment. An example would be small-spotted catsharks, the females of which segregate from aggressive males by sheltering in rocky crevices (Sims *et al* 2001). Whether any physiological effects on such rock-dwelling fish could result from these stronger fields is uncertain. The only evidence relates to fish embryonic development, which has been shown to be delayed by AC B fields of 1 to 100μT (Cameron *et al 1985*; Cameron *et al* 1993). Shallow sandy areas, in particular, are important nursery areas for many fish species (e.g. thornback rays, flatfish, sand eels), but in areas of such substratum, the cables are likely to be buried which would prevent fish (including eggs and juveniles) from encountering the stronger fields.

6.1.3. Marine mammals and chelonians

Marine mammals are strongly linked with the use of geo-navigation by detection of variation in magnetic fields (e.g. Kirschvink *et al* 1986, who correlated strandings with local magnetic minima). However, the ability has not been demonstrated experimentally, and how the sense operates remains unconfirmed. There is no evidence of cetacean migration being affected by sub-sea cable B fields. Harbour porpoise (*Phocoena phocoena*) migration across the Skagerrak and western Baltic Sea has been observed unhindered despite several crossings over operating sub-sea HVDC cables (Walker 2001). Eight species of marine mammals occur regularly in the North Sea; namely harbour and grey seals, harbour porpoises (the most numerous; estimated at 268,000 in 1994), bottlenose, white-beaked and Atlantic white-sided dolphins, and killer and minke whales (SMRU 2001). Most are markedly more common further north, off Scotland. A further fifteen cetaceans and five pinnipeds are known to enter the North Sea sporadically, often during the summer months (SMRU 2001; Hammond *et al* 2005). Owing to their predominantly pelagic existence, with migrations strongly linked to surface waters for breathing, these species are only likely to encounter the B fields generated by EAONE OWF should they dive to feed near the seabed or should they venture into very shallow water. Owing to the rapid attenuation of the B fields with distance from the cables, combined with lack of evidence of effects upon cetaceans, it is expected these mammals will be largely unaffected by the current project. The same is postulated for chelonians (turtles), some species of which are also sporadic summer visitors to the North Sea (e.g. leatherback turtle, *Dermochelys coriacea*; Reeds 2004), for similar reasons.

6.2. iE fields

Again, research into possible interactions between marine fauna and electric fields generated by sub-sea cables is still at an early stage, and information relatively limited. Given the sensitivity of certain marine organisms to electric fields there is potential for effects to occur. There are three main concerns:

- Repulsion
- Confusion with bioelectric fields
- Physiological effects

6.2.1. Invertebrates

No marine invertebrates have been definitively demonstrated as being electrically sensitive (it has been suggested that certain freshwater crayfish may possess an electric sense (Patullo & Macmillan 2007), but evidence remains lacking (Steullet *et al* 2007)). The iE fields expected to be induced are of relatively minimal strength and therefore unlikely to cause detrimental physiological effects to these taxa, supported by anecdotal evidence of benthic invertebrates living directly upon DC electrodes (Nielsen 1986) with no apparent effects (Walker 2001; Swedpower 2003). Therefore, no effects of induced electric fields surrounding EAONE cables are expected among these taxa.

6.2.2. Fish

In general, teleost fish are not believed to be electrically sensitive (except weakly electric fish, such as electric catfishes or knifefishes, but these are almost entirely tropical freshwater species). The marine Perciformes (electric stargazers) do possess electric organs, but appear not to utilise electroreception (Bradford 1986; Bullock *et al* 1983). Species such as salmon, tunas, plaice and cod have been postulated as being electrically sensitive in the past (Regnart 1931; Rommel & McCleave 1973; Kalmijn 1974), but more recent reviews have cast doubt on these abilities (Bullock 1986). Teleosts would probably only respond to strong electric fields of 6 to 15v/m or more, at which levels the fish would be repulsed (Uhlmann 1975; Poleo *et al* 2001). Sturgeons (Acipenseriform fish), for example, have been shown to veer away, or slow when approaching high voltage overhead lines (110kV) passing over the water (Poddubny 1967). However, even the maximum electric field induced around separated and unburied cables likely at EAONE are a number of orders magnitude less than these levels (several thousand µv/m). One exception is the European eel (*Anguilla anguilla*), which has been demonstrated as being sensitive to weak electric AC and DC fields (Berge, 1979; Enger *et al* 1976), and which possesses some life history stages in marine and coastal waters. However, the effect of the iE fields expected for EAONE upon eels would likely be similar to that elicited by B fields (see Section 6.1.2.); minimal and only temporary (Ohman *et al* 2007). Walker (2001), also believed there would be no effects of HVDC upon teleost fish, whilst investigating possible impacts of the Basslink HVDC between Australia and Tasmania. Teleost fish are unlikely to be affected physiologically owing to the weak levels of iE fields expected at EAONE. The teleost fish previously mentioned as being important in the southern North Sea (see section 6.1.2), including migratory species such as salmon, eels and lampreys are therefore likely to be largely unaffected by the iE fields induced by EAONE cables, regardless of design and deployment methodology.

By far the most likely group of marine animals to be affected by any iE fields are the elasmobranchs, owing to their sensitivity to even minute electric fields (5-20nV/m: Kalmijn 1982; Tricas & New 1998). Elasmobranchs are known to be repelled by strong electric fields, which has previously raised concerns that cables inducing such electric fields may act as barriers to movement (e.g. between feeding, mating and nursery areas). Theoretically, this was thought to have the potential to impair growth, health, reproductive success or survival of individual elasmobranchs, which might, in turn, affect population distribution and size. Precisely what magnitude of electric field induces an avoidance response in elasmobranchs is uncertain. Other than use of very strong electric fields (80V & 100A) to prevent large, pelagic sharks attacking divers and surfers, avoidance behaviour has only been documented twice in a few elasmobranchs; when small-spotted catsharks (*Scyliorhinus canicula)* were presented with DC electric fields of 1000µv/m (Gill & Taylor 2001), and when silky (*Carcharhinus falciformis*), white tip reef (*Traenodon obesus*) and zebra (*Stegostoma fasciatum*) sharks were presented with both DC and AC fields of 1000µv/m (Yano *et al* 2000). Neither of these studies was designed to consider a range of field strengths and so it is difficult to be certain of an avoidance threshold. However, other research demonstrated repeated, unequivocal attraction behaviour to DC fields of approximately 60µV/m (Kalmijn 1982; Kimber *et al* 2011), and from personal observation (Kimber pers. obs.[3]), whilst the majority of responses to DC fields of approximately 400 to 600µVm were attraction, some occurrences of avoidance were observed. This suggests that the threshold E field between attraction and avoidance lies somewhere between approximately 400 and 1000µv/m.

The maximum iE fields induced by AC cables associated with offshore wind farms have been demonstrated as being only slightly weaker than the smallest fields shown to elicit avoidance behaviour in elasmobranchs (CMACS 2003; Gill & Taylor 2001). Whilst there has been no evidence of repulsion within operational wind farms to date (bearing in mind there has been little research), in theory at least, stronger fields could cause such repulsion, and therefore potentially act as a barrier to movement and/or migration. Based upon the little information available, current

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[3] Behavioural observations noted during post-doctoral laboratory experimentation, but not pertinent to specific aims of project, and therefore not published.

thinking is that avoidance could potentially occur within close proximity of higher rated AC cables and HVDC cables (avoidance zone).

Table 2 shows that iE fields of more than 400μV/m are not expected for AC cables rated between 33kV and 132kV, with avoidance therefore unlikely. Such iE fields are only expected to occur within 1m or less from the cable surface of 220kV or trefoil 275kV AC cables. Burial would reduce this small avoidance zone; completely should burial be to a depth of 1m (effectively negating avoidance), or to tens of cm should burial be to 0.5m depth (Table 11). The avoidance zone is likely to be larger when considering separated 275kV AC cabling.

Table 11. Elasmobranch avoidance zone distances expected for EAONE AC cables assuming different burial depths

	Avoidance zone distance from cable					
Burial depth (m)	33	75	132	220	275 (trefoil)	275 (separated)
None	0	0	0	<1m	1m	< Further
0.5	0	0	0	Tens of cm	Tens of cm	< Further
1	0	0	0	0	0	< Further

Table 6 shows that for HVDC cabling, iE fields greater than 400μV/m are only expected within a few tens of cm (bundled) or 1m (separated) of 320kV cables, within 0.5m or less (bundled) or 1 to 2m (separated) of 500kV cables, or slightly further for 600kV cables (Table 12). Again, burial would reduce these small avoidance zones; completely for bundled cables of all ratings even at 0.5m burial depth, and to within 1m of separated 500kV cables (or slightly further for separated 600kV cables) should burial be to 1m depth. It should be noted that these distances may extend further when considering iE fields induced by elasmobranchs swimming swiftly through the B field, rather than tidal flow. However, uncertainty exists as to the swimming speed of the relatively small, benthic elasmobranchs in question (large pelagic sharks are often cited as cruising at 0.7m/s and bursting up to 8 to 14m/s), and it is therefore difficult to predict iE fields induced in this manner.

Table 12. Elasmobranch avoidance zone distances expected for EAONE DC cables assuming different burial depths

	320kV		500kV		600kV
Burial Depth (m)	Bundled	Separated	Bundled	Separated	
None	Tens of cm	1m	0.5m	1 – 2m	< Slightly further
0.5	0	0.5m	0	0.5 – 1.5m	< Slightly further
1	0	0	0	1m	< Slightly further

There is considerable uncertainty as to whether laboratory demonstrated repulsion would translate into avoidance of cables in the real world and, if so, whether such effects would be temporary or sustained. It is clear that any species capable of moving away from the seabed into the water column should be able to cross the cable; all elasmobranch species can theoretically do this, although whether predominantly benthic species such as rays would do so to pass by the cable is uncertain.

Elasmobranchs are responsive to E fields below those that elicit repulsive reactions, and utilise them for a number of behaviours; namely prey, predator, mate detection and navigation (Tricas & Sisneros 2004). There is concern that these fish will be confused by anthropogenic E field sources that lie within similar ranges to natural bioelectric fields. Aquatic animals emit weak E fields of three types: those associated with

(a) high frequency alternating currents caused by muscle action potentials (including heart, gill and motor function muscles);
(b) direct currents associated with the difference in potential arising from membranous and epithelial proximity to water in body cavities (mouth, respiratory and anal); and,
(c) low frequency alternating currents caused by the alternating expansions and contractions of body cavities modulating the direct currents.

The extent and strength of these E fields varies significantly among different taxa and in general each species' fields increase in strength with increasing body size (Kalmijn 1972; Haine *et al* 2001). Measurements of these bioelectric fields are difficult and vary between the few studies attempting them, but in general they seem to range between 1µV (small molluscs) to 500µV (small fish). Larger organisms most likely emit bioelectric fields in excess of the latter figure.

Marra (1989) recorded details of four power transmission failures in an AT&T transatlantic fibre-optic cable in the mid eighties. Upon raising the cable for repairs, bite marks and embedded teeth were found at the damaged sections. Further investigation revealed the damage was attributable to shark bites in all four instances. Attraction to iE fields induced around the cable (confusing them for prey) was considered the most likely reason for shark responses. Whether the sharks were harmed by biting the cables is unknown.

Laboratory behavioural studies have demonstrated both AC and DC artificial electric fields stimulating similar feeding responses in elasmobranchs (Kalmijn 1982; Tricas & Sisneros 2004; Kimber *et al* 2011). Recent work using small-spotted catsharks (*Scyliorhinus canicula*) as a model benthic elasmobranch has demonstrated that despite the ability to distinguish certain artificial E fields (strong versus weak; DC versus AC), the shark seemed either unable to distinguish, or showed no preference between similar strength, anthropogenic (dipole) and natural (live crab) DC E fields (Kimber *et al* 2011). In turn, this raises the question of whether these predators might effectively waste time and energy "hunting" electric fields such as those associated with subsea electrical cables whilst searching for bioelectric fields associated with their prey. A recent experiment which involved enclosing a section of sub-sea cable within a suitable area of seabed, using an approach known as 'mesocosm studies', allowed the response of elasmobranch test species to controlled electromagnetic fields (of similar intensity as those expected around offshore wind farm cabling, and therefore more likely to elicit attraction, rather than avoidance behaviour) to be assessed within a semi-natural setting (Gill *et al* 2009). The study provided the first evidence of electrically sensitive fish response to AC EMF emissions from sub-sea, electricity cables of the type used by the offshore renewable energy industry. Some *S. canicula* were more likely to be found within the zone of EMF emissions, and some thornback rays (*Raja clavata*) showed increased movement around the cable when the cable was switched on. Responses were, however, unpredictable and did not always occur, appearing to be species dependent and individual specific. What ecological implications such interactions might have upon the fish is still unclear.

S. canicula have been demonstrated as being able to rapidly adapt (learn) to concentrate upon profitable electric sources (associated with food), and habituate (ignore) non-profitable electric sources, although their memory of these adaptations seemed limited (Kimber *et al* submitted). Such traits would be expected for an opportunistic predator in a variable, coastal environment. This suggests these fish might initially be attracted to anthropogenic E field sources (should they resemble prey species' bioelectric fields), but be able to learn to ignore them relatively quickly during localised, short foraging bouts (as long as they could decipher them, possibly utilising senses other than electroreception). However, over longer time periods and greater distances, the fish may respond to the fields as if encountering them for the first time should they encounter them in the future. Again, the ecological implications of such interactions are still unclear.

As previously mentioned (see Section 6.1.2.), there are a number of elasmobranchs that commonly occur in the southern North Sea. Pelagic species such as the basking, porbeagle and thresher sharks are unlikely to be affected due to their habits leading them to be distant from the seabed and strongest iE fields. Benthic species, which are more likely to encounter the iE fields, include several commercially important species that have also suffered significant population declines, such as skates, rays, angel sharks, nursehounds (*Scyliornihus stellaris*) and spurdogs. TablesTable 7 Table 8 show the distances at which tidally induced iE fields are expected to attenuate to levels comparable to background levels. Within these distances, there is potential for elasmobranch confusion (confusion zone). Generally, confusion zones are not expected for lower rated AC cabling (33kv or 75kV), are limited to within 1m to a few meters for 132kV AC cabling and bundled DC cabling, and to 5 to tens of meters for higher rated AC cabling (220kV and 275kV) and separated DC cabling. Again, it should be noted that these distances may be increased when considering elasmobranchs swimming through B fields at velocities greater than tidal flow, but precise predictions are uncertain. Once again, the ecological significance of such confusion zones is unknown.

Physiological effects upon elasmobranchs are unlikely due to the relatively weak iE fields involved. However, Sisneros *et al* (1998) and Ball (2007) have demonstrated embryonic thornback rays ceasing body movement that facilitates critical ventilatory movement of water upon sensing artificial E fields. This suggested the developing rays were employing detection minimisation behaviour as the E fields were similar to those of predatory animals (such as small, adult elasmobranchs, and larger teleosts and cephalopds). There is potential for EAONE iE fields to affect this behaviour, but there is no evidence to confirm this scenario, and ecological significance is unknown.

6.2.3. Mammals and chelonians

A recent demonstration of electroreception of AC fields in a dolphin (Czech-Damal *et al* 2011) suggests the widely held belief that cetaceans are not sensitive to E fields may be incorrect. However, the authors state that the system appears to be far less sensitive than those used by elasmobranchs (a 460μV/m threshold of sensitivity was established, approximately three orders of magnitude lower than elasmobranchs). In addition to their predominantly pelagic life histories, cetaceans are therefore expected to be unaffected by E fields induced by EAONE cables. Chelonians are also expected to be unaffected, both due to no evidence of electrical sensitivity and their pelagic life histories.

6.3. Sea electrodes

Should sea electrodes be utilised during cable maintenance, once magnitude and propagation distances of EMF, and duration of use are determined, possible factors such as avoidance of strong fields at the anode, involuntary attraction to the cathode (galvanotaxis), in addition to the production of toxic substances such as chlorine and halogenated compounds at the anode via electrolysis should be investigated.

8. Cumulative considerations

It is important to consider possible cumulative EMF effects of different cables, both within the EAONE Project, and with pre-existing operational cables at the site.

The worst-case scenario when considering the number of EAONE cables is Option 2 (see Section 2.1) with 550km of array cabling, 13 HVAC cables measuring 10km each, and 4 HVDC cables measuring 100km each. There is potential for additive or subtractive (cancelling) effects upon EMF, depending upon distance between cables and direction of alignment. B and iE fields predicted for array cabling (three-core 33kV to 75kV AC) are relatively weak, and therefore any potential additive effects are likely to be negligible. The higher rated cables most likely to be utilised for HVAC export cabling (three-core 132kV or 220kV) are expected to generate moderately stronger EMF, but any potential additive effects are only likely to extend a few to 10 meters from overlapping EMF zones, therefore deploying such cables 50m apart (as planned) should prevent such effects. Overlapping EMF zones are likely to be larger when considering single-core 275kV cabling, especially if deployed separately rather than in a trefoil, but such technology is unlikely to be utilised. HVDC cabling EMF may generate reasonably strong EMF in close proximity of cables, especially if considering separated deployment, with potential additive effects extending to tens of meters. Bundling of cables would markedly reduce overlapping EMF zones to just a few meters at most, and deploying sets of bundled cables 50m apart should prevent such effects.

The export HVDC cable corridor passes across two operational sub-sea cables either side of the halfway mark between the proposed EAONE site and the landfall north of Felixstowe. According to engineers, HVDC cables crossing HVAC cables are required to do so perpendicularly to prevent induced currents (iE field) resulting in thermal hotspots and de-rating of the cable. The EAONE export cable corridor is planned to run approximately perpendicularly over each operational cable, thus reducing such affects as far as possible.

9. Conclusions

8.1. Overview of possible effects

Whilst research into electromagnetically sensitive species and the effect of anthropogenic EMF upon them is ongoing and at an early stage, this report reviews all relevant literature (both AC and DC) presently available and compares current theories with estimated EMF generation by the EAONE project. The following effects might be expected:

Magnetic fields

- No effects expected upon marine flora or micro-fauna.
- Possible impairment of navigation and/or physiological effects upon marine macro-invertebrates but only minor, in very close proximity to cables, and smaller effect thought likely for DC compared with AC fields. Possible physiological effects largely negated by burial.
- Possible impairment of navigation effects upon benthic fish, but only small, temporary deviations and only within close proximity to cables. Possible physiological effects largely negated by burial.
- No effects expected upon marine mammals or chelonians.

Induced electric fields

- No effects expected upon marine flora or micro-fauna.
- No effects expected upon marine macro-invertebrates.
- No effects expected upon teleost physiology. Only very minor and brief effects upon navigation expected among certain, benthic teleosts in close proximity to cables, if at all.
- Possible avoidance/repulsion of benthic elasmobranchs by strongest iE fields (potentially a barrier to movement) but limited to within close proximity of cables. A potentially significant impact cannot be ruled out, but there is insufficient knowledge to determine conclusively whether there would be any effect, let alone an ecologically significant one.
- Possible confusion of iE fields with bioelectric fields by elasmobranchs within close proximity of cables. Potential to affect feeding, escaping predators, locating mates, and navigation, although significance unknown.

- No effects expected upon marine mammals or chelonians.

The majority of potential effects of EMF expected to be generated by the EAONE project are expected to be minor and only occurring within close proximity of the cables. The developers plan on burying cables to depths of 0.5 to 5m where possible which will reduce EMF and potential effects upon marine fauna further still.

Owing to their acute sensitivity to EMF, and their use of EMF for such wide ranging behaviours such as prey detection, predator avoidance, searching for mates, in addition to orientation and migration, combined with many species facing severe population declines due to overfishing and habitat degradation (Baum et al 2003) exacerbated by their slow life history traits (Frisk et al 2005), elasmobranchs seem the most vulnerable taxa when considering potential effects of EMF.

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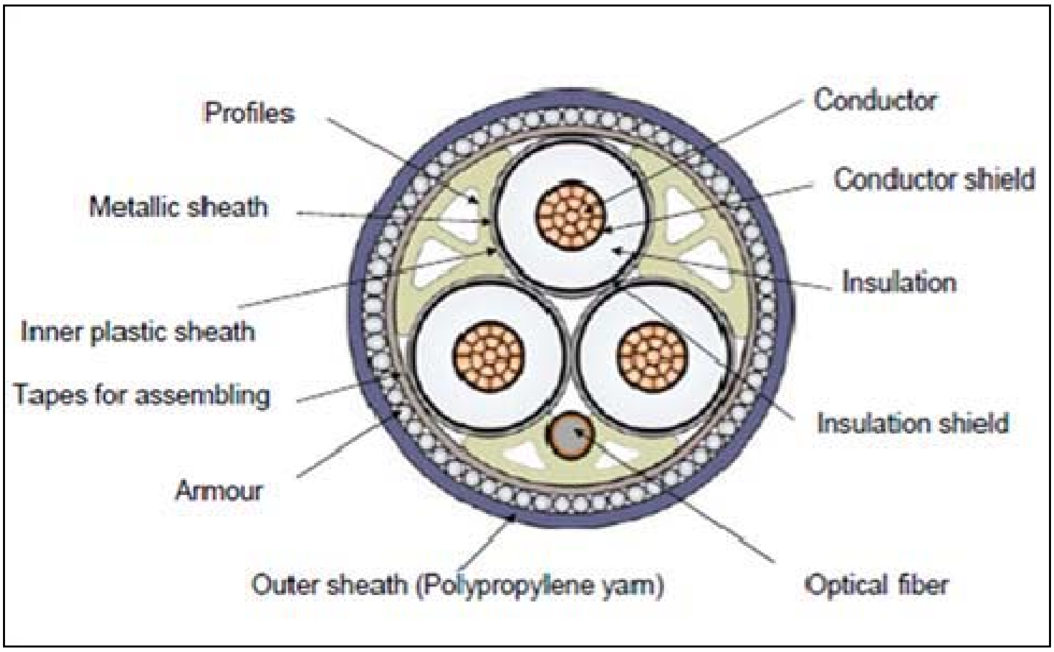
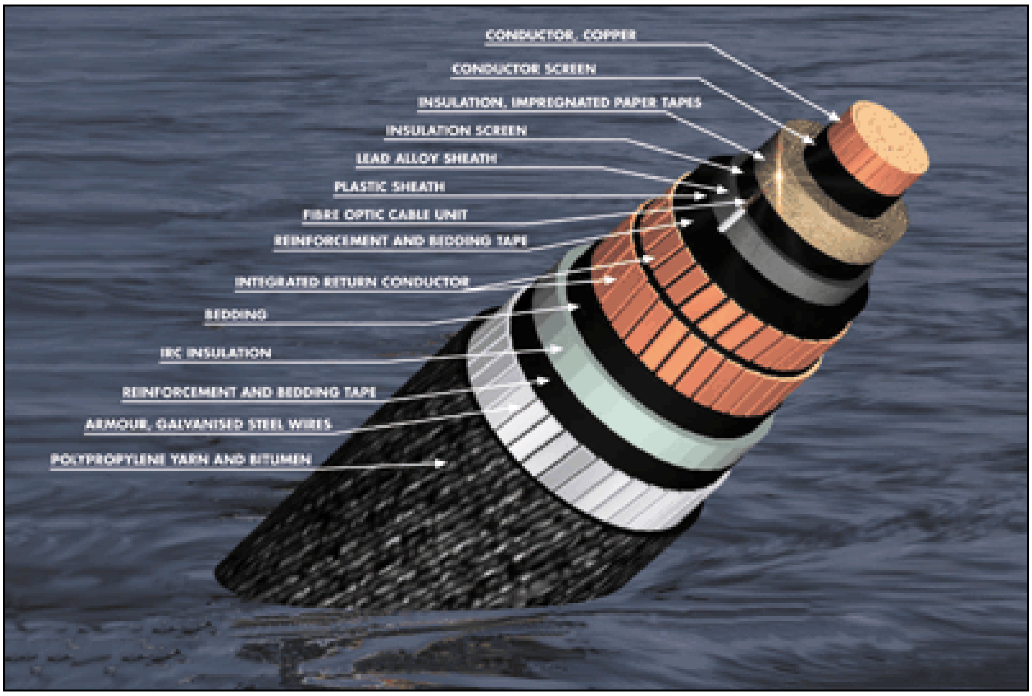
11. Appendices

Appendix 1. 132kV XLPE 3-core cable (courtesy of ABB)



Appendix 2. ±500kV HVDC MIND cable (courtesy of Nexans)



Appendix 9.2 Ends Here