Marine Consultancy & Services B.V.

Bureau Waardenburg
Ecology & landscape

# Potential effects of electromagnetic fields in the Dutch North Sea

## *Phase 1 – Desk Study*

Rijkswaterstaat Water, Verkeer en Leefomgeving


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|---|---|---|---|
| R1r0 | 13-09-2016 | Roelant Snoek (WaterProof)<br>Rinse de Swart (WaterProof)<br>Karin Didderen (BuWa)<br>Wouter Lengkeek (BuWa)<br>Malenthe Teunis (BuWa) | Roelant Snoek (WaterProof)<br>Wouter Lengkeek (BuWa) |
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# EXECUTIVE SUMMARY

A strong development of offshore wind farms (OWFs) in the Dutch coastal zone is foreseen in the coming years. These OWFs will be connected to land by subsea power cables that transport the generated energy to shore. These cables generate electromagnetic fields (EMFs) and induced electric fields (iEFs) in the marine environment.

The impact of these electromagnetic fields on the marine ecosystem is largely unknown. Limited available literature indicates possible disturbance or avoidance at the cables by certain species. However, knowledge about the impact on species that are specifically present in the Dutch North Sea is lacking.

To get more insight in the potential impact of EMFs on species present in the Dutch North Sea, a combined desk study (Phase 1) and experimental pilot study (Phase 2) will be conducted. This report describes the results of Phase 1 (desk study).

## Executive summary


Subsea power cables generate electromagnetic fields and electric fields. Electric fields are shielded by cable sheathing and do not reach the marine environment, however movement through the electromagnetic field, e.g. by water currents, can induce electric fields. Therefore, both electromagnetic (EMF) and induced electric fields (iEF) can be expected to be generated by subsea power cables.

The strength of the fields depends on many factors, like the type of cable (Alternating Current (AC) vs Direct Current (DC)) and the electric current through the cable.

Currently there are various AC and DC subsea power cables present in the Dutch part of the North Sea, which are all perpendicular orientated to the coastline. The strength of the generated EMFs rapidly decreases with distance from the cable, but is most likely in the range that can be detected by marine organisms.

Several taxonomic groups inhabiting European seas are sensitive to EMFs. It is suggested in literature that magnetic fields are sensed by all species groups, whilst electric fields are sensed by invertebrates, bony fish, elasmobranchs and a single dolphin species. Magnetic and electric fields are used by marine organisms for various ecological functions, like orientation, reproduction, migratory behaviour and predator-prey detection.

Since electric fields are inhibited by shielding material, the obvious effects of subsea cables on biota are generated by either magnetic fields or induced electric fields (iEFs). Movement of organisms through a magnetic field creates induced electric fields, with organisms moving parallel to the cable yielding no induced electric field and organism moving perpendicular to the cable magnetic field generating the maximum induced electric field.

The four main effects identified in literature are disturbance of 1) behavioural responses and movement (attraction, avoidance); 2) navigation and migratory behaviour; 3) predator/prey interactions and distribution of prey; 4) physiology, embryonic and cellular development.

There is a general lack of effect studies on effects of EMFs specifically on North Sea species. To gain more knowledge on species and eventually populations, future research has to focus on different categories of effects, key species(groups) and life stages and specifically on field sites and field strengths that are in the same range as those emitted by subsea cables.

## Conclusions

The following main conclusions on the **occurrence of EMFs due to subsea power cables** are formulated:

1) Subsea power cables generate electric (EFs) and electromagnetic fields (EMFs), of which due to shielding of the cable only EMFs reach the marine environment. Movement in EMFs, e.g. by water currents or swimming organisms, also induce electric fields (iEFs). Therefore, both EMFs and iEFs occur around subsea power cables.
2) DC power cables generate stronger but static EMFs, whereas AC cables generate a lower but variable EMFs. EMFs of DC cables is higher than the geomagnetic field, whereas EMFs of AC cables are likely to be lower than the geomagnetic field.
3) In relation to the OWF development in Dutch waters, only AC subsea power cables are relevant since the use of DC cables is currently not foreseen.
4) The strength of the EMFs depends mainly on cable type, voltage and current, which implies that stronger EMFs are generated by OWFs during high wind periods.
5) The strength of EMFs rapidly decreases with distance from the cable. Modelling studies indicate that EMFs are limited spatially (both vertically and horizontally). However, EMFs of both AC and DC cables are likely to reach at minimum up to a number of meters in the water column, possibly more.
6) Burial depth, clever positioning of the cables (e.g. minimum mutual distance), lower currents and better shielding of the cable can decrease the strength of the EMFs that reach the marine environment.

The following main conclusions on the **effects and potential impact of EMFs** are formulated:

7) Sufficient evidence exists in published literature to conclude that marine species can be affected by anthropogenic EMFs. This makes it a human impact that cannot be denied and should be considered in future environmental impact studies.
8) Much is unknown about the effects of EMFs on the marine ecosystem, but considering the vast upcoming increase in offshore wind farms and cables connecting those to the land, further research into the impacts of EMFs on marine life is essential.
9) Four main potential effects due to EMFs are identified in literature:
    - Disturbance of behavioural responses and movement (attraction, avoidance);
    - Disturbance of navigation and migratory behaviour;
    - Disturbance of predator/prey interactions and distribution of prey;
    - Disturbance of embryonic and cellular development.
10) Studies that test the effects of EMFs under realistic EMF-strength conditions are largely absent from literature. Much of the current understanding is based on theoretical evidence or trials with exaggerated experimental EMF-strengths. Determining impact of realistic EMFs on species is therefore a key priority.
11) The EMFs and iEFs generated by subsea power cables in the Dutch North Sea most certainly are in the range that potentially have an effect on the marine environment.
12) Lower EMF strengths, are not necessarily associated with less impact. Moreover weak EMFs can have an important ecological function, such as the little variations in the geomagnetic field used for navigation during migration and the weak fields induced by prey. Knowledge on how the type of EMFs (static, variable, specific frequencies) relates to potential effects is largely lacking.
13) Species on each level of the North Sea food web are potentially sensitive to EMFs. High sensitivity is expected for elasmobranchs (sharks, rays), but also invertebrates, bony fish and marine mammals inhabiting the North Sea can potentially be affected by EMFs. Benthic species, located closer to cables encounter stronger EMFs and hence are more likely to be affected.

14) With the existing lack of knowledge, the occurrence of effects due to EMFs on population level of species in the North Sea cannot be excluded nor confirmed.

## Recommendations

It is recommended for future research to measure the actual EMFs of the subsea power cables in the North Sea under various field conditions. This will give better insight in the potential effects on marine life and also give insight in the possibilities for mitigation measures that can be taken in case necessary.

Furthermore, it is recommended to further study the potential effects on marine life specifically for species that inhabit the Dutch North Sea. Studies should focus on the four effect categories and range from literature studies on natural history characteristics of key species, to experimental mesocosm dose-response studies and field studies in the Dutch part of the North Sea.

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# 1 INTRODUCTION

## 1.1 GENERAL

A strong development of offshore wind farms (OWFs) in the Dutch coastal zone is foreseen in the coming years. Besides the existing farms at Offshore Windpark Egmond aan Zee (OWEZ), Prinses Amalia Wind Park (PAWP), Luchterduinen and Gemini, the wind farm areas Borssele, Hollandse Kust Zuid and Hollandse Kust Noord will be developed. The produced power by the turbines will be transported in the wind farm by infield cables towards the transformer station, from which it will be transported to shore by export cable(s). These power cables produce electromagnetic fields (EMFs).

The impact of these electromagnetic fields on the marine ecosystem is largely unknown. Limited available literature indicates possible disturbance or avoidance at the cables by certain species. However, knowledge about the impact on species that are specifically present in the Dutch North Sea is lacking.

Currently, a number of power cables are present which are positioned perpendicular to the coast line, which potentially forms a barrier for migrating species. Due to the development of new OWFs and placement of new export cables towards offshore transformer stations, the chances of potential impact on these species increase.

To get insight in the potential impact of EMFs on the marine ecosystem, it is necessary to study the presence and strength of the EMFs in the present and future situation in the Dutch North Sea. Additionally, the sensitivity of different species (benthos, fish, elasmobranchs marine mammals) to EMFs in the North Sea and effects up to a relevant level of impact should be addressed.

To get more insight in the potential impact of EMFs on species present in the Dutch North Sea, a study is conducted that consists of a desk study and an exploration of the possibilities for conduction pilot experiments. In this report, the results of the desk study are described.

## 1.2 AIM

The aim of the study is to get more insight in the presence of electromagnetic fields induced by offshore power cables in and towards offshore windfarms[1] and the impact that these fields potentially have on (sensitive) species such as sharks, rays and possibly harbour porpoises.

This study consists of a combination of a desk study and a pilot experiment, for which the following research questions are formulated:

### Primary research question desk study:

- What are electromagnetic fields, how are they created and which factors influence them?
- Is there a reason to assume that electromagnetic fields negatively impact the marine environment? If so, which species potentially negatively affected and can this lead to an impact on population level of these species?

[1] Note that this study focusses on subsea power cables of OWFs, however also other Marine Renewable Energy Devices (MREDs) such as tidal turbines have power cables that produce EMFs.

Follow-up research question (experimental research):

- Is it possible to experimentally study the factors that influence the electromagnetic field strength of buried High Voltage Direct Current (HVDC) or High Voltage Alternating current (HVAC) power cables and the impact of these cables on sharks, rays and potentially other species such as harbour porpoises?

## 1.3 Approach & report outline

The approach of the desk study is shown in Figure 1. The technical part of the study is shown in blue whereas the biological part is shown in green. Both have been studied parallel to each other, but with a constant exchange of knowledge and information during the process. Both parts start general and focus towards a synthesis specifically for the Dutch part of the North Sea.

First, the general physical fundamentals of electromagnetic fields are described in Chapter 2, followed by a description of the EMFs that can be expected due to offshore power cables in Chapter 3. Subsequently, the potential impact due to these EMFs on species in general but also for species present in the North Sea is described in Chapter 4. A synthesis on EMFs for relevant species in the North Sea is giving in Chapter 4. Finally, conclusions on the research questions, recommendations for future research and a proposal for phase 2 of the current project is given in Chapter 6.

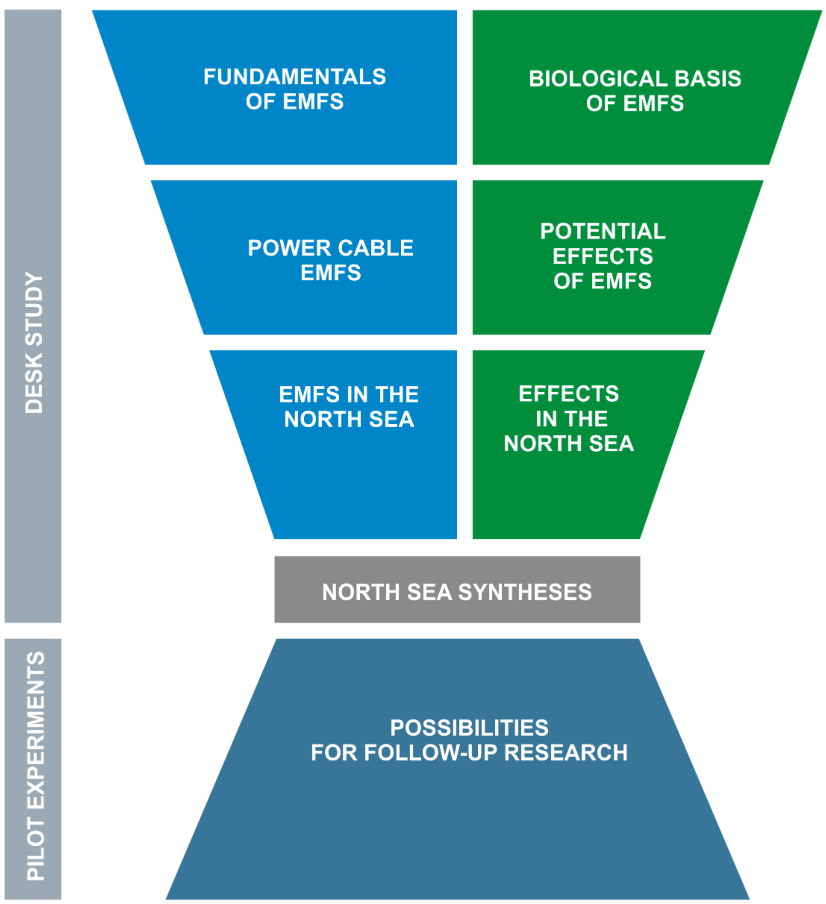


Figure 1: Approach followed for the technical (blue) and biological (green) part of the study, focusing towards a synthesis on the relevance of electromagnetic fields for species in the Dutch part of the North Sea.

# 2 FUNDAMENTALS OF EMFS

To be able to assess the relevance of electromagnetic fields due to offshore power cables in the Dutch part of the North Sea and to be able to explore the possibilities the follow-up research on this topic, it is necessary to understand the fundamentals of electromagnetic fields.

This chapter describes the fundamentals at an understandable level for scientists with little or no background on this topic. To make it of use for understanding the relevance of EMFs specifically for the North Sea at policy level, the essence of the fundamentals is given at the start of each Section.

## 2.1 ELECTRIC FIELDS

**Essence:** Electrically charged particles are surrounded by a sphere of influence, called the electric field. Electrical fields have a strength and a direction. The field strength depends on the charge of particles and the force between particles. Special types of electric fields are radial fields (all directions) for a point charge and homogeneous fields (in a single direction) for two plates having opposite charges. Electric fields are often induced by magnetic fields. The unit V/m is commonly used to describe the electric field strength.

Before describing the fundamentals of electromagnetic fields (EMFs), some basic theory regarding electric charge, which cause the existence of the EMFs, is given.

Electrical charges can either be positive or negative. Like charges repel and unlike charges attract each other (Figure 2). An object is negatively charged if it has an excess of electrons, and is positively charged when it has a shortage of electrons. The object is uncharged when there is neither a shortage nor an excess of electrons. Electric charge is commonly denoted by $Q$ (electric charge of an object) or $q$ (electric charge of a particle). The SI unit of electric charge is the coulomb (C).

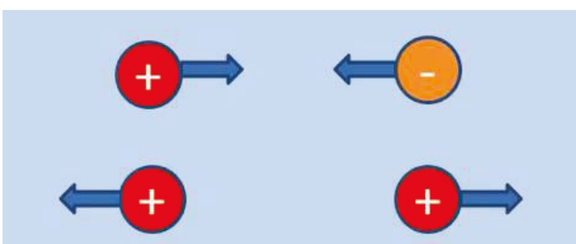


Figure 2: Sketch of a positive and negative charge attracting each other (top) and two positive charges repelling each other (down).

The base of charge is the atom, consisting of electrons, protons and neutrons. Experiments have demonstrated that electric charge consists of integer multiples of elementary charge ($e$), which is approximately equal to $1.602 \cdot 10^{-19}$ C. Protons have a charge of $+e$, electrons have a charge of $-e$ and neutrons are uncharged.

Since like charges repel and unlike charges attract each other, a so called electrical force interacts between static electrically charged particles. This electrical force can be computed by Coulomb's law and depends on the mutual distance (between the centre points of both particles) and the magnitude of both charges

$$F_{el} = f\frac{Q_1 Q_2}{r^2},$$

where $F_{el}$ is the electric force in newton, $f$ is Coulomb's constant ($\approx 8{,}99 \cdot 10^9$ N·m²·C⁻²), $Q_1$ and $Q_2$ are the magnitudes of the two charges (C) and $r$ is the distance between both charges (m).

Electric charge is surrounded by a certain sphere of influence, called the electric field. It is defined as the force felt by a certain object divided by the electric charge of that object. The electric field is a vector field, meaning that besides magnitudes it also has directions. Electric fields are often induced by time-varying magnetic fields (see also Section 2.3) and they converge and diverge at electric charges.

The symbol of the electric field is $E$ and the strength of an electric field is referred to as the electric field intensity. It is defined as the electric force that would be encountered by a positive charge of 1 C. The equation reads

$$\vec{E} = \frac{\vec{F}}{q},$$

Where $\vec{E}$ is the electric field intensity (N/C or V/m), $\vec{F}$ is the electric force (N) and $q$ is the electric charge of the particle (C).

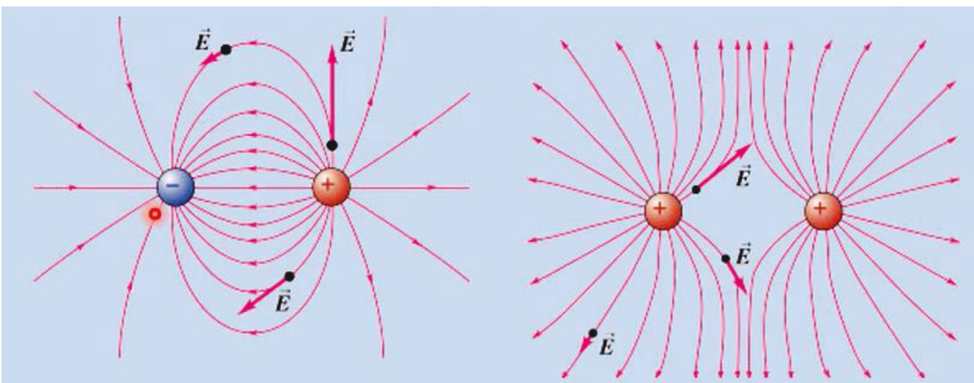


Figure 3: Sketch of electric field lines between a positively and negatively charged particle (left), two positively charged particles (right) and finding the direction of the electric field in different points of the electric fields. It is clear that electric field lines converge (diverge) at negative (positive) charges.

An electric field is visualised using electric field lines (Figure 3). These lines indicate the force that is exerted on a positive charge. Electric field lines are directed from positive charges towards negative charges and are always perpendicular to a conductor. Moreover, they will never intersect. The more electric field lines are present, the stronger the electric field is. The electric field direction in a certain point is equal to the tangent of the electric field line in that point.

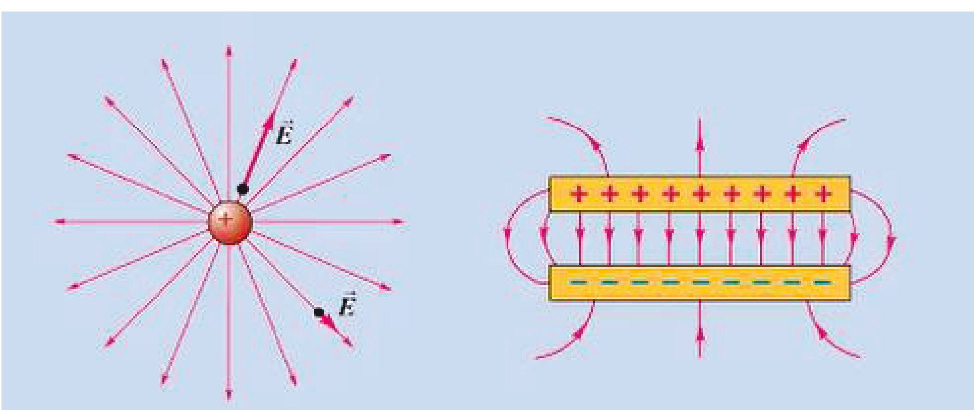


Figure 4: Examples of a radial electric field (left) and a homogeneous electric field (right).

There are two special types of electric fields (Figure 4). Firstly, the electric field of a point charge is symmetrical and goes in all directions (radial electric field). Secondly, the electric field between two metal plates having opposite charges also looks different. The electric field between the two plates has the same strength and direction at all locations and is therefore called a homogeneous electric field. The last important note about electric fields is that within a conductor (a material that allows the flow of an electrical current, which is e.g. the cable itself) the electric field intensity $E$ is 0.

## 2.2 PERMANENT MAGNETIC FIELDS

**Essence:** The magnetic field can be described as the sphere of influence surrounding a magnet. A permanent magnet is made from magnetised material which creates its own continuous magnetic field. The magnetic field develops due to electric currents or due to magnetic properties of materials. Magnetic fields have a direction and strength. The magnetic field strength is indicated by the magnetic flux density. The unit tesla (T) is used to describe the strength of magnetic B fields. Earth has a natural magnetic field with strongest fields at the poles and weakest fields at the equator.

This paragraph describes the fundamentals of magnetic fields, which are closely related to electric fields.

Magnets are objects that produce a magnetic field which attracts or repels other objects. The magnetic field can – comparable to an electric field – be described as the sphere of influence surrounding a magnet. The magnetic field develops due to electric currents or the magnetic properties (magnetic moments) of elementary particles. The magnetic field will in turn influence other electric currents and magnetic moments.

The magnetic field is a vector field, meaning that it is specified at any given point by both a direction and a magnitude (or strength). Interestingly, the term 'magnetic field' is used to describe two different but closely related fields denoted by the symbols $B$ and $H$. This is due to the fact that the magnetic field can be defined in several ways, which is related to the effects it has on its environment. The 'H field' is of lesser relevance and is not further taken into account for simplifying reasons. The term 'magnetic field' in this report refers to the $B$ field only.

Usually, the magnetic field is defined using the force it exerts on a moving charged particle. The force also depends on the velocity of the particle, such as when a charged particle moves in the vicinity of a current-carrying wire. The vector field $B$ is referred to as the magnetic field, which is defined as the vector field necessary to correctly describe the motion of a charged particle. The unit to describe the strength of the magnetic B field is tesla (T).

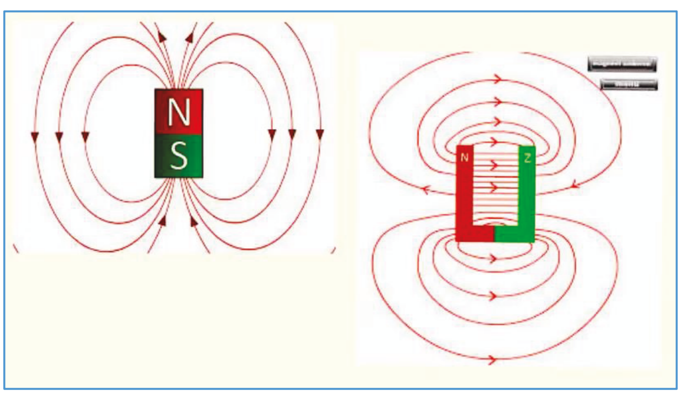


Figure 5: Examples of magnetic fields corresponding to permanent magnets.

Different types of magnets exist. The most common type of magnet is the permanent magnet. This is an object that is made from magnetised material which creates its own continuous magnetic field (Figure 5). The magnetic effect of a permanent magnet will never change. Each magnet has a north and a south pole. Two equal poles will repel each other whilst two unequal poles will attract each other. A magnet can only attract iron, nickel and cobalt (both on the north and south pole), since these three metals all contain small (elementary) magnets.

A permanent magnet can exert forces on a distance due to the magnetic field surrounding the magnet. This magnetic field is visualised using magnetic field lines. Outside the magnet, the magnetic field lines are always directed from the magnetic north pole towards the magnetic south pole. However, the magnetic field lines are also present within the magnet where they are directed from the magnetic south pole towards the magnetic north pole. Each magnetic field line is a loop that will continue indefinitely. Contrary to electric field lines, the magnetic field lines are not always located perpendicular to the magnet. An increase in the number of magnetic field lines results in a stronger magnetic field. As a result, the magnet will be strongest at the magnetic north and south pole. The magnetic field strength is indicated by the magnetic flux density.

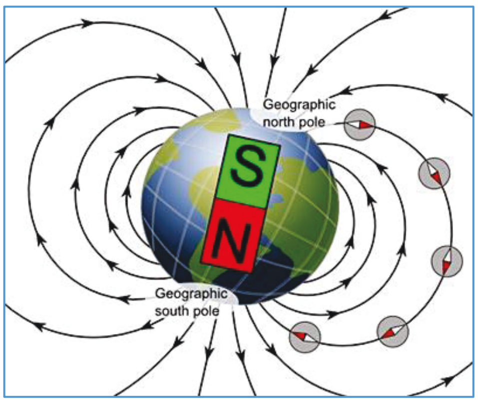


Figure 6: Sketch of earth's magnetic field.

The earth also has a magnetic field (Figure 6), due to the presence of a magnet inside earth. This magnet has its magnetic south pole located near the geographical north pole and its magnetic north pole located near the geographical south pole. As described above for magnets in general, the magnetic field lines in space run from the magnetic north pole towards the magnetic south pole whilst inside earth this is the other way around.

The strength of the earth magnetic field varies over the surface of the earth, with strongest fields at the poles and weakest fields at the equator. Earth's magnetic field has a magnetic flux density which ranges between 30 and 70 µT and is illustrated in Figure 7. In the North Sea, the geomagnetic field strength varies between 49 and 51 µT.

The field strength can also be influenced by geomagnetic storms, which are disturbances in the Earth's magnetic field resulting from solar activity. Minor geomagnetic storms occur approximately 10-20 times per year (intensities vary between 70 to 120 nT), strong storms (200-330 nT) about 1 to 2 times per year and severe storms (330-500 nT) every one to two years (Buchanan et al. 2011).

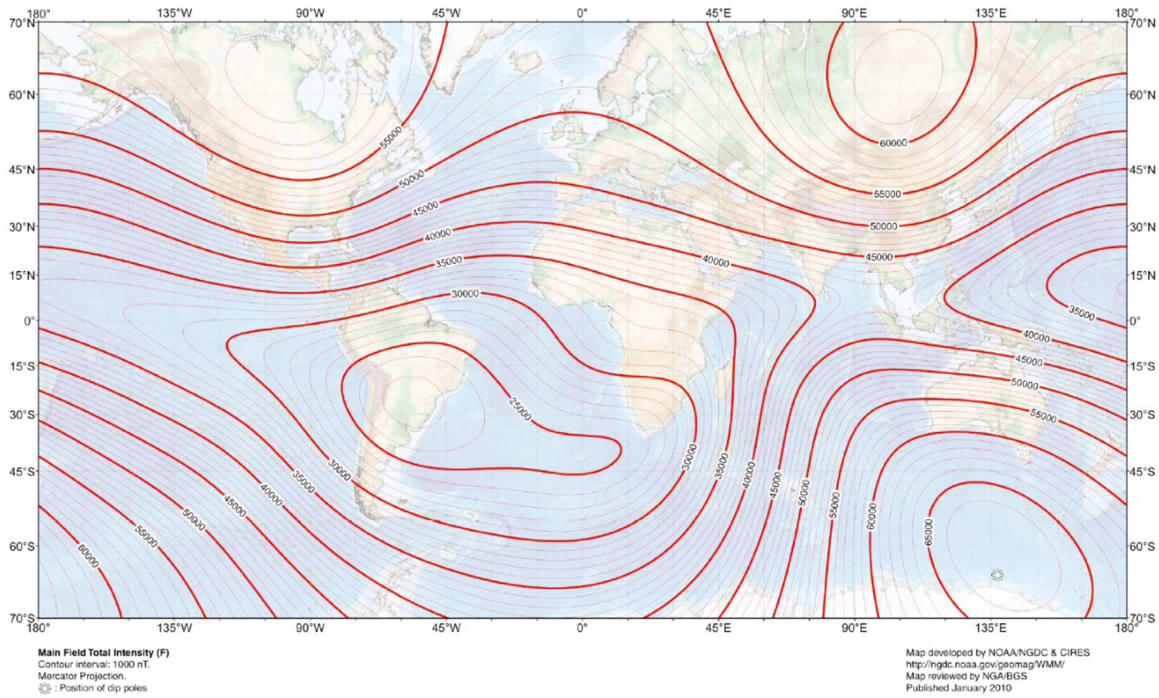


Figure 7: Magnitude of the main geomagnetic field (Contour interval 1000 nT; NOAA,2010).

## 2.3 Electromagnetic fields

**Essence:** Electromagnetic fields are magnetic fields that are generated by an electrical current running through an electric wire. Electromagnetic fields have both a direction and a strength. There are many sources of electromagnetic fields in the marine environment, e.g. offshore power cables, telecommunication lines and oil & gas pipelines. Direct current (DC) cables generate a static electromagnetic field, alternating current (AC) cables generate a variable electromagnetic field. The electromagnetic field strength increases with higher currents and decreases with distance from the wire. The unit Tesla (T) is used to describe the electromagnetic field strength.

If an electrical current flows through an electric wire, a magnetic field will be generated. This field consists of consecutive circles, as shown in Figure 8A. This type of magnet is referred to as an electromagnet. Very strong electromagnets develop when using a solenoid (Figure 8B).

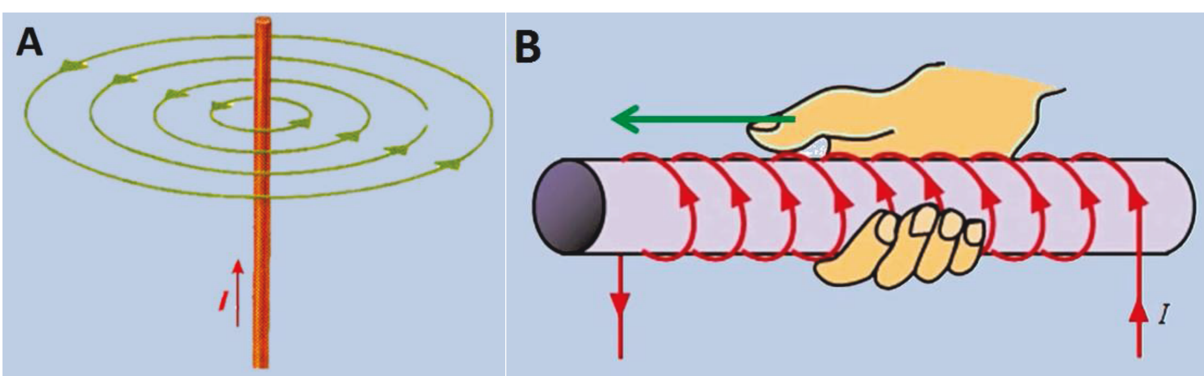


Figure 8: Example of a magnetic field around an electrical wire (A) and through a solenoid (B).

There are a number of potential sources for anthropogenic EMFs. The vast majority is linked to undersea cables which are used for power transportation, telecommunications or submarine communications. Other sources are electrically heated pipelines, antifouling techniques and other electrolysis based sources (Kullnick, 2000). Submarine oil and gas pipelines can be heated through induction (generating a magnetic field) or directly (generating an electric field; Gill et al. 2005). Offshore windfarms generate anthropogenic electromagnetic fields in natural geomagnetic field environments, due to the transport of generated electricity over a long distance by cables which will be surrounded by a magnetic field.

Static electromagnetic fields are a result of direct electric currents (DC), whereas variable electromagnetic fields are a result of alternative electric currents (AC). Both AC and DC power cables are used in OWFs.

### Magnetic Field strength

The magnetic flux density (*B*) describes the strength of the magnetic field and is defined as the force that acts per unit length on a wire that carries current (*I*). The magnetic flux density surrounding a long, straight wire can be computed as

$$B = \frac{\mu_0 I}{2\pi a},$$

where *B* is the magnetic flux density (T), $\mu_0$ is the magnetic permeability of a vacuum (a physical constant with the value $4\pi\cdot10^{-7}$ $N\cdot A^2$), *I* is the current carried by the wire (A) and *a* is the perpendicular distance from the wire to the point where the flux density is being evaluated (m).

The magnetic flux density increases with the electric current and decreases with distance from the wire. This is (partly) illustrated in Figure 9, where denser magnetic field lines (meaning a higher field strength, illustrated by the length of the arrows B) are found closer to the electrical current.

The magnetic flux density increases proportionally by increasing the electric current through a wire or solenoid or by increasing the number of turns in the solenoid. It is also important to realize that magnetic flux density is a vector and therefore has a direction.

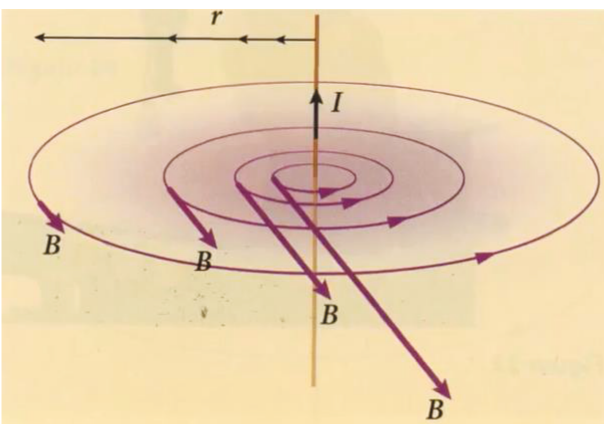


Figure 9: Sketch of the magnetic flux density depending on the distance from the electric wire or density of the magnetic field lines.

## 2.4 ELECTROMAGNETIC INDUCTION

**Essence:** Electromagnetic induction is the generation of a force or voltage in a conductor due to the dynamic interaction with a magnetic field. The Lorentz force is the force exerted by the magnetic field on a moving charge or current in that field. The magnetic flux is defined as the magnetic flux density summed over a certain area and is measured in the unit Weber (Wb). A change in magnetic flux through time is necessary to generate an induction voltage in a magnet.

Magnetic fields can generate a so called induction voltage. This is the production of a force or voltage across a conductor (e.g. a cable) due to its dynamic interaction with a magnetic field. To understand this process, it is important to understand what force is related to a magnetic field.

A magnetic field will exert a force on any moving charge or current that is present in that magnetic field. For example, if an electric wire with an electric current is present in a magnetic field, a force will work on the electric wire (Figure 10). This force is called the Lorentz force, after the Dutch scientist Hendrik Antoon Lorentz, who discovered it during experiments.

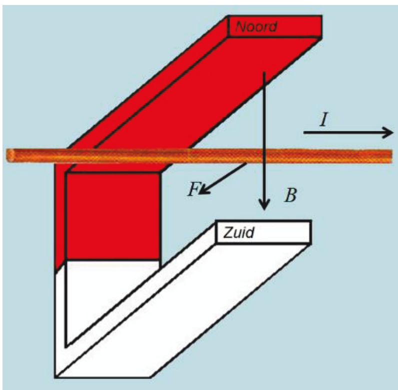


Figure 10: Sketch of the Lorentz force (F) in a magnetic field.

The magnitude of the Lorentz force is proportional to the magnitude of the charge, the magnetic flux density and the velocity of the particles. Moreover, the Lorentz force is always perpendicular to both the magnetic flux density and the electric current. The magnitude of the Lorentz force is given by

$$F_l = B_i q v,$$

where $F_l$ is the Lorentz force (N), $B_i$ is the magnetic flux density perpendicular to the direction of the electric current (T), $q$ is the electric charge of the particles (C) and $v$ is the velocity of the particles (m/s).

Analogous to the Lorentz force, electromagnetic induction depends on movement of electrical charges in a magnetic field (Buchanan et al. 2011). For example, a cable could be located in a changing magnetic field, resulting in an induced electric field.

To explain the concept of electromagnetic induction, we need to define the so called magnetic flux. The magnetic flux through a surface is defined as the surface integral of the normal component of the magnetic field $B$ passing through that surface. In other words, it is the magnetic flux density summed over a certain area. The magnitude of the magnetic flux is determined by the magnetic flux density perpendicular to a surface. In other words, the number of magnetic field lines through a surface. The formula for the magnetic flux reads

$$\Phi = BA,$$

where $\Phi$ is the magnetic flux in Weber (Wb), $B$ is the component of the magnetic flux density perpendicular to the surface (T) and $A$ is the area of the surface ($m^2$). The magnetic flux can be increased by increasing the surface or by increasing the number of magnetic field lines (Figure 11). For a magnetic flux to exist, it is essential that the magnetic field lines pass through the surface. The magnetic flux is 0 when the surface is parallel to the magnetic field lines, since no magnetic field lines pass through the surface.

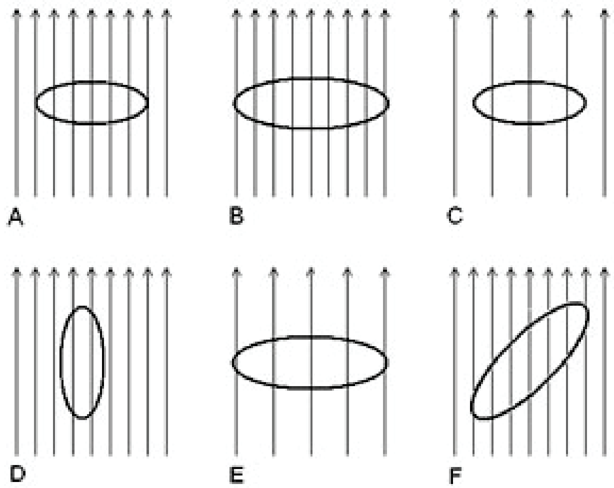


Figure 11: Sketch of the magnetic flux for different surfaces during different positions. It is clear that the magnetic flux depends on surface area, the tilting of the surface and the magnetic flux density.

A magnetic flux is necessary to generate an induction voltage in a magnet. As soon as the magnet starts to move, an induction voltage will be generated. This voltage is defined as the voltage generated in a solenoid by a change in magnetic flux over time. The formula for induction voltage reads

$$U_{ind} = N\frac{\Delta\Phi}{\Delta t} = NA\frac{\Delta B}{\Delta t},$$

where $U_{ind}$ is the induction voltage (V), $N$ is the number of turns in the solenoid (more turns results in a higher induction voltage) and $\Delta\Phi/\Delta t$ is the change in magnetic flux per second (which can be written as the area multiplied with the change in magnetic field per second).

A fast change in magnetic flux through time generates a high induction voltage. The induction voltage will be zero again as soon as the magnet stops moving (flux is zero). Induction is also possible without additional movement, as long as the magnetic flux changes through time.

# 3 EMFS FROM SUBSEA POWER CABLES

Subsea power cables are the main source of anthropogenic generated electromagnetic fields in the marine environment. In this chapter, an overview is given of the electromagnetic fields that are generated by subsea power cables.

First, a general overview is given of the use of subsea power cables, followed by a description of the differences between AC & DC power cables and an overview of the voltages and currents mainly used and expected to be used in the near future. In the next Section, the expected electromagnetic field levels of the different cables will be described. Also, a description of the factors that can influence the electromagnetic fields is given. Finally, an overview of the situation of the Dutch part of the North Sea is given, which specifically aims at describing the potential occurrence of electromagnetic fields in the Dutch marine environment.

## 3.1 Subsea Power Cables

### 3.1.1 Design configurations

Subsea power cables are traditionally used to connect power systems from different countries across water bodies (for example between the United Kingdom and the Netherlands). In more recent years, they are also used for connecting offshore windfarms with the mainland. Due to the strong development of OWFs (as illustrated inFigure 12), the amount of cables will increase in the future.

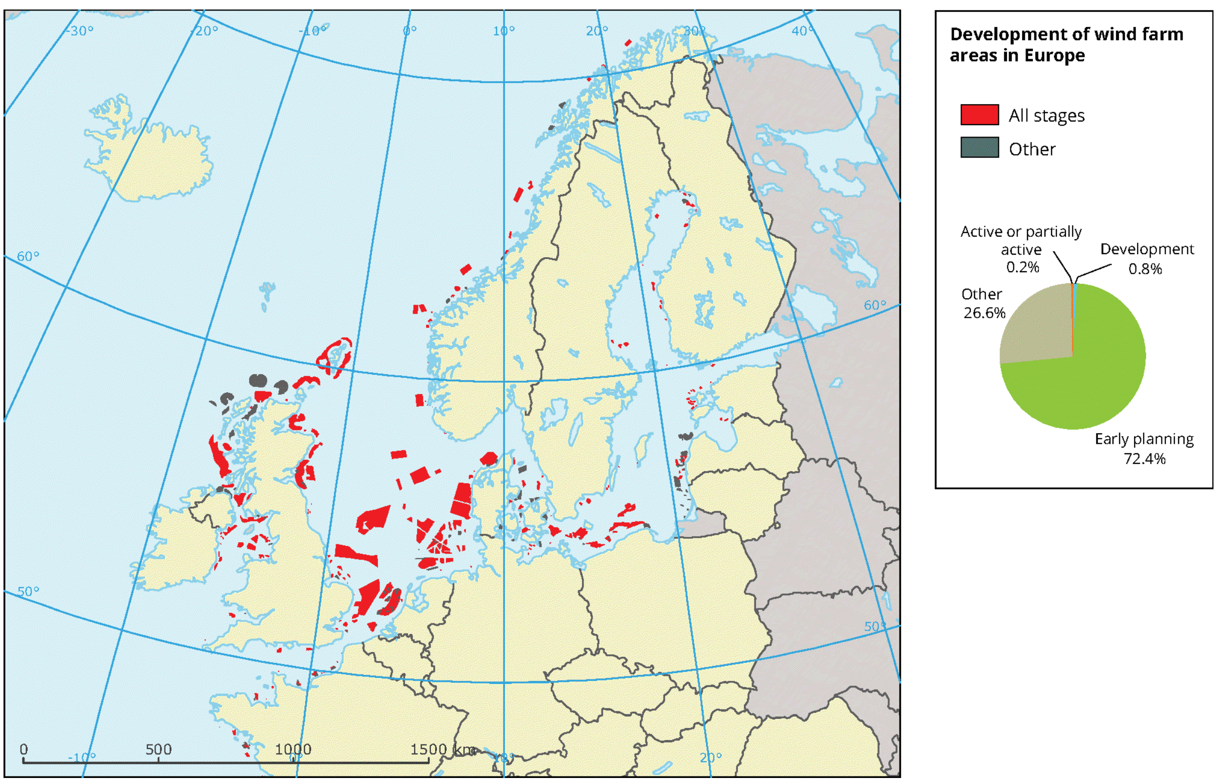


Figure 12: Overview of wind farm areas (June 2015) in all stages of development in Europe. The pie chart shows the different levels of development in % (European Environment Agency).

### Subsea power cables

The subsea power cables that are used to transport generated energy overseas between countries generally cover a large distance and are therefore often High Voltages Direct Current (HVDC) cables (see also Section 3.1.2).

### Infield & export OWF cables

The capacity of OWFs has been strongly increasing over the last years, due to the development of larger wind turbines and an increase in the number of turbines per windfarm. To ensure sufficient capacity for the transport of the generated energy, OWFs are nowadays generally connected to shore by means of High Voltage (HV) cables (referred to as export cables). Meanwhile, the individual cables of each wind turbine are generally connected by Medium Voltage (MV) cables (referred to as infield cables). Offshore transformer/converter stations form the connection between the infield and export cables and the connection to the grid onshore. The typical layout of OWFs is shown in Figure 13. Smaller wind farms relatively near-shore often have a smaller layout, where the power is transported to shore using relatively short, lower voltage export cables (Normandeau et al., 2011).

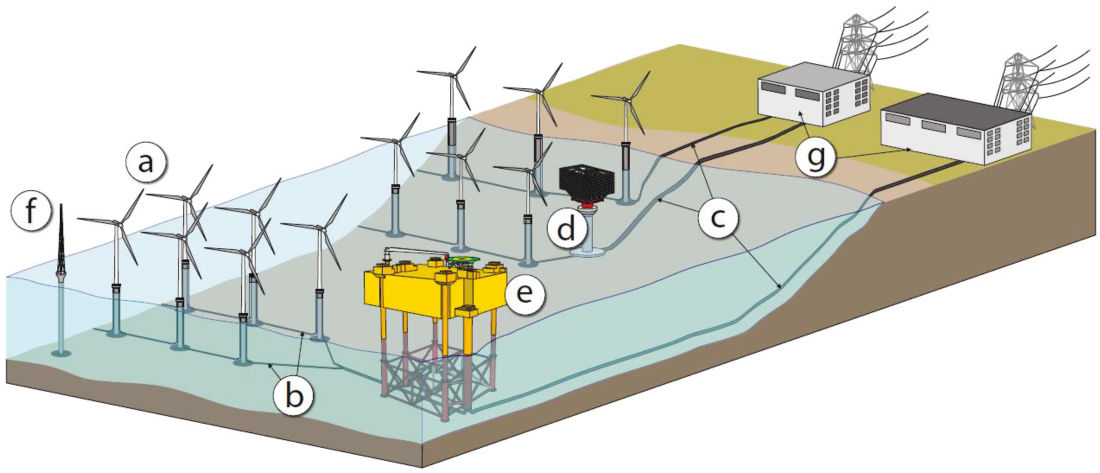


Figure 13: Typical OWF lay-out with the main components of an OWF: (a) Wind turbines; (b) Infield cables; (c) Export cables, (d) Transformer station; (e) Converter station; (f) Meteorological mast; (g) Onshore stations. (figure from Rodrigues, 2016).

Infield cables are often buried approximately 1 meter below the sea bottom, but sometimes also positioned on top of the seabed. For the planned new Dutch OWFs, there is no burial requirement for the infield cables, which implies that they can be positioned on top of the seabed. High Voltage export cables are generally buried in order to minimize the possibility of damage due to anchor strikes, cable scour movement or interactions with fishing gear. Sometimes these cables are not buried, for example near ship wrecks or due to sand waves uncovering the cable (Normandeau et al., 2011). In Dutch waters, the cable burial depth of export cables is checked regularly and reburied in case of surfacing of the cable due to sediment movement.

## 3.1.2 AC vs. DC cables

Generated energy can either be transported by means of alternating current (AC) cables, or by means of direct current (DC) cables. The design characteristics of AC and DC cables are described in detail in

Appendix 4. Relevant information for the understanding of the differences between AC and DC cables is presented in this Section.

In AC cables, the direction of the current through the cable changes with a specific frequency (50 Hz in Europe). AC systems therefore allow bidirectional transfer but also modification of voltage by transformers in the turbines. This means that the voltage can be increased for efficient transport to shore and subsequently be decreased for safe usage by customers.

In DC cables, the current through the cable is always in the same direction. A DC system generally uses a single, high-voltage direct-current (HVDC) conductor at one constant voltage and a return cable to transmit the return current (Normandeau et al., 2011).

AC systems are generally preferred for overhead transmission of bulk electricity. Since wind turbines generate an AC output, generally AC infield cables are used in OWFs. The export OWF cables can however be either in AC or DC, depending on the distance to shore and the amount of energy to be transported. DC systems provide a continuous current that allows for a more efficient power transfer, greater voltage stability and fewer line losses. For this reason, HVDC power cables are generally used for longer distances. However, the initial costs of using a HVDC cable are higher, due to the need of converter stations to convert from and to AC current in the windfarm and on shore.

The decision to use either a HVAC or HVDC export cable is made on a project basis, however it can in general be assumed that at distances less than 50km HVAC export cables are used and at distances more than 100km HVDC export cables are used.

Apart from AC and DC current systems, the cable systems can also differ substantially. Single, unipolar power cable systems are often used but bipolar cable systems also exist. In such a system, the two wires are arranged bipolar in one or two single submarine cables. All these systems will produce different magnetic fields.

### 3.1.3 Power, voltages & currents

The power output of wind turbines depends on the wind force, as illustrated by the power curves of two different turbines in Figure 14. Clearly, the power output increases from wind speeds of approx. 5 m/s (3 Bft) up to approx. 12 m/s (6 Bft), after which a constant output is given.

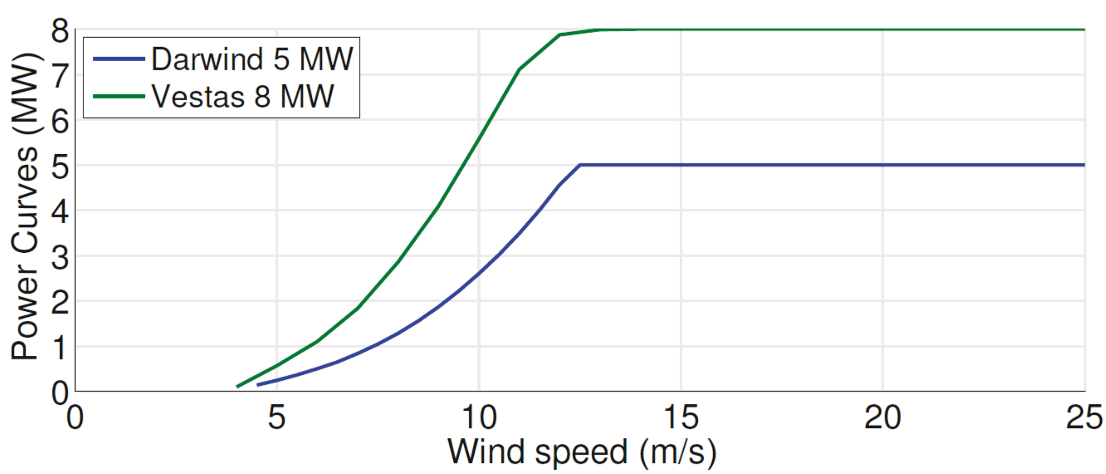


Figure 14: Power curves of two windturbines, showing output power in relation to wind speed (Rodrigues et al., 2015).

For infield cables, generally three-core, AC 33 kV cables are used, although 66 kV cables are foreseen to be used in the near future (Gill et al. 2005; Gill and Bartlett 2010; Rodrigues et al. 2015).

For the export cables to land, 132 kV cables have been commonly used over the years although higher voltage cables (220kV) have already been installed for some OWFs. For the planned OWFs in Dutch waters the use of 220kV HVAC export cables is foreseen (see also Section 3.3). The use of 600kV HV cables is foreseen in the future (Gill et al. 2005; Gill and Bartlett 2010).

The currents that flow through the infield and export cables depend on the power generated and the voltage of the cables. For infield cables, this is in the order of magnitude of 250 A for an 8 MW turbine at maximum output and a 33kV infield cable.

Depending on the export cable specifications, a maximum current can be transported. Therefore, if the energy generated by the windfarm exceeds this maximum allowed current of the cable, it should be either transported at higher voltages or by using multiple cables.

## 3.2 Expected EMF levels from Power Cables

The EMF of subsea power cables is composed of two main components: the electric (*E*) and magnetic (*B*) fields. This is illustrated in Figure 15(a), in which the different fields for a bare cable without shielding material (a) and the situation for AC and DC current cables (b and c respectively) are shown. Both the *E* and *B* fields will be emitted into the nearby environment and the emissions will be static for a DC field (Figure 15b) and alternate at a frequency of 50 Hz for European AC systems (Figure 15Figure 15 c; Gill et al., 2012).

The directly emitted *E*-field from the cable is contained in industry standard high voltage AC and DC cables and does not reach the marine environment, but the *B*-field cannot be fully contained by means of shielding of the cable.

Due to water movement or the movement of an organism through the *B*-field, an induced electric field can be generated in both AC and DC cables (Gill et al., 2012). This electric field is often referred to as the *iE*-field (Figure 15).

However, this is not the sole *iE*-field that is related to subsea power cables. In high voltage AC cables, the *B*-field will rotate together with the alternating movement of the current through the three cores within the cable casing. This rotation of the *B*-field is not contained inside the cable sheathing and will be emitted to the adjacent marine environment where it will induce an *E*-field (Figure 15Figure 15 c). Thus, an AC cable will generate a direct *B*-field (analogous to a DC cable) and additionally induce an additional *iE*-field that is related to electricity production.

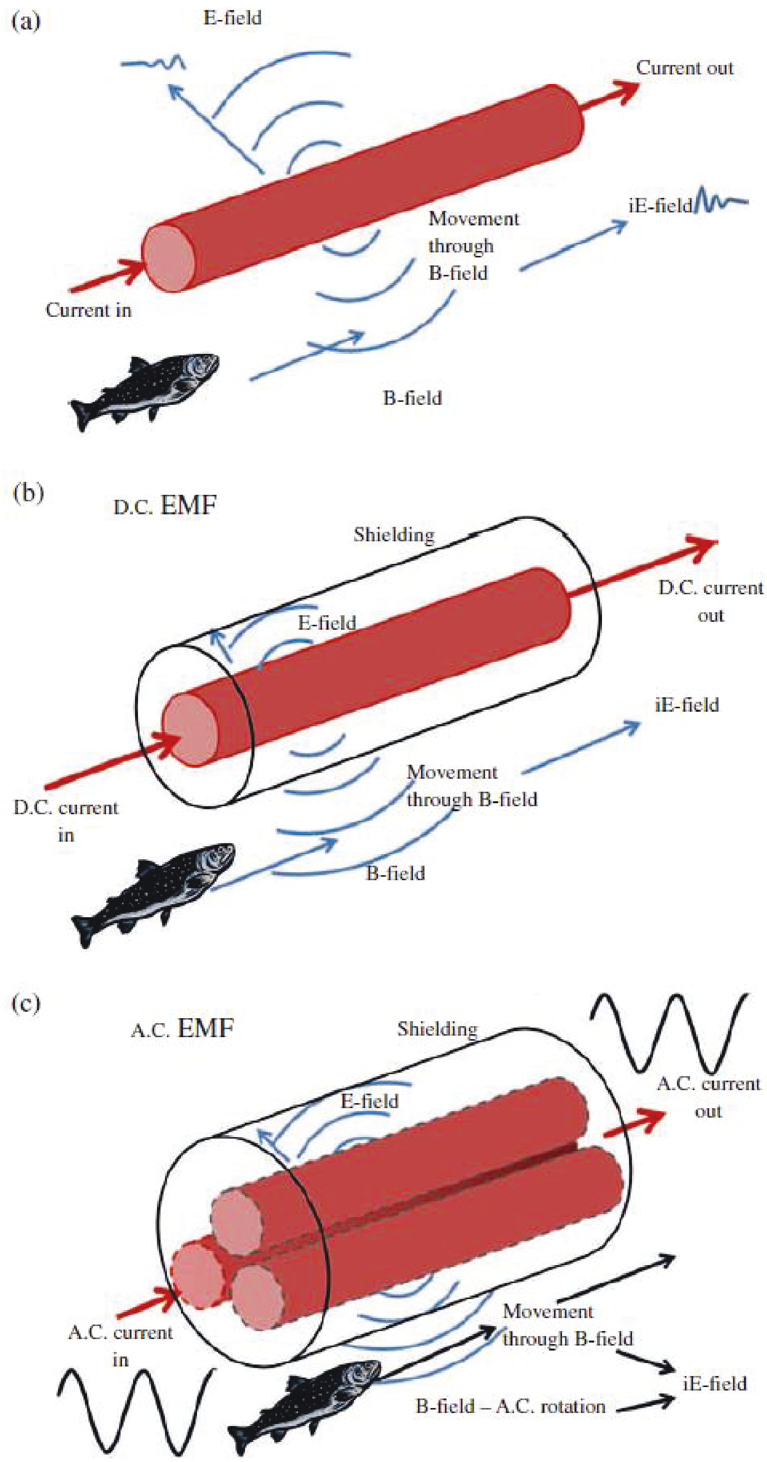


Figure 15: The electric (E) and magnetic (B) fields surrounding a subsea cable. (a) Situation for an unshielded cable. The wave magnitudes indicate sizes of the fields with distance from the cable. (b) A high voltage (HV) D.C. cable with shielding material containing the direct E-field. The iE-field is induced in the fish as it moves through the B-field and by water movement. (c) A HVAC cable showing the three cores with the alternating current following a typical sine wave through each core. The iE-fields are, apart from water and fish movement, induced by the out of phase magnetic field that is emitted by each core. These cause a rotation in the magnetic emission which induces an iE-field in the surrounding water. (Gill et al., 2012).

To reduce the emitted *B*-field, a variety of measures can be implemented. First of all, the cable armouring can be used to shield off the magnetic field. In other words, a higher permeability of the sheathing's magnetic permeability will decrease the magnetic field due to shunting. The effect of this has also been shown by modelling (CMACS 2003; Huang 2005). Apart from that, the AC magnetic fields in sheathing material with high conductivity (ability of a material to conduct electricity) will induce eddy currents that in turn will create an opposing magnetic field. As a result, the magnetic field from the cable will be further cancelled out, which is one of the reasons that EMFs from AC cables are weaker than from DC cables (see next Sections for more detail). Magnetic field calculations from a 138 kV AC subsea power cable have shown that flux shunting resulted in a factor 2 reduction of the magnetic field, where a much smaller reduction is attributed to eddy currents (Silva et al., 2006).

Another important point is that since magnetic fields are vectors they can be summed. This means that two vectors pointing in the same direction can be summed whilst two vectors pointing in opposite direction can be subtracted from each other. As a result, the magnetic intensity of two closely placed parallel wires will increase when the currents in both wires are flowing in the same direction and decrease when they flow in opposite directions (CMACS, 2003; Bochert and Zetller, 2006). Locating the cables closely together can not only lead to a decrease in magnetic field intensity but can also increase the rate at which the field diminishes with distance from the cable. As a result, bundled AC three-phase cables will generate lower magnetic field intensities that will diminish more quickly with distance than single-phase cables carrying similar loads. A DC cable configuration in which the cables are placed closely together and have equal current will have the lowest magnetic fields. Other measures that can be taken to reduce the magnetic field strength are altering the conductivity and permittivity of the cable sheathing material (CMACS, 2003). In theory, it is even possible this way to completely contain the *B*-field, but this is currently not feasible due to practical and financial implications. Apart from that, there is too little evidence to require a major global cable redesign program (Gill et al., 2012).

Typical magnitudes of *B* and *E*-fields associated to power cables vary significantly and differ for AC and DC cables. In the Sections below, an overview of the calculated and measured magnetic field strengths for AC and DC cables is given. Also, an overview of the calculated induced electrical field strengths for AC and DC cables is given.

### 3.2.1 Expected magnetic fields in AC cables

The university of Liverpool has conducted several EMF modelling studies that were related to the CMACs study at the Kentish Flats offshore wind farm site (Gill et al., 2005). This study found that *B* and *E*-fields generated by underwater AC cables are directly proportional to the current load. For example, this modelling study predicted that the *B*-field at the surface of a 33 kV cable was approximately 1.5 µT. The resulting *E*-field would then have a strength of about 40 µV/m. Apart from that, the modelling results indicated that the *E*-field rapidly decreased to only 1 or 2 µV/m at a distance of 10 m from the cable.

The largest modelled *B*-field at the interface between seabed and seawater had a magnitude of approximately 0.33 µT, although this depends on the burial depth of the cable. The related maximum induced *E*-field magnitude would in this case be approximately 2.5 µV/m.

Table 1: Modelled EMF parameters for Industry Standard Cables (buried 1.5 m in seabed; Gill et al., 2005).

| Cable parameter | Cable A | Cable B |
|---|---|---|
| Conductor size ($mm^2$) | 500 | 185 |
| Maximum voltage (kV) | 33 | 33 |
| Maximum current (A) | 530 | 265 |
| Maximum B field in seabed (μT) | 1.5 | 0.9 |
| Maximum B field in sea (μT) | 0.03 | 0.02 |
| Maximum iE field in seabed (μV/m) | 40 | 25 |
| Maximum iE field in sea (μV/m) | 2.5 | 1.4 |

A study by Eltra (2000) investigated the *B*-field strength related to a 33 kV AC cable buried 1 m below the sea floor that connects the Nysted Offshore wind farm in Denmark with the mainland. Operating at maximum capacity (600 A), the *B* field strength was estimated to be approximately 5 μT on the seabed. This indicates the uncertainties of modelling the EMFs, as this is more than three times higher than modelled field strength at comparable maximum voltage and current shown for cable A in Table 1. A study investigating the *B*-field strength associated to the planned Cape Wind project in Nantucket Sound in the eastern USA found a value of 6 μT at the seabed which dissipated quickly to less than 0.6 μT and 0.3 μT within 6 m and 9 m of the cable centre line, respectively (Valberg 2005). All these values are lower than the earth's geomagnetic field at temperate latitudes (which is approximately 50 μT).

In another study, Normandeau et al. (2011) studied the characteristics of 24 subsea power cable projects and modelled the expected magnetic fields for both AC and DC cables. For most of the modelled AC cables (8 out of 10), the magnetic field intensity was more or less a direct function of the cable voltage (varying from 33 to 345 kV), although the separation distance between the cables and the burial depth also influenced the intensity. The magnetic field intensity was predicted to be strongest in the direct vicinity of the cables and to rapidly decrease with horizontal and vertical distance (Figure 16). In cable systems that use two cables, separated by at least a few metres, the magnetic field would appear as a bimodal peak (also included inFigure 16).

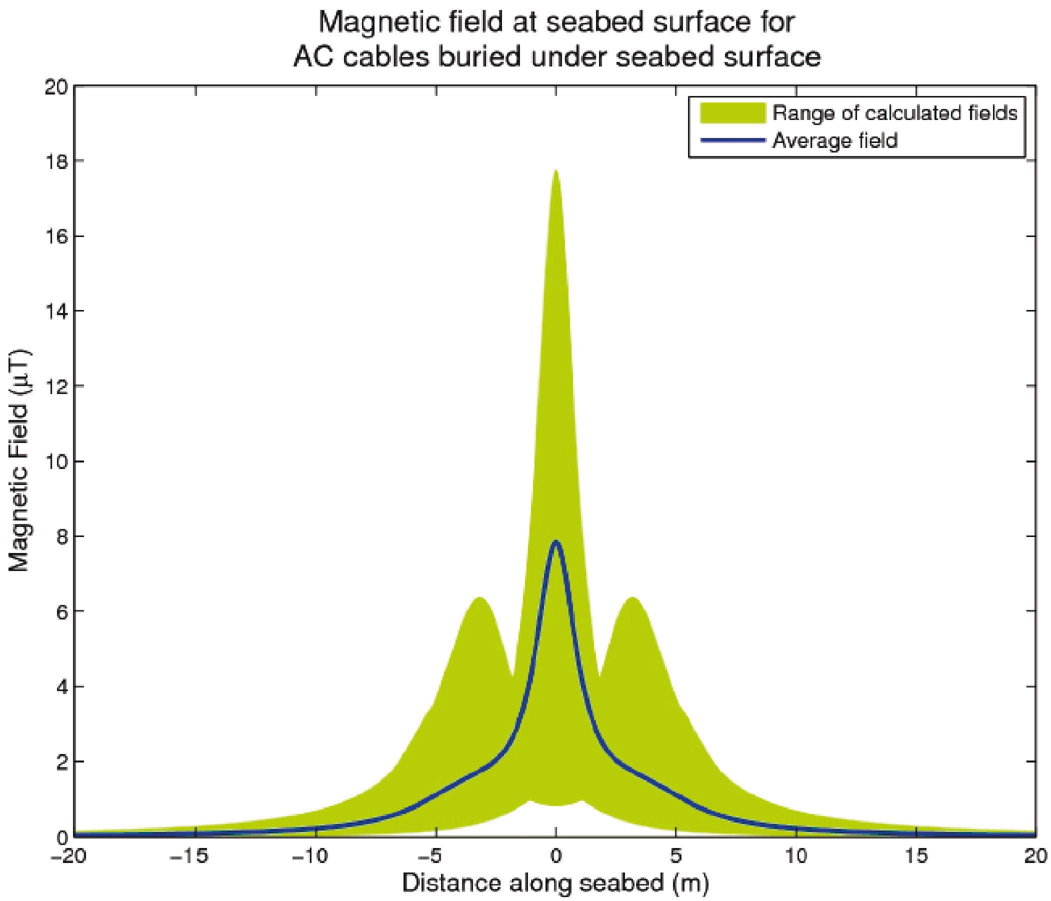


Figure 16: Average modelled magnitudes of electromagnetic field intensity at the seabed for 10 AC cables (Normandeau et al., 2011).

Vattenfall Research and Development AB also calculated magnetic field intensities for a number of standard subsea AC power cables. The cables that were analysed were a 10kV cable (transmission cable to be used at a wave power site in Mayo, Ireland), three different 36 kV cables (internal cables of larger wind/wave power farms or transmission cables for smaller farms) and a 145 kV cable (typical transmission cable for larger wind/wave power farms from the platform to the mainland). For all cables, the basic current was set to 100 A. However, conversion to stronger currents is very easy (see Equation below). The magnetic flux density is computed at the sea bottom, perpendicular to the cable direction. Apart from that, it is assumed that the cable is buried 0,5 metres below the sea floor. This increases the distance between cable and marine life but sediment will not shield the magnetic field (Olsson et al., 2010).

The calculations were performed using the simplified Biot-Savarts law:

$$B = \frac{4\pi \cdot 10^{-7} I}{2\pi r} = \frac{2 \cdot 10^{-7} I}{r} = \frac{0.2 I}{r} [\mu T]$$

Here, *I* is the electric current (A) and *r* is the distance (m) from each one of the conductors in the cable. The model assumes a very long cable where the model is a cross section of the three phase conductors. All model calculations were done with a current of 100 A. The results are shown in Figure 17.

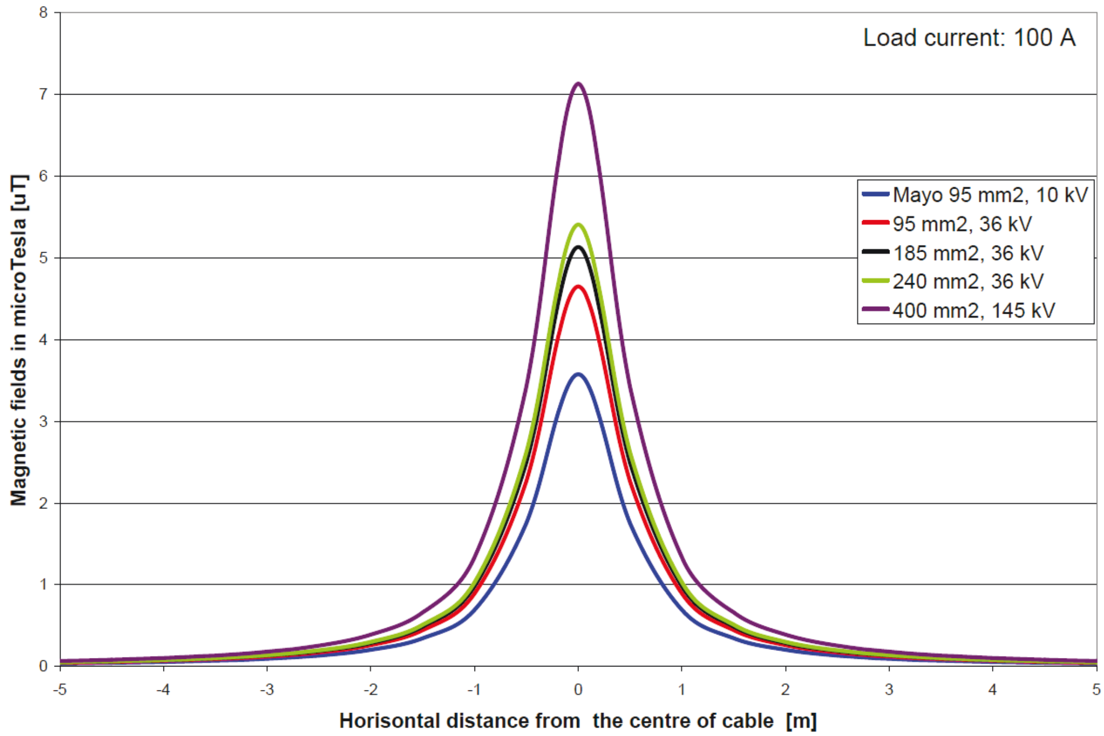


Figure 17: Calculated magnetic field intensities for different types of three phase AC subsea power cables along a line at the sea bottom (Olsson et al., 2010). The cables are buried 0,5 meter under the sea bottom.

The 145 kV, 400 mm$^2$ cable generated the highest *B*-field level (7.1 µT), whilst the 10 kV, 95 mm$^2$ Mayko cable generated the lowest *B*-field level (3.2 µT). As with other studies, the field intensity decreases rapidly with distance and it is below 1 µT at approximately 1 m from the cable. The *B*-field level for all cables at 10-13 m is smaller than 10 nT. This distance increases to 30 m when the current is increased to 500 A. The strength of the magnetic field is proportional to the current and roughly inversely proportional to the distance from the cable. This is also illustrated in Figure 18, which shows the calculated magnetic flux density in relation to the distance from the centre of the cable.

For the planned subsea cable towards the Borssele OWF, EMF strength calculations were conducted for the Environmental Impact Assessment (Witteveen & Bos, 2016). The calculations were done for in total four 3-phase AC cables of 220 kV with a current of 1000 A. It is assumed that the cables in the Western Scheldt are separated by 100 m and at sea by 200 m. A total of three burial depths were considered; 1, 3 and 6 meter.

The calculations indicate that for 1 m depth, the magnetic flux density can reach 23 µT at the sea floor above the cable, which quickly decreases to less than 1 µT at a distance of 5 m from the cable. For a burial depth of 3 and 6 meter the largest calculated magnetic flux density is 3 and 0.5 µT at the sea floor respectively. These values are somewhat higher compared to the values of the previous studies (see Figure 17), which is probably related to the relatively high voltage and currents used for this particular cable.

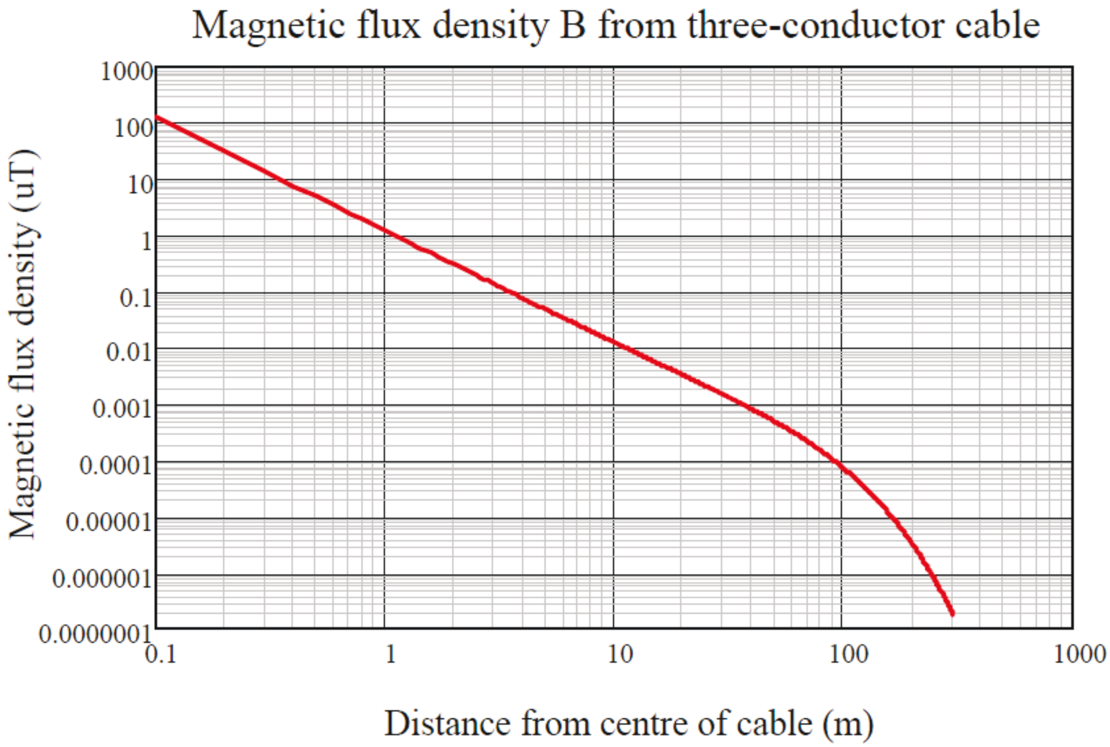


Figure 18: Modelled magnetic flux density in µT from a three-conductor cable, as a function of the distance from the cable. The current is 100 A, the separation between the conductors is 7 cm and the conductivity of the seawater is assumed to be 3.5 Siemens/m.

One of the few studies which actually measured the magnetic field strength and electric field strength related to offshore windfarms is the study of Thomsen et al. (2015). This study measured the EMFs related to the Belgium CPower and Northwind windfarm. Both windfarms are connected to shore using HVAC cables, the CPower windfarm using a 150 kV cable and the Northwind windfarm using a 245 kV cable. An example of the measurements is presented in Figure 19. The figure clearly shows that the electric field is higher for the Northwind cable (approximately 0.07-0.08 mV/m) compared to the CPower cable (0.03-0.04 mV/m). Contrary, the magnetic field strength while crossing the CPower cable for the first time (0.06 µT) clearly exceeds that of the Northwind cable (0.03 µT). However, when crossing the power cables for the second time the magnetic field strength of the Northwind cable (0,03 T) exceeds that of the CPower cable (0.02). This illustrates that measurements can also lead to a variety of results, even for the same cable configuration during the same measurement campaign. The cause of these variations are unknown, but could for example be explained by a local larger burial depth due to sand dunes above the cable.

The EMF strength of the 150kV export cable of the Dutch Prinses Amalia Wind Park (PAWP) has been measured under variable wind conditions, however these measurements have not been conducted at sea but at the beach where the cable comes to shore. At a distance of 1m from the cable, a magnetic field strength between 0.3-0.8 µT is measured while the OWF generated at 94% of its maximum power output. This is in the same order of magnitude as the measurements of the CPower and Northwind windfarm, although those measurements were conducted during calm weather conditions and not at almost maximum generated power output of the OWFs.

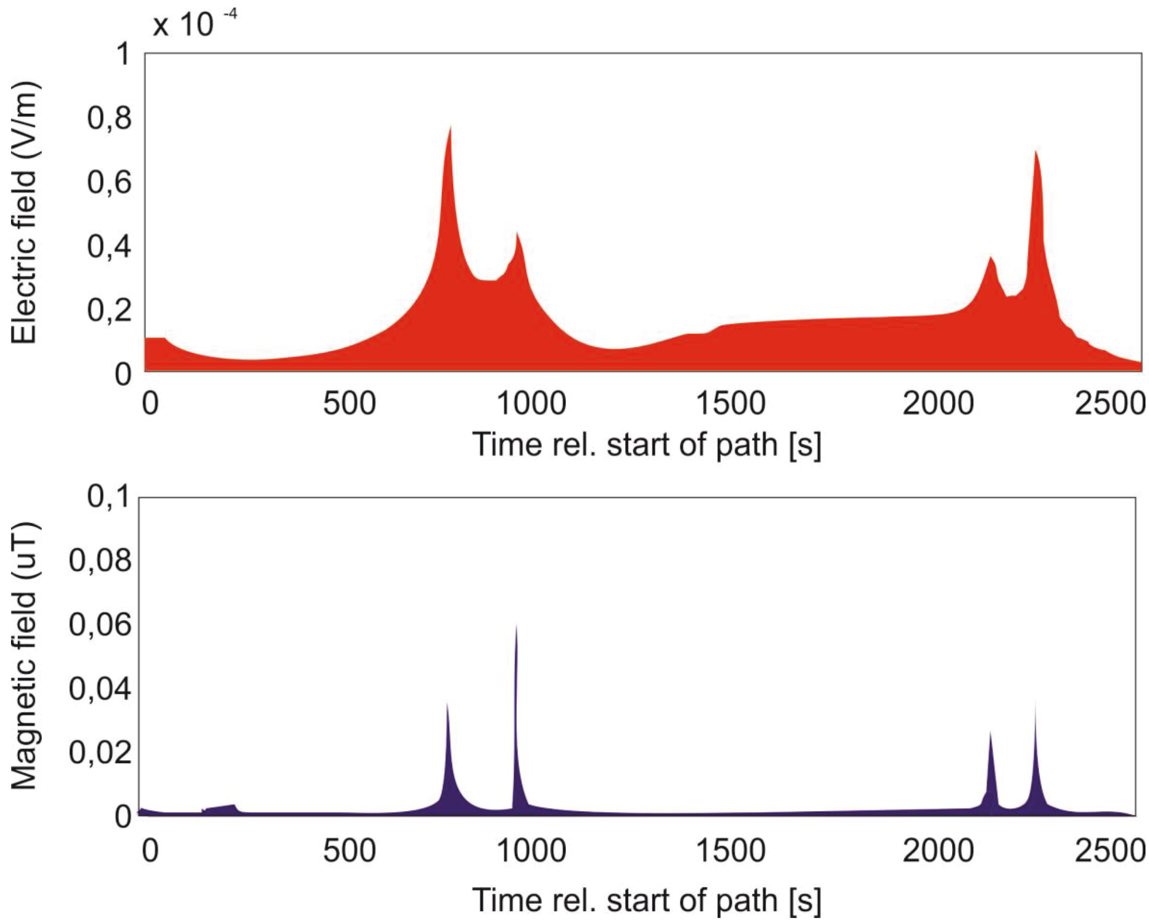


Figure 19: EMF measurements crossing the Northwind and CPower export cables (after Thomsen et al., 2015). The first peak from the left is the Northwind cable and the second the CPower cable. The third is the CPower cable and the fourth the Northwind cable. The upper panel shows the electric field and the lower panel the magnetic field (illustration based on presentation of MARVEN project).

### 3.2.2 Expected magnetic fields in DC cables

Analogous to AC cables, the magnetic field intensity for DC cables also depends on voltage (range: 75 to 500 kV), current strength and cable configuration. In contrast to estimated *B*-field strengths described for AC cables, the related strengths for monopolar DC cables can exceed the earth's magnetic field. The strength of a *B*-field related to a monopolar DC cable is proportional to the distance from the cable (i.e. more distance means a lower magnitude). Due to the partial cancellation of fields from two conductors carrying current in opposite directions, the *B*-field of a bipolar DC cable declines a bit faster compared to AC cables (Foster and Repacholi 2000, Normandeau, 2011).

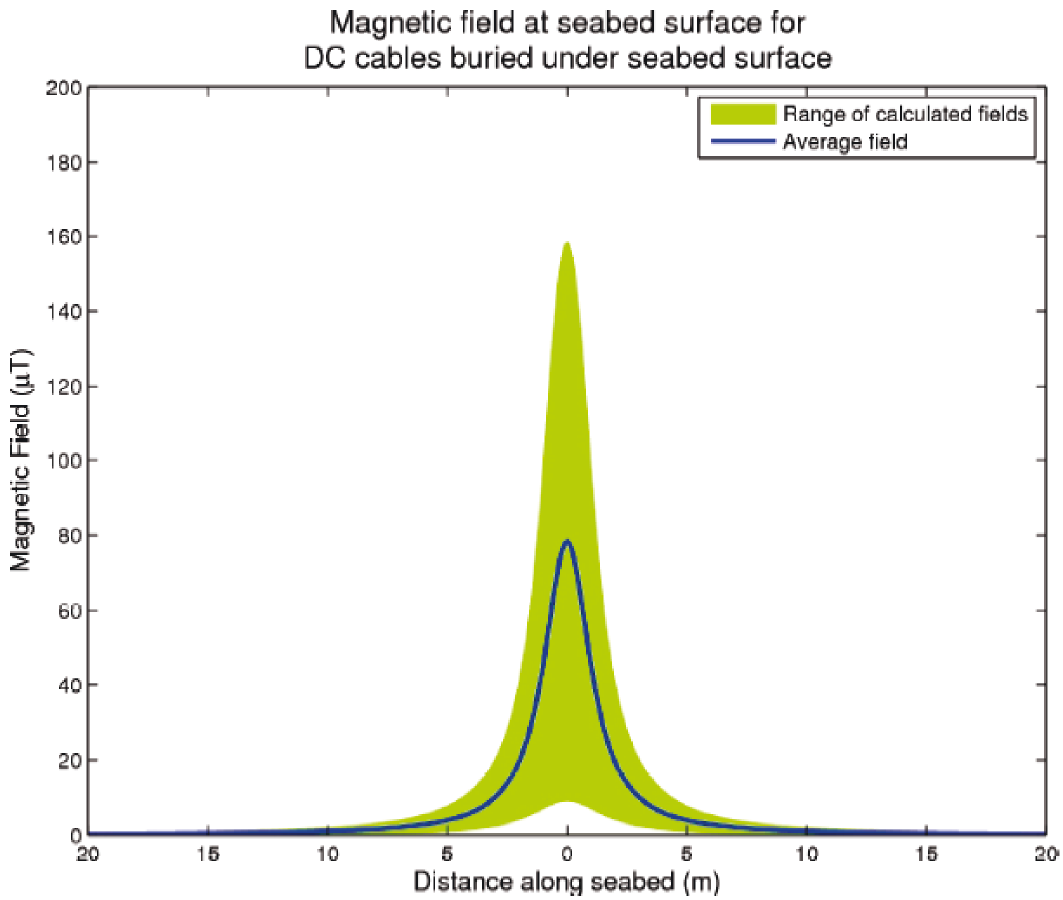


Figure 20: Average modelled magnitudes of electromagnetic field intensity at the seabed for 9 DC cables (Normandeau et al., 2011).

The *B*-field strength of a monopolar cable carrying 1500 A has been estimated to be about 300 µT, declining to 50 µT and 13 µT within 5 m and 20 m respectively (Koops, 2000). Bochert and Zettler (2006) estimated that the B-field related to a single monopolar DC cable carrying 1600 A could reach 3200 µT at the cable surface. They predicted that the strength of this *B*-field would reduce to 320 µT and 110 µT within 1 m and 4 m of the cable, respectively. Obviously these values are significantly higher than for AC cables, but also illustrate the variance in magnetic field strength that can be expected between DC cables with comparable currents. This becomes even more clear when looking at the results of the study by Normandeau et al. (2011), who also modelled the magnetic field strength for various DC cables. Their results are presented in Figure 20. The *B*-field strengths found by Normandeau et al. (2011) are a factor 2-3 lower compared to the values estimated by Koops (2000) and approximately a factor 30 lower than estimated by Bochert and Zettler (2006). An explanation for these large differences could be an increase in scientific understanding over time regarding magnetic field strength calculations. However, all results indicate that *B*-field strengths for DC power cables are much larger compared to AC power cables. This is made clear by Table 2, in which the modelling results of Normandeau et al. (2011) are summarised (both for AC and DC cables), assuming a burial depth of one metre.

Table 2: Averaged modelled magnetic field intensity (µT) for different types of subsea power cables assuming a burial depth of 1 m (Normandeau et al., 2011).

| Type of power | Sample size | Distance above the seabed (m) | Horizontal distance (0 m) (EMF strength in µT) | Horizontal distance (10 m) (EMF strength in µT) |
|---|---|---|---|---|
| AC | 10 | 0 | 7.85 | 0.22 |
| | | 5 | 0.35 | 0.14 |
| | | 10 | 0.13 | 0.08 |
| DC | 8 | 0 | 78.27 | 1.02 |
| | | 5 | 2.73 | 0.75 |
| | | 10 | 0.83 | 0.46 |

A complication of magnetic fields from DC cables is that they influence the intensity of Earth's magnetic field as well as the inclination and declination of the geomagnetic field. Inclination refers to the angle between the horizontal plane and the magnetic field vector at a point in space whilst declination is defined as the angle between the magnetic field and geomagnetic north. Although the geomagnetic field generally has a nonzero declination and inclination, the magnetic field from DC cables will change the apparent intensity and direction of the magnetic north. The influence of the magnetic field from DC cables on the geomagnetic field depends on the orientation of the cables relative to the geomagnetic field. When the cables run perpendicular to the magnetic north, the DC magnetic fields will affect the intensity and inclination angle of the geomagnetic field, but not influence the declination angle. However, when the cables run parallel to the magnetic north, the DC magnetic field will affect the declination angle of the geomagnetic field, in addition to affecting its intensity and inclination angle. This interaction between the geomagnetic field and the DC magnetic field of the cables further complicates the measurement of magnetic fields from DC submarine power cables. The reason for this is that the magnetic field vectors of the DC cable field combine with the magnetic field vectors of the geomagnetic field. As a result, the intensity, shape, and spatial extent of the combined magnetic field (cable + geomagnetic) is strongly depending on the orientation of the cable system with respect to earth's north-south magnetic dipole (Normandeau et al., 2011).

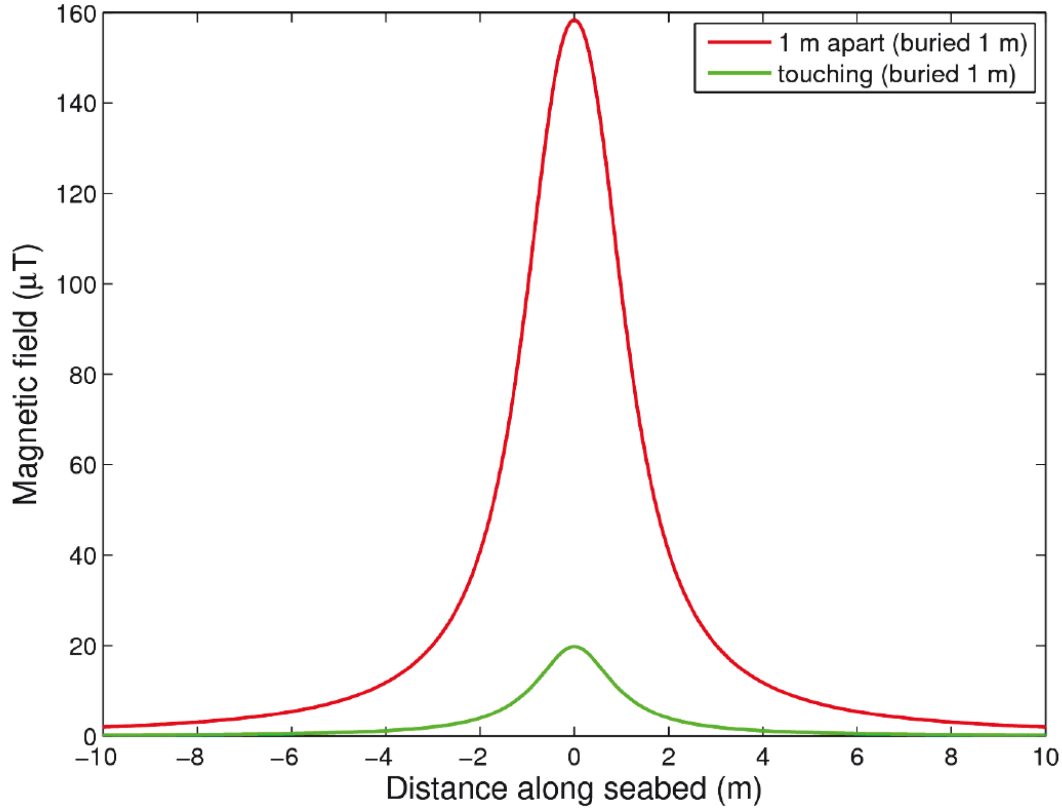


Figure 21: Modelled profile of a DC magnetic field from a subsea 200kV cable operating at 400 MW without taking the geomagnetic field into account (Exponent and Hatch 2009).

An example of the interaction between DC cable magnetic fields and the geomagnetic field is given by comparing Figure 21with Figure 22. Both figures show the modelled magnetic field of a 200 kV power cable operating at 400 MW, but the geomagnetic field is not included in Figure 21 whilst it is included in Figure 22. It is evident that including the geomagnetic field reduces the peak DC magnetic field over the cable by about 31 percent when the cables are separated by 1 m. When the cables are modelled as touching, the geomagnetic field is reduced by about 20 μT over the cable. When the geomagnetic field is not taken into account, the results suggest that the magnetic field would increase by 20 μT over the cable. An increase in the total magnetic field above the background geomagnetic field occurs when the magnetic field vector of the cable is aligned parallel and in the same direction as the geomagnetic field vector. A decrease in the total magnetic field below the background geomagnetic field takes place when the magnetic field vector of the cable is oriented opposite to the vector of the geomagnetic field. As a result, the orientation of a DC subsea power cable with respect to the geomagnetic field determines the resulting total magnetic field (Normandeau et al., 2011).

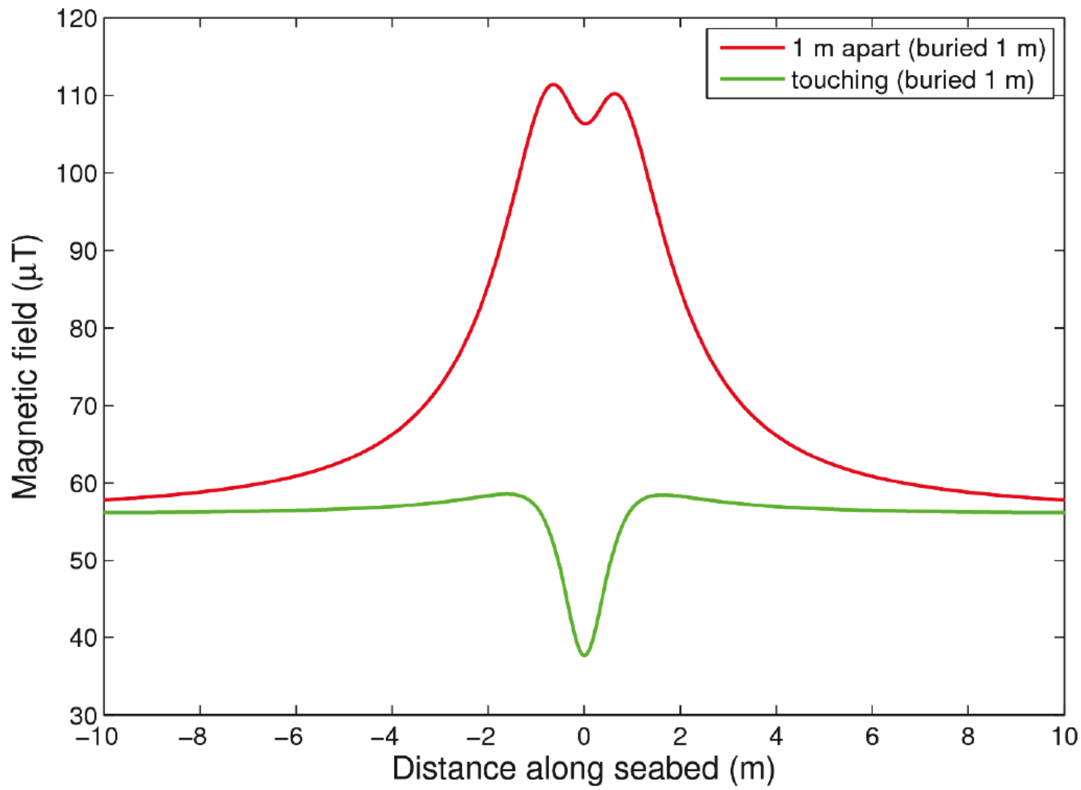


Figure 22: Modelled profile of DC magnetic field from a subsea ± 200 kV cable operating at 400 MW when orientated NNE and including the geomagnetic field (Exponent and Hatch 2009).

### 3.2.3 Expected induced electric fields in AC and DC cables

An induced electric field will be created by movement through a magnetic field or the rotation of a magnetic field. This can be caused by a variety of mechanisms, such as water current movement, an organism swimming through the field or due to the asymmetric rotation of the AC field within the industry standard 3-phase cable. The strength of the induced field depends on the distance from the cable, electrical conductivity of the medium and the speed and orientation of the current or organism with respect to the field. An electric field will not be induced when a water current or organism moves parallel to the magnetic field in the cable. When the water current or organism moves perpendicular to the magnetic field in the cable, a maximum electric field will be induced that is a function of the speed, exact orientation relative to the cable magnetic field and the strength of the magnetic field (Normandeau et al. 2011).

Induced electric fields will be induced by both AC and DC power cables, however the polarity of the induced current would reverse at the same frequency as that of the AC magnetic field.

One form of movement that can induce the electric fields is the movement of water over the cable, e.g. at locations with large tidal differences and / or during storm conditions. This essentially means that this iEF will only be generated where there is movement through the existing EMF. The ecological relevance of these iEFs that can be generated is discussed in Chapter 4. The induction of the electric fields largely depends on the orientation of the subsea cables with respect to the direction of high current flows. Also, effects can be very different in areas along the cable, due to local turbulence that can occur.

Table 3 shows modelled values of the induced electric field strength generated by a 2.57 m/s water current running perpendicular to a DC cable (Normandeau et al., 2011).

Table 3: Average modelled values of induced electric fields from DC subsea power cables (mV/m) with a burial depth of 1 m and a water current of 2.57 m/s (Normandeau et al., 2011).

| Distance above seabed (m) | Horizontal distance (0 m) iEF strength (mV/m) | Horizontal distance (4 m) iEF strength (mV/m) | Horizontal distance (10 m) iEF strength (mV/m) |
|---|---|---|---|
| 0 | 0.2 | 0.03 | 0.08 |
| 5 | 0.02 | 0.02 | 0.01 |
| 10 | 0.008 | 0.009 | 0.007 |

The study by Olsson et al. (2010) modelled electric field intensities around AC cables. The induced electric field is strongly depending on the distance between the conductors in the cable. Furthermore, the induced electric field depends linearly on the current in the cable, which is shown in Table 4. It should be noted that the shielding of the cable has not been taken into account in the calculations. The calculated induced electric field along a profile on the sea-bottom perpendicular to the cable is shown in Figure 23, assuming a burial depth of 0.5, a current of 100 A and a conductivity (ability of a material to conduct an electric current) of 3.5 Siemens/m (S/m). The maximum induced electric field calculated at the sea bottom is 0.8 mV/m.

When the current is increased to 500 A – which is higher than can be expected in infield cables, but lower than can be expected in export cables -, the maximum induced electric field is calculated at 4 mV/m. The distance between the conductors in the cable is a very important factor for the magnitude of the induced electric and magnetic fields.

Table 4: Maximum induced electric field (mV/m) above three different AC cable types carrying 100, 300 and 500 A and buried 0.5 m. The seawater conductivity is 3.5 S/m (Olsson et al., 2010).

| Distance between the three conductors | 100 A iEF strength (mV/m) | 300 A iEF strength (mV/m) | 500 A iEF strength (mV/m) |
|---|---|---|---|
| 35 mm (10 kV cable) | 0.40 | 1.2 | 2.0 |
| 49 mm (36 kV cable) | 0.57 | 1.7 | 2.8 |
| 67 mm (145 kV cable) | 0.79 | 2.4 | 3.9 |

Electric fields can also be induced in the marine environment around AC cables due to the movement of swimming animals in that environment, e.g. fish or marine mammals. The size of the animals and their distance from the cable are important factors determining the field strength. A larger organism at close proximity to the cable will induce a large electric field in compared to a smaller animal located further away from the cable. Table 5 shows as an example the modelled average induced AC electric field in a small shark (150 cm long and 60 cm high) that swims above and parallel to the buried cable.

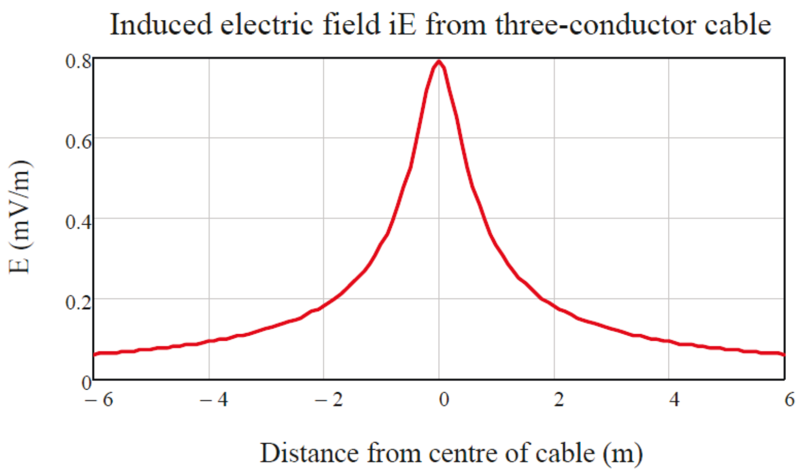


Figure 23: The induced electric field calculated along a profile on the sea bottom perpendicular to a three-conductor AC cable buried 0.5 m assuming a current of 100 A.

Finally, there are also naturally induced electric fields present in the marine environment. Normally, induced electric fields from a cable are much larger compared to what exists in nature although sometimes (for example during solar storms) the magnitude of the naturally induced electric field can be in the same order as the electric field induced from a cable. According to Normandeau et al (2011), background induced electric field strengths can range from 0.5 µV/cm to 0.75 µV/cm in seabeds, while during geomagnetic storms this can increase to 1.25 µV/cm. This is generally lower than the fields induced by the AC and DC cables.

Table 5: Average modelled values of induced electric fields in a small shark for a 60 Hz AC subsea power cable (mV/m) with a burial depth of 1 m (Normandeau et al., 2011).

| Distance above seabed (m) | Field strength (mV/m) |
|---|---|
| 0 | $7.65 \cdot 10^{-1}$ |
| 5 | $3.39 \cdot 10^{-2}$ |
| 10 | $1.24 \cdot 10^{-3}$ |

### 3.2.4 Summary of factors influencing EMFs

In this section a summary of the factors that influence EMFs is given. Also, the factors are described that might influence EMFs, but of which currently knowledge is too limited to provide (quantitative) information.

#### AC vs. DC

Both AC and DC cables generate EMFs. Due to shielding of the cable, electric fields are contained within the cable itself, whereas electromagnetic fields extend outside the cable. The EMF of DC cables is generally stronger compared to AC cables.

AC cables generate a constantly variable magnetic field whilst DC cables generate a static magnetic field. The rotation of the magnetic fields in AC cables induces also an electric field outside the cable which cannot be shielded by the cable.

Due to changing of the current direction in AC cables, EMFs generated might cancel each other out due to changing directions of the field. EMFs of DC cables can also cancel each other out, depending on the distance between the outflow & return cables.

Mutual cancellation of the magnetic fields from cables is achieved by placing the cables close together because of the vector nature of magnetic fields. Placing the cables close together not only reduces the peak magnetic field but it increases the rate at which the field diminishes with distance from the cables. Bundled AC three-phase cables therefore will produce lower magnetic fields that will diminish more quickly with distance than single-phase cables carrying similar loads. DC cable configurations that place cables closer together and with equal current will have the lowest magnetic fields. In the extreme, a coaxial configuration in which a DC power cable is contained wholly inside the return conductor will totally contain the magnetic field (from Normandeau et al., 2011).

### Voltage & electric current

The strength of the EMF increases proportionally by increasing the electric current and is also positively related to the voltage of the cable. Since the current depends on the generated energy by the wind turbines, the strength of the electric magnetic field depends on the wind force, up to the force at which maximum output is generated (approx. 6 Bft). Voltage is constant in the cables, but can differ between infield and export cables.

### Distance from the cable

The electromagnetic field strength strongly depends on the distance to the cable, as the EMF strength strongly decreasing with distance (see for example Figure 20 and Figure 21).

### Cable design

Three-phase AC cables generate three-phase variable EMFs. The three phases of the cables are usually combined in a single cable, which restricts the EMF to the area around a single cable. DC cables often have two cables (outflow & return cable). These can be tied together or place separately, in which the latter case the EMFs are present in a larger area. Locating the cables closely together can not only lead to a decrease in magnetic field intensity but can also increase the rate at which the field diminishes with distance from the cable. Positioning of the cables based on the distance between the cables could therefore be used as a mitigation measure for EMFs in the marine environment.

### Burial depth & water column

No shielding effect of sediment and / or the water column is clearly described in literature. Although modelling outputs suggests that sediment and water have a different shielding effect, no such thing is described in literature. The effect of burial described in literature is simply the enlarged distance between cable and marine environment due to burial.

### Water current

Movements through a magnetic field induce an electrical field in both AC and DC cables. This can be e.g. due to movement of water (tidal currents, wave action) or by the movement of organisms. The orientation of the cable in relation to the main current direction determines the strength of the induced electric field, which is largest at perpendicular angles.

### Background magnetic field

The magnetic field generated by DC cables is able to influence the earth's magnetic field. Therefore, the relative orientation of the cable with respect to the geomagnetic field must be known in order to determine the total magnetic field strength.

## 3.3 Electromagnetic fields in the North Sea

As described above, the electromagnetic field strength depends on a lot of variables, which makes a solid quantification of the expected strength based on cable properties difficult. The main variable of the field strength is the distance from cable, since the strength rapidly decreases with distance.

Based on described literature, a range of expected magnetic field strength for the cables is the North Sea is given. Note that these values are indicative only.

### 3.3.1 Power cables

#### Existing power cables

Figure 24 and Table 6 show an overview of the current and planned export cables in the Dutch part of the North Sea.

There are currently two DC energy transmission cables present, which are the Norned cable (450kV DC, 700MW) between the Netherlands and Norway (not fully shown in figure) and the Britned cable (450 kV DC, 1000MW) between the Netherlands and the UK.

The current OWF's are connected to shore by MV (Offshore Windfarm Egmond aan Zee and HV AC cables (Prinses Amalia Windfarm, Luchterduinen, Gemini).

Additionally, medium voltage infield cables are present in the areas of the offshore wind farms shown in Figure 24. Infield cables currently present are 33kV cables between turbines and offshore HVAC stations.

Based on available literature, the electromagnetic field strength of the export DC cables is 100-300 μT, export AC cables is 5-50 μT and AC infield cables is approx. 5 μT.


Figure 24: Subsea power cables (red: HVDC, orange: HVAC, yellow: MVAC) and current and planned OWFs (current: light blue, planned: dark blue). Figure is compiled based on currently available information, cable routes of the planned wind farm areas are therefore indicative.

### Future power cables

Figure 24 also shows the planned wind areas *Borssele*, *Hollandse Kust Zuid* and *Hollandse Kust Noord* for the Dutch coast. Five offshore AC substations and cable connections to the onshore high voltage grid are foreseen on the three areas. Each connection to the shore will – as currently foreseen - consist of two three core 220 kV AC cables. The cables will be positioned at approx. 200m distance from each other.

In the wind farm areas, 33kV and possibly 66kV infield cables will connect the turbines to the substations.

There are ideas about realizing an offshore windfarm at the Doggersbank (not shown on the map), however no concrete plans have been made at this stage. Due to the large distance to the Doggersbank, it is expected that a HVDC export cable will be used for transport of generated energy to shore.

Table 6: Overview of current and planned subsea power cables in the Dutch part of the North Sea (* no concrete plans) and an indication of the expected electromagnetic field strength at the sea bottom, based on 1m cable burial (overview compiled based on publically available information).

| Name | Status | Type | Voltage (kV) | Maximum power (MW) | Number of cables | Indication of EMF strength (µT) | Indication of induced electric field strength (mV/m) |
|---|---|---|---|---|---|---|---|
| Norned | Realized | HVDC | 450 | 700 | 2 | 100-300 | 0.5-5 |
| Britned | Realized | HVDC | 450 | 1000 | 2 | 100-300 | |
| OWEZ | Realized | MVAC | 34 | 108 | 3 | 5 | |
| PAWP | Realized | HVAC | 150 | 120 | 1 | 5-50 | |
| Luchterduinen | Realized | HVAC | 150 | 129 | 1 | 5-50 | |
| Gemini | Realized | HVAC | 220 | 600 | 2 | 5-50 | |
| Wind area Borssele | Planned | HVAC | 220 | 700 + 680 + 20 | 2 x 2 | 5-50 | |
| Wind area Holland Kust Zuid | Planned | HVAC | 220 | 700 + 700 | 2 x 2 | 5-50 | |
| Wind area Hollandse Kust Zuid | Planned | HVAC | 220 | 700 | 2 | 5-50 | |
| Doggersbank* | - | HVDC | - | - | - | 100-300 | |

## 3.3.2 Other potential sources of EMFs

Besides power cables, EMFs can be generated by telecom cables and the electric heating of oil and gas pipelines. Figure 25 gives an overview of these sources as an illustration of the occurrence of anthropogenic EMFs in the Dutch part of the North Sea. The expected strength of the EMFs is lower compared to HV cables. The main reason for that is that the voltage and electric currents associated with telecom cables and heating of oil and gas pipelines are much smaller compared to electric High Voltage cables.


Figure 25: Cables (green) and pipelines (blue) in the North Sea.

## 3.4 KNOWLEDGE GAPS

Expected field strengths for the subsea power cables in the North Sea are mainly based on modelling outputs. As described in literature and in contact with experts, the accuracy of these modelling outputs is uncertain. There is a strong knowledge gap on the actual electromagnetic field strength that can be expected for the various cable designs, voltages and outputs of OWFs.

There is also a lack of knowledge on the occurrence and strength of induced electrical fields (iEFs) that are induced by movement in the electromagnetic fields generated by power cables.

Also, there is a lack of knowledge on the possibilities for mitigation of EMFs. No literature has been found on the shielding effect of sediment and/or water, this can be identified as a lack of knowledge. Also, the effectiveness of increased cable burial on the EMFs that reach the marine environment and other mitigations such as a higher voltage in combination with a lower current to reduce EMFs are identified as a knowledge gap.

Recommendations to address these knowledge gaps are given in Section 6.2.

# 4 ELECTRO AND MAGNETIC SENSITIVITY AND POTENTIAL IMPACT ON MARINE LIFE

In this chapter, the potential impact of EMFs on marine life is determined by means of a literature review. First, the approach followed in this review to determine this impact is described in Section 4.1.

Next, the biological basis for electro and magnetic-sensitivity of sensitive species(groups) is described in Section 4.2. This Section focuses on biological aspects of different marine organisms (invertebrates, bony fish, elasmobranch species, turtles and marine mammals) and determines if specific species from these defined species groups are sensitive for magnetic and/or induced electric fields.

In Section 4.3, the effect of EMFs on marine life is further elaborated and the potential effect of *increased* and *anthropogenic* EMFs of subsea power cables on the defined species groups is studied. Reported effects from literature are described.

In Section 4.4, a focus on the North Sea region is given. In this Section, effects are determined for North Sea species. Also, if possible the sensitivity range for magnetic (B) or electric (E or iE) fields is given for species(groups). Additionally, the generated and magnetic and electric fields for both AC and DC cables that are expected to occur in the Dutch North Sea are compared to the sensitivity range of the animals that are present in this region.

In Section 4.5 knowledge gaps and directions for future research are reported.

This study is focussed on impacts of EMFs on individual level. Although it is speculated that population-level impacts can occur, no studies addressing population, food-web or community impacts are currently available.

## 4.1 LITERATURE REVIEW APPROACH

Theory suggests there could be a potential negative impact of EMFs on marine organisms. To determine in to what extent these speculations are true, first the sensitivity of species groups is further discussed in the sections below.

Figure 26 gives a schematic overview of the ecological impact of EMFs on marine life. For ecological impact assessment the stressor is defined as anthropogenic EMFs produced by the subsea cables for example of OWFs (as described in Chapter 3). The (severity and scale of) impact depends the receptors of the EMFs: different species(groups) of the marine organisms present in the North Sea with variable sensitivity for magnetic and/or electric fields.

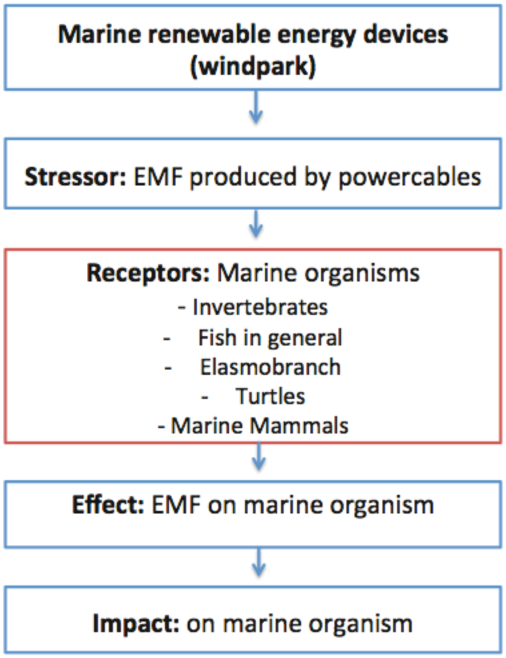


Figure 26 Schematic overview of impact of EMFs on marine life

We used various search engines such as Google Scholar, Directory of Open Access Journals (DOAJ) and various repositories at universities and research institutes. Search terms are "electromagnetic fields, emf, magnetic fields, electric fields" in conjunction with "marine, sub-sea, offshore, mred, marine organisms, benthos, marine mammals, harbor porpoise, sharks, rays, elasmobranch, seal, impact."

The databases are searched for all the information relating to the aquatic species that are considered to be potentially susceptible to electromagnetic fields, that is to say, either the electric field or magnetic field, or both.

A selection was made of suiTable articles based on title and abstract. Sources from outside the North Sea are translated into their application for Dutch coastal waters (see Figure 27). Priority was being given to existing reviews from the past 10 years and new research from the past 5 years. The scope started wide and was soon focused on 1) species in the North Sea, 2) species that appear sensitive to EMFs.

There is no standard list of North Sea species, therefore the review was focused on translating effects of species groups on threatened and declining species according to OSPAR (2016). Since literature of North Sea species appeared to be scarce, all species in the North Sea that were subject to species specific studies are stated, not solely the most common or threatened.

The review first focussed on sensitivity of receptor species(groups) (Fig 26; 27; section 4.2). Next potential effects were addressed (Fig 26; 27; section 4.3) and translated to the North Sea (section 4.4).

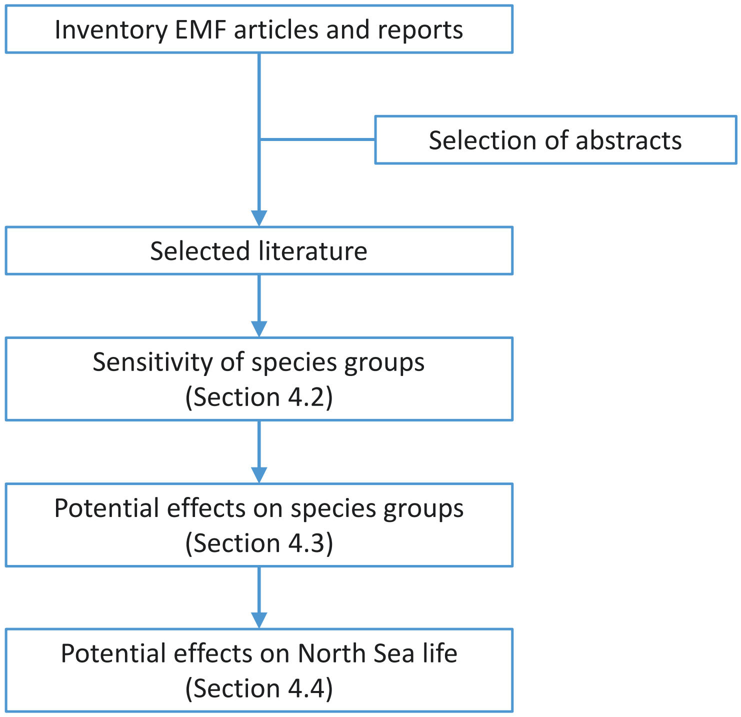


Figure 27 Literature review approach and chapter content

## 4.2 BIOLOGICAL BASIS FOR ELECTRO- AND MAGNETIC SENSITIVITY

**Essence:**

It is known that several taxonomic groups inhabiting European seas are sensitive to EMF. Anecdotal evidence is suggesting that both magnetic (B) *and* (induced) electric (iE) fields are sensed by a diversity of marine species(groups).

Current knowledge suggests magnetic reception is used by a wide range of marine species(groups), especially for orientation and navigation.

Electroreception is mostly used for predator/prey detection and especially known for electro sensitive species that possess ampullary receptors like elasmobranchs and some fishes (e.g. sturgeons, lampreys catfishes). Additional studies suggest the use of electroreception for prey and mate detection in crayfish and for orientation in elasmobranchs.

There are large gaps in understanding the sensitivity of marine species(groups) to EMFs. Since in the marine environment usually a combination of sensory systems is used by species (e.g. information from reception of visual, sound, olfactory and mechanic vibration stimuli) explicit sensitivity to EMFs is difficult to establish. Furthermore, a hierarchical use of sensory systems is suggested, which implies that the sensitivity for EMFs depends on the functionality of other sensory systems as well. For example in elasmobranchs, electrosensing is suggested to be only of importance for the final stages (e.g. last 30 cm) of feeding or detecting others whereas hearing or smell are used at longer distances. Additionally, research on EMFs has so far been mostly restricted to a few species and large mobile adults, while other life stages might be influenced as well.

### 4.2.1 Sensory reception & sensitivity to EMFs

Electro- and magneto-sensitivity in marine life is generally poorly understood and also the physiological pathways of how marine wildlife senses iEFs and EMFs is largely unknown. However, there is some knowledge on the ability to detect these fields as is described below.

#### Sensory reception

Marine organisms just like any other organisms depend on sensory reception to feed, avoid predators, reproduce and migrate along with several other functions (Boemre, 2011). Senses like vision, hearing, touch, chemoreception (taste, smell) and balance are well known and easy to understand. Marine organisms however live in a different environment and their sensory reception mechanisms needs to be adjusted to thrive in underwater habitats. Light is for example limited underwater due to absorption and turbidity of the water. Marine species therefore depend more strongly on senses such as hearing, chemoreception and in certain species electro- and magnetic-reception.

#### Magnetic sensitivity

Marine organisms that are known (or presumed) to be able to detect magnetic fields can be categorised into at least two groups based on their mode of magnetic field detection:

1) Magnetite based detection.
2) Indirect by detection of induced electric (iE) fields;

The first mode relates to species with magnetite deposits that play an important role in geomagnetic field detection in a relatively large variety of organisms such as birds, insects, (Kirshvink 1997) and marine species like turtles, salmonids, whales and elasmobranchs (references in Fisher & Slater 2010). For many of these species of organisms, sensitivity to the geomagnetic field is associated with a direction finding ability (Scottish Marine Renewables SEA, 2007).

The second mode relates to species that are electroreceptive. Electroreceptive organs could also possibly used for sensing magnetic fields, by means of detecting very small fluctuations in the potential difference between the pore and the base of the electroreceptor sack. It is generally assumed that the induced E (iE) field generated by species when they are moving through a B field mode of detection is used for navigation (Scottish Marine Renewables SEA, 2007).

#### Electro sensitivity

Electroreception is the biological ability to perceive natural electrical stimuli. Since salt-water is a much better conductor then air electroreception has been observed almost exclusively in aquatic (or amphibious) animals. The main mechanism of electroreception is the use of specialised ampullary electroreptors and have evolved in elasmobranchs (sharks, skates and rays, see Section 4.2.5), sturgeons and catfish and lampreys. Other species are not known for possessing specialized electroreceptors but are able to detect induced voltage gradients associated with water movement and geomagnetic emissions. The actual sensory mechanism of detection is not yet properly understood (Scottish Marine Renewables SEA, 2007).

### 4.2.2 Cellular processes and embryonic development

The ability to detect EMFs and EFs starts in the embryonic and juvenile stages of life for numerous marine species. Magnetic fields are almost unperturbed by biological tissues and may interact with living systems through magnetic induction (forces on moving ions in solution), magneto-mechanical effects (torques on molecules and ferromagnetic material) and electronic interactions (altering of energy levels and spin orientation of electrons) (Bochert & Zetller 2006). Several studies have found that EMFs alter the development of cells; influence circulation, gas exchange and development of embryos; and alter embryonic orientation (Scottish Marine Renewables SEA, 2007).

### 4.2.3 Invertebrates

#### Invertebrates: Magnetic sensitivity

The functional role for the invertebrate magnetic sense is hypothesized to be for orientation, navigation and homing using geomagnetic cues (e.g., Lohmann et al. 2007, Cain et al. 2005).

Magnetic fields interfere with embryonic development of sea urchins leading to embryonic abnormalities (Sakhini et al., 2004; Levin & Ernst 1997).

Willows (1999) investigated the nudibranch *Tritonia diomedea,* which orientates using the Earth's magnetic field in its natural environment. Animals were displaced from their original locations and movement was monitored over two or more tidal cycles. Most animals appeared to use geomagnetic cues to move in a shoreward direction. It may suggest that shoreward movement represents an adaptation to frequent dislodgement by tidal currents and during predator escape responses. This enables *T. diomedea* to remain close to food sources and mates that are located in nearshore habitats (Boemre, 2011).

Multiple Arthropoda use the magnetic field to orient their body in the right position. Some evidence for a possible magnetic sense in amphipods has been reported. Ugolini (2006) conducted experiments in which cancellation of the geomagnetic field increased body movements in *Talorchestia martensii*, that were described as "scanning" for the magnetic field. Sandhoppers (*Talitrus saltator*) orient themselves towards magnetic fields (Arendse and Kruyswijk 1981). Ugolini and Pezzani (1995) demonstrated that the marine isopod, *Idotea baltica basteri*, possesses a magnetic compass. Lohmann (1985) and Lohmann et al. (1995) found magnetic orientation of the western Atlantic spiny lobster (*Panulirus argus*). *This lobster* undergoes an annual mass migration when thousands of lobsters vacate shallow, inshore areas and crawl seaward in single-file, head-to-tail processions. Lines of lobsters within the same geographical area follow nearly identical compass bearings (Lohmann et al. 1995).

#### Invertebrates: Electrosensitivity

Electrosensitivity of invertebrates is rarely known and studied. Recently however, two studies have reported to find the first evidence of an invertebrate behavioural response to an EF. Freshwater crayfish (*Cherax destructor*) responded to low-level EFs comparable to the type emitted by potential prey items (Patullo & Macmillan, 2007, DC field 3 -7 mV/cm). According to Steullet et a. (2007), the sensitivity of invertebrates for electric fields range from around 3 to 20 mV/cm (Steullet et al. 2007). Crayfish exhibited an attraction response to iEFs. Another freshwater crayfish (*Procambarus clarkii*) also demonstrated responses to EFs at higher intensities (>20 mV/cm) (Steullet *et al.,* 2007, DC field, AC field 4 Hz, 10 Hz, 100 Hz, and 1000 Hz). The strongest responses to the electric field were reported at 4 Hz. Hypothesized functional roles of electrosense include prey detection, predator or mate detection. Patullo and Macmillan (2007) concluded that their investigations with crayfish provide evidence for an electrosense capable of such functions, while Steullet et al. (2007) responded that such evidence remains lacking for invertebrates (Boemre, 2011).

### 4.2.4 Bony fish

Bony fish are known to detect EMFs and EFs. For example, diadromous fish species (migrate between sea and freshwater) can use the Earth's magnetic field for orientation and direction finding during migrations (Gill et al., 2012). Species like lampreys (Petromyzontiformes*)* and sturgeons (Acipenseriformes) are known to be electrosensitive.

#### Fish: Magnetic sensitivity

In fish species, the detection of magnetic fields has been closely related to navigation during long-distance migrations and the location of spawning grounds (Griffen, 1982; Quinn, 1984; Yano et al., 1997; Akesson et al., 2001). Use of the magnetic sense for these functions would explain the ability of fishes like salmon, eel and tuna to accomplish long-distance migrations through the open ocean and for diadromous species (species that migrate between fresh and salt water) to reach their natal tributaries with remarkable precision. Additionally, several fish species use magnetic sense for daily orientation and migrations, as seen for example in the white grunt (*Haemulon plumieri*), European plaice (*Pleuronectes platessa*) and darkbanded rockfish (*Sebastes inermis*) (Quinn & Ogden, 1984; Metcalfe et al., 1993; Nishi & Kawamura, 2006). Despite support among researchers on theoretical grounds, this hypothesis has yet to be underpinned by strong evidence (Walker *et al.,* 2007). Furthermore, the mechanism explaining sensitivity still has to be unraveled. For example, for the migrating flatfish *Pleuronectes platessa*, migration is related to a passive use of iEFs when the animal estimates its drift from the EFs produced by the interaction between tidal and wind-driven currents and the vertical component of the Earth's magnetic field. However, this species may in fact use the magnetite-based mode for navigation during migration (Metcalfe et al. 1993).

Although magnetite has been found in several salmonids, researchers are still puzzled if and how salmonids use magnetic fields for orientation and finding their natal stream. For example, since blockage of magnetic sense had no effect on the ability of sockeye salmon to locate their natal stream it is suggested that visual and olfactory cues are used rather than magneto-reception (Fisher & Slater, 2010 and references therein).

Most diadromous fish are known to be sensitive to the magnetic field and changes in that field. It has become more evident that some species like the European eel (*A. Anguilla)* are able to use cues from the Earth's geomagnetic field for orientation and navigation (Tesch et al., 1992; Walker et al., 2003). Researchers concluded that the Japanese eel (*A. japonica*) is magnetosensitive when all (silver) eels exhibited a significant conditioned response (i.e. slowing of the heartbeat) to an EMF with a strength of approx. 192 µT (Nishi et al. 2004). Moreover, when salmonid embryos and fry (S. trutta and O. mykiss) were raised in artificially modified magnetic fields, they exhibited significantly altered swimming orientations compared to those which had been reared in a natural magnetic field (Formicki et al.,1997, 2004).

#### Fish: Electrosensitivity

To sense electric fields, fish species have developed two systems. Electroreception can be classified either ampullary or tuberous (Bullock, 2005). These two types of reception mechanisms differ in cellular morphology and most important in reception. Ampullae of Lorenzini or similar organs have been found in elasmobranchs, ratfishes, lampreys, sturgeons, and catfishes (Bullock, 2005; Boemre, 2011). These jelly-filled ampullary receptors are reportedly tuned to lower frequency fields (<0.1 to 25Hz). Tuberous receptors are tuned to higher frequency fields (50 to >2000 Hz) and only known in two orders of freshwater electric fishes (Gymnotiformes in South America, Mormyriformes in Africa; Bullock, 2005 Collin and Whitehead 2004).

Several fish species have been reported using electric sense in prey detection, which seems the primary role of the electroreception in fish species (Collin and Whitehead 2004). Feeding response in several species of sturgeons to 50-Hz electric fields have been reported and both physiological and behavioural responses to fields in the range of those produced by prey items are reported for ratfishes as well (Basov, 1999).

Another use for electroreception is that it possibly has a role in reproduction (mate detection and selection). For example, Chung-Davidson et al. (2008) report that responses to DC electric fields among male and female sea lamprey differ at various lifestages.

It is also noted that marine fishes with an electric sense can detect induction voltages (range 5 to 50 uV/m) generated by their movement through the Earth's magnetic field (Peters et al. 2007). These of geomagnetic cues for orientation or navigation is therefore another plausible function for the electric sense in fishes (Boemre, 2011). An overview of responses in some fish species is in UK and Scottish waters listed in Figure 28.

| Species | Common name | Conservation status | Frequency in Scottish and UK Waters | Evidence of response to E fields | Evidence of response to B fields |
|---|---|---|---|---|---|
| *Anguilla anguilla* | European eel | Critically Endangered | Common | ✓[1,2] | ✓[3,4] |
| *Salmo salar* | Atlantic salmon | Least Concern | Common | ✓[5,6] | ✓[5,6] |
| *Salmo trutta* | Sea trout | Least Concern | Occasional | | ✓[7] |
| *Pleuronectes platessa* | European plaice | Vulnerable | Common | ✓[8] | ✓[8] |
| *Thunnus albacares* | Yellowfin tuna | Least Concern | Occasional | | ✓[9-12] |
| *Lampetra fluviatilis* | European river lamprey | Near Threatened | Common | ✓[13,14] | |
| *Petromyzon marinus* | Sea lamprey | Least Concern | Occasional | ✓[15-17] | |

[1] Berge (1979); [2] Vriens & Bretschneider (1979); [3] Enger *et al.* (1976); [4] Westerberg (1999); [5] Moore *et al.* (1990); [6] Rommel & McCleave (1973); [7] Formicki *et al.* (2004) – *juvenile fish*; [8] Metcalfe *et al.* (1993); [9] Kobayashi & Kirschvink (1995); [10] Walker *et al.* (1984); [11] Walker (1984); [12] Yano *et al.* (1997); [13] Gill *et al.* (2005); [14] Akeov & Muraveiko (1984); [14] Bodznick & Northcutt (1981); [15] Bodznick & Preston (1983); [16] Bowen *et al.* (2003); [17] Chung-Davidson *et al.* (2004)

Figure 28 Evidence based list of electromagnetic sensitive teleost fish species and their conservation status (according to the IUCN Red list) in Scottish and UK coastal waters. Superscript numbers show reference sources. E field = Electric Field; B field = Magnetic field. Source and references: Gill et al., 2012.

### 4.2.5 Elasmobranchs

Elasmobranch fish, like sharks, skates and rays, are well known for the detection of EMFs and EFs. Elasmobranch fish are able to sense electric fields by their Ampullae of Lorenzini (Kalmijn, 1982). The primary function of electroreception is to detect prey, because sight for example can be limited.

#### Elasmobranchs: Magnetic sensitivity

Several models are proposed on how elasmobranch fish can detect and use the magnetic field. However there has been no explicit (physiological) proof on how elasmobranch fish detect the magnetic field (e.g. Kirschvink 1989, Kirschvink et al. 2001, Kalmijn 1982, 1988).

Nevertheless, there is evidence that elasmobranch species respond to changes in the magnetic field. The movements of adult hammerhead sharks were for example tracked in Mexico between midwater seamounts separated by a distance of about 20 km. The patterns of repeated movements were strongly correlated with changes in magnetic field intensity along the migration route (Klimley 1993).

Neurophysiology experiments in skates proved that the electrosensory neurons responded to strong and varying magnetic stimuli that are inductively coupled to the electroreceptors (Andrianov et al. 1974, Akoev et al. 1976, Brown and Ilyinsky 1978). The minimum rate of magnetic field variation that elicited a response was 200 µT at 1Hz.

Behaviour studies in the laboratory show that stingrays (Hodson, 2000) and juvenile sharks (Meyer et al. 2005) could be conditioned to respond to the presence or absence of imposed magnetic fields with a strength between 25µT and 100µT. However, if magnets were placed near the olfactory epithelium a response was lacking.

Thus, although it is clear that elasmobranchs can react on changes in the magnetic field, it is yet to be underpinned with comprehensive evidence how the magnetic field is used for orientation and migration of the elasmobranch fish species.

### Elasmobranchs: Electrosensitivity

Electroreception in elasmobranch species is well studied and proven to be used for:

1) **Orientation and navigation:** It is proposed that oceanic and tidal currents that stream through the vertical component of the Earth's magnetic field produce horizontal uniform electric fields that could be detected and used by electroreceptive species. Different hypotheses propose either a passive mode where the relatively constant direction of these fields allow for a constant heading relative to the water current stream or an active mode where a shark that swims through the Earth's magnetic field induces an orthogonal electric field across its head and body, but direct empirical tests are scarce (Kalmijn et al., 1978; 1988). Another hypothesis proposes that electric fields induced by locomotor movements are detected by vertically oriented ampullary canals and centrally integrated with horizontal vestibular information to provide a compass sense.
2) **Detection of prey:** Elasmobranch species can detect weak bioelectric fields produced by their natural prey. Dogfishes and skates for example can detect flounders buried in the sand with the use of electrosensitivity (Kalmijn 1971). Swell sharks are also known to use bioelectric cues to capture prey during normal nocturnal feeding (Tricas 1982). In addition, these and several other elasmobranchs show natural orientation responses toward buried or concealed dipole electrodes (that simulate prey) when motivated to feed (Kalmijn 1971, 1982, Tricas 1982, Kajiura & Holland 2002, Blonder & Alevizon1988). The effective distance of this sense under natural conditions is up to a few centimeters from the source (Boemre, 2011). These studies show that elasmobranch species rely heavily on their electroreceptive capabilities to detect prey.
3) **Detection and location of other individuals:** The round stingray (*Urobatis halleri*) uses electroreception during the mating season. Individuals of both sexes use electroreception to locate buried females from distances of 0.1 - 1 m. (Tricas et al. 1995).
4) **Detection of bioelectric fields produced by potential predators:** The electroreceptors of embryonic and juvenile clearnose skates (*Raja eglanteria*) detect weak bioelectric stimuli produced by potential egg predators like elasmobranchs, bony fishes, marine mammals and molluscan gastropods (Sisneros et al. 1998). Phasic electric stimuli of 0.1 to 1 Hz are also known to interrupt the ventilatory activity of newborn dogfishes, (*Scyliorhinus canicula*) (Peters & Evers 1985). These electrosensory-mediated behaviours may represent an adaptive response during early life history to avoid detection by predators and enhance survival (Boemre, 2011).

Electroreception in elasmobranch fish species is often very sensitive. In general, elasmobranchs experience sensitivity to E-fields between 0,0001-0,0005 mV/m. At these levels – which are expected to occur around the North Sea subsea power cables, these species are generally attracted to the source; however, at 100 mV/m or greater, elasmobranchs typically avoid the source (Kalmijn 1982, Gill and Taylor 2001). Spotted dogfish and skates show cardiac responses to low frequency pulsed fields as low as 0,0001 mV/m (Kalmijn 1966). Round stingrays can behaviourally discriminate the polarity of anthropogenic DC uniform fields and orient to fields at intensities as low as 0, 0005 mV/m (Kalmijn 1982). Moreover, it is shown that orientation responses to small electric dipoles in seawater is already apparent at thresholds of 0, 001 – 0,003 mV/m at distances up to about 0.5 m (Kalmijn 1971, 1982; Kajiura and Holland 2002; Kajiura and Fitzgerald 2009; Boemre, 2011).

### 4.2.6 Turtles

Although the North Sea is not a key habitat for sea turtles, they do occur in these waters. Therefore, the effect of EMFs on turtles is briefly addressed. Sea turtles are not known for their electrosensitivity and do not have the ability to sense electric fields (Boemre, 2011).

#### Turtles: Magnetic sensitivity

Sea turtles migrate in each life stage. Hatchlings migrate towards the open sea and get caught in the large oceans currents (Atlantic gyre). After many years they return towards the coastal waters to feed and eventually when sexually mature they navigate back towards their natal beach to reproduce and lay eggs. Studies suggest that several species of turtle use the earth's B-fields for migration. Sea turtles are able to sense the (Earth) magnetic field at intensities approx. 0.005 and 4000 µT, based on two studies on loggerhead turtles and green turtles. It is expected that other species that have not been studied have a similar sensitivity for EMFs (Boemre, 2011).

Kemps ridley's turtle (*Lepidochelys kempi*), green sea turtle (*Chelonia mydas*), and loggerheads (*Caretta caretta*) all utilize the Earth's B-fields (Lohmann & Lohmann 1996). In a study from Lohmann (2008) researchers observed that hatchlings are able to detect the inclination angle and field intensity from different oceanic regions and that a change in these parameters can affect their course of direction. The same effect is observed in adult turtles. Adult green sea turtles were examined by placing strong magnets on the heads of individuals that were displaced from their breeding island in the Indian Ocean (Luschi et al. 2007). Most of the turtles with magnetic treatment did eventually return to their breeding island, although their routes were less direct than turtles without magnets (Luschi et al. 2007).

### 4.2.7 Marine Mammals

The North Sea is home to several marine mammals (seals and whales). Two phyla are present in Dutch waters, which are the Carnivora (seals) and Cetacea (whales and dolphins). Among marine mammals, magnetic sensitivity has been primarily investigated in cetaceans. Therefore, mainly cetaceans will be discussed. There is no clear evidence of pinnipeds being either magnetic or electro sensitive, however theoretical evidence suggests that reception of magnetic fields enables them to function in the absence of conventional sensory input (Renouf 1991).

#### Marine mammals: Magnetic sensitivity

Whales and dolphins in the northern oceans often migrate seasonally, where in summer they migrate towards northern feeding grounds and n winter they migrate towards southern waters. Despite the knowledge about migration patterns and destinations, much research needs to be done to underpin the hypothesis that marine mammals use a magnetic sense to navigate over long distances (Walker et al.

2003). To date, the evidence for cetaceans' magnetic sensitivity is observational, theoretical (based on correlation studies), behavioural, physiological and anatomical (i.e. the presence of magnetite) (Boemre, 2011).

Nevertheless, the data on magnetic sensitivity is scarce, mainly because (experimental) research on these animals is difficult, due for example their size and distribution. However, there are some (experimental) studies done that provide evidence for the magnetic sensitivity of cetaceans e.g.:

- Dolphins (Delphinidae) show behavioural (i.e. movement, sharp exhalations, and acoustic activity) and physiological (i.e. electrocardiogram) reactions when exposed to anthropogenic EMFs. The results in an experimental study showed reactions to magnetic field intensities of 32, 108, and 168 µT during 79, 63, and 53% of the trials respectively, indicating that dolphins are sensitive to permanent magnetic fields (Kuznetsov, 1999).
- Many whale and dolphin species are sensitive to stranding when Earth's B-field deviates as little as 50 nT (leading to geomagnetic minima). Kirschvink (1990) compared 421 live cetacean strandings to the spatial and temporal variations in the geomagnetic fields from Texas to Maine. Live-strandings were found to be associated with geomagnetic minima (low geomagnetic field strength) in Species that are significantly statistically sensitive include common dolphin (*Delphinus delphis*), Risso's dolphin (*Grampus griseus*), Atlantic white-sided dolphin (*Lagenorhynchus acutus*), finwhale (*Balaenoptera physalus*), and long-finned pilot whale (*Globicephala malaena*) (Kirschvink et al. 1986). Geomagnetic minima are a result of local distortions of the earth's magnetic fields resulting from geologic features. Areas with rock containing materials with magnetic properties increase the total local field and are known as high anomalies. Areas with other geological properties distort the field by decreasing the total field, resulting in low anomalies or magnetic minima (Klinowska 1985).
- Magnetite (able to sense the magnetic field) has been reported in the dura matter (outer membrane surrounding the brain, closest to the skull) of the following cetaceans: Common Pacific dolphin (Zoeger, et al. 1981), Dall's porpoise, bottlenose dolphin, Cuvier's beaked whale, and the humpback whale (Bauer et al. 1985) and in the tongues and lower jawbones of harbour porpoises (Klinowska, 1990).

#### Marine mammals: Electrosensitivity

The only species of marine mammal that is known to be electrosensitive is the Guiana dolphin (*Sotalia guianensis*), using hairless vibrissal crypts on the rostrum of the originally associated with mammalian whiskers, and capable of electroreception as low as 4.8 µV/cm, sufficient to detect small fish (Czech-Damal et al., 2012). These cells are not known to occur in any other dolphin species.

### 4.2.8 Synthesis

Marine species(group) sensitivity to electric and magnetic fields are summarized in Table 6.1.

Table 6.1. Summary of sensitivity of marine species groups to EMFs.

| Species(groups) | Sensitivity: Magnetic fields | Sensitivity: Electric fields |
|---|---|---|
| cellular process and embryonic development | interference with embryonic and cellular development (eg sea urchins), cellular damage in larvae (barnacles) | |

| | | |
|---|---|---|
| Invertebrates | Anecdotal evidence of arthropods and molluscans using magnetic field for orientation (eg nudibranch, amphipods, isopods and lobsters) | Anecdotal evidence of electroreception used for prey detection (eg. crayfish) |
| Bony fish | Used for daily navigation, long distance migration, homing. Magnetite present in several species including salmonids. Strong evidence is lacking. | Several species use electric sense for prey detection.<br>Ampullae of Lorenzini found in sturgeons and catfishes |
| Elasmobranchs | Responses to magnetic field changes described. No explicit proof. | Ampullae of Lorenzini found in elasmobranchs. Used for predator/ prey detection, orientation, navigation |
| Turtles | Earth's magnetic field used for orientation and finding breeding sites. Magnetite present in some species. | no evidence |
| Marine mammals | Magnetic fields used for long distance migration and mapping. Magnetite reported in some species. Sensitive to geomagnetic minima that are correlated to strandings | one species of dolphin uses specialized cells not found in other species |

## 4.3 Potential effects anthropogenic EMFs and iEFs from subsea cables

In this Section, specific studies on the effects of anthropogenic generated EMFs for different marine species groups are described.

**Essence:**

Without substantial underpinning with scientific evidence, a set of theoretical principles on anthropogenic EMFs in relation to effects on marine species are described repeatedly (Gill et al.; 2005 Scottish Marine SEA 2007; Boemre, 2011; MarVen 2015)

1. ***Only magnetic fields (EMFs) and induced electric fields (iEFs) might cause effects***

Since electric fields are inhibited by shielding material (Section 3.2), the obvious effects of subsea power cables on biota are generated by either magnetic fields or induced electric fields. Movement of organisms through a magnetic field induces an electric field. The strength of this iEF depends on the direction of movement in relation to the cables' magnetic field, in which organisms moving parallel to the cables' magnetic field induce no electric field and organisms moving perpendicular to the cables' magnetic field induce a maximum electric field.

2. ***Effects on marine life are restricted to the operational phase***

No sources of electric and magnetic fields are associated with site preparation or device installation (Scottish SEA 2007; Isaacman & Daaborn 2011). However, uncharged cables, that are not fully operational, will possibly yield low-level magnetic fields and associated induced electric fields that potentially affect marine life.

3. ***Effects of elevated anthropogenic EMFs have been observed for embryonic and larval development, invertebrates, bony fishes, elasmobranchs. Theoretical evidence suggests also marine mammals (cetaceans) and marine turtles could be influenced.***

4. ***Field type, strength and configuration will determine species' detectability of anthropogenic fields***

Electromagnetic sensitive organisms in the marine environment can detect both local and larger-scale uniform EMFs (Tricas & New, 1998); these are the predominant type of fields associated with subsea power cables (Gill et al., 2005). Species are more likely to detect EMFs generated by DC cables compared to AC cables due to the higher EMF strength for DC cables. Also, species detection depends on the cable configuration since EMFs can be enforced or cancelled out depending on the distance between cables (see section 3.2). Lower EMF strengths, are not necessarily associated with less impact. Moreover, weak EMFs can have an important ecological function, such as the little variations in the geomagnetic field used for navigation during migration and the weak fields induced by prey.

5. ***Benthic species are more likely to be affected***

Since subsea cable EMF strength decreases with increased distance from the source, fields emitted by a submerged or buried subsea power cables potentially have more effect on benthic species and those present at depth than pelagic species (MarVEN 2015). However, this assumption was never tested (Fisher & Slater 2010). It should be noted that this is likely less pronounced in shallow coastal areas such as the Dutch North Sea. According to the expected EMF strengths in relation to the distance of the cable as described in Section 3.2, the pelagic zone of the North Sea is likely to be for a large part influenced as well.

6. ***Four main potential effect types due to EMFs are identified in literature***

- Disturbance of behavioural responses and movement (attraction, avoidance mate selection);
- Disturbance of navigation and migratory behaviour;
- Disturbance of predator/prey interactions and distribution of prey;
- Disturbance of embryonic and cellular development.

7. ***Studies that test effects of EMF field strengths that match the magnitude of cabling and field studies near cables are scarce.***

### 4.3.1 Potential effect on cellular processes and embryonic development

In Echinodermata magnetic fields have been known to interfere with the embryonic development of for example sea urchins. Sakhnini *et al*. (2004) investigated the influence of static magnetic fields with intensity of 30-50 mT on the early cleavage division of the sea urchin *Echinometra mathaei*. It appeared that the exposure of fertilized eggs to 30, 40, and 50 mT of magnetic fields delayed the onset of early cleavage division. Moreover, the exposed eggs showed a significant decrease in cleaved cells and had more abnormalities, as the intensity of the magnetic field increased. This effect is also seen in early embryonic development of sea urchin embryos from *Lytechinus pictus* and *Strongylocentrotus purpuratus* by delaying the onset of mitosis (Levin and Ernst 1997).

Fish embryos can be influenced by low levels anthropogenic EMFs. When salmonid embryos and fry (*S. trutta, Oncorhynchus mykiss*) were raised in artificially modified magnetic fields, they exhibited significantly altered swimming orientations compared to those which had been reared in a natural magnetic field (Formicki et al., 2004). Effects on embryonic orientation and an increase in embryonic respiration at certain stages of development before organogenesis were observed or several fresh water fish species (e.g. brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mikis*), pike (*Esox sp.*), carp (Cyprinidae).

However, in a study involving chum salmon (*Oncorhynchus keta*) no increase in larval mortality or deformity rates or overall survival in the exposed fish was observed. Furthermore, research on pike embryos failed to show changes in locomotive responses to varying magnetic fields (Formicki et al. 2004).

Barnacle larvae passed between two electrodes emitting a high frequency AC EMF, caused significant cell damage to the larvae and caused the larvae to retract their antennae, interfering with settlement (Leya et al. 1999).

From these studies it can be concluded that EMFs can potentially have effects on the cellular processes and embryonic development of species, although the levels at which these effects are found are generally much larger than generated by subsea power cables.

### 4.3.2 Potential effect EMFs on invertebrates

Previous research provides evidence of responses to magnetic or electric fields within the range generated by subsea power cables in at least three marine invertebrate phyla (Mollusca, Arthropoda, and Echinodermata) (Gill et al., 2005).

Invertebrate species that use the geomagnetic field to guide their movements through an area with a subsea power cable may be confused as they encounter the anthropogenic magnetic field (Gill & Kimber 2005). They may change their direction of travel based on the altered field. Some invertebrates may use a magnetic sense for orientation or homing within a relatively small local range, and homing capabilities that are based on a magnetic sense could be affected in close proximity to cable systems (Boemre, 2011).

Species from the Mollusca phylum tend to react on a (changed) magnetic field by changing their activity pattern. However, to induce this behavioural change, the intensity of the magnetic field has to increase substantially. In *Mytilus edulis*, EMFs can lead to a decrease in hydration and amine nitrogen values (Aristharkhov et al. 1988 at >5 mT). Barnwell and Brown (1964) found a response to a magnetic field in the mud snail (*Nassarius obsoletus*) only when the field was approximately nine times stronger than the local geomagnetic field.

No direct evidence of effects on invertebrates due to EMFs generated by subsea power cables exist. In a study on macrobenthos above and in the direct vicinity of the SwePol Link DC cable, no obvious difference was found in species composition, abundance or biomass one year after construction compared to reference sites (0.1 – 1 nautical mile distance). This suggest that the magnetic and electric field in the vicinity of the cable did not affect benthic resources (Andrulewicz et al. 2003). Also in a study on megafaunal communities around the MARS Cable (Monterey Bay, California) showed no clear effects in local variation of benthic megafaunal communities near the cable (within 50–100 m) and little or no detecTable effect on the distribution and abundance of macrofaunal and megafaunal assemblages on a regional scale (i.e. kilometers). Furthermore, natural spatial and temporal variation in the abundance and distribution of benthic macrofauna and megafauna appeared to be greater than any detecTable effects of the cable (Kuhnz et al., 2015).

There are also several studies of invertebrate species that do not obviously react to an increased or changed magnetic field. For example, the common lobster (*Homarus vulgaris* close relative to the North Sea species *Homarus gammarus*) did not show any response when exposed to a 50 Hz 0.8T magnetic field, a field strength much higher than expected directly subsea power cables (Ueno et al. 1986). Furthermore, a study of Bochert and Zettler (2004) describes that blue mussels (*Mytilus edulis*), North Sea prawns (*Crangon crangon*) and Round crabs (*Rhithropanopeus harrisii*) exposed to a static B-field of 3.7 µT for several weeks showed no differences in survival between experimental and control animals. Also, Dungeness crabs (*Metacarcinus magister*) and American lobsters (*Homarus americanus*) did not react to an increase in magnetic field strength (Woodruff et al., 2012).

Sensitivity tresholds of invertebrates for the magnetic field are reported as being likely to be below 100 nT for DC cables (Kirschvink & Gould 1981, Walker et al. 1984, Boemre, 2011) and below 5 µT for AC cables. Electrosensitive invertebrate species that have so far been studied often have sensitivity thresholds outside the level of induced electric fields from subsea power cables and would theoretically therefore not be impacted by those fields (Boemre, 2011). However, brown shrimp *Crangon crangon* has been recorded as being attracted to B fields of the magnitude expected around windfarms (ICES, 2003). Additionally, shore crabs *Carcinus maenas* showed less aggressive behaviour in fields of magnitudes that match cabling of windfarm cables (Everitt, 2008).

Important to note is that very few marine invertebrates have ever been evaluated for sensitivity to electric or magnetic fields. Also studies on weak iEF fields, in the range of those emitted by invertebrates and their prey/predators, are scarce and studies mainly focused on the behaviour of mobile adults. Life stages like the pelagic larval period are poorly studied. Due to this lack of knowledge, it is not possible to determine the potential impact on most of the invertebrate species and their numerous life stages.

### 4.3.3 Potential effect EMFs on bony fish

The potential effect of EMFs on fish for a particular subsea power cable would depend upon the sensory capabilities of a species, the life functions that it's magnetic or electric sensory systems support and the natural history characteristics of the species (Boemre, 2011). Furthermore, local site conditions determine effect. For a DC cable such as the SwePol link (450kV HVDC), an EMF may be detecTable by fish for over 20 meters on either side of the centerline of the cables (Boemre, 2011). Variations in the local field and orientation of the cable could increase or decrease this distance.

Diadromous fish species encounter EMFs from subsea power cables either during their adult mobile life phases or their early life phases during migration within shallow coastal waters, adjacent to natal rivers. In close proximity these migratory capabilities may be affected by EMFs generated by cable systems (Boemre, 2011).

Fish that undergo a long term migration like the European eel (*Anguilla anguilla*) could be affected by the subsea power cables that can form a barrier in their migration route (Westerberg, 2008; Öhman et al. 2007), however study results on this barrier effect are ambiguous. Westerberg and Begout-Anras (2000) investigated the orientation of silver eels (*Anguilla anguilla*) in the presence of a HVDC subsea power cable. Approximately 60% of the eels crossed the cable, enabling researchers to conclude the EMFs generated by the cable did not form a barrier. Westerberg (2000) reported similar results after investigating elver (a young eel stage) movement under laboratory conditions. Orpwood et al. (2015) found no evidence of a difference in movement due to an AC MF of approximately 9.6 μT in a controlled laboratory setting for silver eels. A mark-recapture study near the Nysted windfarm by Vattenval (2006) showed that 39% of the recaptured eels probably had passed the power cable during their migration whereas more than 50% of the eels probably changed direction after being captured. Furthermore, Westerberg and Lagenfelt (2008) found that swimming speed of silver eels was not significantly lowered around AC cables, although they concluded that more research into eel behaviour during passage over subsea power cables is required to be conclusive on the potential effects. In contrast, some individual eels changed direction while passing over an electrified cable and swam slower, which suggests that they detected the cable's magnetic field (Westerberg, 2008; Öhman et al. 2007). If their migrating routes crosses a subsea power cable, a temporary change in swimming direction, particularly in shallow water (<20m) such as the coastal zone of the Dutch North Sea where the subsea power cables are located, was observed. Nonetheless, eels were not impeded from crossing the cable. Whether a temporary change in direction represents a biologically significant effect, such as a delayed migration, cannot yet be determined (Gill et al., 2012).

Sturgeons also are well known to potentially show a behavioural response when exposed to AC electric fields from electrodes in the water (Basov, 2007) and to AC magnetic fields from overhead power lines (Gertseva & Gertsev 2002, Gill et al. 2005). However, when largemouth bass and pallid sturgeons were studied in mesocosm experiments with EMFs of magnitudes and frequencies representative for AC subsea power cables, no effect on the natural movement and activity patterns of these two species was observed (Bevelhimer et al., 2015).

Fish species that are electrosensitive can be affected by induced electric fields in areas where EMFs generated by subsea power cables are present. The induced electric fields could potentially alter functions such as prey detection or social interaction and reproduction. Prey for example that moves through the geomagnetic field induces an electric field that can be detected by hunting species. Anthropogenic iEFs can therefore have an effect on the predator-prey detection. Feeding response in several species of sturgeons to a 50-Hz electric fields have been reported (Basov, 1999), which makes it possible that these species will invest energy, spend time hunting iEFs that are non-biological and thereby reduce their daily food and energy intake. The induced electric field generated by AC cables may be detecTable by electroreceptive fish more than 10 meters from the cable (Boemre, 2011).

Research suggests salmonid species may be influenced by anthropogenic electric fields. For example, effects range from an elevated heart rate of salmon and eels when exposed to electric fields with strengths of 0.007 to 0.07 V/m to more harmful effects such as electro- narcosis or paralysis when exposed to electric fields with a strength of 15 V/m or more (Fisher & Slater 2010 and references therein). However, there is limited support for the influence by magnetic fields in this study.

### 4.3.4 Potential effect EMFs on elasmobranchs

Many elasmobranch species migrate through coastal waters and can potentially be attracted or repelled by the EMFs generated by subsea power cables. Also resident populations that inhabit areas near cable tracks can encounter similar effects. As a result, distributions and swimming behaviours of elasmobranch populations may be affected by EMFs generated by subsea power cables (Boemre, 2011).

Research on the MARS cable (Montery Bay, California) showed that Longnose skates (*Raja rhina*) were significantly (with a factor 126) more abundant near the cable along sections where the MARS cable is positioned on top of the sea floor (depth ~ 300 meters). The MARS cable most likely generates a weak EMF as local ocean currents flow through the Earth's magnetic field and around the cable (Sanford, 1971), even when the cable was not in operation during the 2008 video survey (Barry et al., 2008). However, when the cable was powered and theoretically produced a stronger EMF, no significant difference in the abundance of skates near the cable compared to 50 m away was found in surveys in 2010 and 2015 (Kuhnz et al., 2015). This indicates that skates are attracted to weak electromagnetic fields, in this case generated by unpowered cables, whereas strong fields lead to no (detecTable) effects.

An important finding is therefore that the effects on elasmobranchs (and possibly also other species) are not linearly related to the strength of the EMF, since weaker fields apparently cause effects in the form of attraction to cables where stronger fields did not show these effects.

Figure 29 Longnose skate aggregation near MARS cable in 2008 (source: Barry et al., 2008).

Effects of EFs on elasmobranchs depend on the frequency of the field. The electrosensory primary neurons in elasmobranch fishes showed highest sensitivity on alternating electric fields (fields from AC cables) between 1-10 Hz. In a bandwidth from 0.01-25 Hz response is only evoked with much stronger field intensities; up to 10x or greater are required to stimulate the electrosensory system (New and Tricas 1997, Bodznick et al. 2003). Thus, based upon neurophysiological studies only the direct sensitivity to weak electric fields generated by AC cables with a frequency of 50Hz is low (Boemre, 2011).

However, despite the low sensitivities found in neurophysiological studies, field studies show a response of elasmobranchs on EMFs due to subsea power cables. Observations of a mesocosm-based study showed that the distribution and behaviour of free-swimming elasmobranchs changed when buried 130kV AC cables were powered (Gill et al. 2009). Some bottom dwelling small-spotted dogfishes (*Scyliorhinus canicula*) were found nearer to the zone where the magnetic field was highest (1-2 m from the cable) when the cable was powered compared to when it was not powered, demonstrating attraction of this species to the cable area. Indications of increased movement by dogfishes and thornback rays (*Raja clavata*) when the cable was powered were also found.

Additional studies on catshark found a highly significant preference (in the form of attraction) for a stronger DC electric field (90 μA preferred over 9 μA) and a less pronounced, but still significant, preference for AC electric fields over DC electric fields was found. In this study, no preference was demonstrated between the anthropogenic and natural (associated with shore crabs) DC electric fields.

Based on the studies described above, it is concluded that induced electric fields from an AC or DC cable can interfere with the following main functions:

- Prey detection: Available data suggest that prey detection and predation is focused on sources of low frequency (i.e., <10 Hz) fields. Since the electrosense functional distance is a few 10s of centimetres in their natural environment, any emission from a cable may provide anomalous cues for these species (Boemre, 2011). Elasmobranch species, like sharks, could be attracted by the cables as if it was a prey. Potentially this could lead to a decrease in fitness, because organisms invest time and energy in searching for non-existent prey.
- Reproductive behaviour: Some ray species are known to use electrosense for detecting potential mates. Potentially, subsea power cables that generate iEFs can have an effect on the reproductive success of species by disturbance of mating behaviour, specifically if subsea power cables are placed

in high reproduction areas of elasmobranch fishes. The effect of subsea power cables on elasmobranchs in reproductive areas or stages remains however for now unknown.

Habituation to anthropogenic electric fields has been observed in laboratory studies with dogfishes. Dogfishes rewarded with food showed significantly more interest in an electrical stimulus than unrewarded dogfishes. In this mesocosm setting and within small temporal and spatial scales, sharks were able to learn to ignore anthropogenic E-fields, suggesting that habituation to iEFs generated by subsea power cables can occur. However, they may well forget these adaptations over larger scales (e.g. when travelling between foraging areas) (Kimber et al., 2011).

It should be noted that the determination of potential effect of EMFs on elasmobranch is based on a limited number of studies for a limited number of species. As a result, it is difficult to draw conclusions on these potential effects that are applicable under all circumstances and for all elasmobranch species. Whereas there are approximately a 1000 living elasmobranch species that differ physiologically and in sensitivity to EMFs and EFs, additionally effects are most certainly context specific, depending on life stage, season and habitat. Therefore, drawing conclusions on potential effects of EMFs on elasmobranchs in general is difficult and it is emphasized that yet extensive research on this subject needs to be done to provide more clarity on this subject (Boemre, 2011).

### 4.3.5 Potential effect EMFs on turtles

Based on the EMFs generated by AC and DC subsea power cables as described in Section 3.3, and their reported sensitivity to magnetic fields is likely that sea turtles are able to detect these fields. Studies showed that anthropogenic magnetic fields can affect migration patterns of sea turtles, and induced a deviation of their original direction (Luschi et al., 2007). Sea turtles that cross subsea power cables that generate a magnetic field could therefore be deviated from their migration pattern. However, evidence is lacking.

### 4.3.6 Potential effect EMF on marine mammals

Studies suggest that cetaceans can sense the geomagnetic field and possibly use it during their migrations. However, whether they solely rely on the geomagnetic field, or also use other cues to navigate is unknown (Klinowska 1985; Kirschvink 1990; Walker 1992).

Despite this lack of knowledge there is a potential for marine mammals to react to local variations of the magnetic field caused by power cable EMFs. Depending on the strength of the EMFs generated, effects can consist e.g. of a (temporary) change in swimming direction, or a longer detour during migration (Gill et al. 2005).

Kirschvink (1990) suggested that total intensity variations of as little as 0.05 $\mu T$ (0.1 percent of the Earth's total magnetic field) were strong enough to influence strandings of marine mammals (Boemre, 2011). Harbour porpoises were not found by Kirschvink et al. (1986) to live-strand consistently at either geomagnetic minima or maxima, suggesting that they may not solely depend on geomagnetic cues for navigation. Harbour porpoises normally occur in relatively shallow waters on the continental shelves, where a number of alternative cues, e.g. temperature, salinity and bathymetry, could be used for navigation.

Based on the study described above, it is expected that marine mammals are also able to detect EMFs generated by AC cables, since the strength of these fields also vary over time. It should be noted though that the small, time varying AC magnetic field predicted from modeling may be perceived differently, or not even detected, by sensitive marine mammals compared to the persistent, static geomagnetic field generated by Earth (Boemre 2011).

Correlation studies also suggest that it is likely that some Cetaceans are able to detect DC magnetic fields emitted from subsea power cables in the direct vicinity (order 50m distance), although it is not known how cetaceans would respond to these fields (Boemre, 2011).

### 4.3.7 Potential effect types of EMF

Specific pathways of effects can be categorized in four main themes:

1) Behaviour: Disturbance of behavioural responses and movement (attraction, avoidance, mate selection)
2) Migration: Disturbance of migratory behaviour and navigation
3) Prey: Disturbance of predator/prey interactions and distribution of prey:
4) Physiology: Disturbance of embryonic and cellular development

These specific pathways of effect originating from electromagnetic field stressors are illustrated and categorized by a PoEmodel (Isaacman & Daborn 2011), as shown in Figure 30.

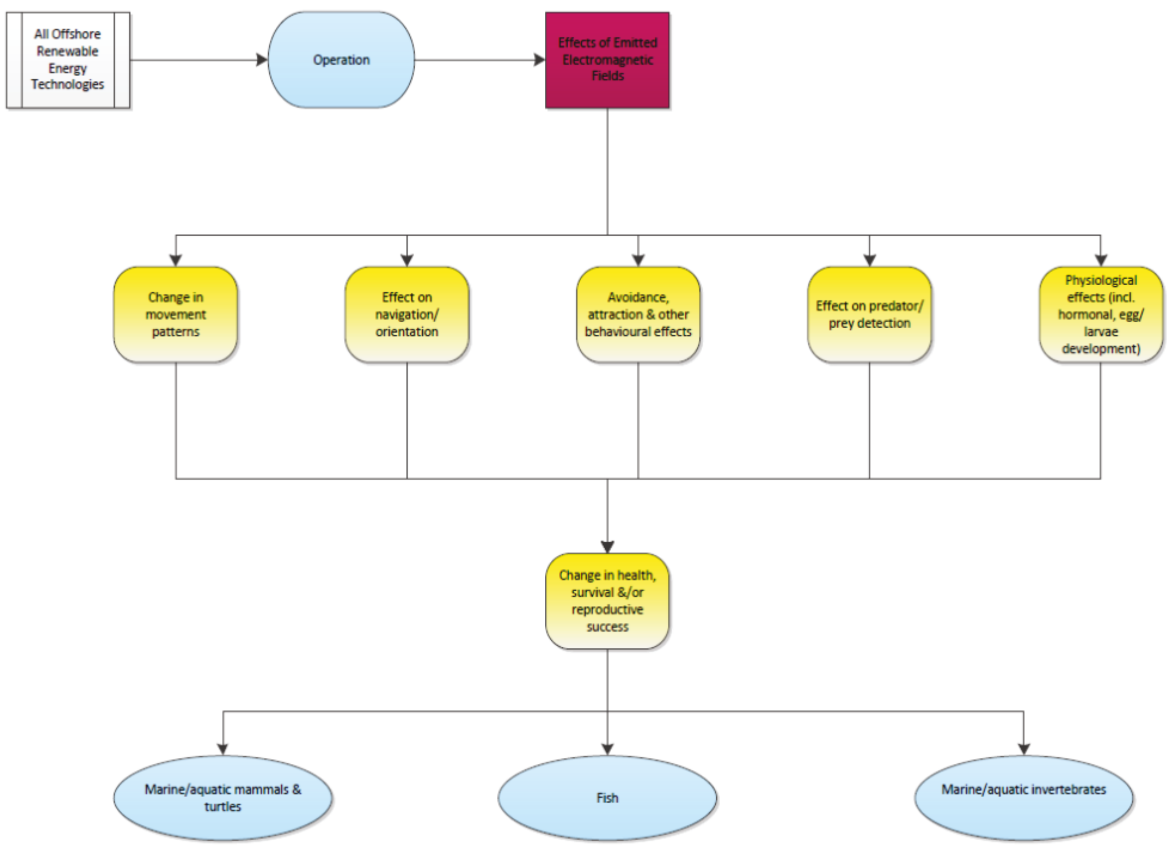


Figure 30 PoE Model for Electromagnetic Field stressors in the operation phase (Source: Isaacman & Daborn 2011).

## 4.4 POTENTIAL EMF EFFECTS ON MARINE LIFE IN THE NORTH SEA

### 4.4.1 Studies addressing North Sea species

The number of studies specifically addressing North Sea marine life are scarce, especially field based studies and studies that address magnetic fields within the range 5-300 uT or iE fields of 0,5-5 mV/m (Fields expected in the North Sea near cables, Table 6, Section 3.3). A selection of relevant or recent studies that report species that occur in the North Sea shown in Table 7.

Based on this Table, it is concluded that the available information on effect of EMFs on species that inhabit the North Sea is too limited to draw conclusions on the potential impact of EMFs generated by subsea power cables in the North Sea. Nevertheless, a description of the potential impact for North Sea species based on literature found on related species is made in the next section.

Table 7 Overview of relevant studies addressing North Sea species.

| Source/ Type of study | North Sea species | Type Fields tested | Conclusion | Discussion |
|---|---|---|---|---|
| Invertebrates | | | | |
| *Orpwood et al. 2015. Laboratory experiment. Movement (passing through a coil) of a migratory species.* | European eel (*Anguilla anguilla*) silver eel stage | AC MF of 9.6 uT | No evidence for difference in movement | Small sample size, nocturnal behavior not included, low field strength |
| *Gill et al 2009. Mesocosm experiment in shallow water. Behavior near powered and unpowered buried cables in Scotland* | Ray (*Raja clavata*), Spurdog (*Squalus acanthias*) and Lesser-spotted Dogfish (*Scyliorhinus canicula)* | maximum of 100A current, 8 uT and 2.2 mV/m | Dogfish is nearer to the cable when powered. Reactions of individuals to EMFs vary widely | No evidence from the present study to suggest any positive or negative effect on elasmobranchs of the EMF encountered |
| *Vattenval 2006: Field study of Nysted cable (Baltic Sea) using quadri directional fykes and mark recapture of eel* | fish fauna: including Atlantic cod, Baltic herring, flounder, European eel | no measurement s of EMF field strengths | European eels appeared to depart from, cod appeared to accumulate close to the cable and plaice and flounder most likely to cross the cable during periods of low power production | Baseline data missing, set up with high complexity and many difficulties, other factors can confine results |
| *Bochert & Zetler 2004; 2006 Laboratory study of Baltic sea specimen exposed to artificial static magnetic fields* | Young flounder (*Plathichthys flesus*), Blue mussel (*Mytilus edulis*), NorthSea prawn (*Crangon crangon*), *Saduria entomon*, Round crab (*Rhithropanopeus harrisii*), *Sphaeroma hookeri, Nereis diversicolor, Asterias rubens, Saduria entomon* | static 3.7 mT field (long term), 2.7 mT (short term) | No difference between control and experimental animals | high field strength |

| | | | | |
|---|---|---|---|---|
| *Kirschvink 1986: Theoretical study correlating strandings worldwide to changes in earth magnetic field* | Atlantic white-sided dolphin (*Lagenorhynchus acutus*), common dolphin (*Delphinus delphis*) | 0, 05uT variation from geomagnetic field | North Sea species are more sensitive to strandings with changes in Earths' magnetic field (geomagnetic minima) | Correlative study not related to subsea cable emission. |
| *Kalmijn 1971 Laboratory experiment. Feeding response to prey and fields emitted by electrodes* | Lesser spotted dogfish *Scyliorhinus canicula,* Ray *raja clavata* | 4 uA | At short range, electricfields act as a much stronger directive force than do the visual and chemical stimuli. (electrodes preferred over fish smell) | Only low magnitude Efields (in range of emitted) by prey tested |

## 4.4.2 Impact on Marine Life in the North Sea

### Invertebrates

There is little evidence that marine invertebrates in the North Sea, like brown shrimp and shore crab react to increased magnetic fields or induced electric fields based on the studies available in literature (Table 7). The sensitivity range reported for several other invertebrates to magnetic fields is several-fold higher (Appendix 5) than the possible fields generated by AC or DC subsea power cables in the North Sea (Table 6, Section 3.3). Important is to note that recent studies mainly focused on the behaviour of adults of mobile invertebrate species and a majority of crustaceans. Therefore, key benthic species are not yet studied and important life stages like the pelagic larval period are poorly studied. Also very few marine invertebrates have ever been evaluated for sensitivity to electric or magnetic fields, and the available data for those that have been studied is limited. This makes it impossible to determine the potential impact of EMFs generated in the North Sea on all inhabiting invertebrates and its life stages. It is emphasized that further research should focus on key species in the food web of the North Sea, sessile species and a diversity of life stages.

### Fish

Several fish species in the North Sea reacted to the magnetic or induced electric field created by subsea power cables. Behavioural reactions related often to their migration pattern, as seen in a study of Cabling at Nystad, DK (Vattenfall, 2006, Table 7):

- European eels appeared to depart the area when they encountered the cable;
- Atlantic cod appeared to accumulate close to the cable;
- European plaice and European flounder elicited a behavioural response; they were most likely to cross the cable during periods of low power production (Vattenfall 2006).

Power cables could therefore lead to an effect on distribution and partition between species groups, which in turn could affect their fitness if for example prey tends to stay outside cable zones. Since the most relevant findings on effects on migratory behaviour are based few species and few recaptured individuals the impact on the most common, endangered or economical valuable species in the North Sea, is still poorly studied.

## Elasmobranchs

Studies on the effects of EMFs on elasmobranch species that inhabit the North Sea region are rare. Attraction to elevated EMF field strengths has been observed in several species of sharks and rays in multiple studies. However, studies of field magnitudes within the range emitted by subsea cables, let alone field studies, are scarce and inconclusive. Furthermore, response differences amongst individuals and habituation have been observed. Since electrosensory primary neurons react on electric fields of 1-10 Hz, reactions outside this bandwidth (i.e. subsea cables of 50Hz) are expected to be only evoked with much stronger field intensities.

A COWRIE-sponsored mesocosm study was designed to examine behaviour of electro-sensitive species confined in the vicinity of powered and unpowered buried cables in Scotland (Gill, et al. 2009). This study showed that the two species of benthic elasmobranchs studied, did respond by being attracted to the EMF emitted, albeit with high variability among individual fish (Boemre, 2011). The results however did not allow for an assessment of the impact on the fish or fish populations.

Also dogfish showed attraction to elevated field strengths with a preference for AC cables. No general assumptions can be made as elasmobranch species tend to react different even among individuals. Furthermore, learning and habituation has been observed in shark species, indicating that they can adapt to anthropogenic electric fields on a local scale.

To gain more knowledge on species and eventually on impact at population level, research has to focus on specific sites, species and specifically on the range of field strengths that are generated by subsea power cables.

## Turtles

The only turtle species that is listed by OSPAR to inhabit the North Sea is the leatherback turtle. This species can react to magnetic fields by deviating from its migration pattern. However, no negative effects have been found caused by the deviation, since in the studies conducted the turtles always managed to find their natal grounds. Most likely they do not solely rely on the earth's magnetic field for orientation and migration, but use other cues as well. The impact of EMFs and iEFs generated by subsea power cables on sea turtles in the North Sea appears therefore to be limited, although this cannot be scientifically substantiated.

## Marine Mammals

The main research on the effect of anthropogenic magnetic fields on marine mammals is done by theoretical studies. Several marine mammals in the North Sea region are known to have a higher possibility of stranding when they cross a magnetic minimum. Migration deviations or stranding probability caused by the emitted field from subsea power cables are not yet studied. However according to these theoretical studies and considering the field strengths emitted by the subsea power cables potential impact on migration and strandings could not be excluded for the North Sea.

## Indirect effects

Since many species in the North Sea relate to others species, indirect effects that accumulate through the North Sea food web can be expected. For example, sea bird species might be impacted by changes in their main food source, if the distribution of benthos species is effected by EMF or predator/prey interactions are disturbed. There are to date no studies on (potential) indirect effects of EMF fields and this impact therefore remains possible but speculative.

## 4.5 KNOWLEDGE GAPS

It is known that several taxonomic groups inhabiting European waters are sensitive to EMF. However, there are large gaps in understanding the response of these animals to the EMFs and the impact of the fields generated by subsea power cables.

What we do know is that to date there is sufficient, but anecdotal, evidence that marine species groups are sensitive to magnetic fields and induced electric fields and *potentially* impacted by anthropogenic EMFs and there is to date *no observation of lethal effects* due to subsea cable EMFs. Elasmobranchs and fish did, in some cases, show reactions to EMFs generated by subsea power cables in the form of attraction or avoidance of the cable. However, individual variation was high and experimental set up would not allow for general conclusions or indications of impact on populations. Whether responses will yield population effects has to be established in the future with specific dose-effect relations for sensitive species.

Furthermore, effect studies of field strengths within the range emitted by subsea power cables, let alone field studies, are scarce and inconclusive and not performed within the North Sea. On overview of the key knowledge gaps for on various aspects for the North Sea region is shown in Table 8.

Whether there are any biologically relevant implications for sensitive species' populations cannot be determined. There are no standards or guidelines for assessing and measuring EMF developed to date and there is no theoretical basis for mitigation measures. Furthermore, international cooperation is essential, since field measurements and experiments dealing with true field strengths of subsea cables are expensive, but indispensable.

Since knowledge gaps exist on different levels there is also a need for a knowledge base specifically on these levels. To create more knowledge on species and eventually populations, research has to focus on priority species(groups) and - life stages and specifically on field sites and field strengths that are in the same range as those emitted by subsea cables, both at maximum and minimum elevation.

To gain more knowledge on species and eventually populations, research has to focus on different categories of effects (behavioural (attraction/avoidance), migration and navigation, predator prey and physiological), key species(groups) and life stages and specifically on field sites and field strengths that are in the same range as those emitted by subsea cables (see also chapter 6).

Table 8 Overview of key knowledge gaps on various aspects.

| Parameter | Main finding in literature | Knowledge gap |
|---|---|---|
| Sensitivity of species(groups) | Anecdotal evidence for electric and magnetic field sensitivity<br>Sensitivity range likely to be higher than anthropogenic EMF fields from subsea cables | Life stages like the pelagic larval period poorly studied.<br>Sessile (benthic) species poorly studied.<br>Key species in North sea foodwebs (Spisula, Ensis, polychaetes) not studied.<br>Species of economic relevance (fish, crustaceans) poorly studied.<br>Endangered/declining species in the North Sea hardly studied.<br>Pinnipeds not studied.<br><br>**Which species(group) should be prioritized based on their sensitivity, knowledge gap, conservation, economic or policy status?**<br><br>**What is the sensitivity of priority species in the North Sea to EMF fields?** |

| | | |
|---|---|---|
| Threshold values of species(groups) | Anecdotal evidence.<br>Few species in the North Sea tested.<br>Tested and threshold values usually very high | Field strengths related to subsea cables not known or tested:<br><br>**What are field strengths of subsea cables in the North Sea (i.e. range of values that is relevant to be tested for marine life)?**<br><br>**What are threshold values for prioritized species?** |
| Effects | Eels and elasmobranchs most susceptible and studied, but effects unclear<br>Link biological effects to potential ecological impacts based on theory, not evidence<br>Food web effects never described. | **Is it possible to translate biological effects to potential impacts?**<br><br>**How are movement and distributional patterns influenced by elevated EMF?** |
| Mitigation measures: cable burial | Attraction or avoidance are observed effects of subsea cable EMF with attraction occurring at low fields strengths and avoidance at high field strengths. Cable burial is used as a standard mitigation measure leading to lower field strengths | **What is the ecological effects of attraction and can it be harmful to populations (e.g. susceptibility to fisheries, starvation)?**<br><br>**Is mitigation via cable burial potentially more harmful than exposure to full field strengths?** |
| Guidelines for assessment and dealing with uncertainty | No guidelines | **What guidelines for EMF assessment should be used and how can uncertainty of effects on marine life be incorporated?** |
| Future research | Discontinuity of ongoing research.<br>Similar species tested in different settings with similar or no effects.<br>Similar species of interest in different seas and countries. | **In what way can corporation between countries lead to a comprehensive approach of dealing with EMF knowledge gaps?** |

# 5 NORTH SEA SYNTHESIS

## 5.1 SYNTHESES OF EMFS IN THE NORTH SEA

Subsea power cables generate electromagnetic fields and electric fields. Electromagnetic fields are not fully shielded and reach into the marine environment, although the field strength rapid decreases with distance from the cable. Electric fields are shielded by the cable sheathing and do not reach the marine environment, however movement through the electromagnetic field, e.g. by water & wave currents, can induce electric fields. Therefore, both electromagnetic (EMFs) and induced electric fields (iEFs) can be expected to be generated by subsea power cables.

The strength of the fields depends on many factors, like the type of current (AC vs DC) and the electric current through the cable. DC cables generally generate a stronger but static EMF, whereas AC cables generate a weaker but variable EMF. The strength increases with the current that flows through the cable. Thus, EMF strength increases with wind power, since the output current generated by wind turbines increases with wind power.

Currently there are various subsea power cables present in the Dutch part of the North Sea, which are all perpendicular orientated to the coastline. Depending on the distance of transport of energy, a selection for AC or DC cables is made. Moreover, for distances <50km AC is preferred, between 50-100 km it can be either AC or DC and >100 km DC is preferred. This implies that for all current and future OWFs in the areas Borssele, Hollandse Kust Zuid and Hollandse Kust Noord an HVAC export cable is / will be used. The voltage of these AC export cables are between 150 – 220 kV. Depending on the current generated by the OWFs, the expected electromagnetic field strength is between 5-50µT. An indicative range of the induced electric field strength is between 0.5-5 mV/m.

The infield cables of the OWFs consist of 33kV MVAC cables, although the development towards 66kV is foreseen. The expected electromagnetic field strength is between 1-5µT and the expected induced electric field strengths is between 1-5 mV/m.

There are currently only two HVDC cables in the North Sea, which are the Norned and Britned cable to Norway and the UK respectively. These cables have a voltage of 450kV and a capacity of 700 and 1000MW respectively. An electromagnetic field strength between 100-300µT around these cables is expected, and an indicative range of the induced electric field strengths of 1-5 mV/m is expected.

The EMF strength rapidly decreases with distance from the cable. No literature has been found on the shielding effect of sediment and/or water, this can be identified as a lack of knowledge. The decreasing effect of cable burial on the EMFs that reach the marine environment is therefore mainly due to the factor 'increased distance'.

EMFs can enforce each other and cancel each other out. The variable EMF field of AC cable caused by the rotating current direction might result in a weaker EMF due to cancellation of the field. In DC cables, the EMFs of the outflow and return cable can either enforce each other or cancel each other out, depending on the cable distance between both.

Due to the magnetic poles of the Earth, the geomagnetic field varies depending on the position on Earth. DC cables can influence the strength of the Earth's magnetic field, which therefore always should be taken into account in the calculation and assessment of the influence of EMFs in the marine environment.

There are many other potential sources of anthropogenic EMFs in the North Sea in the form of telecom cables and oil & gas pipelines. Both active and abandoned cables and pipelines can generate EMFs. There are no strengths described in literature for these sources, which are expected to be lower than the Earth's magnetic field.

## 5.2 Syntheses of potential impact on Marine life

Several taxonomic groups inhabiting European seas are sensitive to EMFs. Anecdotal evidence is suggesting magnetic fields are sensed by all species groups, whilst electric fields are sensed by invertebrates, bony fish, elasmobranchs and a tropical dolphin species. Current knowledge suggests that electric sense is mostly used for predator/ prey detection and especially known for species that possess ampullary receptors, for example elasmobranchs and sturgeons with ampullae of Lorenzini. In elasmobranchs electrosensing is suggested to be of specific importance for the final stages (e.g. last 30 cm) of feeding. Magnetic reception is suggested to be used by a wide range of marine species(groups), and especially for orientation and navigation.

Weak EMFs can have an important ecological function, for example small variations in the geomagnetic field used for navigation during migration and weak induced electric fields used for prey detection.

Since electric fields are inhibited by shielding material, the obvious effects of subsea cables on biota are generated by either magnetic fields or induced electric fields (iEFs). Movement of organisms through a magnetic field creates induced electric fields, with organisms moving parallel to the cable yielding no induced electric field and organism moving perpendicular to the cable magnetic field generating the maximum induced electric field.

Theoretical and observed effects of anthropogenic EMFs include disturbance of 1) behavioural responses and movement (attraction, avoidance); 2) navigation and migratory behaviour; 3) predator/prey interactions and distribution of prey; 4) physiology, embryonic and cellular development.

Numerous studies describe responses of marine biota to anthropogenic EMFs. While this is a large literature base, the main components exist of literature on perception, (theoretical) perception and anecdotal evidence of effects of electric and magnetic fields. Studies based on true anthropogenic field strengths comparable to those emitted by subsea cables are scarce and inconclusive.

There is a general lack of effect studies on effects of EMFs specifically on North Sea species. Furthermore, experimental set-ups and field strengths are often not representative for true field circumstances; hence general conclusions cannot be obtained based on these studies.

A study of OWF EMFs effects on bony fish shows European eels appeared to depart the area when they encountered a cable, whilst Atlantic cod appeared to accumulate close to the cable and European plaice and European flounder were most likely to cross the cable during periods of low power production.

EMF studies on North Sea species of elasmobranchs are rare and often inconclusive. While several studies show a response, i.e. attraction to anthropogenic elevated EMFs, there is a high variability among individuals and additionally habituation has been observed. Effects on marine turtles, marine mammals and indirect effects (e.g. via foodweb and predator/prey interactions) have not been addressed so far.

To gain more knowledge on species and eventually populations, research has to focus on different categories of effects (1-4, see also Section 6.2.3), key species(groups) and life stages and specifically on field sites and field strengths that are in the same range as those emitted by subsea cables. This is elaborated in Section 6.2.

# 6 CONCLUSIONS & RECOMMENDATIONS

The following research questions are addressed in this desk study:

### Primary research question desk study:

1) What are electromagnetic fields, how are they created and which factors influence them?
2) Is there a reason to assume that electromagnetic fields negatively impact the marine environment? If so, which species potentially negatively affected and can this lead to an impact on population level of these species?

### Follow-up research question (experimental research):

1) Is it possible to experimentally study the factors that influence the electromagnetic field strength of buried High Voltage Direct Current (HVDC) or High Voltage Alternating current (HVAC) power cables and the impact of these cables on sharks, rays and potentially other species such as harbour porpoises?

Section 6.1 describes the main conclusions of the desk study and answers research questions 1 and 2. In Section 6.2, recommendations for future research is given, which forms the framework for experimental work to be conducted to address the main knowledge gaps identified in this study. To explore the possibilities for this experimental work, pilot experiments for phase 2 of the current project are formulated in Section 6.3.

## 6.1 MAIN CONCLUSIONS

The following main conclusions on the **occurrence of EMFs due to subsea power cables** are formulated:

1) Subsea power cables generate electric (EFs) and electromagnetic fields (EMFs), of which due to shielding of the cable only EMFs reach the marine environment. Movement in EMFs, e.g. by water currents or swimming organisms, also induce electric fields (iEFs). Therefore, both EMFs and iEFs occur around subsea power cables.
2) DC power cables generate stronger but static EMFs, whereas AC cables generate a lower but variable EMFs. EMFs of DC cables is higher than the geomagnetic field, whereas EMFs of AC cables are likely to be lower than the geomagnetic field.
3) In relation to the OWF development in Dutch waters, only AC subsea power cables are relevant since the use of DC cables is currently not foreseen.
4) The strength of the EMFs depends mainly on cable type, voltage and current, which implies that stronger EMFs are generated by OWFs during high wind periods.
5) The strength of EMFs rapidly decreases with distance from the cable. Modelling studies indicate that EMFs are limited spatially (both vertically and horizontally). However, EMFs of both AC and DC cables are likely to reach at minimum up to a number of meters in the water column, possibly more.

6) Burial depth, clever positioning of the cables (e.g. minimum mutual distance), lower currents and better shielding of the cable can decrease the strength of the EMFs that reach the marine environment.

The following main conclusions on the **effects and potential impact of EMFs** are formulated:

7) Sufficient evidence exists in published literature to conclude that marine species can be affected by anthropogenic EMFs. This makes it a human impact that cannot be denied and should be considered in future environmental impact studies.
8) Much is unknown about the effects of EMFs on the marine ecosystem, but considering the vast upcoming increase in offshore wind farms and cables connecting those to the land, further research into the impacts of EMFs on marine life is essential.
9) Four main potential effects due to EMFs are identified in literature:
   - Disturbance of behavioural responses and movement (attraction, avoidance);
   - Disturbance of navigation and migratory behaviour;
   - Disturbance of predator/prey interactions and distribution of prey;
   - Disturbance of embryonic and cellular development.
10) Studies that test the effects of EMFs under realistic EMF-strength conditions are largely absent from literature. Much of the current understanding is based on theoretical evidence or trials with exaggerated experimental EMF-strengths. Determining impact of realistic EMFs on species is therefore a key priority.
11) The EMFs and iEFs generated by subsea power cables in the Dutch North Sea most certainly are in the range that potentially have an effect on the marine environment.
12) Lower EMF strengths, are not necessarily associated with less impact. Moreover, weak EMFs can have an important ecological function, such as the little variations in the geomagnetic field used for navigation during migration and the weak fields induced by prey. Knowledge on how the type of EMFs (static, variable, specific frequencies) relates to potential effects is largely lacking.
13) Species on each level of the North Sea food web are potentially sensitive to EMFs. High sensitivity is expected for elasmobranchs (sharks, rays), but also invertebrates, bony fish and marine mammals inhabiting the North Sea can potentially be affected by EMFs. Benthic species, located closer to cables encounter stronger EMFs and hence are more likely to be affected.
14) With the existing lack of knowledge, the occurrence of effects due to EMFs on population level of species in the North Sea cannot be excluded nor confirmed.

## 6.2 Recommendations

### 6.2.1 General recommendations

Precautionary principle: Impact due to EMFs on the marine environment can - based on current knowledge - not be excluded. Since Descriptor 11 of the Marine Strategy Framework Directive addresses the introduction of energy and given the fact that the number of high voltage cables will increase strongly due to the development of OWFs in the North Sea windfarms, it is recommended to follow the precautionary principle considering EMFs generated by to power cables until key knowledge gaps have been addressed.

EMFs vs. iEFs: It is concluded that both EMFs and iEFs are generated around subsea power cables. The induced electrical fields depend on movement through generated EMFs. This makes the assessment of iEFs highly challenging, as this implies that iEFs can be generated by many factors (e.g. water current, organisms etc.). It is therefore recommended to focus research at this stage on EMFs generated by subsea power cables.

Furthermore, it is recommended to address the main knowledge gaps on both the technical aspects of EMFs and the potential effects of EMFs on the marine environment with respect to the relation between both, as illustrated in Figure 31. Recommendations on the technical aspects and impact of EMFs are given in more detail below.

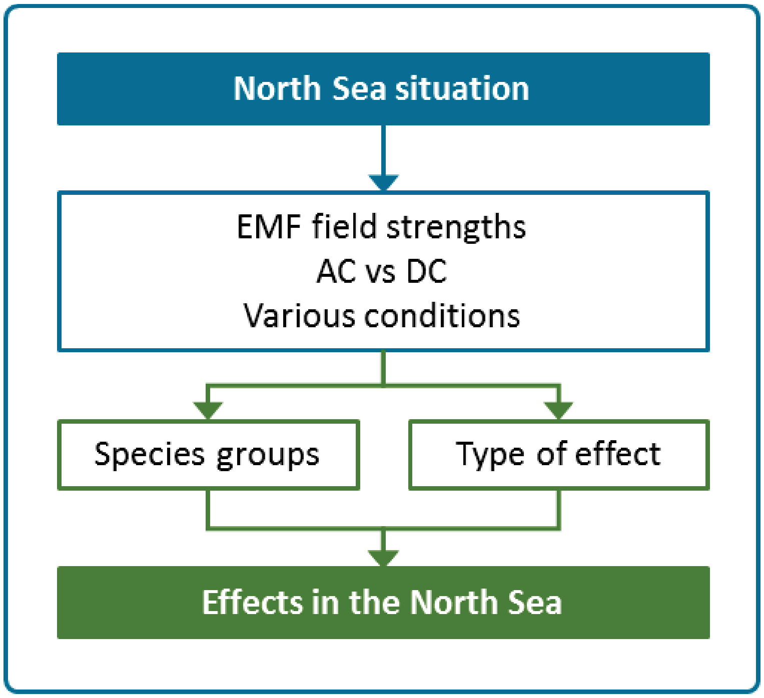


Figure 31 Impact chain of EMFs in the marine environment of the North Sea (technical aspects in blue, impact on marine life in green).

### 6.2.2 Recommendations on technical aspects of EMFs

Although the subject has received an increasing amount of attention over the last years, the actual occurrence and strengths of EMFs generated by subsea power cables in the North Sea are largely unknown. It is recommended to address this knowledge gap by means of the proposed steps shown in the research outline in Figure 32 and described in more detail below.

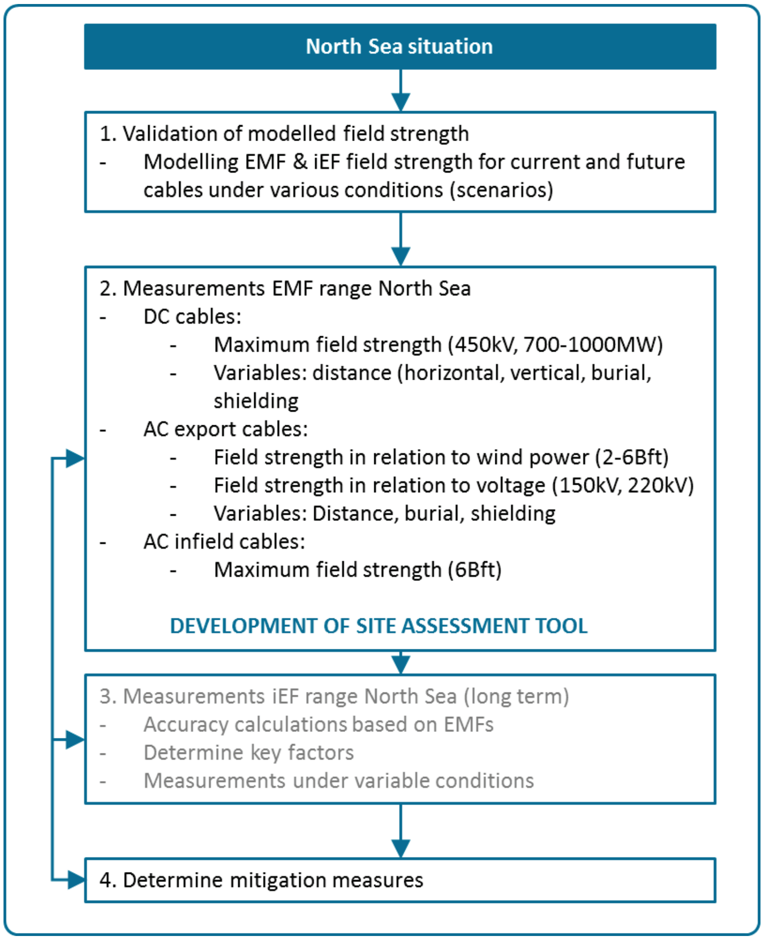


Figure 32 Overview of research to be conducted on technical aspects of EMFs in the North Sea.

## 1) Validation of modelled field strengths (short term)

The strength of EMFs of subsea power cables are generally modelled based on the design of the cables. Assessments are based on these modelled outputs, however validations of these models specifically for the marine environment is lacking. It is therefore recommended to model the EMF strengths of the current and future cable systems under various conditions by means of scenarios and to validate the outputs by means of field measurements (step 2).

## 2) Assessment of true EMF strengths in the North Sea (short term)

Until recently, measuring EMFs under water in the field was not possible. There is a strong knowledge gap on the actual electromagnetic field strength that can be expected for the various cable designs, voltages and outputs of OWFs that occur in the marine environment. We therefore recommend to conduct field measurements for validation of the model outputs and quantify the EMF strength for various conditions in the field.

2a) To this end, we recommend to explore the possibilities of developing an underwater measurement device that can measure EMFs under field conditions and also can be used for the experimental setup to assess impact as described below (step x).

2b) With a measurement device, the first important step is to determine the field strengths from subsea cables in different locations and with different cable types and weather types in both the horizontal and vertical plane. This will provide 3D maps of fields marine species will encounter.

2c) The next step is to study the potential shielding possibilities that can be used for mitigation of effects of EMFs on the marine environment.

#### 3) Measurements induced electrical fields (long term)

Not recommended at this stage, see general recommendations.

#### 4) Determination of mitigation measures (long term)

Depending on the output of the assessment of effects and impacts on populations (see below), it could be necessary to mitigate for potential impact. Since the strength of the EMF rapidly decreases with distance, increasing the burial depth of the cables seems an obvious – but costly - mitigation measure. We therefore recommend to study other possibilities of mitigation measures, such as clever positioning of the cables, shielding of the cable and lowering currents by increasing transport voltage.

### 6.2.3 Recommendations on impact of EMFs on marine environment

All information on EMFs and marine life in the North Sea together shows that there is little or no direct evidence that EMF fields will have no effect on marine species. However, data on both field conditions and response of North Sea species to these fields are lacking. We therefore advise to address the main / highest priority knowledge gaps in order to be able to assess the relevance of anthropogenic EMFs and their impact on the North Sea marine ecosystem.

To address the knowledge gaps, we formulated four relevant research themes which correspond with the four different type of effects identified:

- Disturbance of behavioural responses and movement (attraction, avoidance);
- Disturbance of navigation and migratory behaviour;
- Disturbance of predator/prey interactions and distribution of prey;
- Disturbance of embryonic and cellular development.

These research themes form the basis of the studies that needs to be conducted specifically for the North Sea. Given the lack of knowledge it is not possible to make a solid prioritization of effects that should be studied first. For example, effects on embryonic and cell development seem to be less urgent given the high field strengths at which these effects occur, however the scale and severity of effects can be much larger compared to a locally disturbed predator-prey interaction.

The key knowledge gaps to be addressed that are needed to provide insights on anthropogenic EMFs of North Sea generated by subsea power cables are presented in Figure 33, described in more detail below.

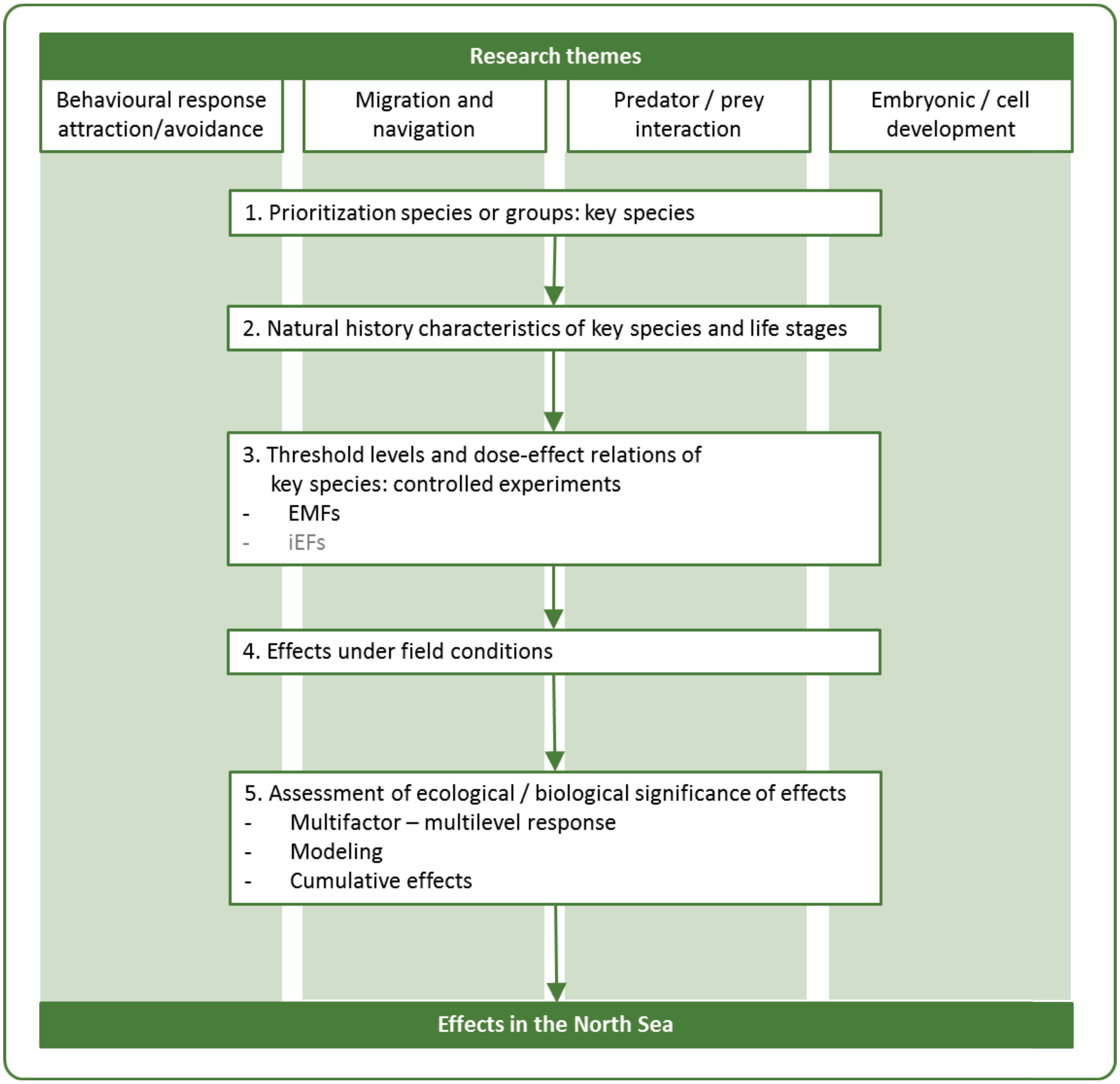


Figure 33: Overview of key knowledge gaps to be addressed.

## 1&2. Prioritize species and incorporate natural history information.

Although effects can occur on all levels of the North Sea food web, we recommend to prioritize on the species groups that are sensitive for EMFs or have a specific conservation status.

Species groups on which research should be focused are: elasmobranchs, migratory fish and benthic bony fish species. Furthermore, benthic invertebrates should be studied to unravel impacts through predator/prey relationships. Additionally, based on theoretical sensitivity and conservation status, effects on marine mammals, including harbor porpoise, should be addressed.

To further prioritize species of interest, apart from sensitivity to EMFs, spatial natural history information in the North Sea is added. Apart from large mobile adults considered so far, other key life forms- and stages should be addressed as well. The spatial information on distribution, important migration routes, spawning and nursing grounds, importance for the North Sea food web and economic activities (i.e. fishing) can lead to a narrower selection of focal species.

### 3. Controlled experiments: Establish behavioural responses, thresholds and Dose-Effect relations for species(groups) to true field strengths

Based on true field strengths measured for the North Sea situation, dose effect relations should be established for certain species(groups). It is important to note that not only the maximum field strength should be used for further testing. Since invertebrates and elasmobranchs seem to be attracted to small field variations, also minimal or average field strengths have to be taken into account. As a first step dose-effect relations can be established under controlled laboratory or mesocosm conditions. We recommend developing a setup with representative AC EMF strengths for the North Sea situation.

### 4a. Field assessment: cable effects and benthic life

Benthic life forms an essential part of the North Sea food web. Alterations in the benthic community can lead to effects on higher tropic levels by changes in predator/prey interactions. We therefore recommend to perform an assessment of benthic life on and around cables in the Dutch North Sea. Using a field study of existing cables in the North Sea, visually comparing the area directly around the cable with areas away from the cable differences in both invertebrate and (benthic) fish communities can be established. For future cables (e.g. NOZ Borssele) a baseline study can add to this picture, as does benthic sampling.

### 4b. Field assessment: migration barrier

An important aspect to address is the barrier function of cable EMFs, especially for migrating species. Experiments that could try to establish directional movement include (baited) trapping around cables with marked or telemetry tagged individuals in the field. Comparable experimental field experiments have been conducted in Long Island, and the involved researchers would like to elaborate this study and include other species (e.g. eel, *Anguilla anguilla*). We therefore recommend to actively find cooperation and make use of existing experience on this matter.

### 4c. Correlative studies of existing data

Extensive datasets of OWFs worldwide that include global positioning of tagged seals and harbour porpoise can provide valuable data to assess the potential effects of EMFs on marine mammals. We recommend reanalysis of such data that could provide information on (or exclude) cable effects (for example reanalysis seal data of Russell et al. (2014) including cable lay outs of Alpha Ventus and Sheringham shoal OWFs to assess migration behavior between wind turbines).

### 5. Model EMF effects, assessment of significance (long term)

EMF field strengths -measured in the field for different cable types and layouts, or in a next step from a validated model- and dose effect relations could be integrated in a population model. Based on population size and other (cumulative) effects, significance for the Dutch North Sea should be addressed.

## 6.3 Pilot experiments 2016 – Phase 2

Clearly the EMF research in the Dutch North Sea is novel and has to be developed. The list of recommendations is extensive and it is important to focus phase 2 of this project such that it is of value for future research. Based on the recommendations, three main components are identified:

1) Measurements of EMFs under field conditions;
2) Controlled experiments for various species;
3) Field studies on impact on marine life.

The aim of phase 2 was to explore possibilities for future research on the impact of EMFs. We therefore propose to focus phase 2 of this project on exploring the feasibility of conducting research on the main components listed above. Given the budget available of phase 2 of this project, exploration of field studies is not feasible. We will therefore focus on exploring the feasibility of measurements of EMFS under field conditions and conducting controlled EMF experiments.

### Measurements of EMFs under field conditions

In this step, we will explore the possibilities of the development of a measurement device for EMFs underwater. Based on the information we have gathered in the project up till now, we expect to be able to develop an instrument that will measure the magnetic field strength of AC cables in the range that is generated by subsea power cables. With this instrument we can potentially make time series of EMF strengths, which can be used to measure along transects crossing subsea power cables.

The instrument that will be developed will be waterproof and submergible, in order to be usable for the mesocosm experiments and measurements at sea.

Actual field measurements in the North Sea will not be possible due to limited budget. We will however make a list of lessons learned and points of attention gained during development that are relevant for future measurements at sea.

Also, we will discuss the scenario's and value of measurements at sea with the Dutch grid operator (Tennet) which is also capable in modelling EMF strengths of different scenarios as recommended.

### Controlled experiments for various species

Based on research needs and money and time constraints and interesting first step is to test species(groups) for field strengths in the range of those emitted by subsea cables. Important members of the food web of the North Sea that have not been tested so far are invertebrates. We suggest to perform a controlled experiment to test reactions to anthropogenic EMFs using polycheates and potentially other benthic species (crustaceans, molluscs). The main aim of this will be to test whether it is feasible to conduct controlled studies with various species in future research.

The experiment will include :

- Set up: Experimental set up with EMFs generated in the range of subsea power cables.
- Testing: Runs of various field strengths on at least one species of polychaete to study behavioural response.

### Elaborate future research

Finally, we suggest in phase 2 of this project to briefly elaborate future research options. Recommendations on future research will be elaborated based on:

1) Expert interviews (international researchers, Imares);
2) More information on existing data;
3) Preliminary data of international research;
4) Technical and economic aspects;
5) Lessons learned from measurements and experimental set ups.

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# 10 APPENDIX 3 – LIST OF SYMBOLS AND UNITS

| Symbol | Property | Units |
|---|---|---|
| *A* | Ampère; unit of electric current | - |
| *A* | Area | $m^2$ |
| *AC* | Alternating current | - |
| *a* | Perpendicular distance from the wire to the point where the flux density is being evaluated | m |
| *B* | Magnetic field/Magnetic field strength/Magnetic flux density | T |
| *Bft* | Beaufort; measure for wind force | - |
| *C* | Coulomb; unit of electric charge | - |
| *DC* | Direct current | - |
| *E* | Electric field/Electric field strength | N/C or V/m |
| *EMF* | Electromagnetic field | - |
| *e* | Elementary charge (approximately equal to $1.602 \cdot 10^{-19}$ C) | - |
| $F_{el}$ | Electric force | N |
| $F_l$ | Lorentz force | N |
| *f* | Coulomb's constant (≈ $8{,}99 \cdot 10^9$) | $N \cdot m^2 \cdot C^{-2}$ |
| *H* | Other way of defining the magnetic field, not used in this report. | A/m |
| *HV* | High voltage | - |
| *Hz* | Hertz; unit of frequency | - |
| *I* | Electrical current | A |
| *iE* | Induced electric field | V/m |
| *MV* | Medium voltage | - |
| *N* | Newton; unit of force | - |
| *OWF* | Offshore windfarm | - |
| *Q* | Electric charge of an object | C |
| *q* | Electric charge of a particle | C |
| *r* | Distance | m |
| *S* | Siemens; unit of electric conductance | - |
| *T* | Tesla; unit of magnetic field strength/magnetic flux density | - |

| | | |
|---|---|---|
| $t$ | Time | s |
| $U_{ind}$ | Induction voltage | V |
| $V$ | Volt; unit of voltage | - |
| $v$ | Velocity of particles | m/s |
| $W$ | Watt; unit of power | - |
| $Wb$ | Weber; unit of magnetic flux | - |
| $\mu_0$ | The magnetic permeability of a vacuum (a physical constant with the value $4\pi\cdot10^{-7}$) | $N\cdot A^2$ |
| $\Phi$ | Magnetic flux | Wb |

## Metric prefixes used in this report

| Symbol | Text | Factor |
|---|---|---|
| M | Mega | 1 000 000 |
| k | Kilo | 1 000 |
| m | Milli | 0.001 |
| μ | Micro | 0.000 001 |
| n | Nano | 0.000 000 001 |

# 11 APPENDIX 4 – DESIGN CHARACTERISTICS OF AC & DC CABLES

## 11.1 Design characteristics of AC cables

Subsea AC power cables are composed of an inner electrical conductor which is surrounded by layers of insulating material and is surrounded by conductive and non-conductive sheathing. In most cases, three cables are bundled together in one large cable in order to carry three-phase currents. Figure 34 shows a sketch of the composition of a typical subsea AC cable, including the metallic sheaths. When the voltages in cable are larger than 138 kV, the phase conductors are often installed as separate cables, which are mostly tied together during installation (Normandeau et al., 2011).

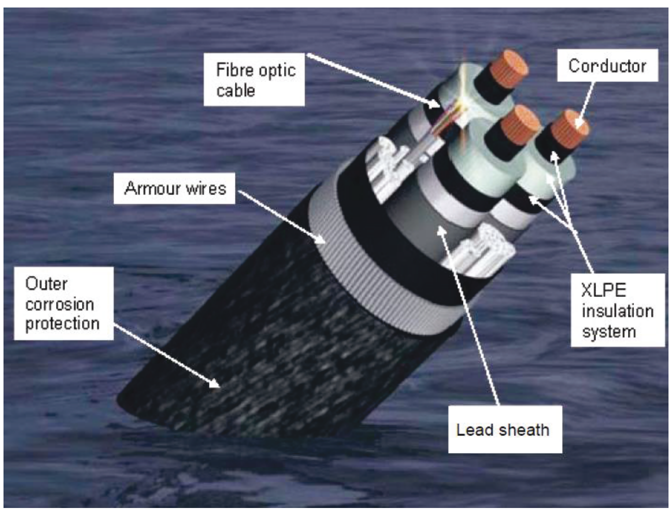


Figure 34: Sketch of a typical subsea high voltage AC cable which displays the three phase conductors and the surrounding sheathing.

Little to no information is available regarding the conductivity and magnetic permeability of sheathing and armour from undersea cables. The total magnetic field intensity outside a power transmission cable depends on current flow on the cable conductors, distance from the cable and the conductor arrangement within the cable. The predominant frequency of the magnetic field in Europe is 50 Hz and in America 60 Hz. However, wind turbines that use power electronic converters generate harmonic currents which in turn produce magnetic fields with a frequency exceeding 1 kHz (Maduriera et al., 2004).

## 11.2 Design characteristics of DC cables

Most subsea power cables are from the AC variant, but DC cable systems are becoming more and more common. This increasing use is mostly attributed to the fact that DC cables can carry power over long distances using only two cables (AC needs three cables) and only limited power loss. Also in DC cable systems, the direct *E*-field is contained within the cable sheathing. Several DC cable systems exist and they all consist of several components. The monopolar DC system is sketched in Figure 35. A rectifier station converts AC power to DC power, a cable transmits the DC power and an inverter station converts the DC power back to AC power. The monopolar DC system uses a single, high-voltage direct-current (HVDC) conductor at one constant voltage. The final component is a return current that is transmitted over a return cable (Normandeau et al., 2011). An example of a DC power conductor with integrated return cable is given in Figure 37.

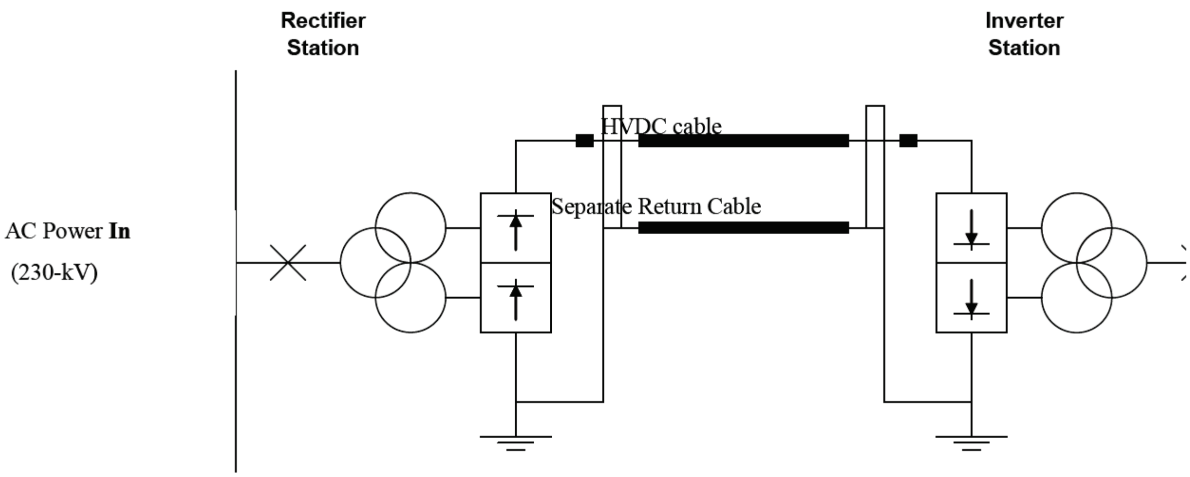


Figure 35: Example of a monopolar DC cable system with a separate return conductor (SRC; Exponent, 2001).

A different monopolar DC cable system makes use of a coaxial cable with a so called integrated return circuit (IRC, Figure 36). This type of cable consists of a high voltage copper conductor, surrounded by insulation, whilst the return current flows over the surrounding concentric cylindrical copper conductors grounded at one end. No current is present on other locations except the centre conductor and the outer return circuit (Normandeau et al., 2011).

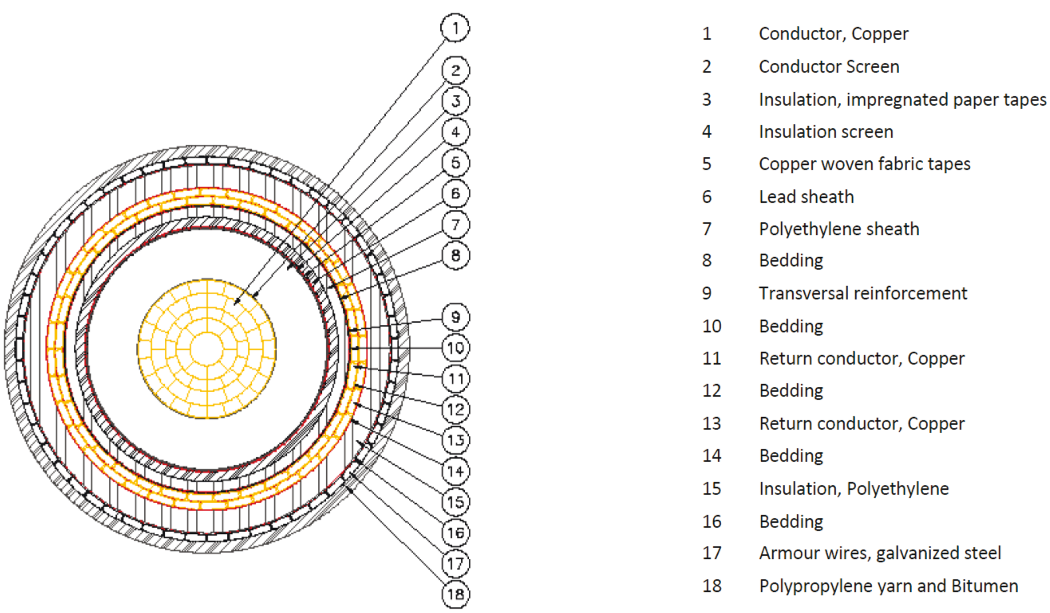


Figure 36: Monopolar DC cable system using coaxial cable with an IRC (Exponent, 2001).

Another system is composed of one power cable (Figure 37), where the return current does not use a return cable (opposed to what is sketched in Figure 37), but instead flows through the ocean from sea electrodes at both ends of the cable. This type of cable design results in larger electric fields, larger magnetic flux densities related to the cables, increased corrosion and generation of electrolysis products. These electrolysis products include oxygen and chlorine at sea electrodes, causing the formation of hypochlorite at the anode and hydrogen, calcium and magnesium hydroxides at the cathode (Koops, 2000). Thus, monopolar DC cables where the return current flows through the sea are not suited for locations where environmental impacts must be avoided.

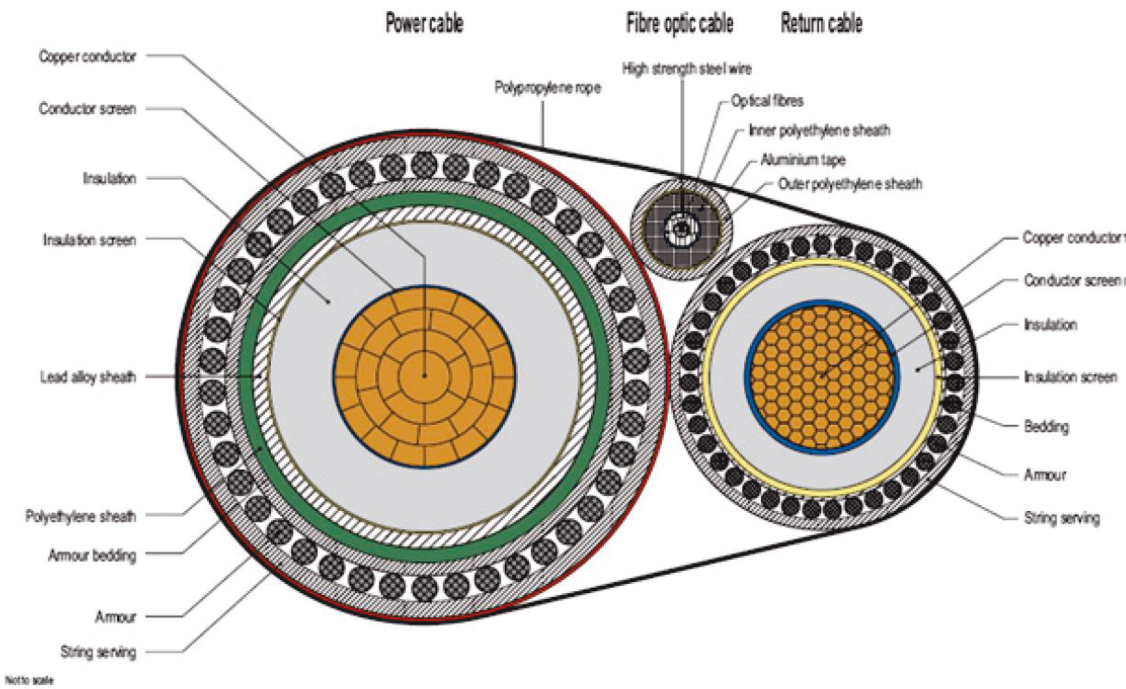


Figure 37 Monopolar DC cable system with a Separate Return Cable (SRC; TPC 2001).

While converting 50 Hz or 60 Hz AC power to DC power, currents and voltages at harmonics of 60 Hz are generated, regardless of the cable system. Therefore, both AC and DC cable systems are equipped with filters at the rectifier and inverter to make sure that the magnitudes of the residual harmonics are minimised. In IRC systems, the harmonic currents on the two conductors would cancel each other out, leading to no magnetic field (Normandeau et al., 2011).

Another type of system is the bipole DC transmission system, in which power is transmitted at two voltages with respect to ground (for example +500 kV and -500 kV). This type of system requires two high voltage conductors with opposite polarities (+ and -) and an additional conductor that serves as a return path for any type of unbalance between the two poles. Also in this type of system, the return path can either be provided by a metal conductor or seawater. Furthermore, the bipolar system can be operated as a monopole system in case one pole is out of service (Normandeau et al., 2011).

# 12 APPENDIX 5 – EMF EFFECTS AND THRESHOLDS OF MARINE LIFE IN THE NORTH SEA

In the Table below, an overview of the marine species of the North Sea and their studied sensitivity and effects of anthropogenic electric or magnetic fields is given. The focus lies on 'threatened and declining species' present in the Greater North Sea (Region II) according to OSPAR (2016), and species reported in literature. Additionally, threshold values (CMACS 2003 and 2005) for species groups are given in Table A5.2

*Table A5.1. Responses and effects of marine species to anthropogenic EMF fields*

| Scientific name | Species(groups) | Response electric or magnetic fields (E/M) | Possibly impacted by EMFs (Y/N/?) | References |
|---|---|---|---|---|
| Invertebrates | | | | |
| *Artica islandica*[1] | Ocean quahog | ? | ? | |
| *Nucella lapillus*[1] | Dog whelk | ? | ? | |
| *Ostrea edulis*[1] | Flat oyster | ? | ? | |
| | Sea urchins | M | Y, delayed cleavage cycle at 30 – 50 mT<br><br>Y | Sakhnini et al., 2004 |
| *Talitrus saltator* | Sandhopper | M, Orient themselves towards magnetic fields | ? | Arendse and Kruyswijk 1981<br><br>Arendse 1987 |
| *Clava multicornis* | Hydroid | M | N, Reproduction was faster at a magnetic intensity of 10 and 20 mT than in control and at 40 mT (a lot higher than EMF) | Karlsen and Aristharkhov 1985 |
| *Mytilus edulis* | Blue Mussel | M | N, no lethal effects from exposure to 3.7 mT DC fields for 7 weeks<br><br>Y, 20 % decrease in hydration and 15% in amino nitrogen | Bochert and Zettler 2004<br><br>Aristharkov et al 1988 |

| | | | | |
|---|---|---|---|---|
| *Idotea baltica basteri* | Isopod | M, Uses the Earth's magnetic field to orient relative to the shoreline | ? | Ugolini and Pezzani, 1995 |
| *Homarus vulgaris* (close relative to *H. gammarus*) | Common lobster | M | N, A field strength five orders of magnitude higher than expected directly over an "average" buried power cable, elicited no response | Ueno et al. 1986 |
| *Rithropanopeus harrisii* | Round Crab | M | N, No lethal effects from exposure to 3.7 mT DC fields for 7 weeks | Bochert and Zettler 2004 |
| *Crangon crangon* | North Sea prawn | M | N No lethal effects from exposure to 3.7 mT DC fields for 7 weeks | Bochert and Zettler 2004 |
| Fish | | | | |
| *Acipenser sturio* [1] | Sturgeon | E/M? | ? | x |
| *Alosa alosa* [1] | Allis shad | ? | ? | x |
| *Anguilla anguilla* [1] | European eel | E/M (M; 0,067 mV/cm) | Y physiological/ behavioural/anatomical | Vriens and Bretschneider 1979, Tesch 1974, Moore and Riley 2009 |
| *Coregonus lavaretus oxyrinchus* [1] | Houting | E/M? | ? | x |
| *Gadus morhua* [1] | Cod | E (2 $\mu$A/cm$^2$) | Y behavioural | Vattenfall, 2006 |
| *Hippocampus guttulatus* [1] | Long-snouted seahorse | ? | ? | x |
| *Hippocampus hippocampus* [1] | Short-snouted seahorse | ? | ? | x |
| *Petromyzon marinus* [1] | Sea lamprey | E (1 to 10 mV/cm) | Y physiological/ behavioural/anatomical | Bodznick and Preston 1983, Chung-Davidson et al. 2004, Chung-Davidson et al. 2008, |

| | | | | |
|---|---|---|---|---|
| *Pleuronectes platessa* | European plaice | M? | Behavioural | Metcalfe et al. 1993 |
| *Platichthys flesus* | European Flounder | M | N, toxicity study - no lethal effects from exposure to 3.7 mT DC fields for 7 weeks | Bochert and Zettler 2004 |
| *Pollachius virens* | Coalsfish | ? | ? | x |
| *Psetta maxima* | Tarbot | ? | ? | x |
| *Salmo salar* | Salmon | M/E (0,5-4,0 mT; o,6 mV/cm) | Y physiological/ behavioural/anatomical | Tanski et al. 2005, Rommel and McCleave 1973, |
| *Scomber scombrus* | Mackerel | ? | ? | x |
| *Scophthalmus rhombus* | Rhombus | ? | ? | x |
| *Sprattus sprattus* | Sprat | ? | ? | x |
| *Solea solea* | Common sole | ? | ? | x |
| | | | | |
| Elasmobranch | | | | |
| *Cetorhinus maximus* [1] | Basking shark | E? | ? | x |
| *Centroscymnus coelolepis*[1] | Portuguese dogfish | E? | ? | x |
| *Centrophorus squamosus*[1] | Leafscale gulper shark | | | |
| *Dipturus batis (Raja batis)*[1] | Common skate | E? | ? | x |
| *Raja montagui (Dipturus montagui)*[1] | Spotted ray | E? | ? | x |
| *Lamna nasus*[1] | Porbeagle | E? | ? | x |
| *Raja clavata*[1] | Thornback skate / ray | E/M (0.01 µV/cm; 0.35 G: induced field = 0.16 mV/cm) | Y behavioural/physiological | Brown and Ilyinsky 1978, Gill et al. 2009, Kalmijn 1966, Kalmijn 1971, |
| *Rostroraja alba*[1] | White skate | E? | ? | x |

| | | | | |
|---|---|---|---|---|
| *Squalus acanthias*[1] | [Northeast Atlantic] spurdog | x | N, Inconclusive results when exposed to EMFs from 36kV AC cable | Gill et al. 2009 |
| *Squatina squatina* [1] | Angel shark | E? | ? | x |
| *Scyliorhinus canicula* * | Small-spotted cat shark | E (0.01 to 0.1 µV/cm) | Y Behavioural/ physiological | Gill and Taylor 2001, Gill et al. 2009, Kalmijn 1966, Kalmijn 1971, Kimber et al. 2009, Peters and Evers 1985 |
| Turtles | | | | |
| *Dermochelys coriacea*[1] | leatherback turtle | M | Y, Adults and hatchling affect in navigation, migration and orientation | Lohmann and Lohmann 1993 |
| Marine Mammals | | | | |
| *Phocoena phocoena*[1] | Harbour purpoise | M (0.05 µT) | Y, theoretical evidence | Kirschvink 1990 |
| *Tursiops truncatus* | Bottlenose dolphin | M (earth's magnetic field;0.05 µT) | Y, behavioural/physiological; anatomical – magnetite in dura matter; theoretical | Kuznetsov 1999; Bauer 1985; Kirschvink 1990 |
| *Globicephala melaena* | Long-finned pilot whale | M (earth's magnetic field;0.05 µT) | Theoretical | Kirschvink, et al. 1986; Kirschvink 1990 |
| *Lagenorhynchus albirostris* | White beaked dolphin | ? | ? | x |
| *Lagenorhynchus acutus* | Atlantic white-sided dolphin | M(0.05 µT) | Theoretical | Kirschvink 1990 |
| *Balaenoptera acutorostrata* | Minke whale | ? | ? | x |
| *Megaptera novaengliae* | Humpback whale | ? | ? | x |

*Table A5.2. Threshold values of marine species groups to EMF fields (source: CMACS)*

| | | |
|---|---|---|
| Cetaceans<br><br>(Whales and Dolphins) | No evidence to suggest impact from DC electric fields (Walker 2001). AC field effects not addressed. | Anecdotal evidence that cetaceans navigate using magnetic fields, but no apparent impacts on cetacean migration from existing cables. |
| Teleost (Bony fish) | No response to fields below 6 V/m. (Uhlmann, 1975). | Some response by European Eels to magnetic emissions from HVDC cables (Westerberg 2000).<br><br>B fields of 1-100μT have been found to delay embryonic development in fish (and sea urchins) (Cameron et al 1985 and 1993, Zimmerman et al 1990) |
| Crustacea | No evidence reported | Prawn showed some attraction to B fields associated with a wind farm cable (ICES 2003). |
| Elasmobranchs (Sharks,<br><br>Skates and Rays) | With respect to research on DC electric fields elasmobranchs are sensitive to electric fields ranging from 0.5 – 1000 μV/m<br><br>Dogfish detect fields at 0.5μV/m Dogfish avoid fields at 1000μV/m although threshold in CMACS (July 2003 and 2005) taken as avoidance with higher fields 100μV or greater.<br><br>Dogfish attracted to field of 10 μV/m at 0.1 m from the source (Gill and Taylor 2001). DC and low frequency AC (0.5-20Hz) E fields are responded to the most.<br><br>The only evidence of shark bites on submarine telecommunications cables associated with 2 forms of induced electric fields: a 50Hz E field of 6.3μv/m at 1m caused by the power feed to the cable and one of 1μv/m at 0.1m resulting from the sharks crossing the B field emitted by the cable. Subsequent laboratory tests were inconclusive (Marra 1989). | Elasmobranches can detect and respond to B fields in the range 25-100μT against the ambient geomagnetic field (approx 36μT) (Meyer et al 2004). |

Source: CMACS (July 2003 and 2005)