Offshore
Wind Evidence
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Programme

# Electromagnetic Fields (EMFs) from subsea power cables in the natural marine environment

Technical workshop
Royal Institution, London
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## Contents

# Executive summary

To advance the understanding of anthropogenic electromagnetic fields (EMFs) from subsea power cables, an interdisciplinary expert workshop was facilitated by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) and the Scottish Government at the Royal institution, London on 17 and 18 January 2023. This workshop project forms part of the Offshore Wind Evidence and Change programme, led by The Crown Estate in partnership with the Department for Energy Security and Net Zero and Department for Environment, Food & Rural Affairs. The Offshore Wind Evidence and Change programme is an ambitious strategic research and data-led programme. Its aim is to facilitate the sustainable and coordinated expansion of offshore wind to help meet the UK's commitments to low carbon energy transition whilst supporting clean, healthy, productive and biologically diverse seas.

Fifteen interdisciplinary participants from England, Scotland, Sweden, Belgium and the USA attended the workshop. The participants were technical experts, in electrical engineering, biology/ecology, oceanography, physics and geophysics, represented by government, industry, academia and research institutes.

After an introduction to set the scene of EMFs in the environment and their relevance to marine species, the workshop was divided in four sessions. The first session focused on the cable characteristics and their influence on the EMFs. The second session tackled the interactions between the natural environment and cable EMFs, in order to estimate the total EMF environment, which presents the EMFs in a more realistic and integrated way. In session three, outputs from session one and two were considered in discussions of how to best incorporate data into models. The last session focused on adding the biological context and determined the key outputs and recommendations from the workshop.

The discussion highlighted several key points. Direct current (DC) and Alternating current (AC) cables are different, therefore there is a clear need to separate the consideration of EMF's based on the type of current applied. The main cable components involved in EMFs for DC are the core (the conductor) and the sheath. In addition, for AC the spacing between the conductors and the time varying magnetic fields will induce time varying electric fields.

Simple estimation or modelling of the EMF of a conductor at a specified point along a cable can be achieved through a quasi-stationary solution and both the magnetic field and the electric field can be calculated by applying Maxwell's equations. A simple 2D model (i.e. at a point along the cable) will provide much of the basic knowledge on the EMFs, whilst a 3D solution will provide greater insight and realism (along the cable and into the surrounding environment). Based on classical formulae accurate 2D estimates can be made for long straight cable runs assuming the quasi-stationarity is valid. However, when including the realities of bends and angles in the cables the complexities may be better evaluated with a non-stationary solution. In this case (and from a 3D perspective) more complex geometrical vector evaluations are required.

When considering cables within the environment there are factors that will affect the EMFs. The seabed (if it has no magnetic properties) will not change the magnetic field but may affect the electric field. Water movement through the magnetic field, will induce electric fields. At the interface between the water and the seabed there is a boundary layer, which is likely to be important in the magnitude of the electric fields produced. Hydrodynamic boundary interface conditions can be taken into account using 3D models and are most appropriate for HVAC cables. This may be particularly relevant when considering the 3D nature of animal movement through EMFs. The cable sheath and bonding arrangements will also affect sheath currents and therefore the EMF from cables.

Understanding the interaction between natural EMFs (e.g. the earth's geomagnetic field) and power cable EMFs requires both measurement and modelling of the components making up the total field. Cable orientation, bundling, or any helical twist will influence EMFs measured at any point. An EMF sensor should measure along three axes. It is acknowledged that measuring the electric field *in situ* is difficult and may require a bespoke solution. The variability in the magnetic field was highlighted as a critical aspect of measuring the total EMF. When considering power cables associated with offshore wind devices, the power generation varies considerably by day and season therefore temporal fluctuations should be considered in both EMF measurements and modelling.

For permitting purposes there is a need for simplified models to define a minimum set of parameters. It was therefore suggested to differentiate between modelling that is useful to have for the purposes of permitting in addition to modelling for research purposes in to determine any effects on marine animals.

A series of key outputs and recommendations were developed, leading to the following actions to enhance the understanding of EMFs emitted by subsea power cables. For ease, they are separated into recommendations that can easily be applied now and those that require research and development, although some may be easily actionable. Collectively, these recommendations will facilitate continued progress towards a clearer understanding of the cable EMFs and potential impacts on species.

**Recommended approach that can be applied now**

1. Two main approaches to EMFs modelling can be taken and broadly categorised as models applicable for permitting and those applicable for research:
   - For both permitting and research models, the essential knowledge, applicable to both DC and AC cables is:
     (a) the basic cable EMFs (i.e. energy emission only)
     (b) the cable EMFs in the marine environment
   - For the purposes of research, additional definition and resolution of the cable EMFs, and the interactions with the marine environment, can be gained by approaches (a) and (b) with:
     (c) research additions to better define the magnetic field component
     (d) research additions to define the motionally induced electric field
     (e) research additions to improve the AC model
2. Permitting models of EMFs are regarded as simple models due to availability of parameters but models can be improved in accuracy once cables are operational.
3. Optimum application of modelling to scenarios should be data driven.
4. When reporting an EMF model or measurement the following should be defined:

    - if it is an AC or DC cable and specifically what is being modelled/measured (magnetic field, induced electric field)
    - if the geomagnetic field is combined in the model/measurement or only the cable EMFs are reported (applicable to DC models)
    - the grounding and bonding arrangement of the cable
    - total length of cable and position along cable of modelled/measured field
5. Measurements of cable EMFs should report the same factors (see point 4 above) in addition to being accompanied with evidence of calibration and the method, including limitations in detection for the magnetic field and/or electric field as well as how the geomagnetic field was handled in the data processing.

**Research and Development**

- Data access should be explored with developers/cable owners, taking account of confidentialities, with the goal of accessing data on power variability and burial depths after cables become operational.
- Data assessment for optimum scenario model building is recommended through commissioned work to explore data in the context of realism and determine the best data to be made routinely available from cable operators.
- Spatial configurations of cables should be verified with industry, particularly for floating offshore wind in order to improve/develop EMFs models; how cables will be positioned in three-dimensional space, the degree of cable movement and geometry of the cable relative to itself (i.e. how bent/straight).
- Exploration of changes in electrical currents along an AC cable and modelling the associated EMFs to understand the realities of power cable EMFs in the marine environment (applicable to both modelling & measurement).
- Incorporation of the water boundary layer through developing a combined model (EMFs, boundary layer, geomagnetic field) and scaling to determine the influence on the EMFs, with a laboratory validation.
- Consideration of motionally induced fields in EMFs modelling, separate to the induced electrical fields associated with the AC cable.
- Determine how to model the total AC field and consider its relevance from the species perspective as well as the ability for regulators and researchers to interpret the model.
- Develop an agreed strategic approach with developers and cable/operators to measure EMFs to enable validation of models.
- Determination of other power cable factors that can influence EMFs, such as temperature of cable materials, power surge protections and potential cable faults as well as potential scenarios to be considered with respect to defining effects on marine species.
- The biological context is important when defining modelling scenarios of EMFs in the environment and this should include defining species detection ranges for intensities and frequencies of electric and magnetic fields. However, it is noted that the knowledge base on species sensitivities requires advancement hence this is a long-term goal to be met through studies of several model species and careful definition of appropriate metrics.
- The knowledge from current literature on the effects of EMFs on species was discussed and it was recommended that where studies are not directly applicable to subsea power cables, it should be clearly communicated.

- Fish/animal movement through the EMFs was deemed to be important to determine their likely exposure and could be informed through the 3D EMFs modelling approach in conjunction with animal movement models. The conductivity of the animal may be influential so should be taken into consideration.

Post workshop there have been specific activities that have provided outputs from the valuable discussions that took place. There is a simple model that can be applied for calculating magnetic fields associated with AC power cables showing how the helical twist of the cable affects the propagation distance of the magnetic field from the cable axis. The EMFs modelling recommended through the EMF technical workshop will feed directly into another Offshore Wind and Evidence Change (OWEC) funded project, FLOWERS – Floating Offshore Wind Environmental Response to Stressors (2022-24). The FLOWERS project has a work package which builds on the EMF modelling and measurement approach(es) developed through the workshop reported here. Finally, communication and knowledge transfer from the expert workshop are important to ensure the agreed approaches and recommendations (considering the natural environmental influences) are known about and referred to by the Offshore Wind (OSW) industry, the wider cable sector, environmental consultancies and also regulatory and advisory bodies. A dedicated webinar will be made available via appropriate media.

Improving the knowledge of EMFs from subsea power cables is integral to the better understanding of the potential effects and impact of EMFs on marine species. Such knowledge is required to support environmental considerations for the sustainable development of offshore wind and the global push for green energy. Better characterisation of EMFs in terms of the component parts (magnetic field, induced electric field) and how they are influenced by the marine environment is foundational to understanding how best to assess species responses to them. This workshop aimed to provide a standardised approach to estimating cable EMFs via agreeing the fundamental aspects for calculating, modelling and measuring EMFs (AC and DC) in 2D and 3D, and consider these in the context of the marine environment. Understanding the EMF interactions in the marine environment needs to take account of the natural electromagnetic field sources and relevant oceanographic considerations, which will influence the EMFs that species will encounter.

# 1. Introduction

It is now recognised that interactions between natural and anthropogenic sources of electric and magnetic fields (EMFs), such as those produced by the currents in subsea power cables (e.g. as used for transmission of electricity associated with offshore wind (OSW) or interconnectors) may have effects on marine species. Therefore, EMFs are sometimes considered an environmental risk for marine species, however, there is a lot of uncertainty about the EMFs associated with subsea power cables and how they interact with the marine environment and species. This uncertainty can lead to EMF questions being raised by stakeholders or during the public consultation phase of the formal environmental assessment for OSW or subsea power cable plans and therefore delay the consenting process. There is evidently a need to set out the current consensus on EMFs associated with subsea power cables and how to both model and measure them in the marine environment, to facilitate the process of proper consideration of the potential impact of subsea cable EMFs in environmental assessments. This document provides an overview of foundational work to enable the development of a consensus from an EMF expert technical group, on how best to determine EMFs in the marine environment. This work will assist stakeholders when assessing anthropogenic EMFs in the context of the natural environment for the purposes of understanding species interactions with EMFs and their potential effects. Better contextualisation of EMFs will therefore assist environmental assessments in planning and consenting offshore wind.

## 1.1. Background

Fixed OSW cables buried within or laid onto the seabed (with or without physical cable protection) emit EMFs into the marine environment. The seabed environment is inhabited by benthic species and species in the waters above the seabed (i.e. the bentho-demersal zone), and the development of floating OSW will present EMF emissions to pelagic species (Hutchison et al., 2020a, b). The EMFs are made up of magnetic and induced electric fields and they will be alternating current (AC) or direct current (DC) in accordance with the type of current and design of the (high voltage) power cable system. The magnetic fields from DC cables are known to combine with the Earth’s geomagnetic field, which will in turn induce electric fields. The magnetic field, whether DC or AC, created by transmitting electricity through a cable can be modelled in a relatively straightforward way based on the cable material characteristics and the applied power (e.g. Hutchison et al., 2021). However, the total EMF environment that a species will encounter is more complex. It includes the cable EMFs, the local geomagnetic field and interactions between the hydrodynamic environment as well as bioelectric fields (these all interact leading to deviations; positive and negative depending on the cable properties – see Hutchison et al., 2020a). Therefore, modelling of the total EMF environment as it would be encountered by the receptors is required. The cable properties and power levels at a given time will influence the intensity and spatial extent of the cable emitted magnetic field, which may further be influenced by the orientation to and interaction with the local geomagnetic field, and the hydrodynamic environment; therefore, these factors need to be considered at biologically relevant scales and modelled in three-dimensions (Hutchison et al., 2020b).

Currently, the uncertainties concerning EMF effects means that interpretation of evidence for and against ecologically meaningful effects of EMFs on species in the environment is difficult. The planning and consenting processes for OSW make use of the best-available evidence for decision making. Such decisions would benefit from an improved knowledge base when assessing EMFs as a potential environmental pressure that EM-sensitive receptor species (both benthic and pelagic) may encounter and subsequently experience an effect. To improve confidence in understanding the extent and intensity of the cable EMFs in the marine environment, a standardised approach to estimating and reporting the EMFs would be beneficial (Hutchison et al 2020b). Furthermore, a standardised approach would allow better characterisation and comparability between estimations of EMFs from different cables and would feed into robust scientific research studies assessing the effects on marine species of encountering operational subsea power cables. This in turn would improve the evidence and provide greater confidence in decision making.

A pre-cursor to the Technical Workshop reported here, were two workshops supported by the Marine Alliance for Science and Technology Knowledge Exchange and Impact initiative (MASTS). These events included one knowledge exchange workshop with policy and decision makers (June 2022), and a second with industry representatives (August 2022). The workshops allowed participants to identify and address communication gaps and strategically plan to address knowledge gaps. In addition, we developed illustrations to communicate the EMFs topic, which is difficult to grasp. The outcome of the workshops was an agreement that there are multiple factors that needed to be addressed to understand the topic which included: the EMFs generated by cables, species encounter rates, how species may be affected, and potential EMF mitigations. To better understand the EMFs, it was agreed that both more realistic modelling of EMFs and *in situ* measurements of EMFs to validate modelling would be beneficial. The specific details discussed at these workshops were used to help shape discussions during the technical workshop reported here.

### 1.1.1. Workshop overview

The EMF technical workshop was funded through the Crown Estate’s Offshore Wind Evidence and Change (OWEC) programme, as a Discretionary project under the theme, “Improving understanding of environmental impacts and benefits”. OWEC has the mission of “facilitating the sustainable and coordinated expansion of OSW in order to help meet the UK’s energy transition targets whilst also supporting clean, healthy, productive and biologically diverse seas”. A key element of the OWEC programme is to facilitate and promote bringing together stakeholders to gather, share and provide evidence that will help advance the OSW sector towards the UK net zero targets, while protecting and enhancing the marine environment.

The first stage to addressing the EMFs knowledge requirement was identified as obtaining agreement between experts from the relevant disciplines on the best way to represent the total EMF environment when considering biological receptors. Therefore, a two-day EMF technical workshop on “***Electromagnetic Fields (EMFs) from subsea cables in the natural marine environment”*** was held at the Royal institution (RI), London on 17th and 18th January 2023. Fifteen interdisciplinary experts attended; including electrical engineers, biologists/ecologists, oceanographers, physicists and geophysicists, representing government, industry, academia and other relevant stakeholders (Annex A, participants list; Fig 1). The workshop was *in-person,* which was important as the topic required extensive discussion and development of the topic area to address the aim and objectives. The workshop was facilitated by Cefas and the Scottish Government and opened with a welcome and introduction from Dr. Andrew B Gill concerning the importance of the venue for the EMF technical workshop.

**Figure 1:** Workshop participants next to Michael Faraday’s statue at the Royal Institution.

### 1.1.2. Michael Faraday’s pioneering EMF research at the Royal Institution

Dr. Gill highlighted the EMF topic history at the RI and why it was selected as the venue. The RI is where the physicist, Michael Faraday, undertook his pioneering studies during the 19th century, into electromagnetic induction. Faraday predicted from his laboratory studies the fluid dynamo principle, whereby an electric current would be induced owing to the motion of water through the Earth's geomagnetic field. Unfortunately, owing to a lack of sensitivity in his instrumentation, Faraday failed in his attempts to demonstrate the fluid dynamo principle, at Waterloo bridge over the River Thames (Fig 2). However, of central relevance to the aim of the workshop is that the fluid dynamo concept was correct, and we now have the understanding and ability to model and measure the induced fields produced. Discussing power cable EMFs in the research environment of Faraday and colleagues served as an ideal basis and inspiration for the participants.

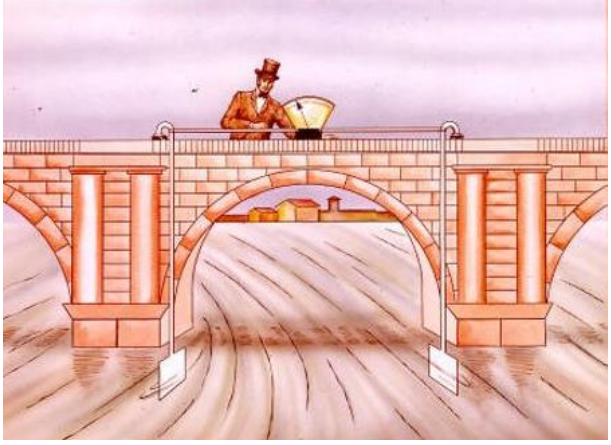

**Figure 2:** Waterloo bridge experiment (Faraday, 1832)

### 1.1.3. Aims and objectives of the workshop

The overall purpose of the workshop was to provide an agreed and standardised approach for estimating the poorly understood environmental energy emission of subsea cable EMFs in the marine environment through facilitated interdisciplinary expert discussion and agreement during the workshop.

The aim of the workshop was met through the following objectives:

1. Agree fundamental aspects for calculating, modelling and measuring EMF in 2D and 3D associated with High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC) subsea cables – through the input of marine electrical engineers and power cable experts.
2. Determine how to account for the cable magnetic field combining with the local geomagnetic field followed by consideration of how best to account for motionally induced electric fields associated with water movement/hydrodynamics – with input from biological oceanographers in addition to the marine engineering expertise.

3. Put the outputs from 1. and 2. into biological context with regard to the EMF that may be experienced by a receptor species.

Through the expert workshop the intended outputs were an agreed approach to calculate and model the EMF in two contexts: (i) the cable EMF emission itself and (ii) the cable EMF emission in relation to the marine environment (i.e. taking account of the local geomagnetic field with interpretation of the influence of hydrodynamic interactions). While the latter were more exploratory, consideration of the importance of different environmental influences allowed a standardised approach to be developed. A standard approach to modelling, measurement and reporting the cable EMF, taking account of the local EMF environment interacting with cable EMFs is important as it will then allow consideration of the EMF and potential effects in relation to the receptive species that inhabit the area. Another element of the workshop was to explore how to encourage and facilitate data sharing applicable to the aforementioned modelling and thereby more readily advance knowledge. Identification of key knowledge gaps and recommendations to improve the agreed approach(es) in the future were to be provided.

### 1.1.4. Workshop format

The workshop was divided into four different sessions with each session building on the previous session (Annex B, agenda). Following brief introductions to each session there was some ‘food for thought’ presented by participants to set the scene (Table 1). The first session focused on the cable characteristics and their influence on the EMF. The second session tackled the influence of the natural environment on the cable EMF emission, in order to estimate the total EMF environment, which presents the EMF in a more realistic way. In session 3, discussions in Session 1 and 2 were considered in discussions of how best to incorporate data into models. The last session focused on the biological context and summarised the key outputs from the workshop.

Following the presentations and Q & A for clarity, we facilitated discussions (Fig 3). The discussions were held in accordance with Chatham House Rules, which meant that comments were not attributed to individual names ensuring that anyone’s comments and perspectives were aired freely and could be taken into account. An exception was made for the presenters (in relation to their own presentation) and scientists who quoted their own work. It was particularly important to capture the wide discussion because we had a range of disciplinary expertise in the room and each participant was encouraged to ensure they understood all the topics being considered. This approach also ensured that we checked the consistency of terms (e.g. a current is electrical to power engineers, whereas it is water movement for oceanographers). Discussions were captured through rapporteur notes. A glossary is in Annex C.

**Table 1: ‘Food for thought’ presentations during each session**

| | Title | Presenter |
|---|---|---|
| | Setting the scene | Andrew Gill and Zoë Hutchison |
| **Session 1** | **Cable EMF emissions** | |
| | The Marine Electromagnetic Environment in the presence of HVDC cables | Robert Olsen |
| | Some Challenges for Magnetic Field & Induced Electric Field Simulation Modelling of the Subsea Cables | Brian Stewart |
| **Session 2** | **Total EMF including the natural environment (the reality)** | |
| | Electromagnetic fields from HV Cables | George Callender |
| | Experiences from measurements of EMF in the ocean | Peter Sigray |
| | Interconnector flows and Tests to verify ability to comply with planning conditions on EMF | Hayley Trip |
| | The geomagnetic field and geomagnetic data | Will Brown |
| | Oceanography for EMF | Jon Rees and Rory Murray O’Hara |
| **Session 3** | **Considerations for incorporating data and models** | |
| | | |
| **Session 4** | **Biological context, key outputs and recommendations** | |
| *further details of participants are in Annex A | | |

**Figure 3:** The group listened to presentations and engaged in discussions.

# 1.2. Setting the scene

## 1.2.1. Summary

Consideration of the effects of electromagnetic fields from power cables on the marine environment has had a patchy history, mainly explained by a lack of knowledge on which to base assessments of the effects. In recent times there has been a renewed interest from stakeholders, which has led to calls for further clarity in the understanding and determination of whether EMFs of relevance to receptive species occur, to what extent and how they may impact these species. The primary driver of the renewed interest is linked to the huge expansion in OSW development and associated cable networks, leading to the understanding of EMFs now being considered a priority environmental topic. Research into possible effects of EMFs on species has used a variety of approaches covering organisms from bacteria and invertebrates up to elasmobranchs and teleost fish (Kirschvink and Gould, 1981; Kimber et al., 2014; Taormina et al., 2020). It has been demonstrated that anthropogenic EMFs do influence the behaviour of marine animals (Gill et al., 2009; Hutchison et al., 2020). Some species, such as migratory eels, salmonids and crustaceans can detect EMFs via magnetoreception, whilst other animal groups, namely the elasmobranchs have a primary sensory system based on electroreception. These magneto- and electro-receptive abilities enable these animals to orientate, communicate and/or detect predators and prey (Rivera-Vicente et al., 2011; Beguer-pon et al., 2015). There was some explanation of the theories of how different electroreceptive and magnetoreceptive animals' sense and detect electric and magnetic field sources. The mechanisms are still not fully understood and there remains some disagreement in the literature. Non-EM receptive species may also be influenced by EMFs, regardless of their sensory abilities. For example, cuttlefish are known to create altered bioelectric fields in the presence of predator-type electric fields (Bedore et al., 2021). Also, early life-history stages of several animal taxa have been recorded as having their development or physiology affected by 50 Hz AC or DC magnetic fields. Yet as these, predominantly laboratory-based studies have begun to increase, there is very little consolidated information on the effects of power frequency electromagnetic fields on marine life in the natural environment.

These fundamental aspects are important for the application of the science to environmental management and decision making. For example, the planning and consenting processes for OSW make use of the best-available evidence for decision making. Such decisions would benefit from an improved knowledge base when assessing EMFs as a potential environmental pressure that EM-sensitive receptor species (both benthic and pelagic) may encounter and subsequently experience an effect. Foundational to this is a better understanding of EMF emissions from cables which can be achieved through modelling and measurements. This will help contextualise existing research findings and target future research to improve the knowledge base on the potential effects of EMF for marine species.

### 1.2.2. Discussion

The sensitivity of different species was discussed, and a suggestion was made to develop a list where effects can be excluded, or thresholds set. It was highlighted, however, that at this point in time the knowledge regarding possible effects is very patchy and incomplete, furthermore it will be species/taxon dependent. It was also raised that before setting out any such list it is necessary to come to some conclusion about what are the effects. It could be that there are positive or negative effects, these then need to be deemed harmful enough effects, to be interpreted as negative impacts on the species/taxon being considered. It was highlighted that understanding the EMF environment, in terms of its extent, the intensity and the temporal occurrence are all important when looking to undertake a suitable environmental assessment. Also, it should not be assumed that the higher the intensity of EMFs the worse the potential for negative effects. In fact, lower intensity EMFs could result in behavioural changes because these signals may be similar to prey and could result in attraction, while unusually high EMFs might repel organism away.

From the early discussion it was clear that to determine whether there could be effects on EM-receptive species was going to depend on what the EMFs are associated with power cables and how they affect the natural EMF environment that the species inhabit and may therefore encounter during their lives. The remainder of the workshop set out to explore, discuss and summarise these aspects.

# 2. Session 1: Cable electromagnetic field emissions

Session 1 focused directly on cable characteristics that influence the EMFs surrounding subsea power cables. The discussion was facilitated by a presentation by Prof. Robert Olsen titled: ‘The Marine Electromagnetic Environment in the presence of HVDC cables.’ The discussion was further facilitated by a presentation from Prof. Brian Stewart, titled: ‘Some challenges for magnetic field and induced electric field Simulation Modelling of subsea cables.’

## 2.1. The Marine Electromagnetic Environment in the presence of HVDC cables

### 2.1.1. Summary

The presentation provided important scene setting for the workshop participants as it highlighted some of the key aspects that are central to the consideration of EMFs from power cables. It was recognised that as DC and AC cables are different there is a clear need to separate the consideration of EMF's based on the type of current applied. Generally, there are multiple cores close together in one cable for AC, but separate single cores offset from one another for DC. The main components involved in the EMFs for DC cables are the core (the conductor) and the sheath. For AC the spacing between the conductors and the time varying magnetic fields will induce time varying electric fields. Prof. Olsen showed how Maxwell's equations are used for calculating fields, noting that there should be a differentiation between the electric and magnetic fields. The current through the conductor induces a direct magnetic field whilst the sheath surrounding the core keeps the direct E-field inside the cable. There is expected to be sheath current for DC cables perfectly grounded at both ends, however if only one end is grounded there will be no sheath current but there will be voltage on the sheath. The magnetic field around two offset conductors with equal and opposite currents depends on the spacing between them and will result in a field that is not the same in all directions (i.e. x and y will differ). In theory they should be parallel but in reality, that is not the case. Simple estimation or modelling of the EMF of a conductor at a point along a cable can be achieved through a quasi-stationary solution, which is defined according to the following assumptions: the cable, carrying the current, is considered to be an infinite straight line; where spatial and temporal changes are relatively slow; the local environment is uniform over the range and duration of interest; and the ocean bottom has been ignored. These are all elements to consider when determining what is needed to obtain a realistic estimate of the electric and magnetic fields from cables.

### 2.1.2. Discussion

- The need to distinguish DC and AC when considering EMFs associated with subsea power cables and differentiate between magnetic and electric fields was recognised.
- There was a point of clarification relating to terminology. The "magnetic field" is often referred to as the B-field (i.e. magnetic flux density) instead of H-field (i.e. magnetic field intensity). $B = \mu * H$, with $\mu$ being permeability of the medium. In most cases $\mu = \mu 0$, the permeability of free space. B-field is used more often as it is easier to measure and interpret.

- The need to consider harmonics was expressed. Harmonics are small deviations from the sinusoidal pattern that describes a current. They are mainly associated with AC systems, but harmonics also arise in DC cables in combination with a converter station, where they are filtered to restrict their levels. Where harmonic currents exist, they should be considered at what level (and hence the level of EMFs generated) and the spectrum involved may be capable of presenting any significant distortion to the existing EMFs.
- However, the relevance of harmonic frequencies to modelling was questioned because they are small compared with the 50 Hz or DC current and therefore make only a small contribution to the magnetic field. The need for simplified models and an avoidance of unnecessary complexity was highlighted. There was thought to be a need for some standardised guidance on this.
- In the context of permitting purposes there is a need for simplified models to define a minimum set of parameters. Detailed cable characteristics, such as the armour (which serves to reduce the field produce by the cable by a factor of 1.5 or 2; see de-Pino-Lopez et al., (2022)) is not usually known at the planning submission stage as the cable still needs to be engineered when the decision-making process is being finalised. Furthermore, some of these detailed aspects of the cable design are regarded as having relatively small effects on the fields produced by the cable.
- There is also the question of how accurate calculations need to be at the permitting stage. It was therefore suggested to differentiate between what is useful to have for the purposes of research into determining any effects on marine animals and what is necessary and relevant for permitting purposes. For permitting a simplified model can be used (including a statement of the conditions for which it is valid).
- The group acknowledged that including the grounding and bonding arrangements of a cable will influence the net current that flows in the sheath of the cable. These sheath currents should be taken into account in the assessment of the magnetic field as they are likely to dominate compared with the field from the phase conductors. The armour on the other hand was only regarded as relevant if it has magnetic characteristics, when it reduces the field by a factor of up to approximately 2 depending on the details of the armour (see del-Pino-Lopez et al., (2022)).
- For twisted cores, which will be present in three phase AC cables, it was highlighted that the magnetic field variation will reduce with distance away from the cable core axis. (This is considered in Session 2 and was explored further post-workshop, Figure 8).

## 2.2. Electric field Simulation Modelling of subsea cables

### 2.2.1. Summary

Whilst it is accepted that a simple 2D model will provide much of the basic knowledge on the EMFs, a 3D solution will provide greater insight and realism. Based on classical formulae (e.g. Biot-Savart Law and Faraday's Law) accurate 2D estimates can be made for long straight cable runs assuming quasi-stationarity is valid. However, when including the realities of bends and angles in the cables the complexities may be better evaluated with a non-stationary solution. In this case (and from a 3D perspective) more complex geometrical vector evaluations are required. Fortunately, there are modelling tools available such as, COMSOL Multiphysics, ANSYS Maxwell, Quickfield and others. Underlying mathematical methods are similar to the simple model, as they too are based on Maxwell's equations. The advantage of these more complex numerical methods is that boundary interface conditions can be taken into account using meshing and direct and iterative solvers and these are likely to be most appropriate for HVAC cables. If the environmental parameters are known (or measurable) then the relationship between the cable current, the B-field and the induced E-field can be modelled. The advantage of the 3D modelling approach is that 'cut-lines' (i.e. the B and E-field profiles in any orientation) can be estimated, this is particularly relevant when considering the 3D nature of animal movement through EMFs. Whilst 3D modelling is possible, the computational complexity and data requirements of 3D modelling are high, and it is important to know what data are/are not available. The conclusion was that whilst the 3D modelling provides potentially important insight, particularly when considering an animal within the EMF environment created by the power cable, further research and analysis is required.

### 2.2.2. Discussion

- For AC cables, the conducting current, at any one point along a cable may differ because of the frequency dependent fluctuations (50 Hz, Europe) and cable core position, which is influenced by any twist in the cable. Therefore, an EMF model based on one point in time at one cable position could be limited. This suggested that 3D modelling applied over a time interval (i.e. seconds) and at different points along the cable axis will be more representative of the EMFs at a particular section of the cable, rather than using a single point estimation.
- It was highlighted that the estimation of the EMFs at any point in the AC model can show the phase relationship between the induced electric field and the magnetic field, which could assist with determination of the EMFs encountered by an animal moving along a 3D trajectory.

- AC cables are generally used over short distances (10’s of km). In reality this type of cable can be longer, however, they are limited by the amount of reactive power required to energise the electrical circuit. Long AC cables need to incorporate a reactive power compensation scheme. For a single side compensation scheme (e.g. onshore) the resultant current (which will determine the magnetic field), is the vectorial sum of active and reactive current and this will increase with distance (Fig 4, blue line).
- With long AC cables normally double-sided reactive power compensation is applied as this has significant positive effect on the cable transport capacity and will lead to the lowest current (i.e. the active current) in the middle of the cable and the highest currents (vectorial sum of active current and half the reactive current) at both ends (Fig 4, green line).
- The result would be that the EMF at the ends of the cable and the middle may be different even if measured or modelled at the same time. Therefore, the position along the cable of any modelling or measurements should be indicated.
- The necessity of using complex numerical 3D models was questioned by some of the group, as analytical modelling is correct, with appropriate assumptions and can therefore give similar results. However, in complex 3D situations over time the more complex models can solve quicker, and they can be linked with fluid mechanics, which is useful when considering water movement and animal movement, which occurs in 3D.
- However, a disadvantage is the heavy costs for a license to use software, such as COMSOL.

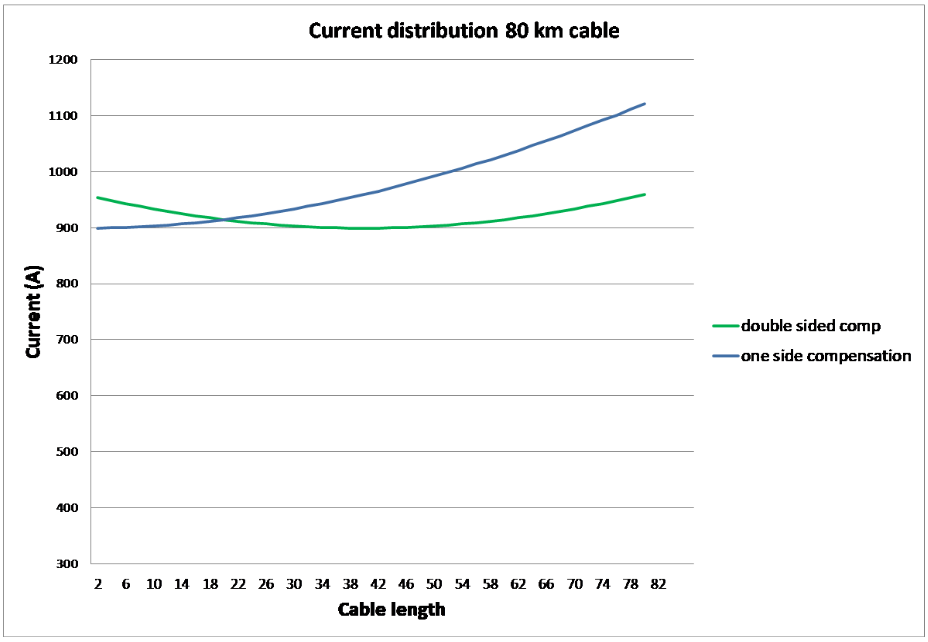

**Figure 4.** Relationship between AC cable length up to 80 km and the apparent current for

one-sided compensation (blue line) and double-sided compensation (green line). Courtesy of Frank de Vries.

# 3. Session 2: Total EMFs including the natural environment (the reality)

## 3.1. Introduction

The present focus of subsea power cable EMFs modelling is to first model the magnetic component created by the current in the cable. This is most applicable to the scenario of DC or AC cables in a static environment. For the AC scenarios, this approach omits the electric field induced by the time varying nature of the AC magnetic field. Additionally, present day EMF modelling does not necessarily consider the influence of the motionally induced electric field which can arise from a water body or animal moving through the magnetic field from the cable. The modelling that is applied, is also most typically focused on the EMFs from the cable and does not consider their combination with the local geomagnetic field. It was highlighted that the geomagnetic field will vary with the geographic location of the cable and that the orientation of the cable and the geomagnetic field will be important components in characterising their combination. It is regarded that there is a strong correlation between measurements and calculations for magnetic fields, as long as the parameters used for the calculations are representative (Swanson 1995). However, models of subsea power cables are typically not validated with *in situ* measurements, particularly for electric fields. Measurements of both magnetic and electric fields were highlighted as something that should be further discussed, in the context of the total EMF and its variability with load on a cable.

The introduction to the session then highlighted the factors in the natural environment which may influence the total combined magnetic field. These included the geomagnetic field, bioelectric fields from animals (e.g. respiratory movements), movement of water (e.g. tides) or animals through the cable magnetic field and the potential for sediment or seabed related factors to have influence. The conductivity of the water was also proposed as an environmental factor that may influence electric fields since export cables will pass through marine (full saline) and transitional coastal waters (estuarine) and possibly freshwater in some cases. The potential for electromagnetic reflections due to contrasting conductivity of the water and seabed were also proposed to the group for consideration. As there are several factors that will determine the overall electric and magnetic fields that an animal will experience and can respond to, therefore the term the ‘total electromagnetic field’ was proposed, hereafter ‘total EMF’ to cover this relatively complex situation.

## 3.2. Measurement of DC and AC cable electric and magnetic fields in the natural environment

Understanding the interaction between natural EMFs (such as the earth's geomagnetic field) and power cable EMFs requires measurements of the components of the total field, which then need to be taken into account when modelling the EMF in reality rather than just the cable EMFs themselves. EMFs are emitted regardless of whether a cable is exposed or buried because the earth is approximately transparent to quasi-static magnetic fields, and therefore it is the electric and magnetic fields that the animal experiences which are the most relevant. To determine the components of the total EMFs the participants began by discussing the measurement of cable electric and magnetic fields in the environment.

The discussion was facilitated by a presentation by Prof Peter Sigray titled:
'Experiences from measurement of EMF in the ocean.'

### 3.2.1. Summary

The presentation used an example of field measurements of both magnetic and electric fields simultaneously using the SEMLA (Swedish Electromagnetic Low-Noise Apparatus), which collected data on EMFs from HVDC interconnectors and an AC offshore wind cable. The magnetic field was measured as close as possible to the seabed (10 cm), using a fluxgate, AD converter, and software to display parameters. The sensor for the electric fields consisted of six electrodes. The main measurement was in the horizontal plane for E-fields. Inaccuracy and distortion come from the sensor platform therefore geometry and long arms reduce these effects. The axis of the cable was crossed perpendicularly to measure the electric and magnetic fields and their propagation away from the cable. The SEMLA was heavy so that it sat on the seabed on skis to allow it to be towed behind a vessel. This type of device works best on a flat sandy seabed. It can be used in a static manner or dragged behind a vessel with the speed of the vessel converted into distance to determine how far away from the cable the magnetic field can be measured. The overarching reason for considering measurements was to determine the combined EMFs and look to investigate how they changed along the cable route. Finally, the presentation provided thoughts on an analytical approach to modelling the EMF to compare with the measurements.

### 3.2.2. Discussion

- Field measurements of subsea power cable EMFs are scarce, however, whilst some show a close match between measurements and models (e.g. Kavet et al., 2016), others have shown the EMFs recorded are not always consistent with the models, especially for the AC case (Hutchison et al 2020). The group identified that this could mean that either the models or the measurements are not good enough or that something is being missed and not taken into account.

- It was noted that there are 'off-the-shelf' magnetometers available, but they vary in the information they can provide – some are too simple as they only inform the user where the cable is, not providing any field intensity measurements. As the EMF has three-orthogonal components, the group highlighted that an EMF sensor should measure along three axes.
- Gradient magnetometers are used for detecting wrecks in archaeology and are very sensitive. Two measurements are made, one in the water column and one on the seabed. These surveys look for magnetic anomaly signatures. The gradient arrangement inherently omits the Earth's magnetic field component from the total measured field. One option is to use a gradiometric arrangement, which consists of two separate fluxgates that effectively subtract the Earth's magnetic field.
- Measuring the electric field *in situ* is difficult. An E-field sensor is very sensitive to disturbance as it can be affected by the equipment itself and external influences. Commercial sensors are difficult to obtain but are available from specialist suppliers, however they are expensive and may require bespoke build to meet the precision and accuracy required.
- The variability in the magnetic field was highlighted as a critical aspect of measuring total EMFs. When considering power cables associated with offshore wind devices, the power generation can vary considerably by day and season. The few examples of magnetic field measurement at sites offshore were during good weather. Therefore, the magnetic fields emitted during higher power generation is underrepresented in the dataset. One solution to measure the magnetic field is to use a static sensor through time to determine the proportional relationship between the power transmitted and the magnetic field, e.g. the Elasmopower project buried a 3-axis magnetometer on a Dutch beach for a year (ElasmoPower - WUR).
- A key point of discussion related to the spatial variation of the EMFs, and an example of a measurement solution was an AUV with a built-in magnetometer (and in some cases E-field sensors) which moves systematically through the environment (e.g. Dhanak et al., 2015; Grear et al., 2022) to cover a specified area for a short period of time. It was noted however that combined magnetic and electric sensors attached to an AUV are expensive and there is a question over the accuracy of the measured E-fields as they can be affected by the measurement platform itself.
- The SEMLA studies showed that a magnetic field is detectable when there is no power transmitted, owing to a maintenance current. For the HVDC case, there was an unexpected E-field up to 100 metres both sides of the cable. The B field was narrower than the E-field, meaning that they were not related, and the sources of the E field was different. The spectral content showed background higher harmonics. It was recognised that peaks are expected as inter-harmonics (where mixing frequencies, intermodulate with each other),

therefore the harmonic frequencies should be specified to determine what is associated with the cable and those from other sources.

- For an HVDC system it was agreed that there may be apparent anomalies in the EMF associated with the rectifier, inverter, grounding, and the capacitor. There could be current leaks running in the grounds, or filters may not be perfect, hence residual frequencies will get through (i.e. not be filtered). Therefore, residual currents may end up on cable’s surface. This means that an understanding of the grounding for the power system being measured will be required.
- It was noted that cables associated with a high-power system are considered better balanced (i.e. currents are more equal and opposite) as the higher the voltage the greater the load.
- The group identified that the way the cables were oriented, or bundled may produce different EMF measurements at any given point. Furthermore, the cables may have helical twist in their design. Moving along the cable the maximum field occurs with periodicity of helical twisting, therefore there is variation in fields associated with the cable physical properties. This configuration will also increase the attenuation of the fields.
- In the wider context of the workshop, the group considered what the effect of the cable properties and position might have from the perspective of an animal. As the depth of the cable below the seabed surface increases the intensity at the seabed surface will go down, however, the apparent width of the magnetic field distribution will be greater (Figure 5). Furthermore, the variation of the magnetic field will approximate to $1/r^2$ for untwisted cable, and with cable twist the result will decrease more rapidly with distance.

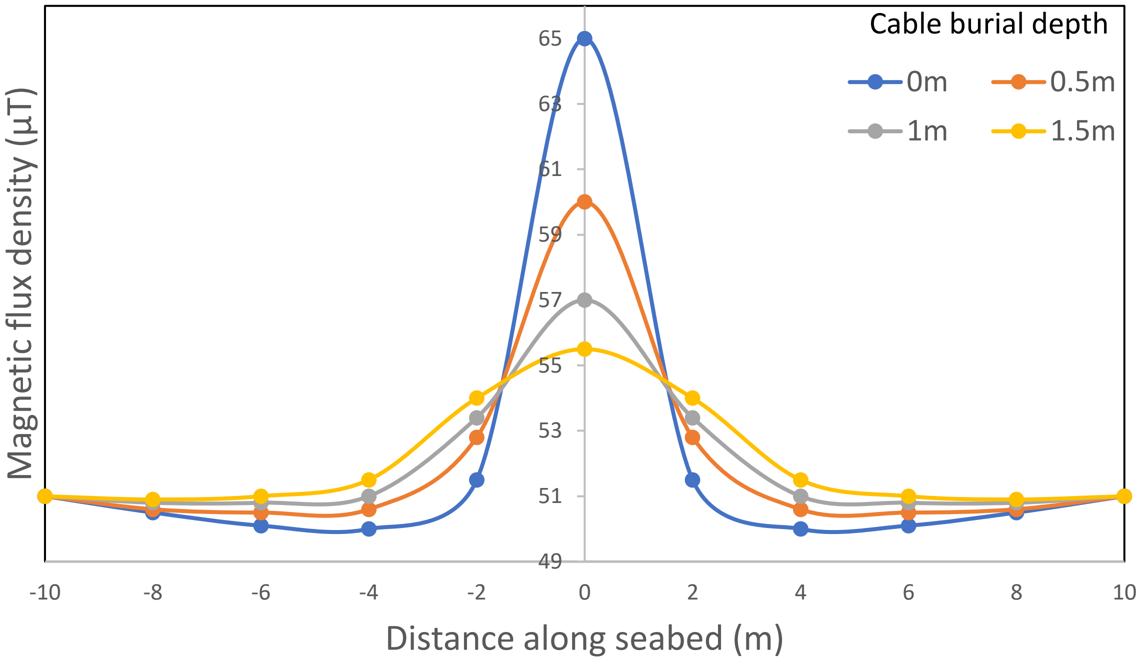

**Figure 5.** An example of baseline model of the DC-MF emitted from a power cable highlighting the reduction in maximum deviation of the B-field (µT) from the surface of the seabed and the widening of the EMF field along the seabed surface as burial depth increases the physical distance between an animal and the cable surface.

## 3.3. Considerations for simulation modelling - an analytical approach

Discussion on the modelling element was facilitated by Prof. Peter Sigray's presentation, titled 'Experiences from measurement of EMF in the ocean' and a presentation by Dr George Callender tited: 'Electromagnetic Fields from HV Cables'.

### 3.3.1. Summary

The presentation set out the basic elements of simulation for HV cable EMFs. It was highlighted that the current flowing through the phase-conductors of the cable must circulate in closed loops (hence net current in the conductors at a point along a cable is zero). 2D model simulations were presented building from a DC monopole to a DC bipole scenario and a separate 3-phase AC simulation. It was highlighted that the basic components for predicting the EMF in the marine environment can use Maxwell's equations coupled with Ohm's Law, $J = \sigma (E + v \times B)$, where electrical current density (J) is a function of conductivity (σ), electric field (E) and the cross product of velocity

(v) and the magnetic flux density (B). In the DC case, the v x B term leads to the creation of electric fields by deploying charge at interfaces, meaning that, without any movement of seawater there is no electric field in the marine environment. For the DC bipole cable, there are lower Lorentz forces on charges, therefore the electric fields created are lower intensity than for a monopole cable. With AC 3-phase systems, the alternating current produces alternating magnetic fields, which induce currents within the metallic components of the cable, primarily the sheath. The changing magnetic vector potential creates electric fields longitudinally along the cable. To a lesser extent induced currents can occur in the environment depending on the conductivity of the water. Several assumptions to simplify the simulations were explained which provide useful points for discussion with the group.

### 3.3.2. Discussion

- The group agreed that, in general, the seabed (if there are no magnetic properties) will not change the magnetic field but may affect the electric field.
- An important point raised was that the electric field, for both DC and AC, is not the same in the seabed and the water; it will vary according to the conductivity properties of the sediment and the salinity of the water.
- When considering water movement through the magnetic field, an electric field is induced. At the interface between the water and the seabed there is a boundary layer, which is likely to be very important in the magnitude of the electric fields produced.
- Velocity of the water is important for the resultant electric and magnetic fields. How large the boundary layer is, depends on the roughness of the seabed (see Session 3). It was suggested that a rough surface would cause a boundary layer of metres whereas for a flat or smooth surface it would be a matter of centimetres.
- The electrical current created by the movement of seawater was noted to return via the sediment, thereby acting as a closed circuit or if the cable is exposed (such as in the water column), current would form a closed loop in the water column.
- With water movement over a cable, the magnetic field is in the plane of the cable, and the electrical field is 90º pointing outwards (away from the cable). Therefore, the magnetic and electric fields have different directional components; it is unknown if this directional difference is important to animals.
- A discussion on the importance of the cable sheath concluded that single point bonding will eliminate sheath currents and therefore decrease the EMF from cables. However, single point bonding is very rare as normally the sheaths are bonded at both ends. Bonding at both ends allows circulating currents in the sheaths, which will increase cable magnetic fields. However, it was noted that there will still be eddy currents circulating within a sheath.
- The AC simulation discussion on sheath currents highlighted the aspect of helical twist, as the sheath currents will be influenced by this twist, and it will influence the main EMFs created by the conductors.

- In an AC cable the conductors are closer to each other than the conductors of a DC bipole cable. The narrower the distance between conductors the greater the cancelling out of the opposing magnetic field, and this can be increased with helical twist. Furthermore, the laying configuration (bundled or unbundled) and the voltage level (i.e. the insulation thickness) will also determine the intensity of the magnetic field.
- In the AC cable, the E-field is dominated by the time changing magnetic field (50Hz/60 Hz), and there are both higher and lower harmonics. Simulation of the harmonics is not easy as there are several reasons for harmonics being caused.
- It was noted that the helical twist does not have an apparent effect on the EMF when considered close to the cable. The field will however change further away, of the order of 3-4 metres depending on the length of the twist (i.e. its periodicity along the length of the cable – see Fig 8).
- Looking at modelling the propagation for an AC cable EMF based on the findings from the field measurements, there appear three regions to consider: very close to the cable where $1/r^2$ dominates (due to nearby phase conductors), medium range represented by exponential attenuation (due to twisting of phase conductors), and distant range where 1/r dominates owing to net currents in the sheath (see Fig 8).
- A question was raised concerning whether sensitive species detect lower frequencies. It was explained that there have been a small number of studies which showed that there can be a behavioural response to 50/60 Hz. Furthermore, lab studies have indicated that species exposed to these frequencies, can show developmental effects.
- The topic of temperature was highlighted because cables heat up the environment around them. Changes in temperature can occur over hours or longer depending on the installation. This may change the electroconductivity of the sediment and also reduced currents in the sheath.

## 3.4. The Earth’s Geomagnetic Field and other natural EMFs

The discussion was facilitated by a presentation by Dr Will Brown titled: The geomagnetic field and geomagnetic data.

### 3.4.1. Summary

The overview of the natural EM fields associated with the Earth (the geomagnetic field, GMF) highlighted that the Earth’s core, of liquid iron, acts as a giant dynamo and is the primary source of this field, slowly changing over years and accounting for around 97% of GMF strength at the Earth’s surface. Some geological formations are permanently magnetised, the part of the GMF that arises from this is known as the crustal (or lithospheric) field. Furthermore, as ocean currents move through the GMF they create motionally induced fields (MIVs). There are also influences outside of the Earth, because the Sun generates an immensely powerful EMF of its own, spitting out charged particles and entrained magnetic fields that hit the Earth's magnetic field creating storms in the magnetosphere. Furthermore, the Sun heats the day side of the Earth's ionosphere, causing motion of the electrically charged particles trapped there, which in turn generates magnetic fields. The natural background EMF will depend on location on the Earth. Factors affecting the intensity and range of EMFs across spatial and temporal scales were introduced. Figure 6 summarises the topic of geomagnetic field sources. There was also an explanation of how data were collected and modelled. These topics formed the focus of more detailed discussion.

- External fields
    - varies rapidly in time
    - from seconds to hours to days
- Crustal field
    - stable over geological time scales
- Main (core) field
    - varies slowly with time

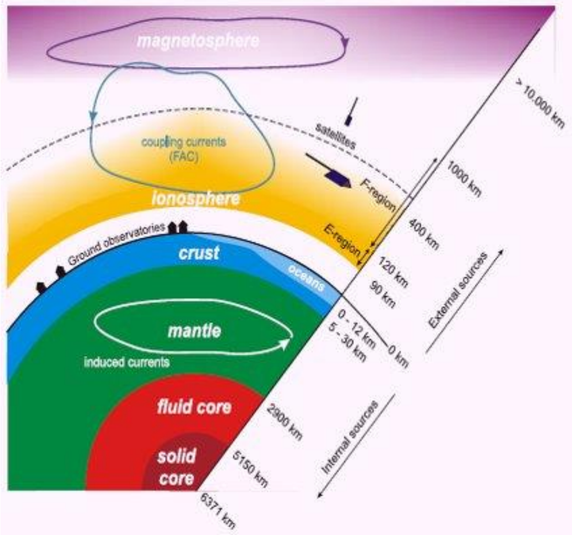

**Figure 6.** Geomagnetic and natural field sources across spatial and temporal scales (Olsen et al., 2010).

## 3.4.2. Discussion

- The group considered how natural EMFs varied. External fields are strongest under the Earth's aurora ovals (i.e. near the north and south magnetic poles). The magnetic field varies between quiet days, from 20 - 40 nT (plus or minus), to stormy days reaching a couple of thousand nT (on an algorithmic scale). This effect is reduced at mid latitudes, though the stronger a storm is, the closer to the equator effects can be seen.
- The EM fields are vector fields that change in time. It was explained that declination (the horizontal angle between geographic and magnetic North) and inclination (the vertical angle at which the GMF points), were important for determining the total field or magnitude of field intensity at a location.
- The time varying scale of the fields was examined further. Solar activity influences the GMF over seconds, minutes, or hours. Daily, the Sun heats the ionosphere, leading to physical movement of hot and cold regions, changing E-

fields, which causes local magnetic fields to peak at midday. Seasonality leads to light and dark hours change – the further away from the equator the greater the difference at any given site. Inside the earth the timescale is over decades and centuries, and for crustal magnetic fields and geology millions of years, which only changes with erosion or volcanic eruption.

- The group then explored what components of the natural field mattered when measuring the fields. All the components (i.e. magnetosphere, Ionosphere, Crust, Core), are included when measuring spatial scale, time scale and amplitude. Understanding each of the components of the natural EMFs and their influence requires regular observations, such as hourly, for a duration of several months.
- Furthermore, the contribution of each component can be modelled and explained (noting, there are some aspects that can't be worked out, however, as they are relatively small, they are regarded as small residual components). The important aspect is that magnitude, spatial and temporal variation scales are very different for each source of the GMF, allowing them to be untangled through modelling.
- When taking measurements through time, external fields are very important, magnitude is down to nanotesla (nT), with the main influence being the Earth's core. There are several smaller signals, such as ocean tides, which can alter the field by 1 or 2 nT.
- Time variation of the magnetic field drives induced E fields in electrical power systems and can have major influence on power supply.
- High frequency varying fields (i.e. radio frequencies) from outside the Earth can be measured at the surface but they don't penetrate very far into the sea. The core/crustal/magnetospheric/ionospheric fields can be measured at the seabed, at Earth's surface or out in space as they are low frequency and at a large enough spatial scale to penetrate water/rock.
- The influence of location and local geology was discussed. Rocks are conductive, therefore current flows through the ground.
- Big magnetic storms can affect high voltage transmission grid, as they flow into the ground then into the grid. Peninsulas are of particular interest for effects on the electricity grid as the contrast between rocks and salty seawater leads to strong current flows and peninsulas are the end points of a grid.

### 3.4.3. Data availability

- The way natural EMFs are measured, and the availability of data was proposed as important to ensure the interaction between power cable EMFs and natural EMFs can be determined.
- It was explained that not everything can be measured therefore natural EMF data are interpolate through modelling based on data from reference stations at different global locations. There are 170 observatories (all on land) across the world, which enable fine scale modelling and prediction of the natural EMFs.

Most of these observatories are found in Europe and North America, so its Northern hemisphere biased.

- The observatories have variometers, which give vector measurements of changing field (to 0.1 nT precision), and absolute instruments, which precisely provide the magnitude of the field; in combination they give absolute vector measurements through time. Observatories are good for monitoring temporal change but not so good for global spatial coverage.
- One key aspect highlighted was that it is important to keep equipment calibrated, that is why observatories are located on land.
- Areas over water bodies are extrapolated as there are no marine monitoring observatories.
- In addition, to observatories, it was identified that satellite data provides continuous coverage, of the entire earth every day. For example, the European Space Agency SWARM system (https://earth.esa.int/eogateway/missions/swarm) has 90 minute orbits, which takes four months for complete coverage of all local times. Satellites provide global data coverage which complements ground observatories and are the primary source of modern geomagnetic measurements for global models.
- For localised data, there are global crustal models, at a resolution of 30 km. For finer resolution, there are local air- or sea-borne surveys, e.g. UK area aerial magnetic survey. These are typically known as anomaly surveys – they record scalar field magnitude only, and remove the background core and external field trends to leave only the residual signal from localised magnetic "anomalies" (e.g. the local geology, buried magnetic materials).
- The group discussed marine surveys and recognised that with close tracking to the seabed the properties of the seabed could be determined. BGS data from North Sea is available at 1 km resolution from aero/marine mag surveys. Intertidal area data may be available.
- Scalar surveys were highlighted as the best approach to understand local anomaly fields, e.g. crustal field or on smaller scales for archaeology. When surveying the magnetometer needs to be distant from the parent vessel and electronics. Gradient surveys (i.e. using the difference between two instruments) are used for small local surveys, as background large scale fields are cancelled out by calculating the difference between two measurements from two points.
- It was noted that in some aquatic areas there may be high resolution data from other activities, such as the oil and gas industry. They use magnetic field sensors to guide drills across the North Sea, or drilling for export cables, underneath sea wall. The magnetic information is used to avoid hitting things.
- In addition, data from unexploded ordnance surveys may be applicable.
- In the UK, BGS holds data archives: aero magnetic surveys, 2 km spacing, with high resolution along the survey line. Low resolution data are publicly available and through licensed data which are of high resolution for commercial, government or academic use.

# 3.5. Measuring EMF from a buried cable

The discussion was facilitated by a presentation by Dr Hayley Trip, titled 'Interconnector flows and tests to verify ability to comply with planning conditions on EMF'**.**

## 3.5.1. Summary

National Grid provided an overview of a study which had been undertaken to define EMFs very carefully from buried HVDC and HVAC cables on land which passed through an airport. There was concern that the magnetic fields produced by the cables associated with the Interconnexion France-Angleterre 2 (IFA2) England-France electricity interconnector could interfere with aircraft operation and hence jeopardise the future safe operation of the airfield (National Grid, 2018). Stakeholders expressed concerns that calculations of magnetic fields were not accurate, and the aim of the study was to demonstrate the accuracy giving confidence in the planning evidence provided. To achieve this, measurements were taken of existing National Grid cables with a range of geometries; on cable samples under control conditions in a test facility and at the airport where a test length of cable was installed. These were compared to calculations performed for each of the situations, noting as accurately as possible the cable geometry and power loading at the time of measurements. Calculations of AC and DC magnetic fields and of compass deviation predicted the actual fields that were produced with considerable accuracy. The limit of accuracy of the calculation was determined by the limit of accuracy of the input parameters. For existing cables, the accuracy with which the current is known can be a limiting factor on the accuracy of calculations. For cables such as the IFA2 interconnector, where the current was known to greater accuracy than previous cable studies, the limit on the accuracy of the calculation was determined by the accuracy with which the positions of the conductors under the ground were known. Power load data of five different interconnectors were presented (incoming power is considered positive, exporting power is considered negative in reporting figures) demonstrating the sizeable changes over short periods of time (Fig 7). Power flow data for UK interconnectors is publicly available at https://www.bmreports.com/bmrs/?q=generation/avghalfhourIC/historic

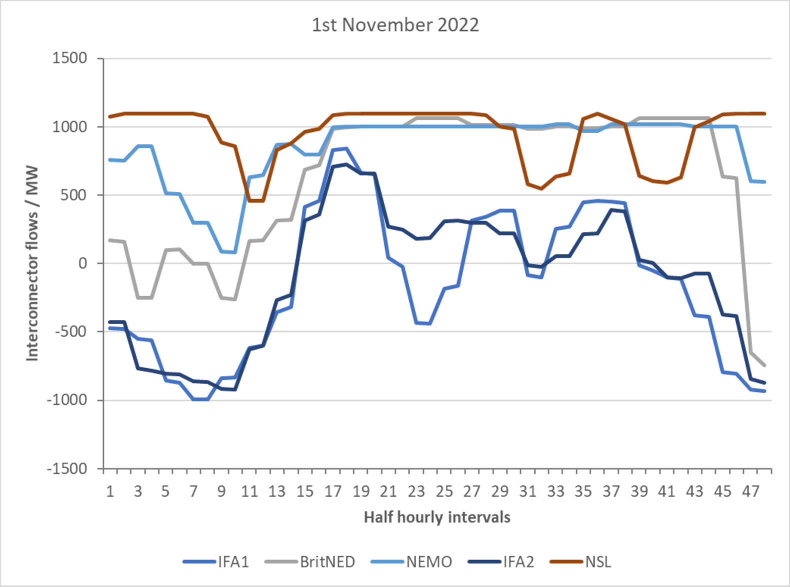

**Figure 7.** Short term variation in power load for five interconnectors.

### 3.5.2. Discussion

- Discussions focused on data access in terms of operational power over time for cables. National Grid indicated that 'historical' data are publicly accessible and would be useful for research purposes. It was clarified that data became historical c.a. 1 hour after the operational time.
- The speed of power change in a cable was discussed and acknowledged that the power load can vary very quickly. DC cables will be relatively stable along the route of a cable but there will be differences along the route of an AC cable which is part of the reason why DC cables are considered a better option for longer transmission distances. The variation in a long AC cable route can be calculated relatively easily.
- It was acknowledged that in an OSW setting, the power load is related to the wind conditions and access to data (power-wind relationship) would be useful to understand variability in the electricity transmission and therefore the EMFs from a subsea power cable. It was further noted there would still be a maintenance current (reactive current) even when there is no power or in the event of cut out.
- Defining the true depth of a buried cable was highlighted as important, however it was agreed to be very difficult to do, even in a controlled experimental setting and therefore requires further investigation.
- The calculation of the power cable magnetic field combined with the geomagnetic field is relatively straightforward mathematically. The National Grid (2018) report provides clear instructions. It is recommended that this approach is tested and validated for determining the combined subsea power cable magnetic field and geomagnetic field.

# 3.6. Oceanographic considerations in the context of EMF

The discussion was facilitated by a presentation by Dr. *John Rees* & Dr. *Rory O'Hara Murray*, titled 'Oceanography for EMF'.

## 3.6.1. Summary

An overview of the methods for measuring ocean currents was provided which includes, for example, mini-landers equipped with acoustic doppler current profilers (ADCPs). It was emphasised that this provides a profile of the full vertical water column and that prior to deployment, care is taken to calibrate the compass, taking into account the local geomagnetic field to ensure accurate readings. The output was exemplified and the ability to see the tidal current in the current speed as well as the residual current (which is a principal driver of sediment transport) was explained. The tidal components (e.g. M2 which is the semi diurnal component due to the moon with a period of 12.4 hours, and typically dominates) may also be identified from the data. Hydrodynamic (numerical) models used to understand different scales of water movement were introduced, such as unstructured grid models, e.g. the Finite-Volume Community Ocean Model (FVCOM) offering fine scale resolution at the coastline, e.g. the the Scottish Shelf Model (SSM) and nested sub-models, and those that model larger scales, such as the 1.5 and 7 km (horizontal resolution) NEMO models of the Northwest shelf Atlantic Margin Model run operationally by the UK Met Office. Building a model begins with data on the bathymetry of the area, the addition of open boundary conditions (water temperature, salinity and tidal water elevations/current), consideration of the transfer of heat from the atmosphere across the domain and data for riverine flows at the coastline). A model of the Pentland Firth and Orkney Waters, focusing on the island of Stroma was used to demonstrate the outputs of a high-resolution unstructured grid model, which include water elevation, velocity, temperature, salinity, dispersion and turbulence parameters. Bed roughness can also be incorporated, e.g. sandwaves and mudflats have different roughness and the model domain can reflect that. Model validation was indicated to be possible via additional data sources, such as sea surface temperature or via *in situ* measurement, like from drifters to verify near-surface water movements in the sea. It was indicated that there are several hydrodynamic models in the UK each with different resolutions depending on needs and examples were offered (Nucleus for European Modelling of the Ocean - NEMO, FVCOM, Telemac).

### 3.6.2. Discussion

- Velocity with regard to distance from seabed was indicated as being important.
- For model resolution it was indicated that more data are not necessarily better. More data will provide finer characterisation, but the relationship is not infinite and more data requires more resource to run models; there is a trade-off.
- The context of horizontal and vertical movements in these models was queried. It was acknowledged that hydrodynamic models did tend to be focused on horizontal movement, but deeper modelling was applicable to oil and gas wells. Many models are 2D depth average, but 3D models with anything from 10 – 40 depth layers are now considered the norm.
- Models were indicated to be suitable in handling storm events. Sediment resuspensions were offered as an example of applicability and the non-linear relationship between wave and current bed shear stress was highlighted.
- Current profiles and near bed boundary layers were discussed. The viscous bed layer is typically considered to be very thin (up to a few cm) and turbulent (classified as either smooth, rough or transitional turbulence) and transitions to the free stream via the boundary layer which is often assumed to be logarithmic (Fig 8). Boundary layers are almost always turbulent and vary in thickness, e.g. relatively thin in deep water with slow current and potentially occupy the whole water column in shallower faster moving water. (Fig 8).
- The viscous bed layer and relevance to species was discussed in that some species burrow into it. Vertical stratification of the water column was considered an important factor in determining these layers and their relevance, as well and oceanographic fronts, gyres, frontal jets and estuarine/freshwater flow.
- There was some discussion on turbulence around mooring cables and if that may be relevant to dynamic subsea power cables. The focus of hydrodynamic models in that context has been on sediment resuspensions.

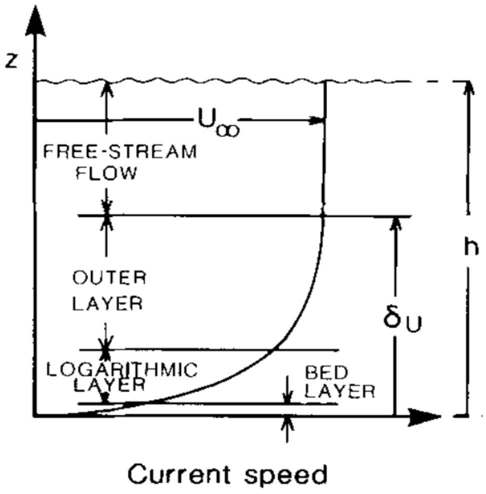

**Figure 8.** Typical water current flow profile and boundary layer thickness (δ), u=velocity, h=distance from the seabed (Soulsby, 1983).

# 4. Session 3: Considerations for incorporating data and models

## 4.1. Introduction

Where Session 1 considered the cable characteristics and emissions, and Session 2 explored the environmental variables that may influence the EMFs in the marine environment, Session 3 was focused on how to bring these aspects together to understand EMFs from the perspective of an animal species. These animals may be species that are known to be electroreceptive, magnetoreceptive or currently not known to be EM-receptive but will encounter the EMF, which may affect them in some way. It was acknowledged that there were many perspectives on the animal species that mattered in this topic area; those of regulators and stakeholders who have raised concerns but to understand the effect of EMFs on any species, we must look to adopt their perspective. Taking the vantage point of the species, that is to consider their position in space and time and how they may interact with a cable EMF was promoted (Hutchison et al., 2020). To do so, it is imperative that we understand several components relating to species that are EM-receptive, such as their sensory sensitivity and ability to detect EMF cues. The importance of those cues throughout the different life stages of species and how they move within the environment during their lives, will determine their likely encounter with subsea cable EMFs. This must be married with knowledge of the cable properties, such as the position in the marine environment, the cable attributes, energy supply at the time of encounter and if the cable is carrying an AC or DC current. It was further emphasized that although models tended to be point measurements on a cable route, the burial depth would change along a buried cable route, and this has the potential to influence the 3D proximity to the EMF source for a species, in addition to the species movement. Therefore, both the position of the animal in the water column/on the seabed and the depth of the buried cable determine the distance from source and the potential exposure to EMFs (if all other factors are constant). This was exemplified using published work on a model migratory species, the American eel (*Anguilla rostrata*) encountering a HVDC cable EMF in situ (Hutchison et al., 2021). It is common to assume that the closer a species is to a cable, the stronger the emission will be, however this assumes that all other factors are constant. In ecological reality, the following factors influence the specific encounter and must be considered together:

- Temporal changes in power levels
- Burial depth & fish position together determine the distance from source
- Temporal extent of exposure
    - Potential for aggregations around scour protections (artificial reef effect) and/or dynamic cabling as a midwater feature

    - Potential for a fish to have multiple encounters with a cable(s) due to how they interact with the cable/protection or due to the routes they travel

### 4.1.1. Discussion following the introduction

The group revisited the basic EMFs modelling that typically occurs, which was essentially a static magnetic field model of a single point on a cable at a given power level. Recapping on discussions over the course of the workshop, the group considered how to improve existing models and the merit of and potential to include natural EMFs, other environmental variables such as heat, boundary layers and wind generation variability. The group further considered what data range would be applicable (e.g. max, min, mean, median). The applicability of one model over another was an important aspect to consider in the context of modelling the electric and magnetic fields themselves but also in how to merge physics with ecology in models.

The discussion was varied and has been categorised below for ease of reading.

### 4.1.2. Discussion - EMF model types

- Discussion on the suitability of different modelling approaches occurred. Of those in the group who were directly involved in modelling it was apparent that both numerical and analytical modelling was applied regularly. There were representatives who used industry standard COMSOL models, and those who relied on excel models. Other software, such as Magnet and Opera could also be used with someone with appropriate expertise. The cost of these software's was discussed with licenses being particularly high for non-academics.
- It was promoted that more than one modelling approach was required; one for permitting and one for research purposes.

### 4.1.3. Discussion - what should be modelled (e.g. scenarios)

- Some members proposed that during the permitting process, modelling should be focused on the worst-case scenario. However, it was acknowledged that what was considered worst case for one species, may differ for the next and that may not be so easily defined as the ‘strongest EMFs’ when considering the biological context.
- In terms of modelling EMFs it became clear that prior to a cable being installed, scenarios were required and not all of the details applicable to a refined model would be available. Following installation, more details would be available that would allow for more refined models to be developed. Predictions at the permitting stage were indicated to be of little value in the research context.
- The group promoted that the biology was important in defining the scenarios that should be modelled and that understanding species sensitivities would enable more sophisticated models with greater relevance to be built. However,

it was equally acknowledged that those sensitives cannot be determined without realistic emissions to base studies on.

- The knowledge from current literature on the effects of EMFs on species was discussed and it was emphasised that where studies are not directly applicable to subsea power cables, it should be clearly communicated. It was further indicated that OSPAR were very focused on thresholds and that should be considered here too.

### 4.1.4. Discussion - data access and applicability for modelling EMFs

- Access to cable data were indicated to be confidential and difficult to access.
- It was suggested that permitted cable owners could be asked to collect data and/or share parameters to enable more sophisticated modelling.
- The group suggested that a simple magnetic field model was fine for a DC model (assumed within a static environment), but that an AC model was a bit more complex as it required some further aspects to be included for both the magnetic and electric field modelling (e.g. cable twist and load balance).
- Power level data were explored in terms of what type of data may be requested – the group proposed maximum, minimum, mode, average and the nature of the load balance for AC 3 phase cables.
- The importance of modelling old versus new wind farm power cables was highlighted.
- Access to power data collected over the course of a year of an operational wind farm, preferably multiple wind farms would be beneficial. However, it was also highlighted that wind farm developers will have forecasted what wind is likely to occur in order to determine power viability and that data could also be used in a scenario.
- It was promoted that someone should be commissioned to properly review the data available.

### 4.1.5. Discussion - incorporation of environmental variables

- It was agreed that the boundary layer would be beneficial to include in a model and suggested that if water current velocity was available for the cable area, it could be combined with an EMF model relatively easily. This could also be combined with the geomagnetic field.
- It was promoted that seasonal change relating to power generation would be worthwhile including.
- It was suggested that the model should be built, the effect on the EMFs scaled and then if determined to have relative consequences for the EMFs, then it should be demonstrated with a cable section in a water tank to verify the model.
- It was acknowledged that the above approach was most relevant to AC cable induced electric fields rather than the magnetic field (although they are inherently linked).

- Fish/animal movement was explored and deemed to be important. Conductivity of the animal may also be influential; however it was noted that the body of the animal may have variable conductivity.
- Different spacing of the DC cables was deemed important as the magnetic field increases with spacing.
- The 3D scenarios were regarded as important, particularly for floating OWFs with dynamic cabling. The cable positions relative to inter-array and export types were explored and need to be verified. The movement of the cable and geometry of the cable relative to itself was also considered an influential factor (e.g. how straight/bent the cable is). The water velocity in the dynamic cable scenario was also acknowledged to be important.

# 5. Session 4: Outputs from workshop

Species may encounter AC and/or DC cables in the marine environment. While there are many advances in biology and ecology that would facilitate understanding the potential encounter with and impact of cable's EMFs, an integral component is to understand the EMFs better. Understanding the physics is achievable through more realistic modelling that can then underpin research on species effects. Ideally models will be verified with EMFs measurement to validate and improve models where lessons are learned from *in situ* data collection. This section reports on the different types of model approaches that were identified through the workshop discussions and outlines a basic model that can be built upon.

## 5.1. EMF model parameterisation

The group considered the specific parameters to include in the permitting and research models for both DC and AC scenarios. Each cable characteristic was considered in turn, along with its applicability to the DC and AC cable scenarios, whether it was applicable to the magnetic or electric fields and if it was considered essential or non-essential to the permitting and/or research model. During discussions, the group considered the DC model followed by the AC model, however, the results of the discussion are combined due to the strong degree of cross-over.

The outcome was a tiered approach to the modelling whereby each level of the model builds on that of the prior level, by adding parameters to refine the model to be more realistic. An overview of the tiered approach is provided below.

For both permitting and research models, essential parameters were categorised by two approaches, applicable to both DC and AC cables:

(a) the basic cable EMF (i.e. energy emission only)

(b) the cable’s EMFs in the marine environment

For the purposes of research, additional definition and resolution of the cable EMF, and how it interacts with the marine environment, can be gained by approaches (a) and (b) with:

(c) research additions to better define the magnetic field
(d) research additions to define the motionally induced electric field
(e) research additions to improve the AC model

In the above breakdown, approaches (a) to (d) are applicable to both DC and AC modelling while approach (e) is specific to AC models only.  The parameterisation of each approach is described below and summarised in Table 2.

**Table 2. Parameters for modelling EMFs, dependent on requirements.** Cable parameters applicable for modelling EMFs for the purposes of permitting and research. Parameters are colour coded according to the applicability to modelling; energy emission only (orange, 1-3), energy emission in the marine environment (blue, 1-5), energy emission as it interacts with marine environment (green, 1-9), and the energy emission as it interacts with the marine environment with consideration of the motionally induced electric field (purple, 1-12), with an additional set of parameters to enhance the accuracy of the basic AC model (purple, 13-18). Applicability to the current type (DC/AC) and type of modelling (permitting (P) and/or research (R)), is indicated. Status reflects if the parameter is typically included in modelling, ready to be incorporated in a model or if further exploration would be required to incorporate the parameter in an EMF model.

| | | | | Parameter | Unit | Description | DC/AC | Model Type | Status |
|---|---|---|---|---|---|---|---|---|---|
| | | | | **(a) Basic Cable EMF (emission only; assumes infinite length of conductor)** | | | | | |
| 1 | 1 | 1 | 1 | Current | amps | The electrical current carried in the cable at a particular point in time. | DC/AC | P / R | Typical |
| 2 | 2 | 2 | 2 | Conductor Axes | x, y in metres | Relative coordinates of the centre of cable conductors so that it can be represented in the model domain. Will include the distance from conductor core to the outer sheath. | DC/AC | P / R | Typical |
| 3 | 3 | 3 | 3 | Cable diameter | metres | Full diameter of the cable as per technical specification. | DC/AC | P / R | Typical |
| | | | | **(b) Cable EMF in Marine Environment** | | | | | |
| | 4 | 4 | 4 | Spatial position | qualitative | Spatial position in the marine/coastal environment; buried in the seabed, surface laid or in the water column. This would be reflected in the cable domain relative to the seabed/water surface, to aid interpretation of the model output. | DC/AC | P / R | Ready |
| | 5 | 5 | 5 | Burial depth (if needed) | metres | Depth of burial is the distance from outer surface of the cable to the seabed surface. 'Target burial depth' is data available prior to cable deployment. 'As laid burial depth' is preferable data once the cable is laid. | DC/AC | P / R | Ready/<br>To be explored |
| | | | | **(c) Research additions** (magnetic field) | | | | | |
| | | 6 | 6 | Geographic location | coordinates | The geographic location is an important factor in determining the local geomagnetic field. The route of the cable and variation in terms of geography should be considered rather than a single point on the cable. | DC/AC | R | Ready – DC<br>To be explored - AC |
| | | 7 | 7 | Altitude | metres | Vertical distance relative to mean sea level for a specific time and date that will allow the geomagnetic field to be determined (x, y, z) for the above geographic location. | DC/AC | R | Ready – DC<br>To be explored - AC |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 8 | 8 | Orientation | degrees | Orientation of the cable relative to the geomagnetic field determines how the cable’s magnetic field and geomagnetic field interact. | DC/AC | R | Ready – DC<br>To be explored - AC |
| 9 | 9 | Protection permeability | henries/metre | If cable protections are used determination of the magnetic permeability would need to be included, if applicable. | DC/AC | R | Ready – DC<br>To be explored - AC |
| | | **(d) Research additions** (motionally induced electric field) | | | | | |
| | 10 | Boundary layer | reynolds number (dimensionless),<br>velocity (m/s) | The water velocity in the boundary layer may be an influential factor in determining the motionally induced electric fields in near seabed scenarios, as well as exposed cable scenarios due to flow around the cable surface.<br>Regional scale hydrodynamic models do not typically output boundary layer flow velocities, however, a logarithmic boundary layer model can estimate this from the near bed velocity from a 3D model. | DC/AC | R | To be explored |
| | 11 | Sediment conductivity | siemens/m | Sediment porosity will influence the volume of water in the sediment and its movement through the sediment, therefore, may influence the conductivity and the resulting propagation of the motionally induced electric field. | DC/AC | R | To be explored |
| | 12 | Water conductivity & velocity | siemens/m,<br>metres/sec | Water velocity and water conductivity (salinity) will determine the motionally induced electric field arising from the emitted magnetic field. | DC/AC | R | To be explored |
| | | **(e) Research additions to improve AC modelling** (to improve accuracy of basic cable EMF emission only model) | | | | | |
| | 13 | Cable laylength | metres | The periodicity of the helical twist of the cable, recorded in metres. | AC | R | Ready |
| | 14 | Sheath current | amps,<br>root mean squared | The sheath current would be determined from the sheath’s dimensions plus the material and/or impedance and the bonding arrangement. [Note: current not usually measured] | AC | R | Ready |
| | 15 | Armour (if magnetic) | metres,<br>henries/m | If the armour of the cable is magnetic, the dimensions of the armour (m) and the permeability of the material type would be included to provide an estimation of the armour screening effect from literature. | AC | R | Ready |
| | 16 | Radius of conductors | metres | The radius of the conductors within the cable’s core (in addition to the core coordinates). | AC | R | Ready |
| | 17 | Harmonics | hertz,<br>amps | The frequency at which the current is oscillating and multiples of that frequency. [The potential influence of the frequency may depend on the marine species sensitivity] | AC | R | Ready,<br>To be explored |
| | 18 | Cable length | metres | The specific position of the model scenario on the cable and total length of the cable (most applicable to the cable in the marine environment). | AC | R | Ready |

### 5.1.1. Essential parameters

At a minimum the essential parameters for modelling the DC magnetic field were the electric current within the cable, the coordinates of the conductor axes and the cable diameter (**Approach (a)**). Additional essential items with regard to characterising the cable in the marine environment included the spatial position of the cable (seabed, surface, water column) and the burial depth (if applicable), which should consider both the target burial depth and the as laid burial depth, when available (**Approach (b)**). Note that prior to cable deployment, modelling for permitting purposes, will only be able to make use of the targeted burial depth. However, following deployment, the 'as-laid' burial depth could be incorporated, which would better define the true EMF emissions that may be encountered by a species. Data access for as-laid burial depths is something that requires exploration as it is not presently commonly used. It is also noteworthy that as-laid burial depths may be correct at the time of deployment but become less representative over time depending on the environment (e.g. sediment movement).

### 5.1.2. Research Additions

Accounting for the combination of the magnetic field with the natural electromagnetic environment (**Approach (c)**) will improve the basic model approaches (a) and (b). The group agreed that the geographic location and the altitude of the cable relative to the mean sea level would allow the geomagnetic field from the core to be calculated at a specific space and time. The orientation of the cable, relative to the geomagnetic field is an important factor in determining the way the three-dimensional fields combine. This is particularly important for DC cables but less well understood regarding the biological interpretation of the AC field in the context of the geomagnetic field. The outcomes of models are typically reported as the total field for the DC cable but not for AC cables, where the cable only field is reported, although it is likely possible to model the total AC field. A further addition to better define the magnetic field is the consideration of the magnetic permeability of any cable protections used. It was emphasised that the cable orientation will vary along a cable route and therefore single point modelling was not wholly representative of the cable EMFs.

Modelling the motionally induced electric field was agreed to be an important component in the context of understanding how species interact with the cable EMFs within the total EMF environment (**Approach (d)**). Additional parameters were identified; however, it was also acknowledged that further exploration was required to define the relative importance of these parameters. In terms of hydrography, the water velocity within the boundary layer was considered to be important both at the level of the seabed for a buried cable emitting an EMF, but also the boundary layer around the cable for exposed cables on the seabed or in the water column (i.e. dynamic cables). For the EMFs of a buried or surface-laid cable, the sediment conductivity would likely be important and influenced by the water conductivity as well as sediment porosity, which controls the movement of water through the sediment. Separate to the sediment, the water conductivity and the water velocity in the water column would also be influential parameters for defining the motionally induced electric field current resulting from water movement through the magnetic field.

While the basic EMF model **(Approach (a) and (b))** defines the AC EMFs, there were specific additions that would add an improved degree of resolution to the model, which may be useful in the context of research (**Approach (e))**. The AC cable twist has cancelling properties on the magnetic field therefore incorporating the cable laylength (periodicity of the twist) will better define the AC EMFs. Incorporation of the sheath current and magnetic properties of the cable armour would be beneficial. The sheath current is defined by the sheath dimensions, the specific material (or its impedance) in addition to the bonding arrangement (i.e. at one or both ends of the cable). The armour material, if determined to be magnetic, would be incorporated in a model by the armour dimensions and the magnetic permeability of the material. In addition to the core coordinates, the radius of the cores would provide better resolution to the outputs of an EMF model. A further addition, to better define the AC field, would be incorporation of the harmonics, described as the frequency of the AC field (50 Hz in the UK and Europe) and multiples (and sub-harmonics) of that frequency. Lastly, due to the change in power transmission efficiency in a long AC cable, the total length and identification of where the specific point being modelled is located along the cable, as this would aid understanding of the variation in EMFs along a cable route.

### 5.1.3. Parameters considered relevant to fully understand the EMFs but not included in the Table 2

Additional parameters were discussed and were considered as useful to know for a complete determination of the EMF environment, however they are not included in the model approaches defined in (a) to (e) (Table 2). It was noted that materials in EMF models may sometimes include the conductor, sheath, insulator and armour but that not all materials are required in all situations. The radius of a core or thickness of a material may be incorporated, where applicable, as defined in approaches (a) to (e) above but is not necessarily required for all materials. For example, the radius of the conductors and thickness of the sheath and the armour (with additional details) will provide additional resolution in approach (e). The conductivity of the sheath (sheath current) or armour (if magnetic) screening effect, are considered important in a high-resolution AC model but were deemed not to be required in the DC scenario. Magnetic permeability was also included in the high-resolution model of the AC model (Approach (e) and may be applicable in the context of the cable protection in the marine environment where it is a magnetic material. Permittivity is a parameter that is required in COMSOL modelling but was deemed as having a negligible influence on the modelling outputs.

Through discussions, it was clear that the group were not yet able to define how to approach defining the motionally induced electric field that results from an animal moving through the magnetic field in a conductive environment. There were several questions raised about how the animal itself, e.g. with different types of skin, may influence the motionally induced electric field as well as how an animal's sensory mechanism may recognise and interpret it.

### 5.1.4. EMF Model Scenarios

In applying the model approaches, (a) – (e), outlined above (Table 2), the group agreed that the single point modelling that is typically undertaken is not representative of the cable as a whole. It would be better to consider the cable route as well as considering a range of electricity currents to account for variations in power transmission. Applicable datasets that would enable the establishment of electrical current variation were discussed, which may include the maximum, minimum, median, mode, and mean currents over time. It was promoted that the best approach should be determined through a proper analysis of model applications.

During the discussions, it was noted that the scenarios modelled in cable plans for offshore wind developments (in the public domain) were variable. National Grid shared the basic scenario that they model for the purposes of permitting. This included the application of the analytical model to determine the maximum EMF at the surface of the cable, the EMF at the minimum burial depth in addition to distances of 1m, 5m, 10m, 20m, which were applied at both height above the cable and horizontal to the cable. Such an approach may be useful applied to subsea power cables.

# 6. Key outputs and Recommendations

Improving the knowledge of EMFs from subsea power cables is integral to the better understanding of the potential effects and impact of EMFs on marine species. Such knowledge is required to support environmental considerations for the sustainable development of offshore wind and the global push for green energy. Better characterisation of EMFs in terms of the component parts (magnetic field, induced electric field) and how they are influenced by the marine environment is foundational to understanding how best to assess species responses to them. This workshop aimed to provide a standardised approach to estimating EMFs via agreeing the fundamental aspects for calculating, modelling and measuring EMFs (AC and DC) in 2D and 3D, in addition to understanding the EMFs in the context of interactions in the marine environment. Understanding the EMF interactions in the marine environment included consideration of the natural electromagnetic field sources and relevant oceanographic considerations, which may influence the cable EMF or help model motionally induced electric fields. These aspects of EMF in the marine environment were considered with the intention of understanding EMFs from the perspective of the species and their realistic encounter of subsea power cable's EMFs. Therefore, the biological and ecological context was an important component that was revisited throughout the workshop.

This section summarises the key points learned through the technical workshop and identifies clear recommendations that could be applied now and those that form future areas of research and development. Throughout the summary, cross-references are made to the workshop sessions should the reader wish to understand the background in more details.

## 6.1. Modelling EMF

Species may encounter AC and/or DC power cables in the marine environment, therefore, discussions on how to model EMFs were focussed on both AC and DC approaches. Species may encounter EMFs from inter-array cables and/or export cables. These cables may also take different positions in the marine environment (fixed on the seabed, buried in the seabed, dynamic cables in the water column) meaning that benthic, bentho-pelagic and pelagic species may encounter AC and/or DC EMFs differently. In defining how best to model EMFs, the workshop considered what to model, the type of modelling approach and platform that may be used as well as the scenarios that could be modelled. There was a general agreement that there were different types of modelling suited to different goals, whether related to permitting or research.

Before considering a model of EMFs or in reporting a model output, it must be made clear if it is AC or DC and which components of the EMFs are being modelled (magnetic field, induced electric field; Session 1). There may be further elaboration if the interaction with the geomagnetic field is considered in the model which would be applicable to the DC magnetic field. A further interaction in the marine environment that should be considered in modelling, in the future, is the motionally induced electric field. In reporting the cable model, the grounding and bonding arrangements of the cable sections should be clearly stated as they will influence the net current that flows in the cable sheath (Session 1).

It was agreed that with the present stage of knowledge, analytical methods, whilst missing some of the detail, should be sufficient for determining levels of EMFs emitted into the environment from a subsea power cable that can be applied when considering the potential environmental impact for a species (Session 1). However, numerical and analytical modelling both have their place, and a variety of modelling platforms are available which may include Excel, industry standard platforms such as COMSOL as well as software such as Magnet and Opera (Session 3). The group were of the opinion that it was not necessary for a single modelling platform to be adopted to enable standardisation and rather the focus should be on standardising the parameterisation according to needs and the scenarios applied (see Table 2, Session 4).

It was clear from the workshop that for model parameterisation, a simple model is applicable for the DC magnetic field, but a more complex model is likely needed for AC EMFs (Session 3). In theory, the three phases of an AC cable are in balance, therefore the modelling would consider the simple case of three straight conductors. However, in reality the AC conductors are unequally loaded and therefore not balanced between the three cores, and the three conductors are often twisted too (Session 2). The imbalance across the three cores results in an induced electric field from the cable, and the period (lag) of the cable twist is influential to the resultant AC EMFs and therefore these factors need to be accounted for in a realistic model. In addition, there is a need to consider the induced electrical fields associated with the AC cable and the eddy currents separately (Session 1). Eddy currents were not considered further in this workshop and remain an area to explore in more detail.

Generally, DC cables are a better option than AC cables for long distance electrical transmission, due to better energy transfer efficiency. However, it was highlighted that even over the distances where AC cables are used, there are changes in the electric currents along the cable (see Figure 4). This change along a cable and how to model the associated EMFs was agreed as a current knowledge gap and is something the group highlighted should be addressed to better understand the realities of power cable EMFs in the marine environment (Session 1). It was recommended that the position along the cable of any modelling or measurements should be indicated when reporting EMFs, particularly if the cable is long and has reactive power compensation (Session 1).

An important outcome of this workshop was the identification of different modelling for different objectives, which were broadly categorised into models for permitting and models for research purposes (Session 1, 3 and 4). For both, permitting and research models, essential parameters were categorised by two approaches, applicable to both DC and AC cables (Table 2):

(a) the basic cable EMFs (i.e. energy emission only)
(b) the cable EMFs in the marine environment

For the purposes of research, additional definition and resolution of the cable EMFs, and the interaction with the marine environment, can be gained by approaches (a) and (b) with:

(c) research additions to better define the magnetic field
(d) research additions to define the motionally induced electric field
(e) research additions to improve the AC model

Approaches (a) to (d) are applicable to both DC and AC modelling while approach € is specific to AC models only. The parameterisation of each approach is described in detail in Session 4 and summarised in Table 2. Note that during the permitting process, there are limited cable parameters available and so models will be necessarily limited to the basic ones, however, once operational, further model parameterisation will be possible and model improvements could be applied (Session 3). Data considerations are reported in more detail below.

The application of the model approaches to different scenarios was deemed an important consideration. Applicable scenarios will vary depending on the goal of the EMFs modelling and should not necessarily focus on the perceived worst-case scenario; it should consider the biological context to help frame needs (Session 3). For example, there is a common assumption that the worst-case EMF scenario results from the maximum possible load in a cable (i.e. maximum capacity). The worst-case EMF scenario, however, is unrealistic and will only occasionally occur due to fluctuations in energy transfer, and the levels of magnetic and induced electric fields at maximum loads, which may be relevant for some species, but not for others. Data availability will drive the development of the best scenarios to model and to obtain a more realistic overview of EMFs that species may encounter. It was also acknowledged that the worst-case EMF scenario should be dually driven by species understanding in terms of what levels of EMFs different receptive species may be able to detect. Note though that this is not an easily discernible evidence gap and would be applicable for multiple species, therefore remains a long-term goal.

In terms of the spatial configuration of cables that may influence what EMFs species will encounter, there were several factors that were considered important for scenario building. For DC cables, where there may be multiple cables laid within a cable corridor, spacing between DC cables was an important factor in EMF modelling (Session 3). The 3D spatial configuration was deemed important, particularly for floating OWFs with dynamic cabling and cable position verification from industry is required. The movement of the cable and geometry of the cable relative to itself were also considered important factors (e.g. how straight/bent the cable is) (Session 3).

## 6.2. Cable Data Access to Support Scenario Development

Access to cable data was a theme that came up repeatedly during the workshop discussions. Data from offshore wind farm companies and/or subsea cable companies are not readily accessible. In many cases, data may be considered confidential. However, the merit of being able to access data was clear and is considered a high priority to progress.

The electrical current in a subsea cable is dependent on the load to be transferred at any one time. This will vary between cables and their roles (e.g. inter-array, export) and may also be a function of the energy being harnessed from the wind resource (Session 2). The group agreed that power data would be exceptionally useful in defining the most realistic scenarios for EMFs and specifically, the intensities of EMFs that a species may encounter. For offshore wind power, knowledge on the power in the cable related to the wind conditions would be useful and facilitate understanding the variability in the electricity transmission and therefore the EMFs emitted by a power cable (Session 2) It was suggested that even if power data were not readily accessible, wind forecast data may be used by developers during the planning phase and may offer insight when operational data are not yet available.

For a buried operational cable, the determination of true burial depths is required when considering the distance of a species from the source of the EMFs (Session 2). However, it was acknowledged that determining true burial depths was a difficult task and data availability may be limited to target and as-laid burial depth data. It was suggested that some companies could monitor burial depth remotely. Exploration of burial depth data access with developers was deemed a priority.

Data access (power and burial depths) remains a key point to explore further with permitted cable owners (Session 3). It was acknowledged that National Grid time series data on power transmission can be made available on request and interconnector data are made publicly available to download once it is considered 'historical' (c.a. 1 hour after operation; Session 2). There are also numerous literature sources which specify emissions from terrestrial cables which may offer some insight into magnetic fields, however, they would be more likely to be driven by consumer demand and interpretations may be limited.

A commissioned piece of work to explore data in the context of realistic model scenario development was promoted (considering; max, min, mode, mean, seasons, annual or other) (Session 3). Access to an annual data set from one or more wind farms would be most beneficial in developing realistic scenarios to be modelled and would greatly assist researchers in studying species effects with proper subsea power cable context. This may also enable recommendations on which data would be most useful if it could be made routinely available, thereby improving the realism of model scenarios over time.

## 6.3. Modelling EMFs with interactions in the marine environment

Subsea power cables occur in the coastal and marine environments and therefore have the potential to interact with natural sources that may influence the EMFs and ultimately how a species encounters it. The most commonly addressed natural variable source is the Earth's geomagnetic field, although there are often incorrect assumptions that minimise the potential importance of a cable EMFs to a species. For example, a common but inaccurate assumption is that if the cable's magnetic field is lower than the local geomagnetic field it can be considered negligible. Evidence indicates that small gradients of change in the geomagnetic field are biologically relevant and in some cases cable magnetic fields and geomagnetic field will interact. The workshop gave full consideration of potential sources of natural electromagnetic fields and their relevance to cable EMFs in the context of species effects. It was also noted that some existing human metal structures have magnetic signatures that may have an influence at particular locations, such as near steel bridges. Additionally, the workshop focussed on the potential hydrodynamic and oceanographic factors that may influence the induced electric current of an AC cable and the motionally induced electric field applicable to both AC and DC cables, as well as how modelling the motionally induced field may be achieved.

### 6.3.1. Consideration of the natural electromagnetic environment

According to present knowledge the interaction of the Earth's geomagnetic field (GMF) with power cable EMFs is only applicable to the DC case, because the time varying nature of AC magnetic fields is different to the static nature of the GMF. There are suggestions that AC magnetic fields may superimpose on the GMF and when considering motionally induced fields too, this may have some relevance to marine animals; a topic that requires further research.

It is well established that the orientation of the field components (i.e. their geometry) is important to understand, for determining the interaction of the geomagnetic field and DC cable magnetic fields. Natural EM fields are vector fields that change in time and with geographic location. The declination, and inclination are important for determining the field geometry and magnitude of field intensity at a specific geographic location. The geomagnetic field is subject to daily and seasonal fluctuations but is typically considered to be a constant. Discussions revealed that whilst the geomagnetic fields span all time and spatial scales the most relevant components are the earth's core, and the magnetosphere (Session 2).

When looking to integrate the geomagnetic field with cable EMFs modelling, it is important to know what level of variation is relevant in terms of what may influence the cable EMF and ultimately the species (Session 2). The geographic location must be known when interpreting data on natural EM fields and therefore should be known when determining the total EM environment (Session 2). Vector (variometer) measurements are relative, therefore the integration of any other EMF sources (such as a power cable) with the geomagnetic field requires absolute data (Session 2). When measuring EMF in the natural environment, the orientation of the measuring instruments should be specified if the geomagnetic field information is in vector form. Furthermore, measurements should be referenced to a base station at the time of day that the measurements are taken because the base station records daily variations which could influence the calibration (Session 2). If no vector data are available then only scalar (magnitude) measurements can be obtained, which are not appropriate for the modelling of the EMFs.

In terms of incorporating the natural electromagnetic environment in the cable models, the parameters required are the geographic location, the altitude which was considered the vertical distance relative to mean sea height for a specific date and time, and the orientation of the cable relative to the geomagnetic field (Table 2, Session 4). The calculation of power cable magnetic field combined with the geomagnetic field is relatively straightforward mathematically. The National Grid (2018) report provides clear instructions. It is recommended that this approach is applied and validated for determining the combined subsea power cable's magnetic field and geomagnetic field. (Session 2).

It was acknowledged that magnetic storms can affect high voltage transmission grids and terrestrial grid owners take steps to protect against surges, however there is a knowledge gap with regard to how subsea transmission grids may be affected and if similar protective actions are undertaken. This knowledge gap may be important in the context of understanding how EMFs behave in the marine environment and if there is potential that species may encounter cable EMF surges during magnetic storms.

### 6.3.2. Consideration of Water Movement

In a conductive environment, such as saline water in coastal and marine habitats, water moving through the geomagnetic field generates a motionally induced electric field, also known as motionally induced voltage (MIV). Similarly, in a conductive environment, water movement through the cable's magnetic field will also produce a motionally induced electric field for both DC and AC cable EMFs. In addition, to water movement MIVs, AC magnetic fields will induce an electric field, which occurs from the time varying electrical current within the cables, with or without water movement (Session 2). Some receptive species may be responsive to these motionally induced fields; however, it is not a component of natural or cable EMFs that is usually studied in the context species.

In terms of understanding the total EMF environment from the perspective of the species, the MIVs remain an uncharacterised aspect. However, they may serve as important cues for receptive species, as many species rely on natural rhythms to trigger behaviours or physiological mechanisms. Alternatively, it is possible that MIVs provide an indirect magneto-receptive cue. Therefore, it is plausible that species may respond to MIVs associated with cables, or they could mask or disrupt important bioelectric cues or processes.

Of the oceanographic environmental parameters that were explored, the boundary layer was deemed to be most applicable to cable EMF models. The boundary layer is typically referred to in association with the seabed and would be most applicable to EMFs from cables buried in or laid on the seabed and around any protective structures, however, it was also deemed applicable to the water velocities around the dynamic cables in the water column (Session 2 and 3).

In mathematical terms, an important factor to note is that the induced electric field is strongly dependent on the cross product of velocity (v) and the magnetic flux density (B), i.e. v x B (Session 2). Therefore, water velocities in the boundary layers could be very influential on the resulting induced electric fields created (because of the v x B term) and therefore should be taken into consideration for understanding changes in the EMFs emitted near the cable (cm to m scale) (Session 2).

It was further considered that the influence of the boundary layer could be combined in a model of the cable magnetic field with the interaction of the geomagnetic field. The most valid approach to developing this type of model would be to use the current velocity and develop a hydrodynamic model to be incorporated with an EMF model, which could then be scaled, such as model should be validated in laboratory tests to confirm the influence of the boundary layer. The applicable hydrodynamic model resolution will need to be explored (Session 2). This type of modelling was considered most applicable to model the induced electric field of an AC cable (Session 3 and 4) but also in the context of MIVs arising from water movement in a conductive environment, in combination with the magnetic field of a DC or AC cable (Session 4, see Table 2).

## 6.4. Measuring EMF

While modelling EMFs is beneficial to characterising the electric and magnetic fields (Table 2), models need verification. Lessons can be learned when measurements are taken that would not become apparent through modelling alone. For this reason, measuring EMFs will help validate the recommended models and contribute to a better understanding of cable EMFs and subsequently improve studies that assess how species may respond to them. Measuring EMFs from cables is still relatively rare and while there are examples of different methods, there is still no standardised approach. Discussions focussed on the lessons learned from those who have been involved in measuring EMFs in the marine environment and on land (see Session 2 for further context).

The group agreed that obtaining measurements of the EMFs is critical to determining the total EMF. Regardless of how the measurements are undertaken (e.g. towed device, Autonomous underwater vehicle, AUV), a 3-axis fluxgate magnetometer should be used as a minimum to measure the direct magnetic field from the cable. Any EMF equipment used requires evidence of calibration. When measuring EMF in the natural environment, there is a need to know the orientation of the measuring instruments if the geomagnetic field information is measured in vector form. Furthermore, measurements should be referenced to a base station at the time of day measured, as the base station records daily variation (Session 2 - GMF).

At the present time, electric field measurement at levels relevant to biological receptors requires bespoke equipment that minimises the influence of the equipment itself and external factors on the measurement obtained (Session 2). Electric field sensors are very sensitive to disturbance.

When taking measurements from an HVDC cable, the influence of the power system (as a whole, e.g. transformers and rectifiers) should be considered as there may be resultant anomalies when measuring EMFs (Session 2). Current flows will depend on the armour and fibre of the cable and depending on the current coupling there may be electric fields on the cable’s surface (Session 2). Harmonic frequencies are likely to be recorded during measurements and therefore should be specified to determine what is associated with the cable (i.e. 50 or 60 Hz and multiples) and those from other sources (Session 2). Where an AC cable is being measured at a particular point along the cable, the helical periodicity of a cable should be taken into account in the interpretation of the data (Session 2).

The group strongly recommended that EMF-based surveys of net currents in offshore windfarm power cables should be conducted. How exactly this is achieved, would benefit from engagement with offshore wind companies and cable operators. The deployment of EMF sensors (for magnetic fields and/or electric fields) to verify models would be beneficial. In alignment with trying to improve models to be able to consider realistic scenarios, the collection of data to verify those models would be of greatest use. This means that data collection over time frames that span the variability in power transmission would be most useful for interpreting the EMF environment changes from the perspective of the receptive species. Species encounters may be brief but data collection from cables over longer time frames will enable realistic encounters to be determined using absolute data on cable EMFs and knowledge of species movement behaviour. Similarly, these aspects can be modelled if data availability (physics and biology) is sufficiently robust.

The group did not spend time discussing the applicability of standardising reporting data collected however standardisation, in alignment with model reporting is recommended.

## 6.5. Factors associated with receptive species

The final goal of this workshop was to improve the ability to consider the potential effects and impacts EMFs have on species by better understanding the characteristics of EMFs from both AC and DC cables. Further consideration of the species abilities to detect and respond to electric and magnetic fields and how this applies to subsea cable EMFs was regarded as important. The current literature on EMFs and species effects is patchy, and it was agreed that specification of thresholds and ranges of sensitivity for both EMF intensities and frequency would be needed. This is also in line with OSPAR recommendations (Session 3). However, it was noted that this is not a small undertaking given the state of knowledge on receptive species, their sensory mechanisms and metrics that would facilitate thresholds to be determined. A range of model species would also need to be considered.

In addition to the encounter rate, another important factor to integrate into the topic is the movement of species to understand the motionally induced electric fields created both in the water and in the animal. However, it was acknowledged that the understanding on the conductivity of the animal is likely lacking and influential (Session 3).

The variability of the EMFs will determine the potential exposure of an animal to power cable EMFs. In the context of power cable twisting, it is acknowledged that the periodicity of the twist varies the EMFs emitted. This is an important aspect in being able to model the EMF, however, when animals are close (i.e. within the cable periodicity) it will not matter to the animals how the EMF varies as they will experience the field within the twist.

# 7. Summarised Recommendations & Research Areas

From the above key outputs and recommendations, the following actions to enhance the understanding of EMFs emitted by subsea power cables are provided. For ease, they are separated into recommendations that can easily be applied now and those that fall under the category of research and development. Please note though, that some of the research areas may be easily actionable. Collectively, these recommendations will facilitate continued progress towards a clearer understanding of the cable EMFs and potential effects/impacts on species.

## 7.1. Recommendations to apply now

1. Different approaches to EMFs models can be taken and may be broadly categorised as models applicable for permitting and models applicable for research.
    - For both permitting and research models, essential parameters were categorised by two approaches, applicable to both DC and AC cables (Table 2):
        - (a) the basic cable EMFs (i.e. energy emission only)
        - (b) the cable EMFs in the marine environment
    - For the purposes of research, additional definition and resolution of the cable's EMFs, and the interactions with the marine environment, can be gained by approaches (a) and (b) with:
        - (c) research additions to better define the magnetic field component
        - (d) research additions to define the motionally induced electric field
        - (e) research additions to improve the AC model
2. Permitting models will be simple models due to availability of parameters but models can be improved once cables are operational to define the EMFs more accurately.
3. Optimum application of modelling to scenarios should be data driven (see research recommendations).
4. When reporting an EMF model or measurement the following should be clearly defined:
    - if it is an AC or DC cable and specifically what is being modelled/measured (magnetic field, induced electric field)
    - if the geomagnetic field is combined in the model/measurement or only the cable emission is reported (applicable to DC models)
    - the grounding and bonding arrangement of the cable
    - the total length of the cable and position along a cable of the modelled/ measured field
5. Measurements of cable EMFs should report the same factors (see 4. above) in addition to being accompanied with evidence of calibration and the method including limitations in detection for the magnetic field and/or electric field as well as how the geomagnetic field was handled in the data processing.

## 7.2. Research and Development

- Data access should be explored with developers/cable owners taking account of confidentialities with the goal of accessing data on power variability and burial depths after cables become operational.
- Data assessment for optimum scenario building is recommended through specifically commissioned work to explore data in the context of realistic model scenario

development, and determination of the most beneficial data to be made routinely available from cable operators.

- Spatial configurations of cables should be verified with industry, particularly for floating offshore wind in order to improve/develop EMF models; how cables will be positioned in three-dimensional space, the degree of cable movement and geometry of the cable relative to itself (i.e. how bent/straight).
- Exploration of changes in electrical currents along an AC cable and how to model the associated EMFs in order to better understand the realities of power cable EMF emissions into the marine environment (modelling & measurement).
- Incorporation of the boundary layer in an EMF model with the suggestion of defining the best hydrodynamic model, developing a combined model (EMF, boundary layer, geomagnetic field) and scaling to determine influence on the EMF with a laboratory validation if deemed appropriate.
- Consideration of motionally induced fields in EMF modelling which must be considered separately to the induced electrical fields associated with the AC cable (modelling).
- Determine how to model the total AC field (cable AC magnetic field and geomagnetic field combined) and consider its relevance from the species perspective as well as the ability for regulators and researchers to interpret the model.
- Develop a strategic approach to measure EMFs enabling validation of models; engagement with developers and cable operators is recommended.
- Determination of other power cable factors that can influence the EMFs, such as temperature of cable materials power surge protections and potential cable faults as well as any potential scenarios that should be considered with respect to defining effects on marine species.
- The biological context is important when defining modelling scenarios of EMFs in the environment and this should include defining species detection ranges for intensities and frequencies of electric and magnetic fields. However, it is noted that the knowledge base on species sensitivities requires advancement, hence this is a long-term goal that will require studies of several model receptive species and careful definition of appropriate metrics.
- Fish/animal movement through the EMFs was deemed to be important to determine their likely exposure and could be informed through the 3D EMFs modelling approach in conjunction with animal movement models. The conductivity of the animal may be influential so should be taken into consideration.

# 8. Post Workshop Outputs

## 8.1. Calculating magnetic fields associated with AC power cables

The importance of understanding the magnetic fields from the twisted three-phase (AC) cables, such as those that are used for offshore wind inter-array electrical connections, as well as some export cables was highlighted during the workshop. The twist is a design feature which is required during cable laying to reduce the risk of cable bends. From a magnetic field perspective, the twisting will reduce the field produced at distances greater than pitch of the twist, compared with cables that have parallel conductors.

Following the workshop, Drs Renew and Tripp applied an easily accessible way to calculate these fields using an analytic solution, that can be set up within an excel spreadsheet. The outputs were in good agreement with those from complex numerical methods published by del-Pino-Lopez et al., (2022). Using this it is possible to come up with easy-to-apply rules of thumb about the fields from these twisted three-phase cables.

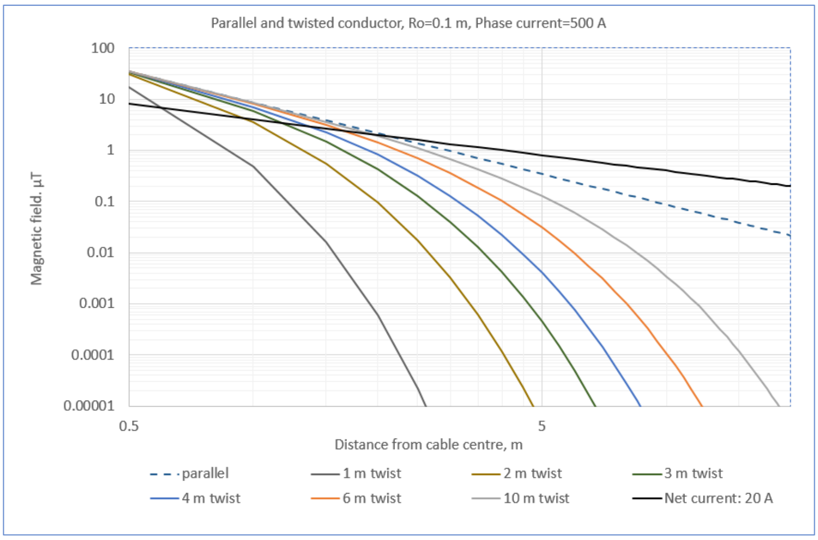

**Figure 9.** Example output of the twisted AC cable modelled with a phase current of 500 A, conductor radius (Ro= 0.1m). The dotted line is the B-field variation for a parallel-conductor cable (i.e. no twisting) and the coloured lines show the significant reduction in the field with distance from the twisted cable with pitch lengths ranging from 1 m to 10 m. The thick black line shows the field from 20 A (i.e. 4% of 500 A) of net current.

The fields measured from operating AC cables have a 1/r variation indicating that there is small net current (i.e. zero phase sequence current) flowing in the cables which might be as much as 4% of the phase current, which is the dominate field source. Figure 9 clearly shows that the dominant field comes from the net current down to distances from the cable which are a fraction of the twist pitch.

## 8.2. Applying Workshop Outputs

The EMF technical workshop outputs will feed directly into a follow-on project, also funded by OWEC, titled FLOWERS – Floating Offshore Wind Environmental Response to Stressors (2022-24). The FLOWERS project focuses on addressing poorly understood environmental stressors associated with floating OSW and one of the work packages will build on the EMF modelling and measuring approach(es) developed through the workshop reported here. There is a period of field measurement of B-fields at different geographical locations around the UK to assist with verifying model components. A subsequent part of the FLOWERS EMF work package is to assess potential EMF encounter rates between selected sensitive species and EMF emitted by cables, particularly areas planned for floating turbines.

## 8.3. Communication of Workshop Outputs

Communication and knowledge transfer of the outputs from the expert workshop are important to ensure the agreed approaches and recommendations (taking into account the natural environmental influences) are known about and referred to by the OSW industry, the wider cable sector, environmental consultancies and also regulatory and advisory bodies.

The workshop outputs will assist with understanding EMFs, their importance to marine species, and how they can be estimated. A dedicated webinar for OWEC and wider stakeholders will take place and will be made available via appropriate media with advice from Cefas comms and The Crown Estate comms teams.

# 9. Acknowledgements

This workshop was supported by the UK Crown Estate OWEC (Offshore Wind Evidence and Change) programme. We would like to thank all the expert participants for their engagement both during and after the workshop. Furthermore, their comments on the draft report ensured the text was technically correct.

We would also like to thank the staff of the Royal Institution for assisting with the workshop running smoothly.

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# 11. Appendices

## 11.1. ANNEX A: Participants

| Name | Role | Organisation |
|---|---|---|
| Andrew Gill | Lead | Cefas |
| Zoë Hutchison | co-lead | Scottish Government |
| Marieke Desender | coordinator | Cefas |
| Brian Stewart | Engineer | Univ Strathclyde |
| Peter Sigray | Oceanography/physics | KTH Royal Institute of Technology, Sweden |
| Frank de Vries | Engineer | Tennet, Netherlands |
| Will Brown | Geomagnetic field modeller | British Geological Survey |
| Rory Murray - O'Hara | Oceanographer | Marine Directorate |
| Chijioke Obiekezie | Engineer modeller | WSP |
| Mike Clare | Geoscience | National Oceanographic Centre |
| Hayley Trip | EMF scientist | National Grid |
| David Renew | Power cables and network expert | National Grid |
| Bob Olsen | Engineer | Washington State Univ, USA |
| George Callender | Modeller | Univ SOTON |
| Jon Rees | Oceanographer | Cefas |

## 11.2. ANNEX B: Agenda

***AGENDA***

Day 1. Tues 17th Jan 2023

| Time (GMT) | Topic | Leads/Presenter(s) |
|---|---|---|
| 09:00 | Welcome and participant introductions | Andrew |
| 09:30 | Setting the context for the workshop<br>• Introduction - the need to consider EMFs in the environment (incl. 2D and 3D)<br>• Agenda items and workshop approach<br>• General Q & A | Andrew<br>Zoë<br>Andrew<br>All |
| 10:30 | *Coffee / tea break* | |
| Session 1 | Cable EMF emissions | |
| 10:50 | Subsea power cables and EMFs<br>Discussion on cable characteristics<br>• Agree key cable characteristics to take into account for HVDC and HVAC | Andrew<br>All<br>All |
| 11:45 | The basis of estimation of EMF<br>• Fundamentals of EMF estimation and parameters<br>• Pro's and con's of simple estimation | Andrew and Bob<br>All<br>All |
| 12:45 | *Lunch* | |
| 13:30 | Intro to modelling for power cables<br>• Key considerations for EMF modelling<br>• Insights from other EMF models<br>• Pro's and Con's of EMF models | Andrew<br>Brian<br>All<br>All |
| 15:30 | *Coffee / tea break* | |
| Session 2 | Total EMF including the natural environment (the reality) | |
| 16:00 | Introduction to total EMF | Andrew / Zoë |
| 16:15 | *In situ* measurement and considerations for modelling total EMF field - magnetic and electric fields<br>• Discussion on measurement of EMF | Peter & George<br>All |
| 17:30 | The natural EMF environment<br>• Discussion on potential influences of natural EMF on cable EMF | Andrew and BGS<br>All |
| 18:15 | *Break before dinner* | |
| 19:30 | *Dinner at the Royal Institution* | |
| 22:00 | End of day | |

Day 2. Wed 18th Jan 2023

| **Time** | **Topic** | **Lead / Presenter(s)** |
|---|---|---|
| 09:00 | Recap of Day 1 agreements and Day 2 agenda | Andrew |
| Session 2 | Total EMF (cont./) | |
| 09:20 | Total EMF environment (data and modelling) –<br>• Oceanographic factors<br>• Sediment/seabed factors<br>• Discussion | <br>Andrew<br>Jon and Rory<br>All<br>All |
| 10:30 | *Coffee / tea break* | |
| Session 3 | Considerations for incorporating data and models | |
| 10:50 | The EMF environment for marine receptors associated with subsea power cables<br>• How do we incorporate environmental characteristics and data with cable EMF | Zoë<br><br>All<br>All |
| 12:30 | *Lunch* | |
| 13:15 | EMF total field model estimation and measurements<br>• Key principles for joint modelling/estimation<br>• Agree key aspects and parameters<br>• 3D models (floating wind cables and EMF)<br>• Pro's and con's of agreed approach | Andrew<br>All<br>All<br>All<br>All |
| 15:00 | *Coffee / tea break* | |
| Session 4 | Outputs from workshop | |
| 15:30 | Recommendations for modelling and measurement of EMF in the context of the real environment<br>• Policy and planning aspects<br>• Key chapters / sections<br>• Recommendations<br>• Key knowledge gaps | Andrew<br><br>Zoë<br>All<br>All<br>All |
| 16:45 | Round-up and next steps | Andrew |
| 17:00 | End of workshop | |
| All = free discussion by all participants | | |

## 11.3. ANNEX C: Glossary

| Term | Description | Unit (if applicable) |
|---|---|---|
| Bonding arrangements | Connection of metallic parts of a cable to the same electric potential so no current can be carried | |
| Boundary layer | Layers of water flow at different velocities found as the interface between a surface and a fluid (e.g. the water and seabed or cable surface) | Velocity (m/s) |
| B-field: B | Magnetic flux density<br>$B = \mu_r * H$, where $\mu_0 B = H$ | Tesla [T] |
| Current: I | Movement of electric charge over a period of time through a cable | Amperes [A]<br>= Coulombs [C]/sec |
| Current density (J) | Amount of current passing through a unit area = $\sigma E$ | Amperes [A]/$m^2$ |
| Eddy currents (engineering) | Circular electric currents induced by a changing magnetic field | |
| Eddy currents OR Motionally induce voltage (MIV)<br>(hydrodynamics) | Electric field induced in the water as a result of the water moving through the Earth's geomagnetic field | |
| E-field: E | Electric field strength, mostly described by voltage gradient but also current density ($A/m^2$) can be used. | Volts [V]/m |
| Electric charge (q) | Basic property of matter that exhibits a force (attraction or repulsion) on any other charge, | Coulomb [C] |

| | | |
|---|---|---|
| | which governs how it is affected by electric or magnetic fields | |
| Electrical conductivity: $\sigma$ | A material's ability to carry an electrical current, the reciprocal of resistivity | Siemens [S]/m=1/Ωm |
| Electrical permittivity: $\varepsilon$ | Polarizability of a dielectric (insulator) | Farad [F]/m |
| Electrical induction: D | Displacement electrical field $D=\varepsilon E$ | Amperes [A]/m$^2$ |
| Total EMF | The *in-situ* combination of all electric and magnetic field sources (geomagnetic field, ocean currents, cable EMFs). The EMFs encountered by a receptor (species) | |
| Harmonics | Frequency components of that describes electrical currents or voltages (e.g. 50 Hz). Harmonic frequencies are integer multiples of the fundamental frequency | Pattern or cycle per second<br>=Hertz [Hz] |
| H-field: H | Magnetic field intensity | Amperes [A]/m |
| Lorentz force (F) | Combination of electric and magnetic force on a charge owing to electromagnetic fields | |
| Magnetic permeability: $\mu$ | The measure of magnetization a material obtains in response to an applied magnetic field<br>$\mu_0$ = the permeability of free space<br>$\mu_r$= relative permeability | Henries [H]/m |
| Power | Amount of energy expended per unit of time = (volts x amps) | Watt [W]=joules/sec |

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Cefas

## World Class Science for the Marine and Freshwater Environment

We are the government’s marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners. We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK’s commitments to a better future (for example the UN Sustainable Development Goals and Defra’s 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge.  Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

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