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Electromagnetic fields and the Marine Strategy Framework Directive Descriptor 11 - Energy

Rijkswaterstaat

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DEFINITIONS AND ABBREVIATIONS

Abbreviation	Description
AC	alternating current
B-field	magnetic field
DC	direct current
EMF	electromagnetic field(s)
GES	Good Environmental Status
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
(i)E-field	(induced) electric field
MONS	Monitoring-Onderzoek-Natuurversterking-Soortenbescherming (Nature Strengthening and Species Protection Monitoring Survey)
MSFD	Marine Strategy Framework Directive
Wnb	Wet Natuurbescherming (nature conservation law)
WOZEP	Windenergie Op Zee Ecologisch Programma (wind energy at sea, ecological programme)

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INTRODUCTION

1.1 Introduction

The European Marine Strategy Framework Directive (MSFD) obliges EU member states to protect the marine environment in Europe. The goal of the MSFD is to "*protect the marine ecosystem and biodiversity upon which our health and marine-related economic and social activities depend*". To achieve this goal, all EU Member States should reach and/or maintain a Good Environmental Status (GES) in 2020 (Art. 1.1) [lit. 1]. This GES is defined as: "*The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive*". Eleven Descriptors, summarized below, are used to further define the GES. They each apply to a different topic such as biodiversity, marine litter, or food web interactions. Descriptor 11 of the MSFD applies to the artificial introduction of energy in the marine environment, stating: '*Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment*'.

1. **Biodiversity is maintained**
2. **Non-indigenous species do not adversely alter the ecosystem**
3. **The population of commercial fish species is healthy**
4. **Elements of food webs ensure long-term abundance and reproduction**
5. **Eutrophication is minimized**
6. **The sea floor integrity ensures functioning of the ecosystem**
7. **Permanent alteration of hydrographical conditions does not adversely affect the ecosystem**
8. **Concentrations of contaminants give no effects**
9. **Contaminants in seafood are below safe levels**
10. **Marine litter does not cause harm**
11. **Introduction of energy (including underwater noise) does not adversely affect the ecosystem**

So far, policy and research have mostly focused on this one aspect of energy input: underwater noise. However, to achieve the MSFD-goal of an overall Good Environmental Status of marine waters, all energy inputs need to be taken into consideration. This also includes electromagnetic fields (EMF) emitted by subsea power cables.

The main cause for recent increased interest in EMF is the global increase in offshore wind demand (see Appendix I for an indication). The Dutch government expects to install an offshore wind capacity of at least 38 GW by 2040, and even more in the years thereafter. To collect the power from the wind farms and transport the energy onshore, the use of subsea power cables is required. However, the currents passing through these cables create electric and magnetic fields, potentially affecting marine life.

Rijkswaterstaat has therefore requested Witteveen+Bos to provide an overview of the state of knowledge on this topic, to model the existing anthropogenic EMF levels in the North Sea, and to provide advice on if and how to implement EMF in the MSFD. Especially considering the speed of development of offshore wind, in combination with potential cumulative effects species occurring in the North Sea, it is important to quickly gain more knowledge about the potential effects of anthropogenic EMF on the marine environment.

Since this is a relatively new field of research, not much is known about the impact of EMF on marine fauna. It is known that a broad range of marine species use the Earth's magnetic field for orientation and migration, having an "internal compass" or even a "magnetic map". In addition, elasmobranchs (sharks and rays) are known to be sensitive to electric cues, for finding prey and conspecifics (potential mates). In this literature review, all relevant scientific literature on (the impact of) electromagnetic fields on different species groups occurring in the North Sea is collected, summarized and clarified in the light of the MSFD goals.

1.2 Goal

This report aims to [1] provide insight into the current status of the knowledge on electromagnetic fields and the potential impacts on the marine environment, [2] assess the current state of EMF in the Dutch North Sea, in order to [3] advise on implementation of EMF in Descriptor 11 of the Dutch Marine Strategy Framework Directive.

1.3 Process and methods

1.3.1 Literature review

The search for literature in this review is constructed using the snowballing-method. The starting point when using this method is collecting a handful of key references: high-ranking, elaborate review papers and reports [lit. 2]–[lit. 5]. From there, the literature to which these key references referred ("who was cited") and the literature referring to these key references ('by whom was it cited') are retrieved. As such, both backward and forward "snowballing" is conducted. Papers are first included or excluded based on titles, abstracts, publication venues (congresses) and authors, then the final inclusion/exclusion is based on the full paper [lit. 6]. For additional verification, the relevance of these citations is checked using the search engine in Scopus. The snowballing loop is ended when either no new literature is found, or after a certain amount of hours spent per species group.

Then, the berry-picking approach is used for further identification of qualitative research reports [lit. 7]. The berry-picking approach is focused on including relevant references that were left out the more structured snow-balling technique. By browsing the Knowledge Base Thethys, aimed at knowledge on offshore wind impact, additional research papers or "grey-literature" (meaning papers or reports that are not peer reviewed, and might have another origin then scientific study) are selected. This way, any potential 'bubble-effect' the snowballing-method might have is balanced by the new information the berry-picking approach yields.

Lastly, through a systematic literature review on Scopus using pre-defined search queries any literature overlooked is implemented in the review. Combining these three methods allows for a robust and traceable way of data collection, all of the included references are listed in Chapter 7.

1.4 Reading guide

Chapter 3 presents an extensive literature review on several subtopics regarding electromagnetic fields in the marine environment: the technical aspects of EMFs, potential impact on different species groups, and specific information on species in the North Sea. Chapter 4 then focusses on the EMFs resulting from subsea power cables on the Dutch continental shelf, using model calculations and field measurements. This results in possible impact zones around the cables. In Chapter 5, policy steps are discussed based on the Marine Strategy Framework Directive, the Good Environmental Status and monitoring and impact reducing measures. In addition, the most recent research and ongoing research is presented here leading to a research strategy. Chapter 6 states the recommendations for the implementation of EMF into the MSFD.

2

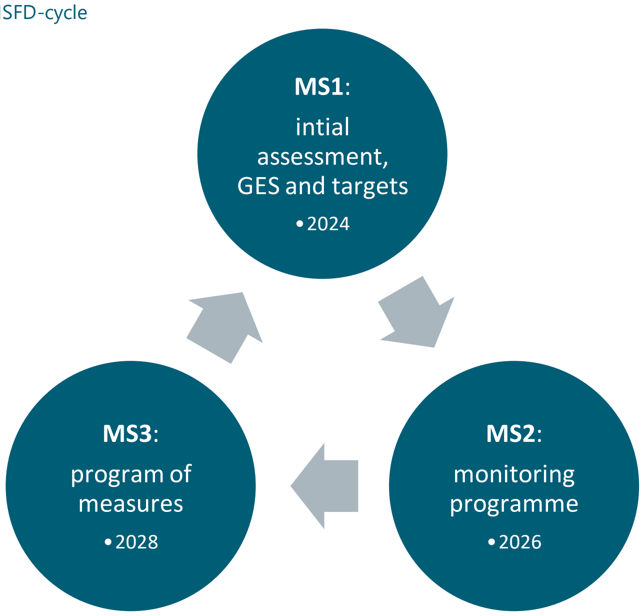
THE MARINE STRATEGY FRAMEWORK DIRECTIVE

Within the Marine Strategy Framework Directive (MSFD), electromagnetic fields fall under Descriptor 11 (the introduction of energy into the marine environment). Within this descriptor, there has mostly been a focus on underwater noise. As such, the implementation of noise into the MSFD can provide a useful framework for implementing EMF into the same framework. Therefore this chapter will briefly discuss the MSFD in relation to underwater noise.

2.1 The implementation of noise into the MSFD

The implementation of underwater noise (divided in continuous noise and impulsive noise) into the MSFD has followed 6-year cycles, divided in periods of two years: Marine Strategy Part 1 (MS1), Part 2 (MS2) and Part 3 (MS3). In short, MS1 includes the initial assessment of the current environmental status in the light of Descriptor 11, and an overview of the Good Environmental Status that should be achieved with accompanying targets and indicators. MS2 consists of the monitoring programme, and in MS3 a program of measures is defined. The results from the monitoring programme in turn provide input for assessing the environmental status, assessing the progress that has or has not been made, and assessing the effectiveness of measures [lit. 8]. This cycle is summarized in figure 2.1.

Figure 2.1 The summarized MSFD-cycle



2.1.1 Initial assessment and Good Environmental Status (MS1)

Making an initial assessment of the state of the marine environment can be done using a habitat-oriented and/or a species-oriented approach. With a habitat-oriented approach, the area affected by the stressor (in this case, noise) is assessed in space and time. With a species-oriented approach, it is assessed which percentage of a certain species population is affected by the stressor. In either case, in order to do this, representative or indicator species must be selected which are or could be negatively impacted.

Indicator species can be selected based on several factors, such as representative response to the stressor, a known sensitivity in combination with an population (already) under stress, or because of the simple reason that there is data available. In the case of impulsive noise, the following aspects were considered when choosing an indicator species [lit. 9]:

1. **hearing sensitivity;**
2. **vulnerability to sound;**
3. **data availability;**
4. **sensitive time period;**
5. **compatibility with assessment under other MSFD descriptors;**
6. **threat status.**

Based on these factors, in the North Sea the harbour porpoise *(Phocoena phocoena)* is considered suitable for the assessment of underwater noise [lit. 10]. In the case of continuous noise, similar aspects were proposed to be taken into account for selecting an indicator species, slightly more detailed than for impulsive sound [lit. 8]:

1. **documented sensitivity to the stressor, either in scientific literature or expert judgement;**
2. **data availability;**
3. **whether species are listed as protected in any (international) convention/agreement/legal instrument, like the IUCN Red List;**
4. **whether species are listed as protected under the Habitats Directive - also since it is likely there will be data available;**
5. **whether species are listed in the Joint Research Centre reference list of marine species and habitats with relevance to the MSFD;**
6. **special characteristics or considerations, like commercial value, maintaining biodiversity, or concern to the public;**
7. **whether species supply vital ecosystem services like nutrient cycling or water filtration.**

An indicator species has not been selected yet for continuous noise - the harbour porpoise and Atlantic cod are currently being considered.

When relevant species and/or habitats are decided upon, the next step is to establish threshold values. Below these threshold values, there is no significant biological effect of underwater noise on the chosen species in a certain area.[1] This is called the LOSE: Level for Onset of Biologically Significant Adverse Effects [lit. 8]. For the impact of impulsive noise on the harbour porpoise, these are defined in decibel (dB re 1 μPa). The duration of the exposure is expressed in pulse-block-days (PBD's, based on the activities in a certain area) and on models, resulting in *porpoise disturbance days*: the number of days harbour porpoises are disturbed by impulsive underwater noise.

[1] In the MSFD context, the Dutch North Sea is divided into grid cells. Then, it is decided whether a grid cell is significantly affected by anthropogenic noise or not.

For continuous noise, the LOSE is expressed in Excess Level: the sound pressure level in excess of the background sound pressure level. A measure for the duration is the Dominance (JOMOPANS[1]), which gives the percentage of time the Excess Level exceed LOSE. For the North Sea, the LOSE is chosen to be 20 dB.

2.1.2 Monitoring (MS2)

Monitoring is an important part of the MSFD-cycle, since data collection provides knowledge for the environmental assessment and an indication whether impact reducing measures work. Monitoring underwater noise is now mostly done using acoustic modelling, (in combination with) Passive Acoustic Monitoring (PAM), tagging of marine mammals, and/or using drones or cameras [lit. 11]. This, compared with improved modelling techniques, provides valuable information about for instance the effects and magnitude of pile-driving noise, shipping lanes, and seismic surveys. This way, the size of the disturbed area can be predicted and risks can be assessed for the indicator species.

2.1.3 Program of measures (MS3)

The potential negative impact of underwater noise is quite linear: higher levels usually mean a greater negative impact. These impacts range from masking, to disturbance, to temporal hearing loss, to permanent hearing loss, to even immediate death. Measures can therefore focus solely on noise reduction: lower noise levels equal less impact. For instance, several measures are now being developed to mitigate the impulsive noise of pile-driving, through the development of innovative piling techniques [lit. 12], [lit. 11]. It is the role of the government to set limits to the amount of noise that is allowed. The industry is then challenged to develop techniques to meet the limits. Measures that can be taken by the government could be 'silent areas' or speed reductions. Incentives for shipping industry can also be developed.

2.2 Timeline

The first initial assessment of the Dutch part of the North Sea was made in 2012, after which the monitoring programme and program of measures followed in 2014 and 2016. In 2018, the second MSFD-cycle started with MS1 - a new environmental assessment was made using the latest knowledge and experience from the first cycle. Now, the threshold values were included. In 2023, after completion of the second cycle, the process and the findings around the Descriptor 11-implementation will again be evaluated and revised. In 2023 the European Commission will review the MSFD, and probably the MSFD will be adapted based on the findings.

The third MSFD-cycle will start in 2024. In the 2026 monitoring programme, EMF-monitoring can be included within Descriptor 11. Then, in 2028, a program of impact reducing measures can be implemented if deemed necessary. Finally, in 2030, the defined GES can include EMF as another form of energy input into the marine environment. In order to achieve this, first the current state of knowledge around EMF needs to be assessed which is conducted in chapter 3.

[1] Kinneging, N.A. and Tougaard, J. (2021) Assessment North Sea. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (Jomopans), February 2021.

3

STATE OF KNOWLEDGE ON THE EFFECTS OF ELECTROMAGNETIC FIELDS

3.1 Introduction

To adequately address the potential impacts of electromagnetic fields (EMF) on the marine environment, it is necessary to understand the technical aspects. These include the different characteristics of electric fields (E), induced electric fields (iE) and magnetic fields (B); the differences between alternating and direct currents (AC/DC); the impact of cable design; used measures and units; and naturally occurring electric and magnetic fields in the marine environment. After this technical summary, the potential impact of EMF on North Sea species is discussed in the second part of this chapter.

Table 3.1 Measurements and units relevant for the technical aspects of EMF

Measurement	Abbreviation	Unit	Details
magnetic field	B-field	T (tesla)	earth's magnetic field: between 30 and 70 μT, comprises of an x, y and z direction
electric field	E-field	V/m (volts/meter)	often more relevant is the nV/cm or μV/cm range
induced electric field	iE-field	V/m (volts/meter)	often more relevant is the nV/cm or μV/cm range
frequency	f	Hz (1/s)	direct current: 0 Hz
			alternating current (Europe): 50 Hz

3.2 Electromagnetic fields

Both electric and magnetic fields occur naturally in the marine environment. The most important natural magnetic field is the Earth's magnetic field, which has field strengths varying between 30 - 70 μT. In the Dutch North Sea, the field strengths are roughly 50 μT [lit. 13]. On average, this results in a latitudinal change between 2 and 5 nT per kilometre [lit. 14]. This magnetic field is more or less static and has a frequency of roughly 0 Hz. The field strengths vary slightly locally due to changes in the magnetic elements in the liquid layer of the earth's crust.

Through interplay between the rotation of the Earth and its magnetic field (B-field), the conductivity of seawater, and motion caused by currents and tides, induced electrical fields (iE-fields) are created [lit. 15]. Depending on the geographical location and surroundings, these fields are in the 5-500 nV/cm range. Following the same principles, iE-fields are created when there is movement through the B-field, for instance caused by animal movements. On top of that, every living organism emits a very small bio-electric field itself, caused by electrically charged atoms in cells and tissues. The specifics of these bio-electric fields are poorly understood, yet it is known that some marine predators can sense these bio-electric fields, which helps them find their prey [lit. 16]. This electrosensitivity is further discussed in paragraph 2.2.

Besides the natural electric and magnetic fields, human activities are an additional source of E-fields and B-fields in the marine environment. When electricity is transported through power transmission cables, electric and magnetic fields are created. The primary electric field caused by this electricity transport is usually not emitted into the marine environment, because cables are insulated with cable protection materials. The magnetic field does protrude into the marine environment.

Power transmission cables used in offshore environments can transport electricity either with an alternating current (AC) or a direct current (DC). The magnetic field created by DC cables is, like the current, static. It does not change direction and it stays in the same position. AC currents on the other hand create weaker (although not per definition smaller) magnetic fields than DC currents. These magnetic fields have a frequency, and they do change direction. This rotating B-field causes the induction of another iE-field in the marine environment, besides the E-field created by the power cable itself. AC-cables thus create an electrical as well as a magnetic field, an iE-field caused by the rotating magnetic field, and an iE-field when there is movement through the magnetic field. Thus, the total electromagnetic field (EMF) on a certain location is composed of multiple electric and magnetic components.

Besides the power system (alternating or direct), another aspect of cable design is the difference between three-core or three-phase design (HVAC) and bundled or separated cables (HVDC). Bundled (bipolar) DC cables bundle the two cores (with positive and negative voltage) into one armoured cable. This minimizes the total emitted B-field, because the two magnetic fields partly cancel each other out [lit. 17]. When the cables are not bundled, a lesser (or no) degree of cancelation takes place and the overall emitted B-field is larger. For subsea alternating currents, the use of a three-phase cable is common. The magnetic field emitted by these three-core AC cables can be reduced by helically twisting the cables, also causing a degree of cancellation of the rotating B-field [lit. 18],[lit. 2]. If the three phases are slightly out of phase the B-field can increase. The distance of the cores in relation to each other has an impact of the B-field emitted. The larger the distance, the higher the B-field.

Within wind farms, often AC cables are used since they are more (commercially) beneficial to transmit power over distances <50 km. These cables are referred to as infield cables. For longer distances, either HVAC (high voltage alternating current) or HVDC (high voltage direct current) cables are used, to be converted back again to AC one arrived onshore [lit. 19]. Future wind farms in the North Sea, located further offshore than most existing wind farms, are likely to mainly use HVDC cables. The same applies to the power cables connecting the Netherlands with other countries, such as Norway and the United Kingdom, named interconnector cables. As such, several types of EMF can be found in the North Sea.

The degree of EMF emission into the marine environment lastly depends on burial depth of the subsea cables. Often, the minimum burial depth of subsea cables is one meter - as is required in the Netherlands by the Water Act [lit. 20]. As a result, the magnitude of the EMF emitted to the water column and to the surface of the seabed, which is further discussed in chapter 3, decreases [lit. 17]. Important to note is that this does not necessarily mean that the potential effect of the emitted EMF also decreases, because some marine animals can sense the smallest anomalies in EMF. This is further discussed in paragraph 3.3.

Even if offshore wind turbines (or other offshore energy installations) are turned off, a deviation from the Earth's magnetic field can be observed around the cable. This is caused by the anomalies in EMF created by the metal cables themselves, even when there is no current running through the cables. In addition, a small base current (or maintenance current) directed offshore, is always present in power cables. In [lit. 2] for instance, this base current was 16 A for a DC cable, resulting in maximum magnetic field strengths of ~0.4 μT. However, in [lit. 21] no B-fields and E-fields were recorded around an unenergized cable.

The intensity of the total EMF at a certain location thus depends on the power system (AC/DC), the power that is transported through the cables, cable characteristics and design, burial depth, environmental factors (currents, movements) and the Earth's magnetic field strength in that particular place. Therefore, the emitted EMF along a cable transect can be highly variable. To properly assess the potential impact of EMF one should consider these variables combined with species distribution, to properly calculate the likelihood of encountering EMF and possible effects (on population level) [lit. 15]. Chapter 4 further elaborates on these aspects affecting EMF emissions.

3.3 Impact on species

In this review, the potential impact of EMF on North Sea species is discussed for marine mammals, fish, and invertebrates. Both between and within these groups, there are large differences in sensitivity to electric and magnetic fields. Research to the potential impacts of EMF is limited and focuses on 1) impacts on survival, 2) physiological impacts (like effects on oxygen consumption rates or cell division), 3) behavioural impacts (such as attraction or repulsion), and 4) embryonic development. If the amount of research conducted to North Sea species is limited for certain taxonomic groups, existing research to close relatives (occurring elsewhere) is discussed.

If species use the Earth's magnetic field for orientation, this means that they can sense small anomalies in magnetic field strengths, in the order of nT. Magnetic fields emitted by cables are usually in the order of µT. The same applies to species that use their electrosensitivity for hunting prey - these species are sensitive to anomalies in µV/cm and in the ~10 Hz-range [lit. 14]. Important to keep in mind is that not all studies investigating the potential effects of EMF on marine species focus on realistic EMF-values, and due to high costs and complicated logistics, the amount of field research is limited.

3.3.1 Sea mammals

Seals

Pinnipeds, like the harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*) are not known to be electro- or magneto-sensitive [lit. 11], [lit. 22]. They do not have electroreceptors, and the Earth's magnetic field does not seem to play any role in orientation and navigation [lit. 23]. Therefore it is likely that there is no significant effect of EMF on this species group.

Porpoises

It is thought that cetaceans are magneto-sensitive, and use the Earth's magnetic field for orientation and navigation. This assumption is largely based on the location and occurrence of whale strandings [lit. 24]–[lit. 26], which are correlated with areas showing a low intensity of the geomagnetic field. There is, additionally, some experimental evidence for electroreception in the bottlenose dolphin (*Tursiops truncates*) [lit. 27] and in a species not occurring in the North Sea, the Guiana dolphin (*Sotalia guinaensis*) [lit. 28], [lit. 29]. These species respond to electric field stimuli, with detection thresholds in the µV-range. The potential electro- or magnetosensitivity of porpoises (*Phocoena phocoena*), the most abundant cetacean in the Dutch North Sea [lit. 30], has not been studied specifically and hearing is considered the most important sense for this species [lit. 31]. So far, impacts of EMF on cetaceans have not been observed and are considered unlikely (personal communication dr. S. C. V. Geelhoed, Wageningen Marine Research).

3.3.2 Fish

Most studies to the potential effect of EMF on marine species has been focused on fish, especially chondrichthyans, because of their known electro-sensitivity [lit. 32], [lit. 33]. Within the chondrichthyans, the most relevant group in the North Sea are the elasmobranchs: sharks and rays. Secondly, diadrome fish have been a topic of interest. These fish use their magneto-sensitivity to successfully migrate between fresh and salt water over large distances. This magneto-sensitivity can already visible in early embryonic stages of development [lit. 34].

Elasmobranchs

Elasmobranchs are electroreceptive, meaning they can detect (i)E-fields [lit. 33]. Several species also seem to use the Earth's magnetic field for navigation [lit. 35], and to respond to magnetic stimuli [lit. 32]. Because of this, this species group (which includes sharks, and rays) is currently considered most susceptible to the potential effects of EMF. These species are expected to be able to sense changes in electric fields of 0.005 µV/cm, and changes in magnetic fields from 0.002-0.005 µT [lit. 14].

High electric field levels, in the order of magnitude of several V/m, have been used as a shark deterrent to protect people and marine equipment from shark attacks. These strong fields are generally successful at keeping sharks at larger distances [lit. 36] (in a way, the same applies to strong EMF generators used for minimizing the thickness of biofilm growing on offshore structures [lit. 37]). Similarly, strong magnets (in the order of tens-hundreds of mT) seem successful in repelling elasmobranchs [lit. 38]. Low field strengths do not have this effect. On the contrary, research suggest that EMF in the order of magnitude found around offshore power cables can cause forms of attraction and increased foraging behaviour in elasmobranchs.

Although there is limited research to elasmobranchs that occur in the North Sea, research to the closely related little skate *(Leucoraja erinacea,* 39 individuals*)* showed attraction, increased overall activity and increased foraging behaviour when exposed to EMF from HVDC cables [lit. 39]. In this field experiment, the skates travelled larger distances, and the results suggest these species rest less when exposed to this kind of EMF. Whether these behavioural changes have impacts on population levels, is unknown.

Previous mesocosm-research to the thornback ray *(Raya clavata)* conducted around a 50 Hz AC cable, did not find a predictable effect of EMF on thornback ray behaviour, although the distance travelled was not measured [lit. 21]. In that same experiment, the effects on the small-spotted catshark *(Scyliorhinus canicular)* and the spiny dogfish *(Squalus acanthias)* were studied. These species, like the thornback ray, are found in the North Sea. Although some of the individuals analysed in this study did seem to respond to EMF, there was no consistent pattern or trend found in their behaviour [lit. 21]. Research on juveniles of the thornback ray did find an increase in active behaviour when exposed to a 450 µT AC (50 Hz) or DC field, although only during midday and not in the morning [lit. 40]. The studies to date do not show an direct impacts on physiology or survival but indicate (subtle) behavioural changes.

It has also been suggested that elasmobranchs can learn and habituate when their foraging response to anthropogenic E-fields is not rewarded [lit. 41]. In their natural habitats, they also seem to learn to ignore non-profitable stimuli, like they ignore hard-to-catch prey [lit. 42]. However, due to the large differences in current strengths, amount of cables, burial depth and other variables, in practice habituation is deemed unlikely [lit. 17].

Diadrome fish

Diadrome fish, like salmonids, eels and sturgeons, use (among other environmental cues) the Earth's magnetic field to successfully migrate between spawning and feeding grounds [lit. 43]. As such, these species can sense small differences in magnetic field strengths, suggesting they could be affected by anthropogenic EMF. Field research to the Chinook salmon (*Oncorhynchus tshawytscha*) after installation of a 200 kV HVDC subsea cable in the San Francisco Bay, did not find an effect of EMF on the successfulness of migration through the bay [lit. 44]. Fish did cross the energized cable slightly more often than the non-energized cable. Both some level of attraction as well as repulsion was observed, leading to slight misdirection. However, environmental factors such as temperature, discharge and currents had more influence on transit times through the bay [lit. 44].

Another salmonid, the rainbow trout *(Oncorhynchus mykiss*, larvae) showed no signs of stress when exposed to a 10 mT DC or 1 mT AC field (50 Hz) in laboratory conditions [lit. 45]. These field strengths also did not affect survival or growth of rainbow trout larvae [lit. 46]. The authors did suggest EMF might perhaps affect feeding behaviour in early live stages. In a different study to rainbow trout larvae, toxicity on cellular level (irregularity and deformation) was observed after a 40-day exposure period to this 1 mT 50 Hz EMF [lit. 47]. In addition, exposure to a static 10 mT field led to relatively more asymmetrical development of the inner ear bone - exposure to a 50 Hz 1 mT field did not have a significant effect [lit. 48]. Whether these effects have significant consequences for survival is unknown. Although the rainbow trout does not occur in the North Sea, these results could indicate the potential effects of EMF on salmonoids in general.

The European eel *(Anguilla anguilla)* shows migratory behaviour from the Sargasso Sea to coastal and freshwater habitats in Europe and Africa. While the magneto-sensitivity of European eels was already known [lit. 49], latest findings suggest magnetic map orientation of the European eel to the Gulf Stream System [lit. 50], and thus the ability to sense small changes in the Earth's magnetic field. In the Baltic Sea, tagged eels showed a temporary decrease in swimming speed around a 130 kV AC cable, about which the underlying mechanisms are unknown [lit. 51]. This had no effect on total migration, and there are no indications this temporary decrease has significant effects on migration success of the European eel, especially considering the large distances these species travel [lit. 51]. Field research along an offshore cable trace in Denmark also did not find any indication the emitted EMF had effect on the (migratory) behaviour of eel, drawing similar conclusions [lit. 52]. Correspondingly, eels did not display differences in movement or swimming activity when exposed to a 9.6 μT 50 Hz AC field in laboratory settings [lit. 53].

Other fish

Larvae of the lesser sandeel *(Ammodytes marinus)*, an important food source for seabirds and marine mammals*)* are thought to be neither attracted nor repulsed by EMF from HVDC cables [lit. 54]. In this research, larvae from the Norwegian North Sea were exposed to magnetic fields in the 50-150 μT range, which had no effect on survival, swimming direction or spatial distribution.

In addition, sea lampreys (*Petromyzon marinus)* and perhaps lampreys in general are thought to be electro-sensitive [lit. 55], [lit. 3]. Whether there is any effect of subsea power cables on these species is unknown.

Lastly, flatfish might be exposed to EMF in the North Sea disproportionally. Since they are bottom-dwelling species, they naturally habit close to the (buried) offshore cables. It is hypothesized that plaice might be able to sense the Earth's magnetic or associated electric fields, because of their orientation skills [lit. 56]. In addition, a study found a significant difference in the number of European flounder (*Platichthys flesus*) that migrate over a cable emitting a small versus a large electromagnetic field [lit. 52]. During low levels of EMF (lower than 50 MW, since direct EMF measures were not available) flounders passed the cable more often than during high EMF-levels. Lastly, in a toxicity study where flounders were exposed to a 3.7 mT field (DC) for a period of 7 weeks, no difference in mortality was observed [lit. 57].

So far, the effects of EMF emitted by offshore cables on fish, vary between species groups. Elasmobranchs mostly seem to show potential changes in behaviour, in the form of increased activity or foraging behaviour. No significant negative effect on survival, embryonic development or physiological processes has been observed. For diadrome fish, embryonic development has been studied more extensively. Although no effect on survival and only minimal effects on behaviour have been observed, effects on early development cannot be ruled out. Other species groups might be able to detect EMF, but effects on survival, physiological processes, behaviour or embryonic development are either unknown, or in de case of the lesser sandeel and flounder, limited.

3.3.3 Invertebrates

Most research to invertebrates focusses on the ability of species to orient themselves using the Earth's magnetic field, thereby presenting magneto-sensitivity [lit. 58]. While salmonids and turtles can navigate specifically towards their goals using their magneto-sensitivity (magnetic map species), amphipods and isopods mainly seem to have a polarity compass. This means they have the ability to sense where the magnetic north and south is, but do not have the ability to orient towards exact locations.

The impact of anthropogenic magnetic fields and possible electro-sensitivity is not well known, and few studies have been conducted to this topic. So far, electroreception with specialized receptor cells has only been observed in vertebrates [lit. 59]. Direct effects of EMF on survival rates of invertebrates have not been found. In [lit. 58], the studies (conducted before 2021) investigating the effects of EMF on invertebrates are summarized. These effects range from small behavioural changes to effects on embryonic development.

Crustaceans

Research to the effects of EMF on marine crustaceans has been conducted on shrimps [lit. 60], isopods [lit. 60], crabs [lit. 60]–[lit. 62], lobsters [lit. 63], [lit. 64] and crayfish [lit. 65].

Field experiments on spiny lobsters (occurring in the Mediterranean and other warmer waters) have shown that these species navigate using the Earth's magnetic field [lit. 66]. By using this cue on top of other sensory stimuli, these species can migrate successfully, even when other environmental cues are lacking. Whether the EMF associated with subsea cables affects this ability is not known. In one study investigating the effects of a very strong 703 mT DC field on spiny lobsters, repulsion was observed [lit. 63].

For lobsters such as the American lobster (*Homarus americanus*) magneto-sensitivity has not been scientifically proven, but is deemed possible because of their (migratory) behaviour [lit. 39], [lit. 67]. Exposed to EMF from a HVDC cable, American lobsters showed slight changes in behaviour, and showed relatively more exploration of the sea bed [lit. 39]. This is one of the few studies in which sensitivity to EMF is studied in field, with real EMF values (with measured maxima of 14 µT). Recent research to larval development of the European lobster (*Homarus fammarus,* occurring in the North Sea) showed a significant decrease in larvae size when they were exposed to 2.8 mT EMF (DC) through embryonic development [lit. 68]. In addition, exposed larvae showed relatively more deformations and decreased swimming ability.

A similar decrease in larvae size was seen in the edible crab larvae (*Cancer pagarus*), a common North Sea species, exposed to the same 2.8 mT (DC). The same species, adult edible crab, showed attraction to a 2.8 mT DC magnet-equipped shelter in previous research, compared to control shelter [lit. 61]. Lower field strengths (500 - 1000 µT) had the same effect, and attracted edible crabs at the expense of roaming behaviour [lit. 69]. In addition, physiological effects were observed in the form of signs of stress. EMF with field strengths of 250 µT did not have significant effects on behaviour or physiology. Field research around operational cables also showed that cables do not form a barrier or obstacle for the edible crab [lit. 70].

At the west coast of the United States, a field study to rock crabs (*Metacarcinus anthonyi* and *Cancer productus*) did not find any evidence for either attraction or repulsion by EMF. In this study, crabs were placed in cages close to an energized and a non-energized submarine cable. After 1 and 24 hours, their location in the cage relative to the cable was observed, to see whether attraction or repulsion occurred. No significant differences were found between the energized and the non-energized cable, concluding neither a positive or negative effect of EMF on these species [lit. 62].

Marine isopods (*Idotea baltica*) and crustaceans (such as the amphipods *Orchestia cavimana* and *Talirus* species) also have a magnetic compass, and are able to orient themselves using the Earth's magnetic field [lit. 71]. The North Sea prawn, an isopod, the round crab and common starfish did not show a response to a 2.8 mT DC magnetic field [lit. 61]. In a different study to the North Sea prawn (*Crangon crangon*), the round crab (*Rhithropanopeus harrisii*) and the isopod *Saduria entomon*, no effects on mortality were observed when exposed to an even higher DC field (3.7 mT) for 7 weeks [lit. 57].

Molluscs

The blue mussel *(Mytilus edulis)* is abundant on hard substrates in the North Sea. Recent research to the potential effect of EMF on feeding behaviour, suggests that filtration rates and valve activity are not affected by exposure to a 300 µT DC field [lit. 72]. In addition, no effects on mortality are observed when exposed to a 3.7 mT DC field for 7 weeks [lit. 57]. For another North Sea species, the Baltic clam *(Limecola balthica)* 12-day exposure to a 1 mT 50 Hz field lead to molecular irregularities on cell level (abnormal cell division) [lit. 47]. Potential effects on survival are unclear.

In one sea slug, the nudibranch *Tritonia tetraquetra* magneto-sensitivity has been researched, and their sensitivity is deemed likely [lit. 73], [lit. 74]. In another mollusc *(Onchidium struma),* exposure to a 100 µT 50 Hz EMF stimulated an immune response, perhaps with beneficial effects [lit. 75]. Again, whether this response affects survival or growth, or has significant consequences on population level, is unknown.

Other invertebrates

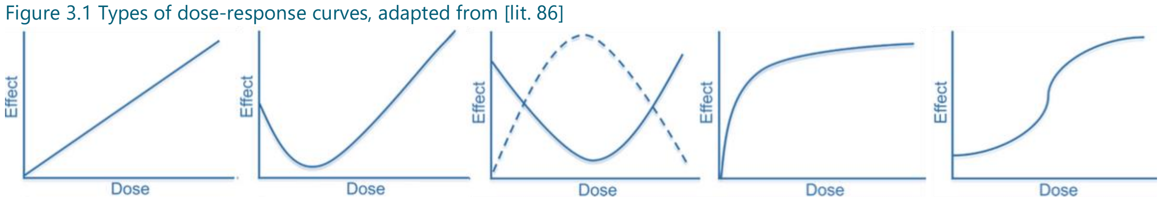
Lastly, the common ragworm (*Hediste diversicolor*) increased its sediment reworking activity when exposed to 1 mT, 50 Hz (AC) EMF [lit. 76]. Besides a slightly lower ammonia excretions, no other significant effects, like on food consumption and other physiological processes were observed - and neither avoidance nor attraction to the EMF was observed. Unlike the Baltic clam, the common ragworm did not show significant effects on (abnormal) cell division after 12-day exposure to a 1 mT 50 Hz field [lit. 47].

In short, exposure to EMF can attract crabs and lobsters, can cause exploratory behaviour to increase, and in this light, can increase stress in crustaceans. This effect seems to be very subtle, and so far no impact on survival has been observed. For crabs and lobsters, effects of EMF on embryonic development have not been researched with realistic EMF-values. On other invertebrates, such as molluscs, it seems effects on cell division cannot be ruled out. However, effects on behaviour and mortality have not been observed.

3.3.4 Discussion

Relatively few studies have been carried out in the field, addressing true field strength values in a relevant environment. This complicates extrapolating the impacts of EMF on individuals and/or species to potential impacts on population or ecosystem level. This is especially important since there are differences in responses to high and low field strengths - although high magnetic fields can work as a deterrent for some species, low field strengths could attract the same individuals. In addition, the effects are not universal and do not only vary between species, but also between individuals of the same species. Therefore, which type of response curve (as visualized in figure 3.1) is applicable to EMF impacts, is yet unknown.

Figure 3.1 Types of dose-response curves, adapted from [lit. 86]



If the spatial impact is rather limited and impacted animals are only displaced a small distance, the impact on the individual or population could be rather limited. If, on the other hand, species are attracted or confused and therefore fruitlessly spending energy that cannot be used for maintenance, growth or reproduction, the effects could be visible on population level.

Besides, in laboratory research to the larval stages of fish and crustaceans, so far the impacts of continuous exposure to EMF are addressed. At sea however, continuous exposure to EMF is unlikely. Currents can transport larvae of these species over large distances, in practice likely resulting in only brief exposure to EMF. Sessile species on the other hand, are more likely to be exposed to EMF continuously.

Another complication is that a lot of research does not include cable characteristics (type of cable, design, material used, burial depth) in their assessment, or makes an estimate about these characteristics. In order to make an adequate assessment and to determine potential dose-response relationships, these values need to be known. Overall, the studies to animal behaviour so far show large differences between individuals. This is an indication that the effects, if they are there, are subtle.

In addition, in field research distinguishing the effects of EMF (on marine organisms) from other effects of offshore cable installation remains a challenge. Other effects of cable installation are, for instance, heat emission in the surrounding sea water and the so-called 'reef effect' [lit. 77], [lit. 78]. If offshore cables have hard substrate cable protection, these hard substrates can be colonized by a variety of species, especially when there is high structural complexity [lit. 79], [lit. 80]. This way, there usually is higher food availability around cables compared to the surrounding, bare environment. This, in combination with the fact that offshore cables are usually accompanied with no-fishing zones (creating a 'reserve effect' [lit. 81]), can lead to an increase of benthic biomass and diversity, which potentially attracts associated predator species. In [lit. 82], for instance, higher species diversity and abundance was observed around power cables compared to the natural surrounding habitat, although no differences were observed between unenergized and energized cables. Although the other effects of cable installation are beyond the scope of this review, when addressing potential effects of EMF (and when conducting field research in areas with hard substrate cable protection) these processes should not be overlooked.

In this chapter, the potential effects of EMF on marine species, with a focus on species occurring in the North Sea, has been discussed based on recent field studies, laboratory experiments, and mesocosm research. This summary indicates which species, based on the available knowledge, are likely to be sensitive to the potential effects of EMF, and which species are less prone. In order to evaluate whether marine species in the North Sea will be affected by EMF in practice, it is necessary to explore which field strengths occur (and are likely to occur in the future), and where EMF are emitted into the marine environment. This is discussed in chapter 4.

4

ELECTROMAGNETIC FIELDS FROM SUBSEA POWER CABLES IN THE NORTH SEA

The previous chapter describes the studies conducted to the potential effect of EMF on marine species of the Dutch North Sea. In order to determine whether these potential impacts will come into effect, it is important to determine the magnitude of EMF emissions from subsea power cables in the North Sea. In addition, since the number of offshore wind facilities (and therefore, cables) will increase in the coming decades, it is important to start addressing potential (cumulative) effects resulting from large-scale offshore wind development.

Measuring magnetic fields can be done by using magnetometers. These devices can measure the total magnetic field at a certain location - natural and anthropogenic sources combined. Measuring electrical fields is, however, more complicated. Especially measuring very low induced electrical field values in the water column remains a technical challenge [lit. 83]. This is why many model calculations usually lack the necessary field verifications. In this chapter, model calculations - based on cables in the North Sea - are presented. In 4.2, these models are compared with field measurements, in order to calculate possible impact zones in 4.3.

4.1 Model calculations

4.1.1 Model description

The magnetic field levels (in μT) of subsea power cables located on the Dutch continental shelf were modelled using values and cable characteristics summarized in table 4.1. The model comprises 23 years, from the first cable installation in 2006 up to the planned cables until 2030, excluding the newly planned cable routes of the 'Aanvullende routekaart windenergie op zee 2030, kamerbrief d.d. 10 juni 2022'. The cable characteristics were obtained from publicly available documentation (voltage and power) and where lacking, assumptions were made (for instance for cable core separation).

Table 4.1 Cable characteristics of wind farms on the Dutch Continental Shelf

Wind farm	AC/DC	Purpose	Voltage (kV)	Power (MW)	Distance between conductors (m)	Modelled magnetic field range
OWEZ	AC	OWF export cable	34	36	0.060	0.0 - 1.8 μT
PAWP	AC	OWF export cable	150	120	0.078	0.1 - 5.2 μT
Luchterduinen	AC	OWF export cable	150	129	0.082	0.1 - 5.8 μT
Gemini	AC	OWF export cable	220	6,000	0.100	0.1 - 11.3μT
Borssele	AC	OWF export cable	220	700	0.106	0.1 - 13.9 μT
HK(z)	AC	OWF export cable	220	700	0.106	-
HK(n)	AC	OWF export cable	220	700	0.106	-
HK(w)	AC	OWF export cable	220	700	0.106	-

Wind farm	AC/DC	Purpose	Voltage (kV)	Power (MW)	Distance between conductors (m)	Modelled magnetic field range
TNW	AC	OWF export cable	220	700	0.106	-
IJver	DC	OWF export cable	525	2.000	0.200	1.2 - 122.7 μT
Norned	DC	Interconnector	450	700	0.13	0.3 - 32.7 μT
Britned	DC	Interconnector	450	1,000	0.119	0.4 - 42.8 μT
Cobra cable	DC	Interconnector	320	700	0.13	0.5 - 46.0 μT
Neuconnect	DC	Interconnector	525	1,400	0.13	0.6 - 58.9 μT
Vikinglink	DC	Interconnector	500	1,400	0.13	0.6 - 56.1 μT

Physical background model

The calculations presented here are carried out and visualized using a model developed based on the Biot-Savart law. The Biot-Savart law is expressed as follows:

$$\vec{\mathrm{B}}(\vec{r}) = \frac{\mu_0}{4\pi}\int_C I\frac{d\vec{l} \times \vec{r}}{\vec{r}^3}$$

The magnetic field ($\vec{\mathrm{B}}$) is dependent on the magnetic permeability (μ_0), the amount of current (I) that flows through the cable, the geometry or direction of the cable ($d\vec{l}$) and the distance to the point at which the magnetic field is computed ($d\vec{r}$). When the distance between the cable and the point at which the magnetic field is to be computed is much smaller than the cable length, then the above equation can be simplified to the following:

$$B(r) = \frac{\mu_0 I}{2\pi r}$$

The above equation shows that the magnetic field is directly proportional to current flowing through the cable and inverse proportional to the distance r. The above equation computes the magnetic field for a single cable. In case of DC and AC cables there are multiple cables with different phases that need to be accounted for. Using the method shown in [lit. 84] the total magnetic field at a certain point can be computed as a result of the different phases of the different cables.

4.1.2 Results

Magnetic field levels

The power that is transported through the cables varies almost constantly and is therefore difficult to present. In the Netherlands the minimal required burial depth is -1m, as described in the 'Water Act'. We have chosen to show the maximum levels under different circumstances (wind levels/power transported through the cable), as presented in figure 4.1. This figure shows the levels for OWF export cables as well as interconnector cables on the Dutch Continental Shelf (see figure 4.3 for a map). In practice, this includes wind farms that are currently either in the planning/construction phase or the operational phase. Of the AC connections OWEZ (Offshore Wind Farm Egmond aan Zee), PAWP (Princess Amalia Wind Farm), Luchterduinen, Gemini, and Borssele are all operational. HK(z) (Hollandse Kust Zuid), HK(n) (Hollandse Kust Noord), HK(w) (Hollandse Kust West) and TNW (Ten Noorden van de Wadden) are either under construction or planned and the magnetic field levels are likely comparable to the Borssele wind farm. For the DC connections, Norned, Birtned, the Cobra Cable, Nordlink, Neuconnect, Viking Link and IJmuiden Ver are in the planning phase (figure 4.2).

The figures show magnetic field strengths for the full capacity of the wind farm (maximal), average capacity for both summer and winter, and minimal capacity when there is no wind or when the park is undergoing maintenance. It is evident from the figure that the magnetic field levels have been steadily increasing over the last 23 years. This is mainly caused by the rate at which the magnitude and size of wind farms and turbines have been increasing in the last few years.

Figure 4.1 Minimal (no wind/maintenance), maximum and average summer and winter modelled magnetic field strengths from wind farm cables in the North Sea for alternating currents (AC)

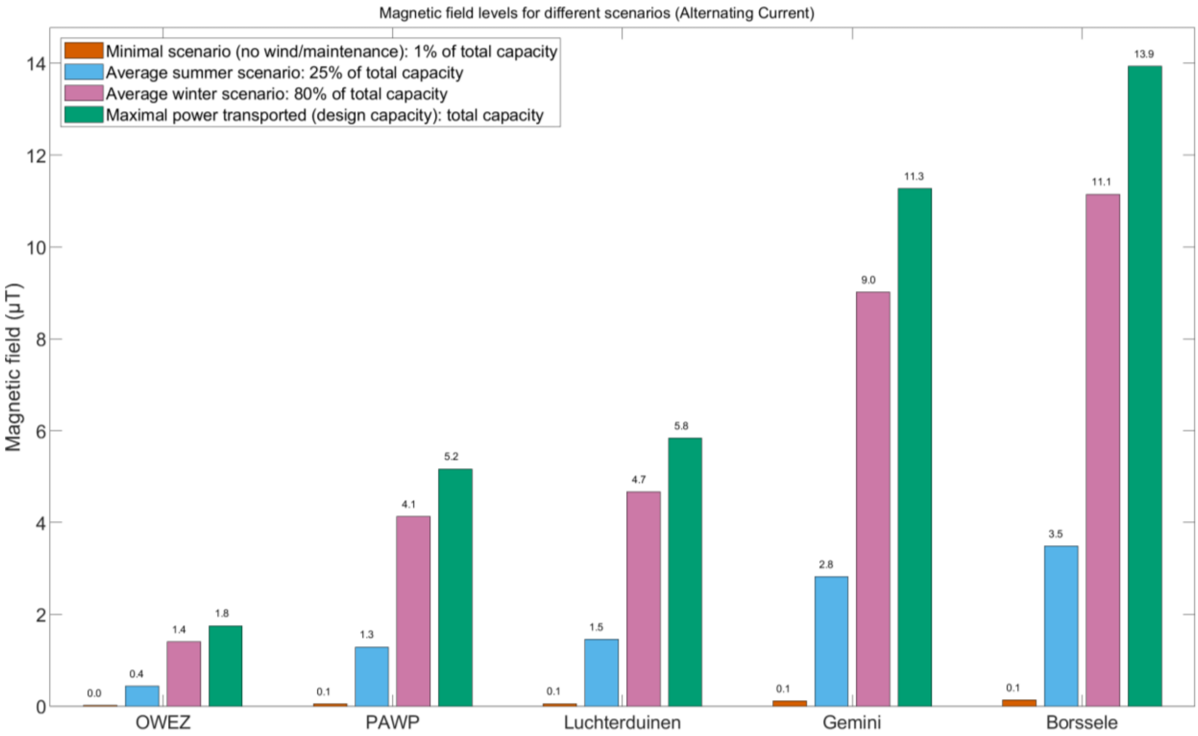
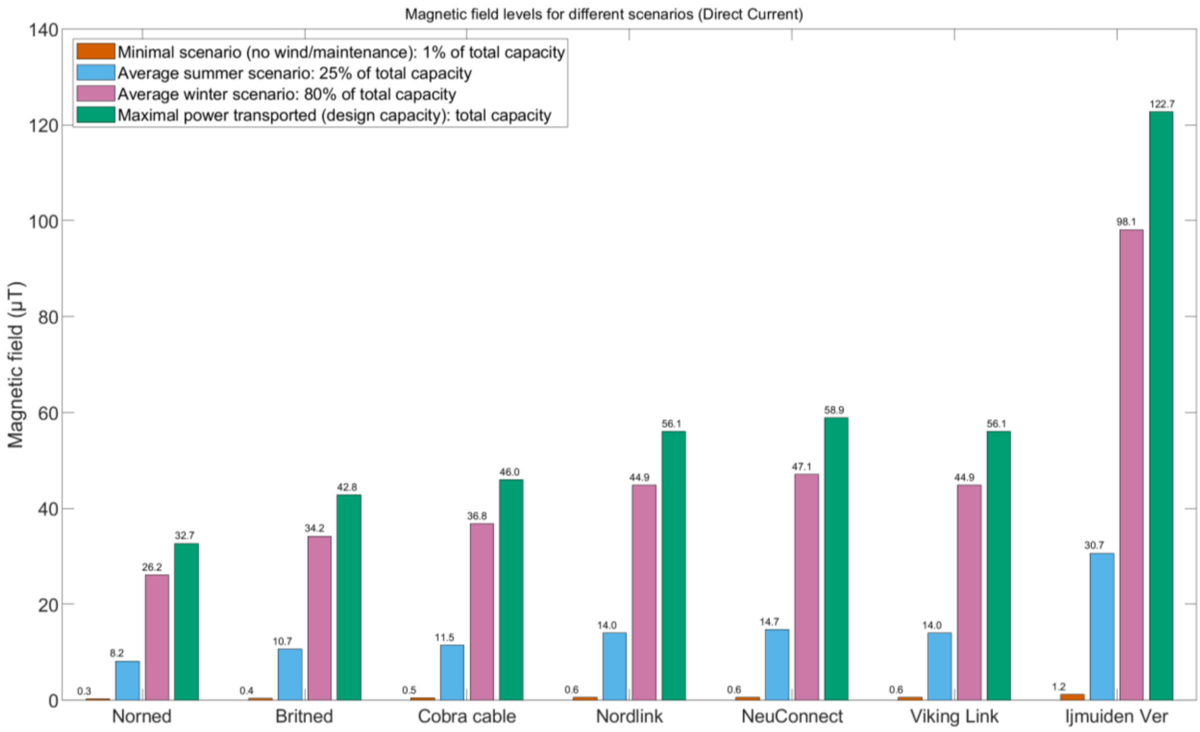


Figure 4.2 Minimal (no wind/maintenance), maximum and average summer and winter modelled magnetic field strengths from wind farm cables in the North Sea for direct currents (DC)

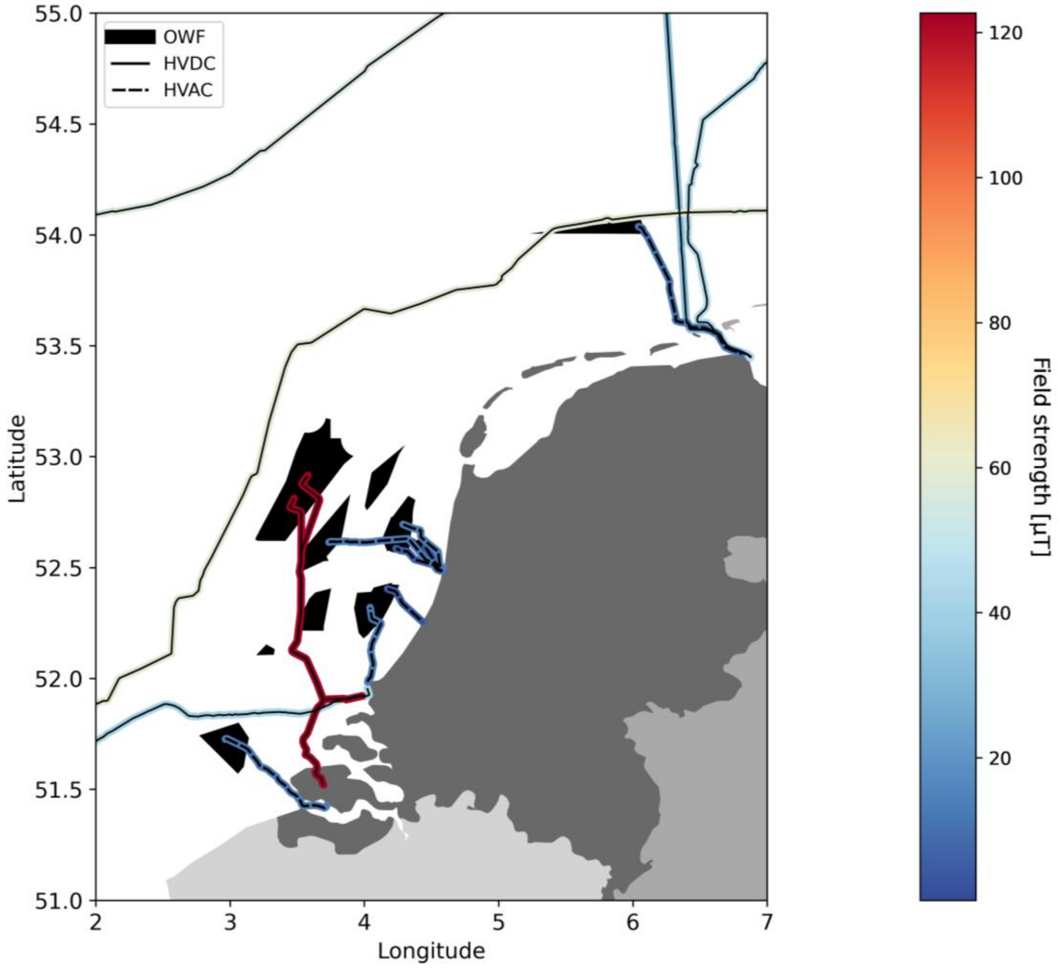


Magnetoscape

All of the offshore wind export and interconnector cables on the Dutch continental shelf are visualised in a map in Figure 4.3. The colourbar indicates the level of modelled magnetic field levels based on the maximum transport capacity scenario. The overview shows the landscape of anthropogenic magnetic fields, or the *magnetoscape* of the North Sea. Note that the cable thickness is not to scale, as the actual diameter of a three-phase AC cable is circa 30 cm.

The figure shows that species that migrate along the Dutch shore (from Zeeland to Germany) cross up to 13 cable systems. A cable system may include up to four cables spaced between 50 and 250 metres apart. The map shows that due to the length of the cables, as well as the size of the offshore wind farms, the areas with EMF-emissions from subsea power cables are difficult to avoid.

Figure 4.3 Wind farm locations and cable characteristics in the North Sea, with magnetic field strengths (DC and AC cables)



Radial dispersion

In order to assess the impact of EMF, it is important to not only understand the peak levels, but also the extent to which the EMF protrudes in the environment. In figure 4.4, the magnetic field strengths are modelled for the alternating current export cables, with the same scenarios as presented in Figure 4.1. The distance from the cable is visualized on the x-axis, and the field strength on the y-axis. Although the maximum height of the EMF differs between locations, the affected area around the cable remains relatively similar with different cable characteristics. This is due to the relatively quick attenuation of the magnetic field, because the magnetic fields caused by the different phases of the different cables partly cancel each other out. This phenomenon is further explained below. In figure 4.5, the magnetic field strengths are modelled for DC cables. For increased readability, the reader is referred to the digital version of this report.

Figure 4.4 Magnetic field strengths at varying distances from the cables, for AC cables in linear scale (above) and logarithmic scale (below)

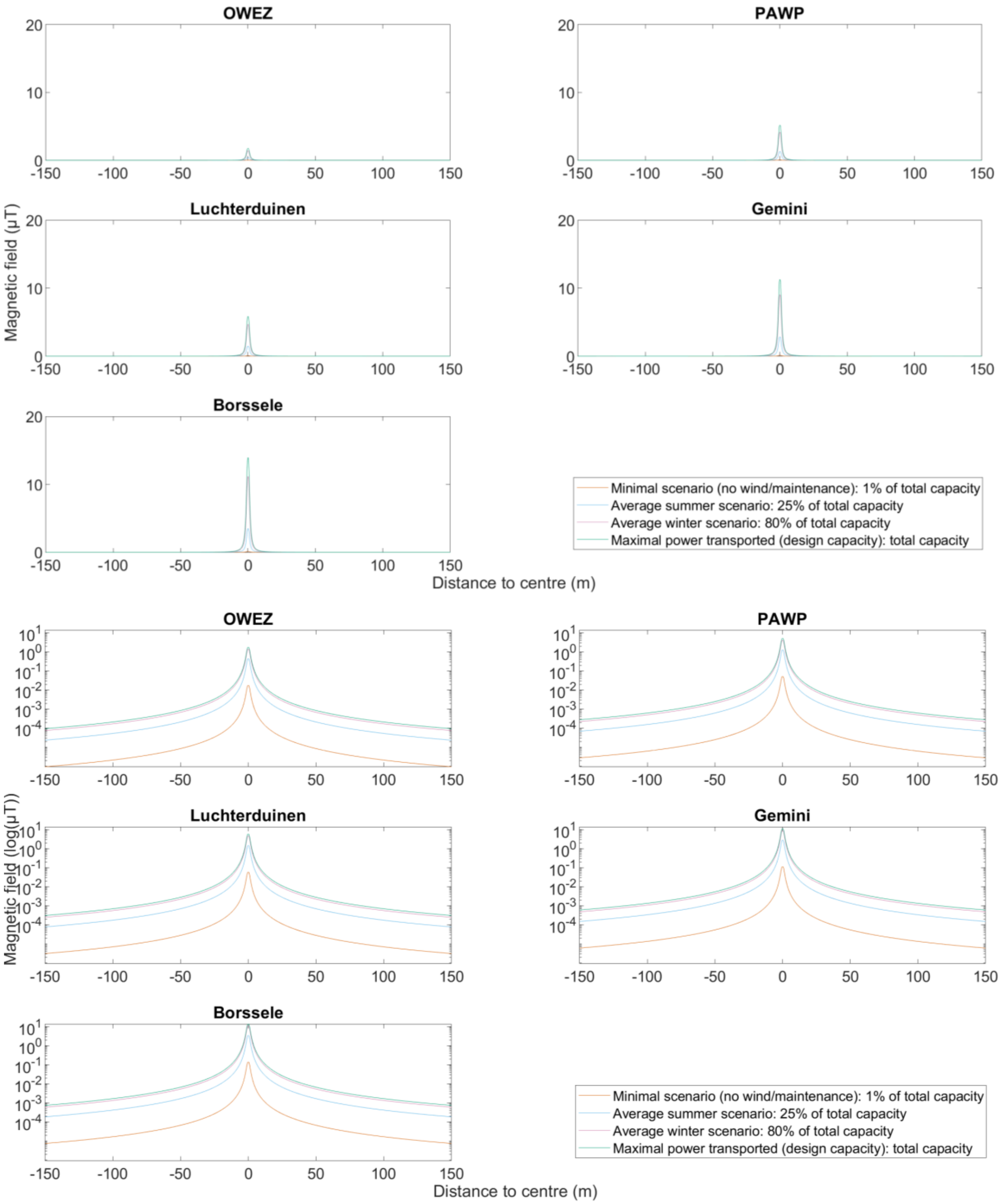
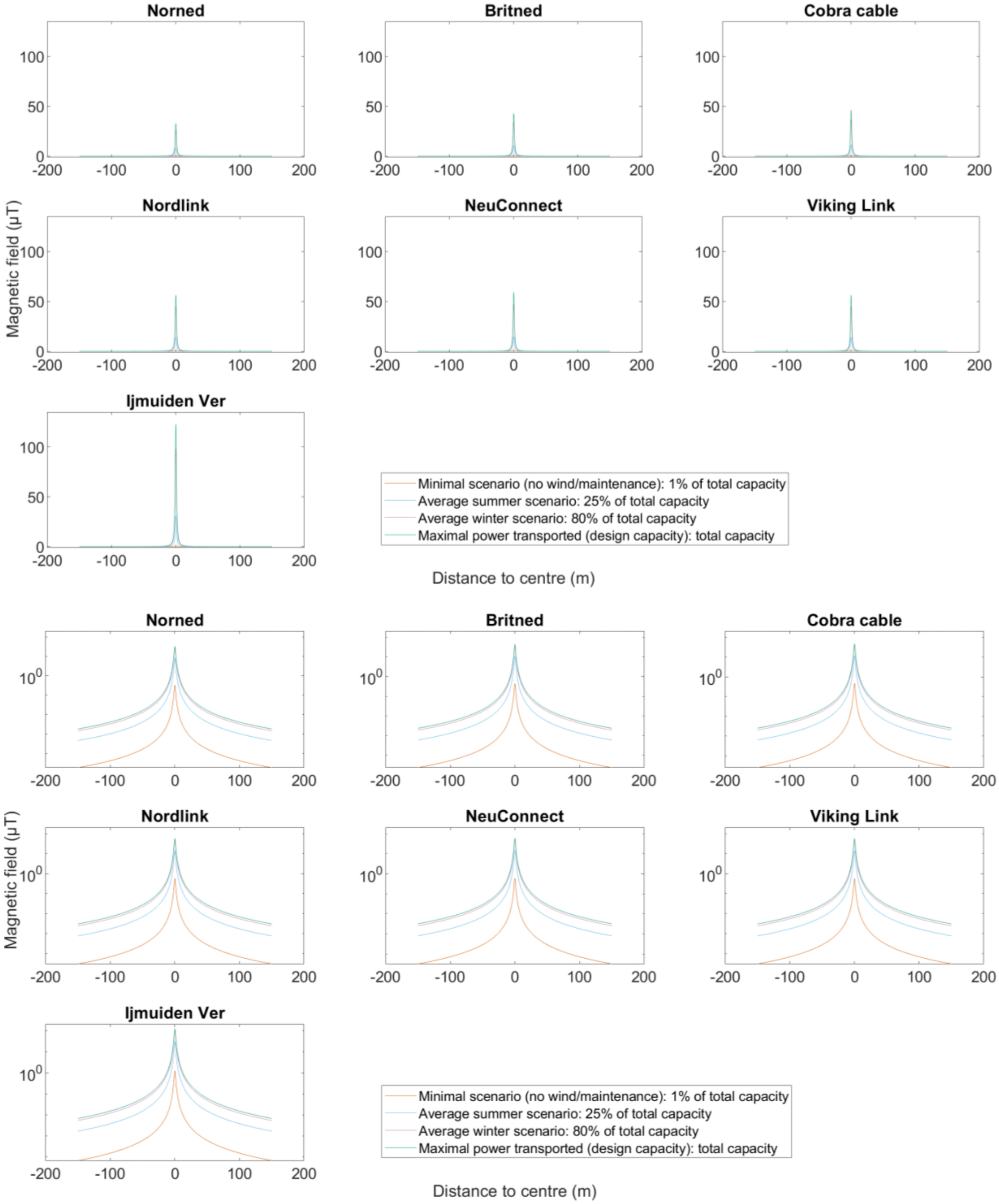


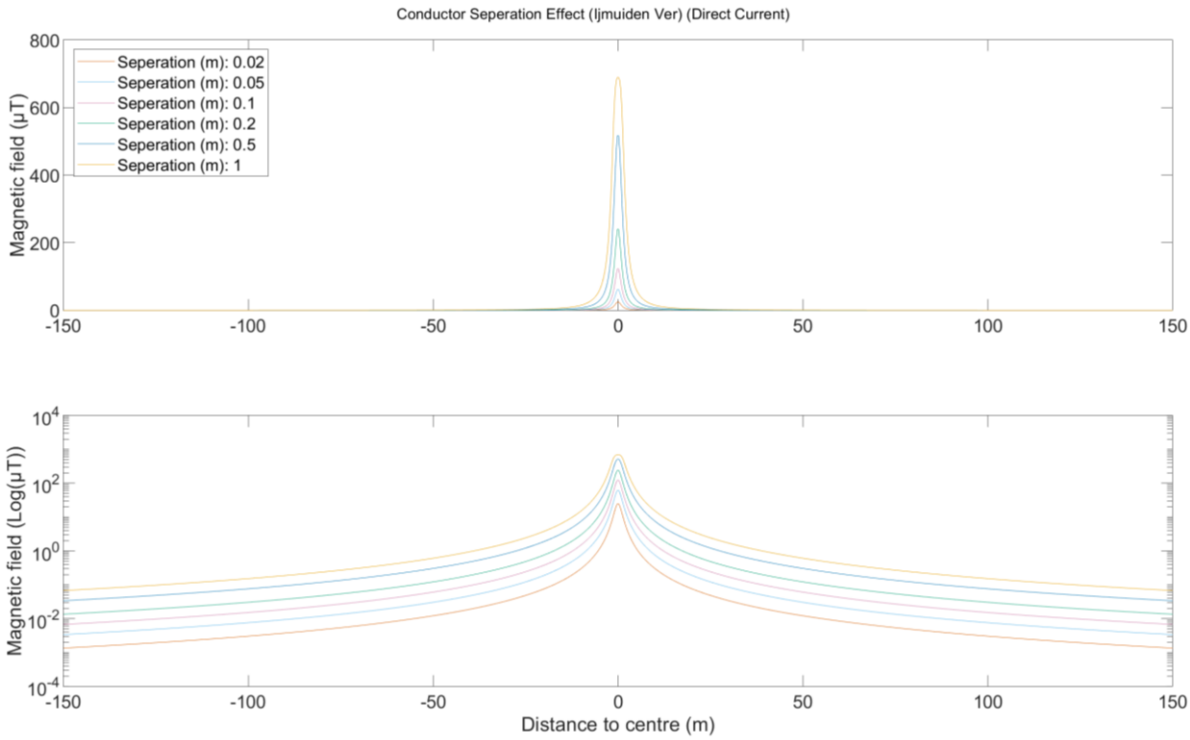
Figure 4.5 Magnetic field strengths at varying distances from the cables, for DC cables in linear scale (above) and logarithmic scale (below)



(Un)bundled

Many cable characteristics contribute to the strength of the emitted EMF. One of them is the bundling of cables. DC cables can be laid bundled (e.g. two conductors in one cable, or two cables close to each other) or separate from each other. This affects the strength of the emitted EMF, because the EMF from the cables partly cancel each other out. The figure below (figure 4.6) shows the influence of the distance between the poles on magnetic field levels in micro Tesla (μT). Separating the two poles significantly increases the magnetic field levels. This is especially visible in the second plot (please note the log-scale for the magnetic field strengths).

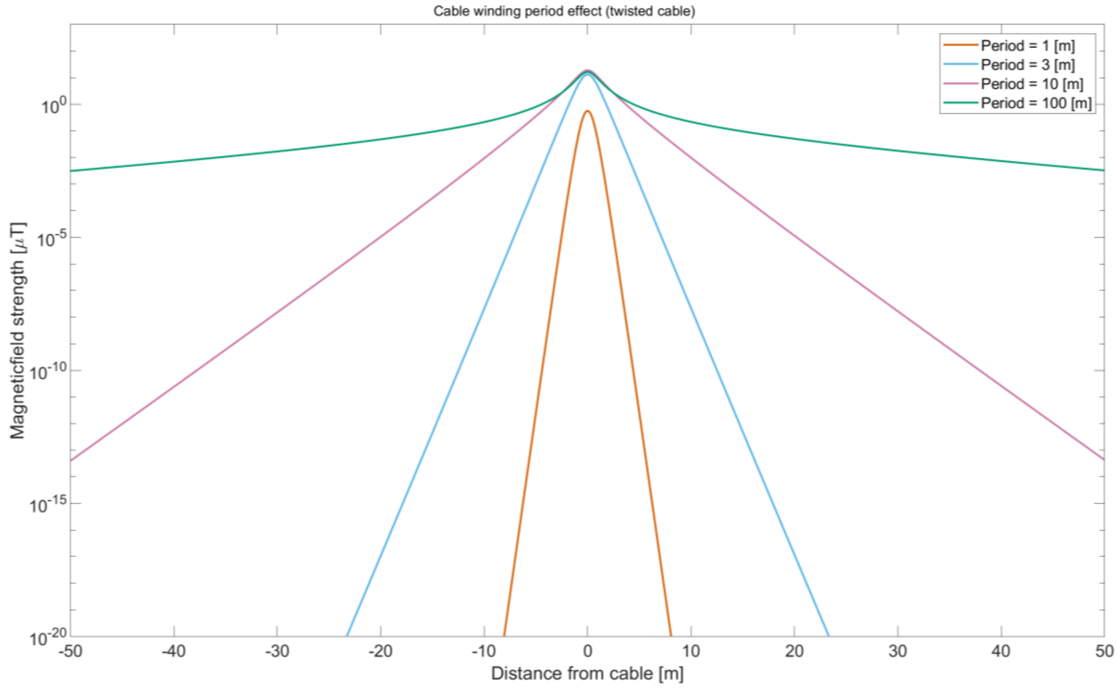
Figure 4.6 Overview of magnetic field levels in micro Tesla (µT) in relation to distance between the poles for direct current subsea power cables linear scale (above) and logarithmic scale (below).



Cable twist

Contrary to DC cables, HVAC cables are usually three-phase cables. Inside these cables, the three cores helically twist around each other. The distance (in meters) in which the three cables make a complete 360° turn, has a large influence on the resulting magnetic field. Figure 4.7 shows the reduction of the total magnetic field for several cable twist distances, due to partial cancellation of the fields. The EMF strengths presented in this report are likely an overestimation or worstcasescenario, since the cable twist is not taken into account.

Figure 4.7 Impact of different cable twist distances on the magnetic field of an alternating current subsea power cable



The computation of magnetic fields due to twisted cables changes considerably compared to the computation of the magnetic field due to non-twisted cables. In [lit. 85] it is shown that for twisted pair cables the magnetic field decreases approximately exponentially over distance, while for non-twisted cables the magnetic field decreases approximately inversely proportional to the distance. This effect is shown in figure 4.7, where it can be observed that the attenuation of the magnetic field increases for decreasing cable twist distances. This means that for carefully designed cable twist distances the total impacted area by the magnetic fields can be decreased considerably compared to the impacted area for non-twisted cables.

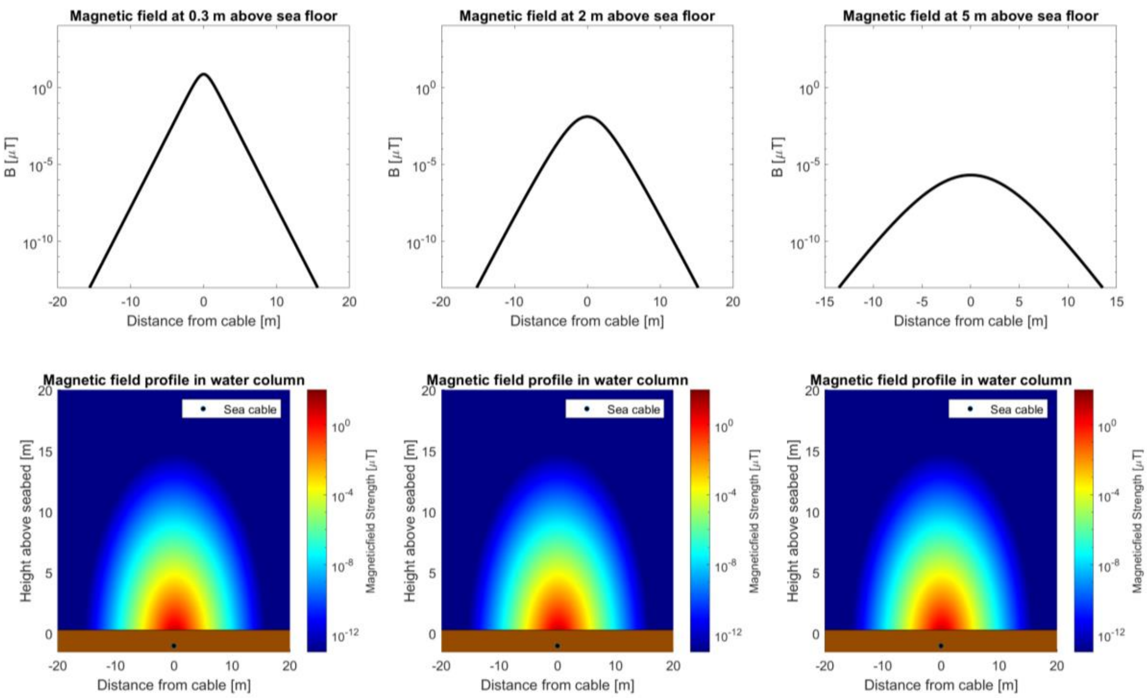
This twist distance is not well known with cable owners. Besides the twist resulting from the production process of the cables, it is likely the laying process plays a role. Offshore cables are laid from cable laying vessels, where the cables are stored in carousels (or reels) on deck (see for example Figure 4.8). This results in a twist or thorax in the cables. In order to predict the EMF levels with more accuracy detailed information on the cable twist is required from the cable manufacturer, installation companies and/or owner. In order to facilitate future magnetic field calculations for environmental impact assessments, it would be advisable to request to disclose the cable twist distance.

Figure 4.8 Example of a cable-laying vessel. Source: Van Oord

Exposure

As the field is extruding in all directions from the cable, the field is not only impacting the seabed horizontally, but it is also extending into the water column. The figure below (figure 4.9) shows the height of the magnetic field at different distances from the cable. These figures are modelled with the parameters from the HVDC IJmuiden Ver cable.

Figure 4.9 Exposure to DC magnetic field, at different positions in the water column based on the cable characteristics for IJmuiden Ver. The total magnetic field is shown as a line graph (a) and as a density distribution (b), with increasing distance from the seabed moving from left to right. The cable is buried at 1.5 m below the seabed

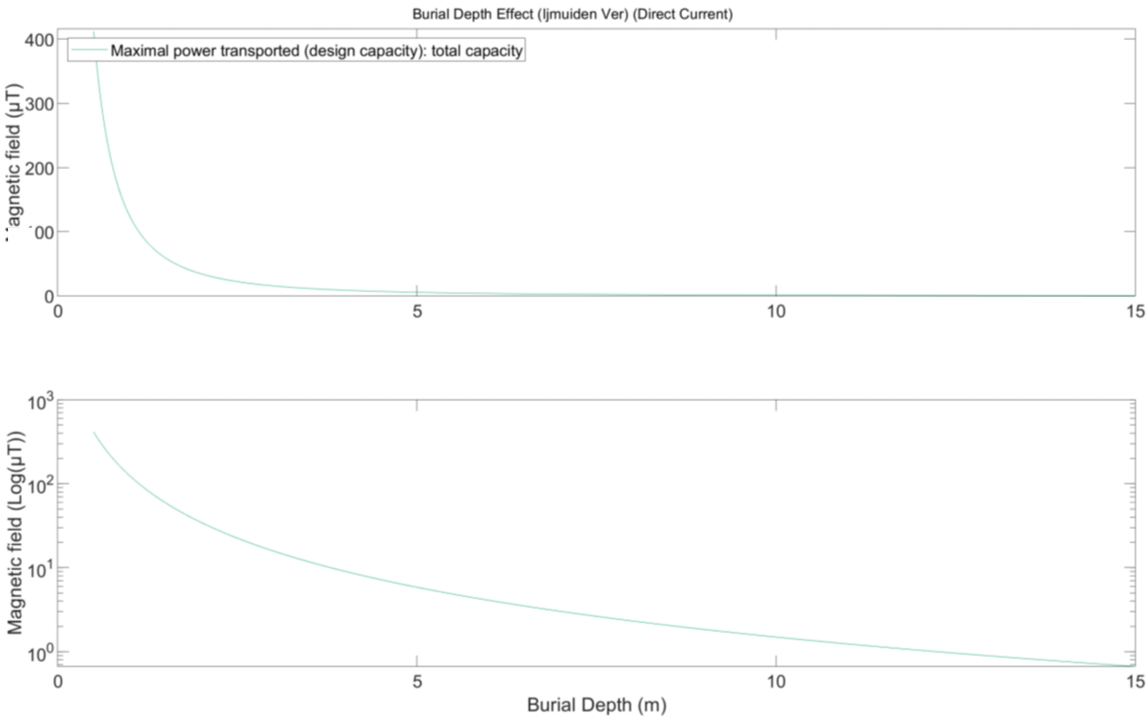


When an animal, such as a fish, crosses the cable at 0.3 meters from the seabed, it experiences field strengths orders of magnitude higher than when it would cross the cable 5 meters from the seabed. As such, in deeper waters, animals have the option to avoid (higher levels of) the EMF produced by the cables. In shallower waters this is not possible. Therefore, the impact of EMF might be higher close to shore compared to further offshore.

Burial depth

Lastly, burial depth affects the strength of EMF emitted into the water column [lit. 81]. The sediment itself does not have an effect on the EMF-emission, but the distance between the EMF source and a possible receiver increases. To illustrate this, figure 4.10 visualizes the effect of burial depth on the EMF levels that are emitted into the water column, again with a log scale in the bottom picture and a linear scale in the top picture. However, the EMF is still emitted into the sediment, possibly affecting benthic organisms, and there are several other considerations that have to be taken into account when considering increasing the burial depth. These are further discussed in chapter 5.

Figure 4.10 Illustrated maximum magnetic field levels in micro Tesla (μT) in relation to the burial depth of a subsea power cable



4.2 Field measurements

The data presented above provide insight in the modelled magnetic field levels that can be expected on the Dutch continental shelf and the effects of bundling and burial depth. These values differ from the reported field measurements. Several magnetic field measurements are reported in literature, of which an overview is provided in table 4.1 (AC) and table 4.2 (DC). As the (induced) electric fields are difficult to measure in water, there is limited knowledge available on these levels. To our knowledge only Dr. Peter Sigray from the Royal Institute of Technology in Stockholm has a pioneering approach and is able to measure the electric fields as described in [lit. 39].

In general, it is difficult to use the reported measured values in literature to compare to the modelling results as key information needed for interpretation is often lacking such as: power transported though the cable at the time of measurement, burial depth, and cable characteristics. It is evident that measured EMF values table 4.2 (AC) and table 4.3 (DC) are generally lower than modelled EMF levels (table 4.1).

However, Snoek et al. (2020) [lit. 5] found that the potential impact range resulting from measured values can be up to 5 times higher than modelled. In [lit. 5], measurements on the Dutch continental shelf detected EMF 24.5 meters on either side of the cable, with power transported generated by wind levels at 3-4 Bft. The authors state that the impact range would likely be even higher with stronger winds. Thompson et al (2015) also conclude that levels measured at Belgium offshore wind export cables were higher than calculated. A possible explanation for the discrepancy between measured and modelled values is that theoretical transported power does not always reflect the actual transported power or that there is an imbalance between the three phases in AC cables. There are also other types of discrepancies between modelled and measured levels as [lit. 39] reported alternating currents that were measurable hundreds of metres from the cable, recorded at direct current cables.

Table 4.2 Measured magnetic fields for alternating currents (AC) cables - 3 phase

Cable specifications	Maximum levels above GMF (μT)	Distance from the cable (m)	Reference
34 kV; 108 MW	0.008 - 0.020	1.5 - 2.0	[lit. 5]
150 kV; 120 MW	0.015 - 0.039	1.5 - 2.0	[lit. 5]
150 kV; 129 MW	0.004	1.5 - 2.0	[lit. 5]
50 Hz, 51±9 A	Not measured	1.0 - 1.5	[lit. 86]
50 Hz, not measured	0.004	1.0 - 1.5	[lit. 86]
50 Hz; 70 A	0.017	15	[lit. 86]
125 kV generator; 100 A	8.0	1.5	[lit. 21]
36 kV; 100 A	6.5	2	[lit. 21]
36 kV; 100 A	0.23	2.5 - 4	[lit. 21]
33 kV; 50 A	0.048	0	[lit. 87]
11 kV; 60 A	0.056	0	[lit. 87]
432 A	6.54	0.5	cited in [lit. 5]
436 A	0.125	2	cited in [lit. 5]

Table 4.3 Measured EMF for direct currents (DC) cables - bipolar

Cable specifications	Maximum levels above GMF (μT)	Distance from the cable (m)	Reference
-	0.7	1	Snoek et al., 2021 (in prep)
300kV; 330 MW; 0 A	0.46	1.3	[lit. 88]
300kV; 330 MW; 16 A	0.64	1.3	[lit. 88]
300kV; 330 MW; 345 A	14.3	1.3	[lit. 88]
660 MW; 500 kV; 1320 A	20.7	1.3	[lit. 88]
660 MW; 500 kV; 660 A	4.7	1.3	[lit. 88]

4.3 Possible impact zone

As discussed in chapter 2.3 and in [lit. 14], if species use the Earth's magnetic field for orientation, this means they can sense small anomalies in magnetic field strengths, in the order of nT (2-5 nT). Therefore, the possible impact zone is defined in this report as the area in which EMF-values are 5 nT or higher. Based on this threshold and the model results presented in paragraph 4.1, the EMF emitted by the IJmuiden Ver export cables are measurable 180 meters from the cable.

Table 4.4 Impact zone calculated based on the 5 nT zone and the length of the cable on the Dutch Continental Shelf.

Cable	Length within Dutch Continental Shelf (km)	Amount of cables	5 nT zone (m)	Affected area (km^2)
Norned	57	1	89	10,2
BRITNED	101	1	103	20,8
Cobra cable	98	1	106	20,8
Neuconnect	349	1	121	84,5
Viking Link	203	1	118	47,8
Ijmuiden Ver (alpha)	163	1	180	58,7
Ijmuiden Ver (beta)	146	1	180	52,6
OWEZ	15	3	62	5,7
PAWP	27	1	71	3,9
Luchterduinen	25	1	74	3,7
Gemini	91	2	104	38
Borssele	67	4	230	61,6
HK(z)	42	4	230	38,8
HK(n)	33	2	115	15,1
HK(w)	64	4	230	59,4
TNW	82	2	115	37,9
Total	1565	30	-	559,5

The area (in square kilometres) affected by the electromagnetic fields from the export cables of the 10 wind farms and interconnector cables (5) analysed in this study, which are 30 cables, totals almost 660 km^2. This is approximately 0.8 % of the NCP. The 5 nT contour differs from roughly 60 meters for the OWEZ cable, to 180 meters for the IJmuiden Ver cables.

Besides the export cables, the inter-array cables within the wind farm create a field of disturbance. Wind farms are occupying 954 km^2 in 2023 (including Egmond aan Zee, Prinses Amalia Luchterduinen, Gemini, Borssele, HK(z), HK(n)), and 2.600 km^2 in 2030 (including HK(w), TNW, IJmuiden Ver, Nederwiek and Lagelander, of which the last two are not included in this analysis). This is 4.5% of the Dutch North Sea in 2030. Thus, by that time, more than 5% of the Dutch North Sea will be affected by EMF from subsea power cables. Especially considering that the measured extent of the EMF from subsea power cables [lit. 5] is possibly larger than the modelled values presented here, the affected area might even be considerably larger. Note that this number does consider that the whole area within an offshore wind farm is subject to EMF. In reality there might be areas within the park that are not influenced as the monopiles are placed further apart with increasing monopile capacity. However, given the 'network' like structure of the inter-array cables, we feel it is a fair assessment that the entire park is influenced.

Although an impact zone can help in interpreting many different influences of EMF as for example reduced foraging area, it is not a suitable parameter to measure a possible barrier effect. The barrier effect, for example creating (temporary) confusion that may result in attraction, reduced swimming speed, or migration route deviation should be considered by number of crossings, tanking cumulative effects in consideration.

Important to note here is that Table 4.4 (and figure 4.3) presents a 2D-visualisation. However, the impact of EMF decreases towards the surface, since the distance from the source increases. Depending on local bathymetry and burial depth, either the entire water column is affected or only a limited part is. The modelling results show that in the shallow waters of the North Sea, the entire water column is part of the impacted (5 nT) zone.

5

IMPLEMENTATION OF ELECTROMAGNETIC FIELDS IN THE MSFD

The literature and modelling review in chapter 2 and 3 showed that there is insufficient knowledge about the possible impact of EMF on species living on the Dutch continental shelf, while the expected affected area could be considerable. Filling this knowledge gap will give policymakers a basis to decide on policies and a program of measures, in order to achieve a GES in the light of Descriptor 11. In this chapter suggestions are made to successfully implement the current knowledge about EMF into the MSFD.

5.1 Initial assessment & Good Environmental Status (MS1)

To make an assessment and define the Good Environmental Status in the light of EMF-emissions, indicator species should be selected. This could be done using relevant guidelines presented in chapter 2, which are adapted to EMF and summarized into seven criteria below:
1. Species' sensitivity to electric and/or magnetic fields.
2. Species' sensitivity to the potential impact of anthropogenic EMF.
3. Data availability, including the potential to gather more data in laboratory or field settings.
4. Protection under any convention/agreement/legal instrument and threat status (including the OSPAR Convention and the IUCN Red List).
5. Protected under the Habitat's Directive.
6. Listed in the Joint Research Centre list of relevant species for the MSFD.
7. Special commercial or social value.

In chapter 2, several species groups are discussed, elaborating on their sensitivity to (the effects of) EMF and data availability. This is the first step in choosing indicator species - if species are not known to be sensitive to electric or magnetic fields, they might not be suitable as an indicator species for this stressor. The same goes for data-deficient species groups. Table 5.1 summarizes the suitability of species discussed in chapter 2, that occur in the North Sea, that could be potential indicator species for the impacts of EMF on the marine environment.

Table 5.1 Potential for selection as indicator species for the EMF impacts. Dark blue = meets criterium, light blue = partly meets criterium, white = does not meet criterium

	Sea mammals		Elasmobranchs		Crustaceans		Diadrome fish	Other Invertebrates	
#	harbour porpoise	harbour seal/ grey seal	thornback ray	small-spotted catshark	edible crab	European lobster	European eel	common ragworm	Baltic clam
species' sensitivity to electric and/or magnetic fields								unknown	unknown
species' sensitivity to the potential impact of anthropogenic EMF									
data availability, including the potential to gather more data in laboratory or field settings									
protection under any convention/agreement/legal instrument and threat status (including the OSPAR Convention and the IUCN Red List)	*		*		not assessed				
protected under the Habitat's Directive									**
listed in the Joint Research Centre list of relevant species for the MSFD									
special commercial or social value									

* Least Concern on the IUCN Red List, but protected under the OSPAR Convention.

** Indirectly protected, through habitat type H1110_B as a typical species.

Based on the selection criteria above and the evidence available in literature, marine mammals like the harbour porpoise, harbour seal and grey seal do not seem suitable. Although there is relatively a lot of data available about these species' distributions and behaviour in the North Sea, there are no signs that electric or magnetic cues are of special importance to these species, nor that anthropogenic EMFs are affecting these species (chapter 2 and [lit. 22]–[lit. 31]).

Considering fish, elasmobranchs are the species group most sensitive to EMF. Research has shown some effects on behaviour, and especially increases in activity have been observed. The species that are most common in the North Sea, as well as species that are relatively well studied, are the thornback ray (*Raja clavata*) and small-spotted catshark (*Scyliorhinus canicula*). In addition, these species can be maintained in laboratory settings, allowing for experimental EMF research. Although both not protected under the Habitat's Directive, the thornback ray is protected under OSPAR.

The edible crab *(Cancer pagarus)* and European lobster *(Homarus gammarus)* are commercially relevant crustaceans, which, based on the available literature, seem to respond to EMF in some situations even though their ability to sense EMF has not been verified [lit. 39], [lit. 64], [lit. 68], [lit. 69]. On the other hand, both species are not protected under the Habitat's Directive, are considered Least Concern on the IUCN Red List and are not listed on the MSFD reference list. In addition, as commercial species the threat of (over)fishing might out way any more subtle effects of EMF. This could also be the case for other species.

In addition, a diadrome fish species could be selected, like the European eel (*Anguilla anguilla*). The European eel is listed as critically endangered under the IUCN Red List, and research has shown these species might be susceptible to EMF, although no significant negative impacts have been observed. However, there is a high chance diadrome fish occurring in the North Sea will be exposed to EMF, since there are many cables operational and planned located in close proximity to the coast, possibly crossing migration routes.

Species that are relatively easy to gather more data about in laboratory or field settings, are the Baltic clam and common ragworm. These invertebrates are abundant in the Dutch coastal areas. While not legally protected under any convention (besides indirectly in the case of the Baltic clam), and while it is unknown whether these species can sense EMF, they might be susceptible to its effects.

Summarizing the findings from table 5.1, elasmobranchs might at this moment be most suitable as an indicator species, in the sense that this species group is considered most sensitive to electromagnetic fields and research has been conducted to these species. Although more is known about the behaviour and distribution of sea mammals, and other species are listed as threatened under the IUCN Red List or are protected under the Habitat's Directive, for many species it is yet unclear whether there are significant effects of EMF on survival, reproduction, or behaviour. This needs to be considered when deciding on indicator species for the effects of EMF on the marine environment. For adequate implementation into the MSFD, it is necessary to further investigate the suitability of potential indicator species based on the presented, or similar, criteria.

5.2 Monitoring (MS2)

In order to determine GES for EMF there are two aspects important to consider: the technical and the ecological side. The monitoring part of the MSFD-cycle should focus on [1] a better understanding of EMF in het marine environment to determine the status of EMF in the marine domain and [2] the potential impact on marine life.

5.2.1 Technical monitoring

In order to assess the potential environmental impact of EMF on species, not only indicator species, but also units of assessment are required. As described in chapter 2 and 3, research to EMF currently lacks a universal standard of conducting research and reporting results. Therefore, there are large differences in the reported levels of EMF in the marine environment. The same applies to monitoring the effects of EMF and accurately drawing conclusions from these data. Efficient monitoring can lead to an improved understanding of electromagnetic fields as well as an improved understanding of EMF impacts on marine life, which is necessary to define the GES. In addition, monitoring is essential in order to validate models and predictions.

For EMF it is relatively easy to measure magnetic fields but measuring electric fields remains a challenge. Current monitoring techniques are not yet capable for measuring induced electric fields, with very low field strengths. Emitted EMFs can also vary greatly with varying circumstances. Not only cable design, like discussed in Chapter 2, plays a role. Current strengths usually differ during the day, caused by the varying levels of energy transported. In the case of offshore wind farms, variable energy levels are caused by periods with no wind and strong winds.

Another factor to consider is the location of measurements. There are multiple ways to carry out EMF-measurements. Measurements can be taken around a cable transect at sea, either along a cable or across one. This gives an overview of how EMF-strengths differ with varying distances from the source. In addition, point measurements can be taken, assessing changes over time and in different weather circumstances. If the cable situation is allowing, measurements can be taken on land - which is less costly and challenging, and can also accurately describe EMF strengths that can be extrapolated to EMF-strengths at different water depths.

5.2.2 Ecological monitoring

Parallel to understanding the technical side of EMF more knowledge is also required relating to the ecological side. Understanding how EMF influences the ecology of species will contribute to determining or contributing to GES. Depending on the monitoring plan ecological monitoring can provide information on presence/absence, abundance and diversity and behaviour. Tagging studies, bait cam studies or trawling surveys have been used previously to look at impact of EMF on marine species.

Ecological monitoring in the field is costly and complex and is therefore (where possible) aided by experimental or laboratory research. The controlled circumstances of the laboratory allow for dose-response relationships. In addition, laboratory research can provide a valuable tool to determine behavioural effects, if the study design takes the ex-situ circumstances of the animals into considerations. Lastly when more information is collected through monitoring and laboratory works, modelling can help with determining the impact of EMF by combining effects with encounter rate.

5.2.3 Monitoring plan

A combination of field work and laboratory work is required to collect all information needed to determine GES. Hutchison et al. (2021, [lit. 17]) have drafted a very clear and concise research framework, which is included in this report as **Fout! Verwijzingsbron niet gevonden.** (technical EMF research) and Figure 5.1 (impact on marine life). Translating the suggestions from Hutchison et al in view of the MSFD, first steps for technical and ecological monitoring are described below.

Technical monitoring Improving understanding of electromagnetic fields

To improve our understanding of electromagnetic fields and their characteristics in different environments, the following steps could be taken:

- Measuring magnetic (and if possible, electric) field levels with long term monitoring stations.
- Stimulate the market to develop suitable sensors by creating demand.
- Developing models that account for/explain the differences currently observed when comparing results with field measurements and including future cables with larger capacities.
- Ensuring vital information for EMF level prediction and interpretation is divulged by the cable owners (as daily/seasonal power transport patterns, specific cable design as core separation), possibly by including the disclosure of the information as a permitting requirement.

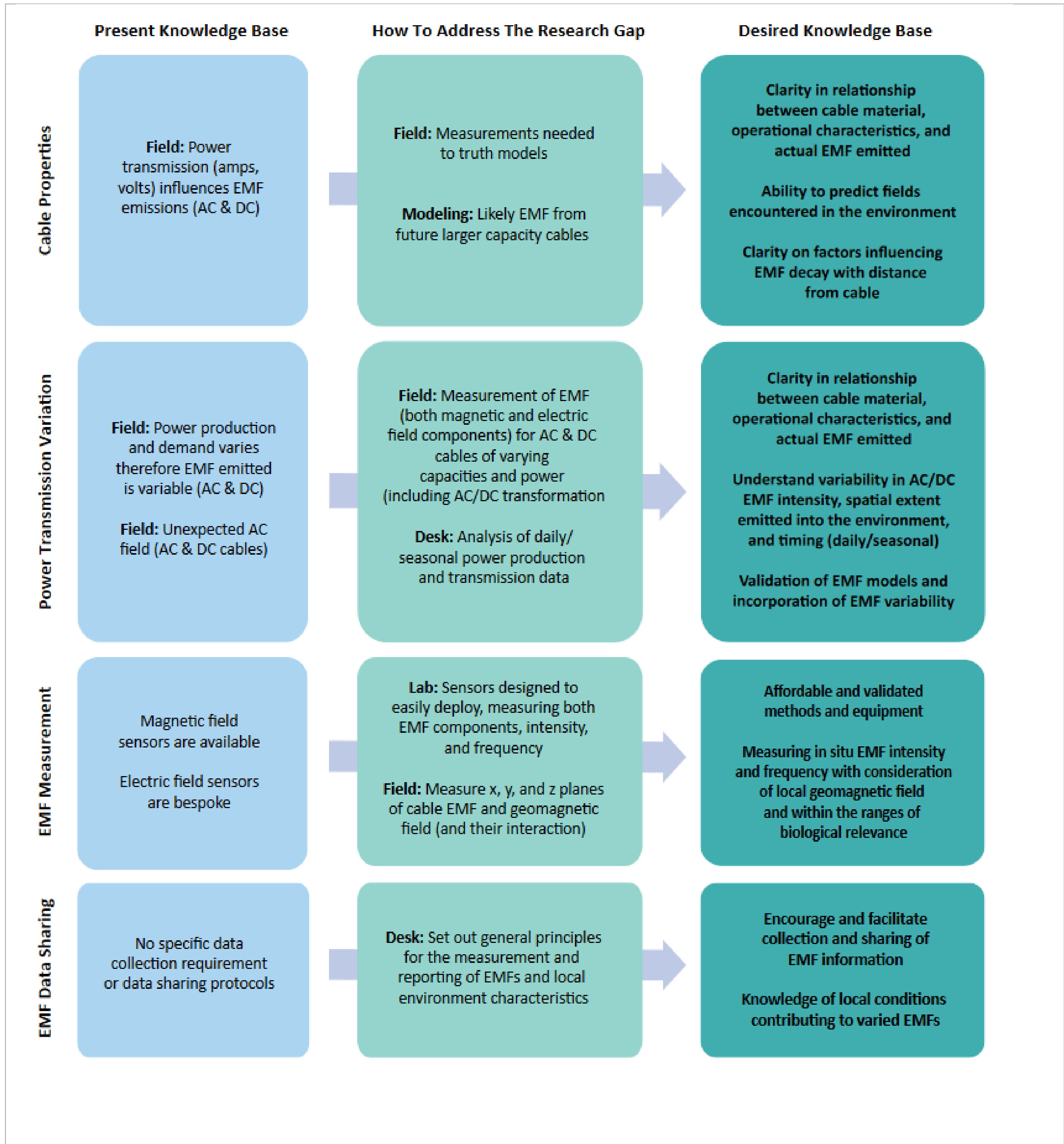
- Participate in international workgroups as the OSPAR task force EMF, in order to set collaborative measurement -and modelling standards.

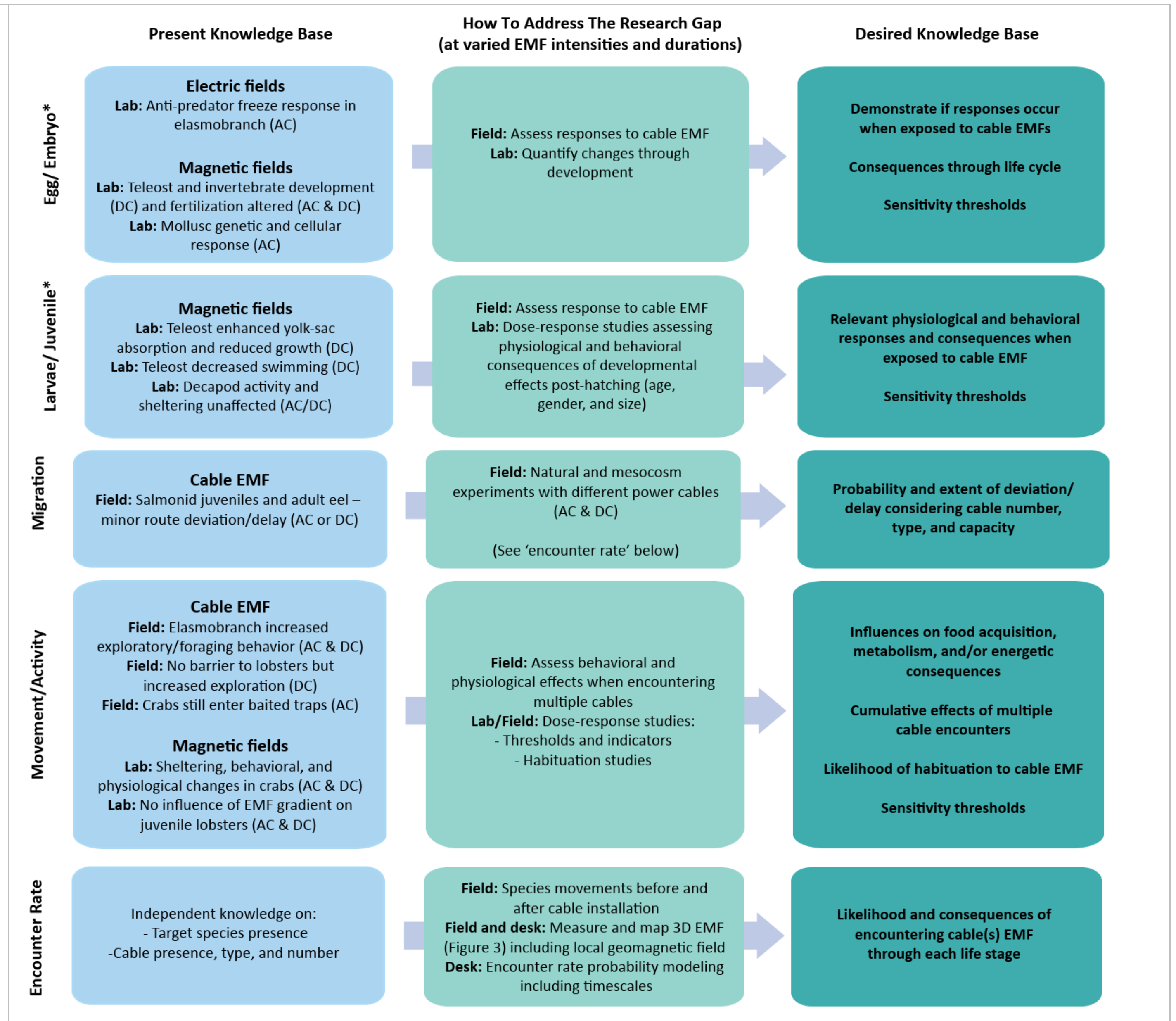
Ecological monitoring Understanding (potential) impact on marine life

In order to improve our understanding about the potential impact of EMF on marine life, a species specific dose-response curve for indicator species should be developed, focusing on different life stages:

- Embryonic phase
  - Assess responses to EMF
    - Continuous exposure to sessile species (like elasmobranch eggs) in laboratory settings.
    - Short term exposure to mobile species (like lobster larvae) in laboratory settings.
- Adult - migration
  - Natural (potentially tracking studies) and mesocosm experiments with different power cables (AC & DC).
- Adult - movement/activity
  - Dose-response studies: thresholds and indicators & habituation studies.
  - Field studies (potentially with BRUVs) assess behavioural and physiological effects when encountering multiple cables.
- Encounter rate
  - Both in relation to migration routes and within the home range.
  - Encounter rate probability modelling including timescales, based on the specific ecology of indicator species and seasonal difference in EMF.

Figure 5.1 From Hutchison et al 2021 Pressure related present and desired knowledge base. The present knowledge base is summarized (left) bridged to the desired knowledge base (right) by methods addressing knowledge gaps (centre)





* Consider in relation to population fecundity and mortality to determine any significance of impact

Figure 5.1 From Hutchison et al. (2021). Receptor related present and desired knowledge base. The present knowledge base is summarized (left) and is bridged to the desired knowledge base (right) by methods addressing knowledge gaps (centre). Sensory, life history, and movement ecology are integrated. Field and laboratory methods require careful consideration of species and experimental endpoints.

A monitoring plan should be detailed in respect of available budget, international research efforts (see section 5.4) and research strategy (see section 0).

5.3 Program of measures (MS3)

Because of the potentially negative impact of EMF on marine species, it is important to take measures to reduce any negative effects. A complication is that the potential negative impact is not per definition linear. Potentially, lower levels in the range of prey animals might have more impact than higher levels that are simply avoided (see chapter 3.3 and [lit. 88]).

Still, the area that is affected by EMF-effects can be minimized when EMF-emission is limited as much as possible. And, combining or reducing the number of cables also reduces the encounter rate. Several proposed measures therefore focus on that part, for instance by increasing burial depth [lit. 3]. Increasing the burial depth is however a costly and technically challenging measure which might not be feasible in all sediment types. There are other considerations that might influence (increasing) the burial depth, among which is ensuring sufficient cover to protect the cable from damage through anchoring or fisheries activities.

For AC, measures include helically twisting three-phase cables in order to have parts of the EMF cancel each other out, resulting in an overall lower EMF-emission (chapter 4.1, [lit. 17], [lit. 81]). For HVDC, bipolar cables can be grouped into two-core cables to minimize the affected area. Currently, there is some discussion whether future subsea power cables should be laid joined or separated. Advantages are that less trenching operations are required, although heat dissipation and repair operations become more complicated, because the cables can only be bent in one direction [lit. 89]. If research would indeed indicate that high magnetic fields are negatively impacting marine life, joining cables could be an interesting mitigation option. More research and development on joined cables and installation techniques could further explore this possibility. The possible measures for reducing EMF-emission are summarized in table 5.1.

Table 5.1 Possible impact reducing measures for the impact of EMF [lit. 2], [lit. 73], [lit. 84], [lit. 11], [lit. 90]

Proposed measure	Description	Implications	financial implications
use adequate shielding	shielding of the cable minimizes the emission of E-fields (note: not of iE-fields)	is already implemented on large scales in offshore projects	€
increased burial depth	decreasing the EMF-emission into the water column by burying cables deeper into the seafloor	expensive for offshore developers, and does not eliminate the emitted EMF	€€-€€€
helically twisted AC cables	by twisting the cables, the emitted EMF is minimized	production and installation process might need to be altered	€-€€
grouped/two-core DC cables	by grouping power cables, the effect of EMF remains local and limited	reduces number of trenching operations, but complicates repair operations, needs to be technically feasible without overheating	€-€€
avoiding areas of special ecological interest	when planning cable transects, vulnerable/threatened/ecologically important habitats should be avoided as much as possible	close collaboration ecologists and developers required	€-€€€
Cable straights	Combining several cables in one cable route, reducing the chance or number of encounters	Extensive planning, production and installation process might need to be altered	€€

5.4 Current research and policy

5.4.1 Research projects and programmes

A successful implementation of EMF impacts into the MSFD depends on accurate implementation of the latest scientific knowledge about the topic. Currently, there are several research projects starting up or ongoing with relation to the potential effects of EMF on marine life. In table 5.2 we provide an overview of the projects that we are currently aware of in the European Union and the United Kingdom. This overview is focused on elasmobranch research as this could be an important indicator species (see 4.2), but several research programmes to other species have also been included. In addition to the projects mentioned in the table, several PhD and postdoc-researches such as the lead authors of [lit. 54] and [lit. 17], work on the impact of EMF in the marine environment and are involved in research projects around this topic. Most likely there are more projects, on other species, ongoing that we are currently not aware of. Discussions with international counterparts could provide insight in other research efforts.

Table 5.2 Current research projects regarding EMF and elasmobranchs

name	topic	contact person
CEM FISH	acoustic telemetry stations and tagged fish, executed by RTE	Lisa Garnier, Marseille (FR)
OASICE	laboratory experiments with various species and developing monitoring methods	Luana Alberts, Brest (FR)
FISHOWF	acoustic telemetry stations and tagged sharks, cumulative impacts	Pierre LaBourgade,(FR)
MaREI	acoustic telemetry stations and tagged sharks, migration behaviour	Damien Haberlin (IE)
RBINS	impact of EMF on embryonic development of elasmobranchs, cephalopods and crustaceans	Silvia Paoletti (BE)
ElasmoPower	impact of EMF on elasmobranchs, combining laboratory and field work	Annemiek Hermans (NL)

Besides these laws and policies, ministries, expert groups and research institutions are involved in several programmes investigating anthropogenic impacts on the marine environment and the cumulative effects of offshore wind energy development. Examples of this are WOZEP (wind energy at sea, ecological programme), which makes cumulative effect assessments with the KEC (framework for assessing ecological and cumulative effects). The MONS-programme (Nature Strengthening and Species Protection Monitoring Survey) aims to improve our knowledge about the North Sea ecosystem during ten years of monitoring and research. Knowledge gathered in these programmes can contribute to establishing a solid knowledge base about species occurring in the North Sea and effects of EMF. The WOZEP program has co-funded the ElasmoPower project (see table 5.2). The KEC program currently has no research ongoing on EMF, as far we know. There are research objectives for EMF included in MONS. However, depending on the available budget, it is yet unclear whether this research is going to be carried out.

5.4.2 Relevant policies

Whether and how the state-of-the-art knowledge about EMF and possible impact reducing measures can be implemented, depends partly on Dutch laws and policies. Below an overview of relevant laws and policies is provided:

- In the Netherlands, the **Offshore Wind Energy Act** allows the government to decide on the locations for offshore wind farm development, within the boundaries set in the National Water Plan. These locations, the characteristics of the future wind farms and the accompanying permit requirements are then presented in Wind Farm Site Decisions, published by RVO (Netherlands Enterprise Agency). In preparation of these Site Decisions, RVO commissions studies outlining the applicable laws, environmental impact assessments and other site characterisation studies. This policy tool could be used to develop knowledge on, for instance, species movements before and after cable installation. For future wind farms, it is becoming increasingly important to contribute positively to marine ecology, since this has recently been added to the RVO criteria. Therefore, wind farm developers taking ecological measures - such as EMF reducing measures - have a higher chance of winning wind farm tenders.

- Concerning electromagnetic fields, the **Water Decree** is relevant. In the Water Decree, it is decided that offshore cables located within three kilometres of the low-water line should have a burial depth of at least three meters [lit. 91]. Outside these three kilometres, the cable should be buried at least one meter deep. If these varying burial depths are applied, lower EMF-strengths are emitted into the water column close to the coast, compared to further seaward. This effect is visible in Figure 4.10.
- Another relevant act is the **Nature Conservation Act** (Wet Natuurbescherming). The NCA protects, among other things, Natura 2000 protected areas and plant and animal species. In the Offshore Wind Energy Act, the basic principles of the NCA are adopted in the sense that a significant negative effect of offshore wind farm development on the natural features of that site, are not permitted. Therefore, if EMF emissions from inter-array or export cables would significantly affect the natural environment, this could have consequences for Site Decisions. Implementing EMF-reducing measures would then become a requirement for site development. For the current offshore wind export cables of TenneT (Net op Zee Borssele and Hollandse Kust zuid, Noord en West Alpha) the permits include a requirement to monitoring the effects of EMF on marine mammals and fish (see text box below, only in Dutch).

Monitoring

30. De vergunningshouder legt 8 weken voor de start van de gebruiksfase schriftelijk of per email (wetnatuurbescherming@minez.nl) een Monitorings- en evaluatieplan ter goedkeuring aan het bevoegd gezag voor. In dit Monitorings- en evaluatieplan wordt vastgelegd op welke wijze en met welke frequentie zeezoogdieren worden gemonitord. De monitoring heeft als doel om vast te stellen of en zo ja, in welke mate er negatieve effecten op zeezoogdieren optreden door elektromagnetische velden van de onderzeese kabels.

31. Het Monitorings- en evaluatieplan geeft verder aan hoe en met welke frequentie de resultaten van de monitoring worden gerapporteerd aan het bevoegd gezag.

32. Het Monitorings- en evaluatieplan dient te worden bijgesteld indien de tussentijdse resultaten, gelet op het in het voorschrift 29 aangegeven doel, naar het oordeel van het bevoegd gezag daartoe aanleiding geven. Dergelijke tussentijdse wijzigen behoeven de schriftelijke instemming van het bevoegd gezag alvorens zij worden doorgevoerd.

33. Indien tenminste 5 jaar na de inwerkingtreding van deze vergunning de resultaten van monitoring daartoe aanleiding geven hetgeen zal moeten blijken uit een door vergunninghouder in te dienen evaluatie, kunnen de voorschriften 29 tot en met 31 op schriftelijk verzoek van de vergunninghouder worden ingetrokken.

When considering recommendations on the subject of EMF, it is necessary to keep the relevant laws and regulations, as well as the ongoing research, in mind.

6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Little is known about the effects of electromagnetic fields on marine life. From what is known it clear that cable routing and habitat of sensitive species overlap. Is seems that, at least for some species, the level and frequency of anthropogenic EMF overlaps with the sensory range of the animal. Based on the results of available studies, further research is required, particularly due to the large scale role out of offshore wind farms and associated cables.

If the impact zone is defined as having EMF-values are 5 nT or higher, the EMF can extent up to 60 meters from the smaller OWEZ cable, to 180 meters for the bigger IJmuiden Ver cables. Levels of AC cables are lower than levels for DC cables, in part due to the higher levels of power transported through DC cables. Including the wind farms which have inter-array cables generating EMF, more than 5 % of the Dutch North Sea can be under the influence by EMF from subsea power cables by 2030. It is therefore important to determine if and what is the impact of EMF on marine life. Note that the size and strength of an EMF is dependent on the power transported, so on low-wind days, the impact zone will be considerably less.

The implementation of underwater sound in the descriptor 11 of the MSFD seems like a suitable example for the consideration of EMF. After formulating seemingly suitable criteria to select an indicator species elasmobranchs seem the most appropriate given there known sensitivity to EMF and the available research data. However, for many species it is yet unclear whether their sensitivity range is and if there are significant effects of EMF on survival, reproduction, or behaviour. For adequate implementation into the MSFD, it is necessary to further investigate the suitability of potential indicator species based on the presented, or similar, criteria detailed in this study when more data becomes available.

An (international) research effort could focus on [1] the technical aspects (measuring and modelling electromagnetic fields and the propagation from subsea power cables) and [2] understanding (potential) impact on marine life focussing different life stages and including laboratory studies (dose-response experiments) and field studies. If monitoring and research give cause to consider mitigation measures there are several options that can be explored, including using adequate shielding, increased burial depth, using helically twisted AC cables or grouped/two-core DC cables and considering cable routing, working with cable straights or avoiding areas of special ecological interest.

6.2 Recommendations

In section 5.2, the necessary steps to close the research gap are addressed. The research agenda is elaborate and should be a shared responsibility for between government, industry (manufactures, installation companies and operators) and universities/knowledge institutes. In addition, as the surrounding countries bordering the North Sea also have a MSFD obligation, as well as large offshore wind expansion plans, a common research agenda could divide the research load. Such a joint approach has been successfully implemented for underwater noise by for example the ICG Noise of OSPAR.

When setting a research agenda for the Netherlands, there are various tools and sources of knowledge available, which could work together:
- Wind Farm Site Decisions & MEAT criteria (Most Economically Advantageous Tender).
- Nature Act permits.
- Water Act permits.
- research programs such as WOZEP, MONS and KEC.
- NWO calls.
- Other industry related tools as TKI grants.

In Wind Farm Site Decisions and permits, cable owners could be requested to provide details about cable characteristics and the expected magnitude of the EMF emissions. In addition, especially in Nature Act permits, it could become a requirement to assess the potential impact of EMF on species occurring in the affected area, based on the latest scientific insights. Making these assessments is only possible when research programs, NWO calls and other grants fund EMF research, and data is openly available about this topic.

In order to achieve this, coordination between representatives of the involved parties is crucial. A first step could be to organize a workshop for these representatives, with the goal to harmonize goals and research priorities. This could focus on [1] a common research agenda and [2] determining the applicability of different tools.

7

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Appendices

APPENDIX: (FUTURE) OFFSHORE WIND DEMAND

Figure I.1 Planned, constructed and commissioned wind farms in the North Sea. Source: 4coffshore.com (2022)