

Rate of encounter EMF

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SUMMARY

One of the research topics within Wozep is the potential effect of electromagnetic fields (EMF) from offshore power cables on marine species. In this project, specifically the potential effects of *infield* cables on North Sea species has been studied, with two main research goals: gaining insight into which legally protected species could be at risk of disturbance by EMF from infield cables in the Dutch North Sea, and understanding under which circumstances (how, when, and where) these species may be affected.

The first step was to model the extent and variability of EMF from infield cables, based on cable specifications. Secondly, a risk-ranking for species protected under the Environment and Planning Act, Natura 2000, and/or OSPAR has been performed. This was based on a literature review, scoring each species on their susceptibility to EMF, life-history traits and expected rate of encounter. Thirdly, research recommendations have been specified per wind farm, based on species distribution data (in the North Sea).

The results show that EMF around infield cables is driven by the amount of current, the distance to the cable, the cable design (including lay-length, cross-section and arrangement) and the burial depth. Affected area and volume within the wind farms have been calculated and visualised for 33 kV (older wind farms) as well as 66 kV (newer wind farms) cables. Newer wind farms, with higher voltages and larger turbines, generally produce higher currents and larger EMF footprints.

The risk assessment shows that of the policy-relevant benthos, the flat oyster (*Ostrea edulis*) has the highest risk score. For migrating fish, this is the sea lamprey (*Petromyzon marinus*). For elasmobranchs, the thornback ray (*Raja clavata*) and spotted ray (*Raja montagui*) are at highest risk, and for marine mammals it is the harbour porpoise (*Phocoena phocoena*). Research recommendations are to investigate the effects of EMF on flat oysters and *Sabellaria* (as a slightly lower scoring but still policy-relevant species) under controlled laboratory conditions, applying the exposure values presented in this report.

Regarding the calculations and the modelling, the most important piece of information that is missing, is information about the lay length (cable twist). Seeing the large impact the lay length has on the extend of the EMF, gaining knowledge on this is crucial. This will eventually result in realistic modelled scenarios, improving the quality of the risk assessment for EMF-sensitive species.

NEDERLANDSE SAMENVATTING

Een van de onderzoeksgebieden binnen Wozep is het effect van elektromagnetische velden (EMV) van stroomkabels op het mariene milieu. In dit project zijn de potentiële effecten van infield-kabels op Noordzeesoorten onderzocht, met twee doelen: inzicht geven in welke wettelijk beschermde soorten mogelijk risico lopen op verstoring door EMV van infield-kabels in de Nederlandse Noordzee, en begrijpen onder welke omstandigheden (hoe, wanneer en waar) deze soorten mogelijk worden beïnvloed door EMV.

De eerste stap was het modelleren van de omvang en variatie van EMV van infield-kabels, gebaseerd op kabelspecificaties. Vervolgens is een risico-inschatting uitgevoerd voor soorten die beschermd zijn onder de Omgevingswet, Natura 2000 en/of OSPAR, op basis van een literatuuronderzoek. Elke soort werd hierbij beoordeeld op gevoeligheid voor EMV, soortspecifieke eigenschappen en verwachte trefkans met EMV. Tot slot zijn verspreidingsgegevens van deze soorten op de Noordzee gebruikt om onderzoeksprioriteiten per windpark te kunnen geven.

De reikwijdte van het EMV rond infield-kabels wordt bepaald door de stroomsterkte, de afstand tot de kabel, het kabelontwerp (inclusief lay-length, dwarsdoorsnede en opstelling) en de begraafdiepte. Zowel de beïnvloede oppervlakte als het volume binnen de windparken zijn berekend en gevisualiseerd voor 33 kV (oudere parken) en 66 kV (nieuwer parken) kabels. Nieuwere windparken, met een hogere spanning en grotere turbines (vermogens), leveren doorgaans hogere stromen, wat leidt tot een grotere reikwijdte van het EMV.

De risicobeoordeling laat zien dat van het beschermde bodemleven, de platte oester (*Ostrea edulis*) de hoogste risicoscore heeft. Voor migrerende vissen heeft de zeeprik (*Petromyzon marinus*) de hoogste risicoscore. Bij elasmobranchen zijn zowel de stekelrog (*Raja clavata*) als gevlekte rog (*Raja montagui*) in de hoogste risicocategorie geplaatst, en van de mariene zoogdieren heeft de bruinvis (*Phocoena phocoena*) de hoogste risicoscore. Aanbevolen wordt om de effecten van EMV op de platte oester en *Sabellaria* (een iets lager scorende, maar nog steeds beleidsrelevante soort) onder gecontroleerde laboratoriumomstandigheden te onderzoeken, waarbij de blootstellingwaarden uit dit rapport worden toegepast. Wat betreft berekeningen en modellering is de belangrijkste ontbrekende informatie de lay-length (de draaiing van de kabel). Gezien de grote invloed van lay-length op de omvang van de EMV is het van groot belang hier meer kennis over te krijgen. Dit leidt uiteindelijk tot realistische gemodelleerde scenario's, en verbetert de kwaliteit van de risico-inschatting voor EMV-gevoelige soorten.

1

INTRODUCTION

1.1 Background

The Wind at Sea Ecological Program (Wozep), initiated by the Ministry of Economic Affairs (now Ministry of Climate and Green Growth) and managed by Rijkswaterstaat, aims to address knowledge gaps about the effects of offshore wind farms on the North Sea ecosystem. Wozep covers research to effects on birds, bats, marine mammals, benthos, fish, and ecosystem functioning; and for instance, supports the Framework for Assessing Ecological and Cumulative Effects (KEC), assessing the cumulative impacts of offshore wind farms on protected species.

One topic on which the effects on protected species is not yet sufficiently researched within Wozep is the potential effect of electromagnetic fields (EMF). In relation to this subject, Witteveen+Bos conducted a literature review in 2022 concerning EMF in relation to the Marine Strategy Framework Directive (MSFD), which was updated in 2024 [1]. In addition, a workshop was organized with policymakers to further explore this topic and in 2023, a 'work plan for EMF' was developed to investigate how EMF can be integrated into appropriate policy instruments and research programs. Here it was concluded that Wozep is a suitable research program to further investigate the effects of EMF on marine species and more specifically, the effects of EMF emitted by infield cables (within wind farms) on these species (see text box).

Infield and export cables

The intensity, extend, and type of EMF emitted by subsea cables is determined by several cable characteristics, including cable type, cable orientation, voltage, and transported currents. Because of this, the EMF emitted by infield cables (cables connecting individual turbines with the offshore platform) differs from the EMF emitted by export cables (transporting energy from the offshore platform to the mainland). Export cables in the Netherlands are HVAC cables (High Voltage Alternating Current, up to 220 kV) and will in the coming years also include HVDC cables (High Voltage Direct Current, 525 kV) for wind farms located further offshore. Infield cables are always HVAC cables, with lower voltage levels than export cables (66 kV in newer wind farms, 33 kV in older wind farms). Furthermore, the orientation of the wind turbines in a wind farm results in a relatively high infield cable density within a more or less confined area - as opposed to the export cable, which solely connects two locations.

In the Netherlands, research to the effects of EMF has primarily focused on export cables [1], [2], [3], [4]. However, as the emitted EMF strengths differs between the cable types, the effects of EMF of export cables on marine species might be different than the effects of EMF of infield cables on the same species.

The objective of this study is twofold:

- 1 gaining insight into which legally protected species could be at risk of disturbance by EMF from infield cables in the Dutch North Sea;
- 2 understanding under which circumstances e.g. how, when, and where these species may be affected.

1.2 Scope and methods

This study follows three steps:

- the first step is to model the extend of EMF from infield cables in offshore wind farms of the 2030 Roadmap. EMF modelling is done based on cable specifications, where provided by the cable owners;
- in step 2, the species protected under the Environment and Planning Act and OSPAR are ranked on potential susceptibility to EMF effects from infield cables. This is based on a literature review on their sensitivity to EMF, life history traits, and expected rate of encounter with EMFs;
- then, using species distribution data of the Dutch North Sea (average densities, locations of important spawning areas) this ranking is detailed further, to prioritise research in different wind farms.

1.3 Reading guide

In chapter 2, the infield cables in the North Sea are described from a technical perspective, cable specifications are summarized, and the results of the EMF modelling are presented. Chapter 3 describes the species which have been included in the risk assessment, and ranks those species based on expected severity of effects (based on species' sensitivity to EMF, their protection and conservation status) and expected rate of encounter with EMFs (based on life history traits, depth range and seasonal occurrence in the North Sea). In chapter 4, more detailed distribution data of the North Sea species is included, in order to specify potential research priorities in different wind farms in the Dutch North Sea. Chapter 5 concludes with a summary of the results, policy recommendations and recommendations for future research.

2

CABLE SPECIFICATIONS AND WIND FARMS

2.1 Wind farms in the Dutch North Sea

This chapter provides an overview of the current and planned wind farms in the Dutch North Sea, the technical specifications of their infield cables, and the resulting extent and intensity of the EMF from these cables.

2.1 Infield cables

2.1.1 Technical specifications

Moving charges (such as a current in a cable) generate an EMF as described by Maxwell's equations. The resulting electromagnetic fields follow from these equations and are (mainly) dependent on two main factors: the amount of current passing through the cable, and the distance from the cable. A higher current results in an increase in amplitude of the EMF, whereas the amplitude of the EMF decreases with a larger distance to the cable.

For three-phase AC cables (the type of cable that is used as infield cable in wind farms) the EMFs produced by the three cable cores (the three conductors inside the cable) interact. These three cable cores transport currents simultaneously but in different phases, and as a result, the EMFs from these cables partially cancel each other out.

In order to accurately model the EMF generated by infield cables, insight into several technical parameters of such cables is required. For the reader interested in more details, an electrodynamics textbook should provide the required background information (e.g. [5]). An overview of the infield cable characteristics of the cables on the Dutch continental shelf that are needed to calculate the EMF are presented in table 2.1. The cross-sectional area per cable has an impact on the spacing of the cable cores, which in turn affects their relative position to one another and the degree of cancellation. The lay length, which represents the length at which the three phases complete a complete twist around one another, further impacts the amplitude of the resulting EMF. Generally, a smaller cross-sectional area and a shorter lay-length result in a decrease in amplitude of the EMF for a given position. Thirdly, the average burial depth gives an indication on the required distance for EMF in order to reach the surface of the seabed.

The voltage used for the cable of the turbine string along with the capacity of the turbine and the number of turbines per string, can be used to determine the design current (maximum current the cable can theoretically transport). The current through each cable is dependent on the number of turbines connected to the string. At the tail of the string, the generated current of only one turbine will be transported, resulting in a relatively small current (and relatively small EMF). Further up the string, more generated currents will be added to the cable, resulting in an increase in current and EMF strength.

The yield of the turbines is dependent on the amount of wind, which is heavily dependent on the season. In real scenario's, the design current will not be met and assumptions on the actual current passing through the infield cables will have to be made. The expectation is that on average 25 % of the maximum design current will pass through the cables in the summer, whereas on average 80 % of the maximum design current is expected during winter [1]. With these parameters known, the transported current as a function of the position on the string can be calculated, which in turn is used to calculate the distribution of the EMF around the cables.

Table 2.1 describes the cable specifications of wind farms of the 2030 Road Map. Column 2 describes the cable type, in which the cross-section area (times three, for three phases) can differ for different sections of the cable, as cables with a larger diameter can transport stronger currents. The voltage has been 66 kV since Borssele, and as shown in column 4, turbine capacity has steadily increased since OWEZ. This leads to higher expected currents in newer wind farms (column 5). The current strengths are calculated for three-phase cables with a power factor of 1,0. For example, for OWEZ the current can be calculated by dividing the power by the voltage (i.e. $2 \times 12 \text{ MW} / 33 \text{ kV} = 727 \text{ A}$). In turn, each individual phase has a current equal to 727 A divided by the square root of 3, resulting in 420 A. The presented currents strengths are the current strengths in the cable section closest to the substation.

Burial depth is assumed to be similar in each wind farm, with an average of 1 m. This is a worst-case scenario, as burial depth is often larger for safety reasons.

Table 2.1 Cable specifications of offshore wind infield cables in the Dutch North Sea

Wind farm	Cable type (cross-section area, shielding)	Voltage	Turbine capacity & turbines/ string	Expected current (summer, winter, maximum design)
OWEZ	3 x 120 mm ² , XLPE	33 kV	2 MW, 12 turbines/string	105 A, 336 A, 420 A
Prinses Amalia	3 x 120 mm ² , XLPE	33 kV	2 MW, 8 turbines/string	70 A, 224 A, 280 A
Luchterduinen	3 x 120 mm ² , XLPE	33 kV	3 MW, 5-8 turbines/string	105 A, 336 A, 420 A
TNW (Gemini)	3 x 95 mm ² , 3 x 300 mm ² , 3 x 500 mm ² , 3 x 630 mm ² ,	33 kV	4 MW, 7-8 turbines/string	140 A, 448 A, 560 A
Borssele	3 x 140 mm ² , XLPE	66 kV	8 - 9,5 MW, 7 - 8 turbines/string	166 A, 532 A, 665 A
Hollandse Kust (zuid)	3 x 180 mm ² , XLPE	66 kV	11 MW, 6 turbines/string	144 A, 462 A, 577 A
Hollandse Kust (noord)	3 x 180 mm ² , XLPE	66 kV	11 MW, 6 turbines/string	144 A, 462 A, 577 A
Hollandse Kust (west)	3 x 200 mm ² , XLPE	66 kV	14 MW, assuming 5 turbines/string	153 A, 490 A, 612 A
Ijmuiden Ver	3 x 200 mm ² , XLPE	66 kV	not yet operational	not yet operational
Nederwiek	3 x 200 mm ² , XLPE	66 kV	not yet operational	not yet operational
Doordewind	3 x 200 mm ² , XLPE	66 kV	not yet operational	not yet operational

2.1.2 Expected magnetic fields

The expected magnetic field is calculated with the formula for the magnetic field around an infinite wire, as shown below.

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

Here, B is the magnetic field in T, μ_0 is the vacuum magnetic permeability (roughly equal to $4\pi \cdot 10^{-7} \text{ N}\cdot\text{A}^{-2}$), I the current through the wire in A and r the point of measurement of the magnetic field in m (distance from the wire). For multiple wires, the superposition principle can be applied, simply resulting in the sum of the three individually generated magnetic fields to be the resulting magnetic field. As the wind farms use a three-phase cable, where the phases lag behind each other such that the sum of their currents equals 0, this results in a significant reduction in the resulting magnetic field. However, as the three phases cannot share the exact same position within the cable, there will still be a non-trivial resulting magnetic field.

In order to create an accurate representation of the different wind farms, two sets of cable types will be used. The first is used to describe the wind farms which operate on 33 kV cables, while the second is used to describe the wind farms which operate on 66 kV cables. In addition, the geometry of the different strings per wind farm is assumed to be equal for all farms. This simplification allows for easy comparison between different wind farms.

The 33 kV represents a possible offshore wind farm, chosen to allow the modelling of different EMF scenarios. A total power of 32 MW was chosen with eight turbines per string, which corresponds to a power of 4 MW per turbine. The resulting effective current then equals roughly 70 A per turbine, and a design current of 560 A per string. As a higher current also generates more heat, the cross-section area of a single phase was chosen to be dependent on the amount of current it transfers. From the tail segment to the head segment of the string, the cross-section areas chosen were 95, 95, 95, 300, 300, 500, 500, 630 mm².

The expected magnetic field for the first and last segment in a string for a 33 kV cable is shown in figure 2.1. In figure 2.2, the corresponding modelling results are shown. The four different scenarios are shown by the four curves in each segment, where the bottom curve (orange) corresponds to the no wind/maintenance scenario, the second from the bottom curve (blue) is the summer scenario, and the top two curves (they basically overlap) correspond to the winter and design capacity scenario.

Figure 2.1 Worst-case scenario of the electromagnetic field radius on scale, for a power cable from turbine 1 to turbine 2 (left) and turbine 8 towards the offshore substation (right) (33 kV, 70 A)

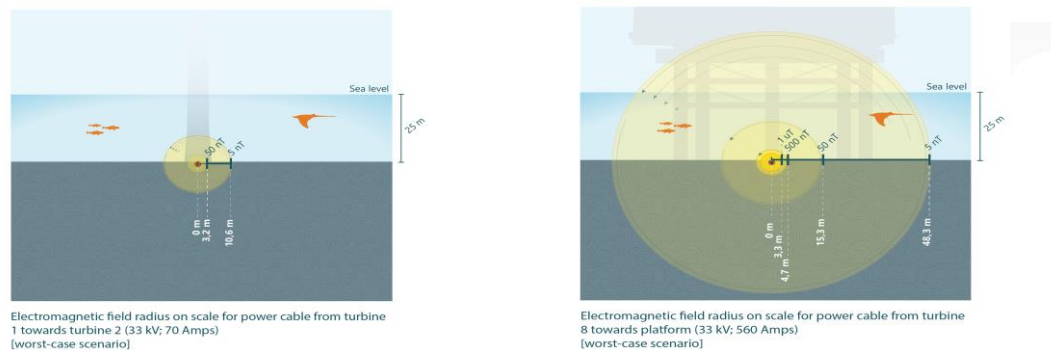
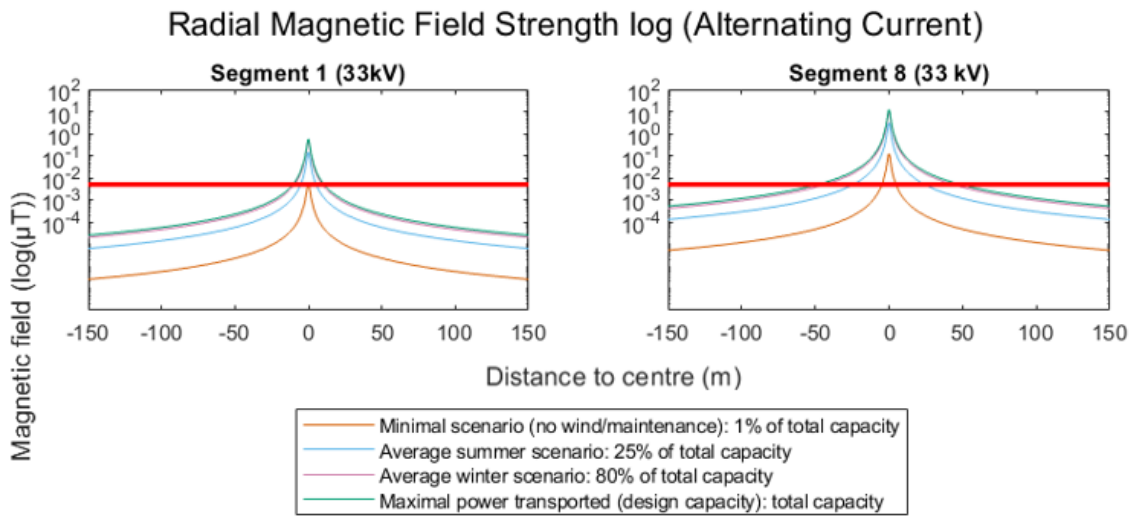
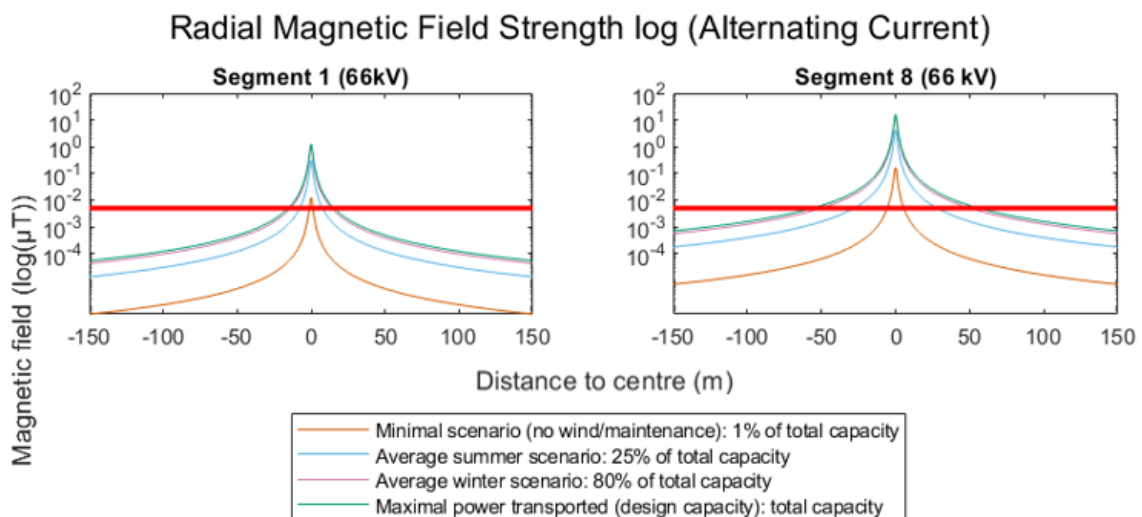


Figure 2.2 Magnetic field strength (log μT) per cable segment as a function of distance to its centre for 33 kV cables. The red line represents the 5 nT contour



For the 66 kV representation (figure 2.3), a total power of 76 MW was chosen. This corresponds to a power of 9,5 MW per turbine, which corresponds to an effective current of 83 A per turbine. The string was chosen to have at most eight turbines connected to it, resulting in a design current of 665 A. The cross-section area of a single phase was chosen to be dependent on the amount of current it transfers. From the tail segment to the head segment of the string, the cross-section areas chosen were 300, 300, 300, 500, 500, 630, 630, 800 mm^2 .

Figure 2.3 Magnetic field strength (log μT) per cable segment as a function of distance to its centre for 66 kV cables. The red line represents the 5 nT contour

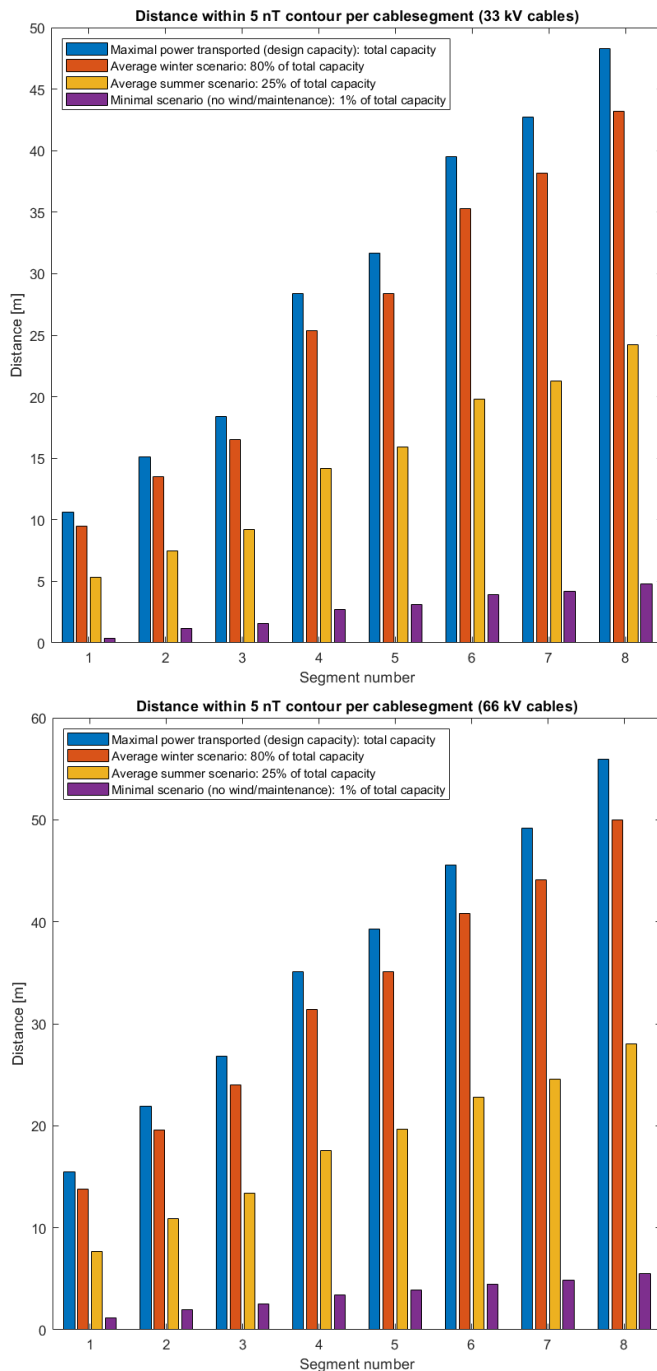


It can be seen that the magnetic field strength falls off with the distance to the centre of the cable, in a similar fashion for all of the scenarios. The magnitude of the magnetic field of the last segment, however, is much larger than the magnitude of the first segment. This is attributed to the increased amount of current passing through the last segment when compared to the first segment. As a result, the last segment has a bigger radius of influence for a similar magnetic field threshold value.

The lower limit of 5 nT is shown in the visualizations, as this limit is often used in ecological research. It is assumed that species using the Earth’s magnetic field for migration will be able to sense deviations from the Earth’s magnetic field of at least 5 nT [1]. As such, this level will be used as the outer limit of the potential impact area.

The distance within the threshold value of 5 nT has also been calculated per cable segment, for the 33 kV and 66 kV wind farms, as shown in figure 2.4. In this case, segment 1 corresponds to the cable in between the last and second-to-last turbine in the string, et cetera. Segment 8 is the cable segment closest to the offshore substation. Again, segments closer to the head of each string generate a magnetic field with a bigger amplitude.

Figure 2.4 Radius of the 5 nT contour, for different cable segments for 33 kV cables (above) and 66 kV cables (below)



2.1.3 Lay-length dependency

The lay-length of three-phase cables is a parameter usually not provided by the cable manufacturer. Simulations show that the resulting EMF is strongly dependent on the lay length. The distance from the centre of the cable within the 5 nT (nanotesla) contour as a function of the lay length is shown in figure 2.5. The results are also shown in table 2.1. A lay length of 'infinity' corresponds to the (straight) parallel cable case.

The extend of the 5 nT contour can be seen to decrease significantly for a shorter lay-length, as the distance compared to the parallel cable case decreases in the most extreme case by a factor of ~ 40 (table 2.1). Despite the strong dependence on lay-length, the lack of documentation of the lay-length for cables in wind farms makes it difficult to define a specific lay-length. Therefore, the worst-case of an infinite lay-length will be assumed in the remainder of the EMF study.

Figure 2.5 EMF radius from the cable within 5 nT contour for different lay-lengths (at design capacity)

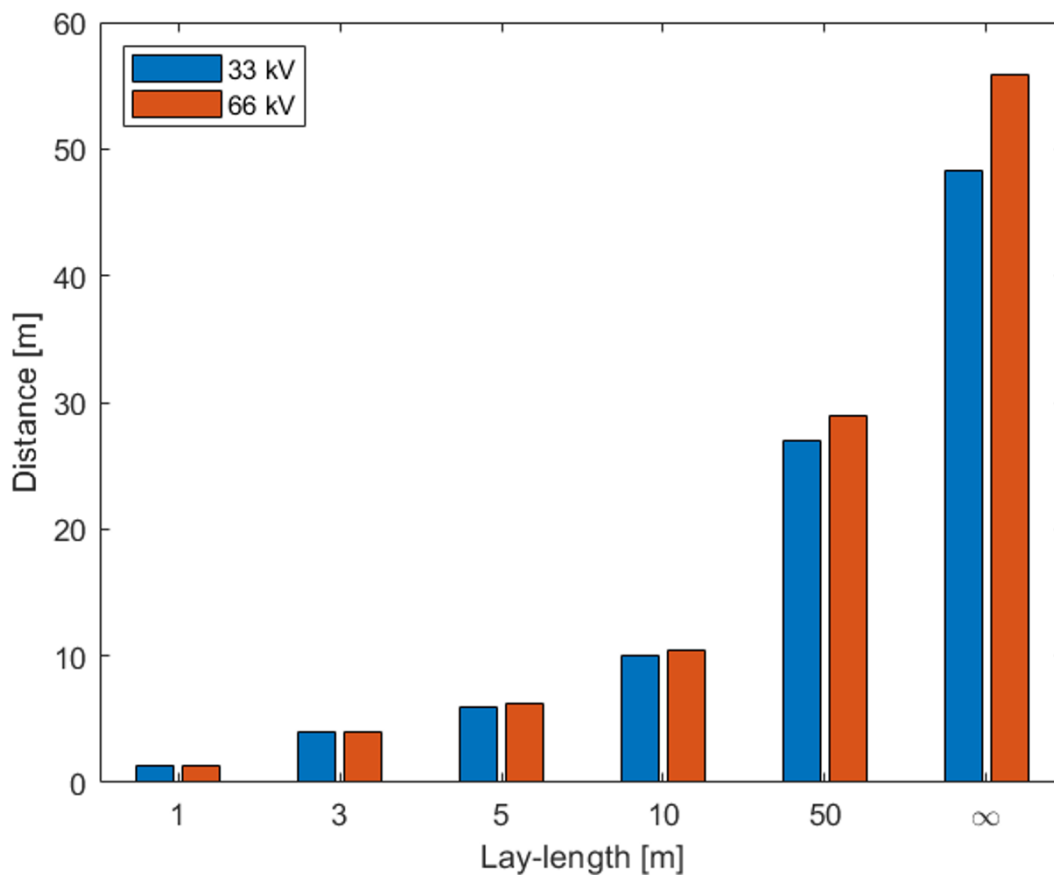


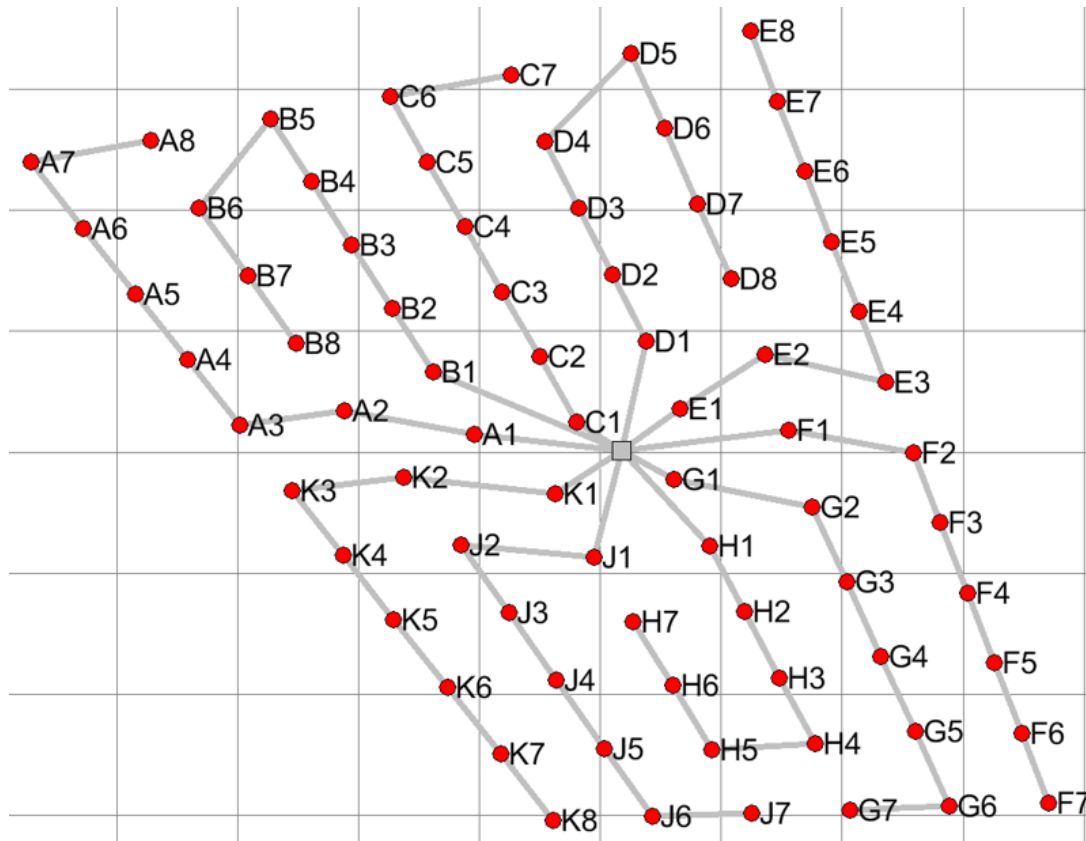
Table 2.2 Distance from cable within 5 nT contour for different lay-lengths

Lay-length [m]	1	3	5	10	50	∞
distance within 5 nT contour (33 kV) [m]	1,4	4,0	6,0	10,0	27,0	48,3
distance within 5 nT contour (66 kV) [m]	1,4	4,0	6,2	10,5	29,0	55,9

2.1.4 Area influenced by EMF

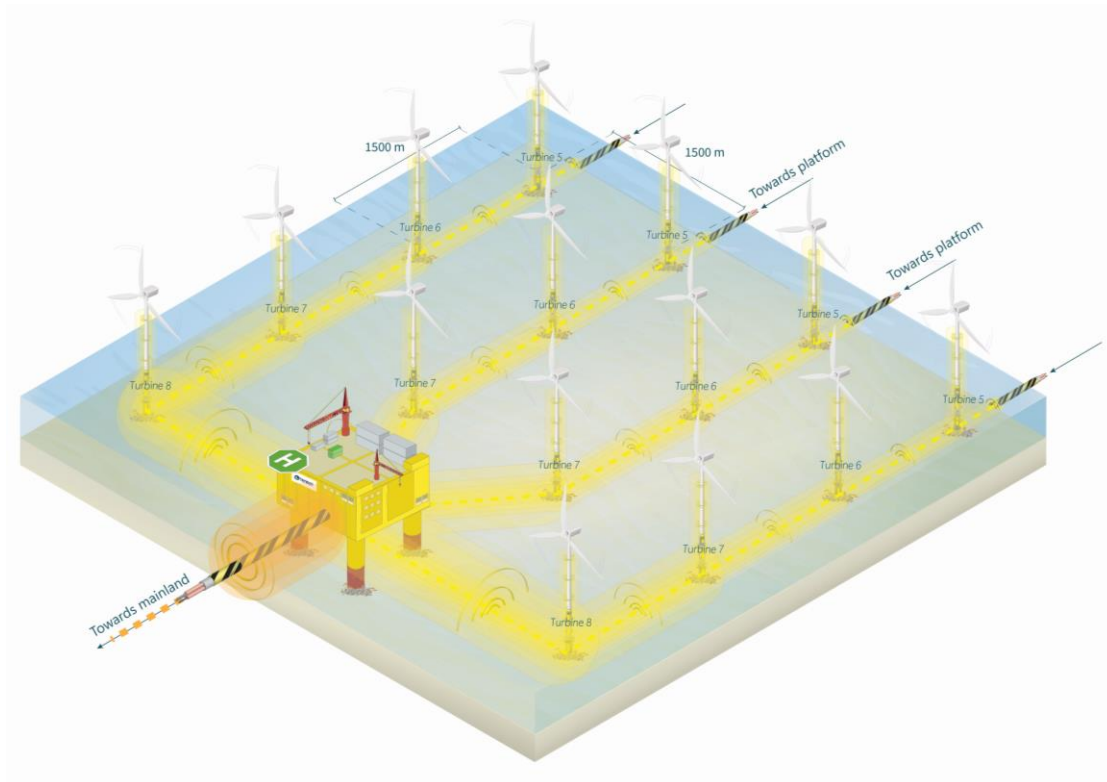
An overview of the total area of the seabed influenced by wind farm cables was created in order to map the extent of EMF potentially impacting marine species. For the geometry of the strings, the representation as shown in figure 2.6 will be used for each wind farm. As every square covers an area of 1 km², this representation covers an area of ca. 31,7 km².

Figure 2.6 Representation of geometry of the strings for the wind farms



An increase in influenced area arises when approaching the centre point in the wind farm (the offshore substation), as both the current carried by the cables increases, and the distance in between the cable cores increases as the cables are larger (table 2.2). For example, the current between points A8 and A7 will only be the current generated by turbine A8, whereas the current between points A2 and A1 will be the sum of currents from turbines A8 through A2. The potential impact area near the offshore substation will thus be larger than near the edges (also see figure 2.7).

Figure 2.7 Visualisation of the extent of EMF in a windfarm, with increasing EMF strengths towards the offshore substation



The area influenced per cable segment was calculated by multiplying the diameter of the 5 nT contour (2 times the EMF radius) by the length of the cable segment. The influenced area per cable segment was then summed up, and divided by the total area of the wind farm to obtain the area ratio (the ratio between the total wind farm area, and the area affected by EMF).

Results

The radius of the 5 nT contour per cable segment for each scenario, for both the 33 kV and 66 kV cable, have been shown before in figure 2.4. Again, segment 1 corresponds to the cable in between the last and second-to-last turbine in the string, et cetera. Segment 8 is the cable segment closest to the offshore substation.

The results are also visualised in figure 2.7, emphasizing the 3D-component of the magnetic fields, as they cover both the seabed and the water column. Close to the offshore substation, the EMF reaches a maximum, as multiple cables come together, and those cable segments carry the strongest currents. This results in high EMFs.

The percentage of the total area of the wind farms falling within the 5 nT contour are shown in table 2.3. The wind farms operating at 66 kV have a bigger area percentage, an increase of approximately 20 % compared to the wind farms operating at 33 kV. This is attributed to the slightly increased currents and slightly bigger distances between the individual phases of each cable.

Table 2.3 Area percentages for the different scenarios for the 33 kV and 66 kV wind farms

Wind farm voltage	Area percentage (design capacity)	Area percentage (average winter)	Area percentage (average summer)	Area percentage (maintenance)
33 kV	10,6	9,5	5,3	1,1
66 kV	13,0	11,6	6,5	1,3

These percentages however do not reflect the 3D-component accurately, since only the affected *area* has been calculated, and not the affected *volume*. Therefore, a similar calculation has been done to calculate the affected volume within a wind farm that lies within the 5 nT threshold.

It is not entirely clear how the current is transported from each turbine into the infield-network, but it is assumed that the net currents inside the monopiles equals (at most) the yield of a single turbine (and no cancellation of the magnetic field occurs).

In combination with the overlapping volume between the cables on the seabed and the vertical cables, it is difficult to formulate the exact addition that the vertical cables provide (especially as their directions also do not align). Therefore, as an approximation, a relative 5 % of volume fraction has been added to the calculated volume fraction.

Finally, the depth of the water column is assumed to be constant over the area of the wind farm, and equal to 25 meters. Therefore, for cable segments which have a 5 nT contour below 25 meters, the affected volume is simply the area of the semicircle multiplied with the length of the segment. For segments which have a 5 nT contour greater than 25 meters, the part exceeding the surface of the water has been subtracted from the calculated volume.

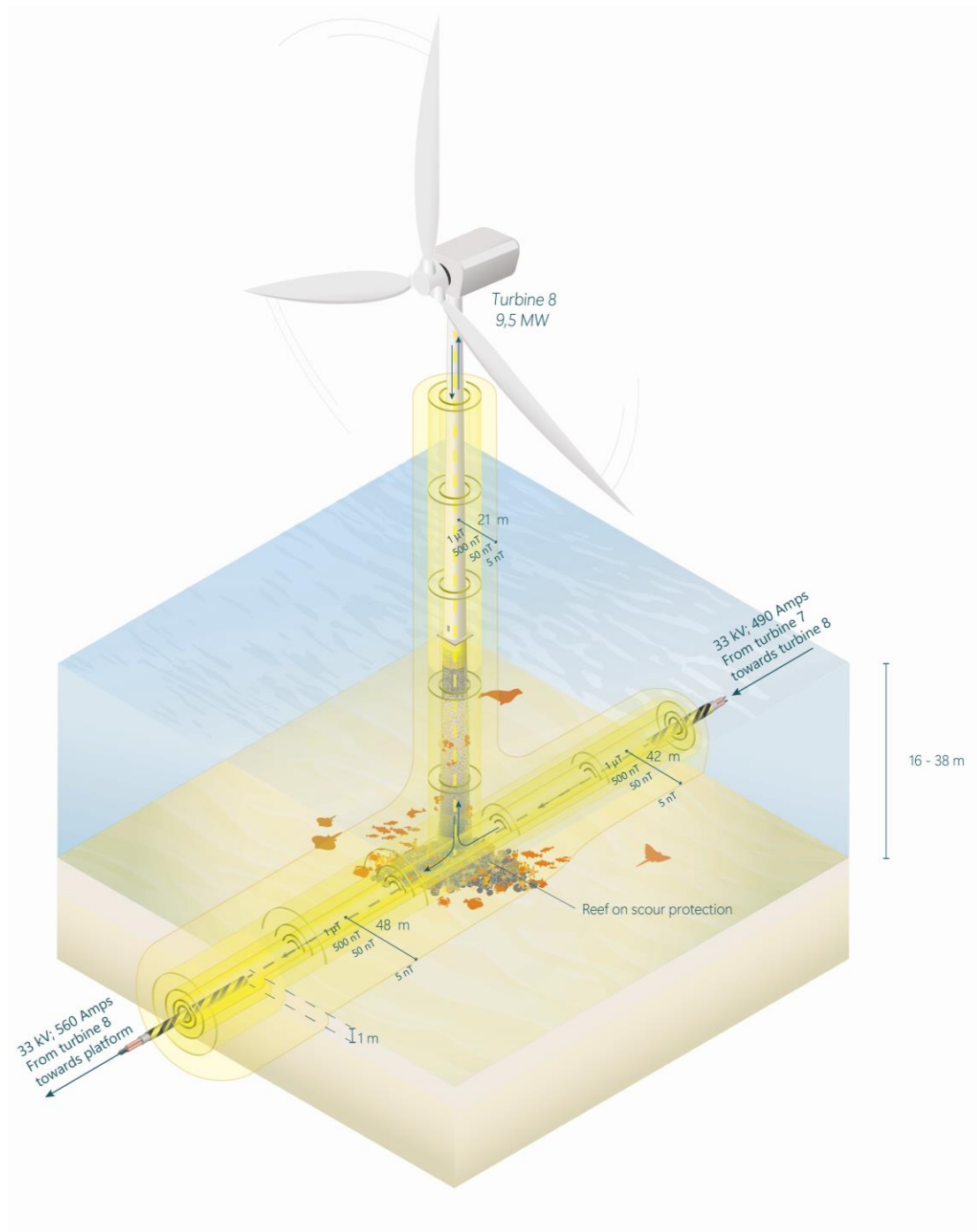
With these parameters known, the calculated volume fraction for the design capacity is shown in table 2.3. The radius of the 5 nT contour around a single turbine is around 4 to 5 times smaller than for the design current. The volume fractions are slightly lower than the area percentages, with the 66 kV wind farm once more slightly above the 33 kV wind farm.

Table 2.4 Volume percentages at design capacity for the 33 kV and 66 kV wind farms

Wind farm voltage	Volume percentage (design capacity)
33 kV	9,2
66 kV	12,2

Figure 2.7 zooms in on a single turbine, with the extent of the EMF shown to scale, which does visualise this vertical component of EMF from infield cables.

Figure 2.7 Visualisation on the extent of EMF around a turbine, with higher EMF strengths around the erosion protection. Note: the distances between the magnetic field segments are not drawn to scale in order to improve the visualization of the concept; however, the overall magnetic field boundaries are shown to scale



The method used to obtain the area ratio does introduce some errors (focusing on the 33 kV wind farms):

- the overlap of influenced area of nearby segments has been disregarded (mostly present near the centre of the wind farm). This implies that certain areas have been counted multiple times due to being positioned in the area of influence of different cable segments. This would occur mainly near the centre offshore substation where the cables converge, on the first 10 % of the first cable segment. Therefore, this introduces an overestimate of approximately 1,25 %;

- the sum of EMF of nearby cable segments could result in an increase of areas that would fall above the 5 nT threshold. For example, the EMF at a given point could be 4 nT due to the influence of a cable from string A, and similarly also be 4 nT due to the influence of a cable from string B. The individual EMFs would fall below the threshold, whereas the sum would fall above the threshold. The radius of EMF for a threshold of 2,5 nT is estimated to increase by approximately 40 % when compared to the 5 nT radius. The area of overlap would mainly occur near the centre of the wind farm, on 5 % of each first cable segment. Therefore, an underestimate of approximately 0,625 % is introduced.

For the 33 kV wind farms, the points above lead to an estimated error margin (overestimation) of the influenced area of 0,6 %. For the 66 kV wind farms, the same reasoning as above still applies. However, the influenced area is approximately 20 % greater. The estimated error margin (overestimation) of the influenced area for the 66 kV wind farms is therefore 0,7 %.

2.1.5 Differences between wind farms

A detailed comparison between the different wind farms is difficult to calculate, as parameters such as cable diameter per segment and geometry of each individual string is not known for the majority of the wind farms. Therefore, a general qualitative analysis will be provided in this section.

In order to describe the differences between wind farms, several assumptions have to be made. The cross-section area of a single phase is assumed to be equal to the values used in the earlier representation (i.e. 300, 300, 300, 500, 500, 630, 630, 800 mm²; from tail to head for the 33 kV farms). Furthermore, the area of each wind farm is assumed to be independent on the total power of the farm. The main factor for comparison in this case becomes the design current.

Of the four wind farms using a 33 kV operating voltage for their cables, TNW (Gemini) has the biggest (expected) design current of 560 A. OWEZ and Luchterduinen have an expected design current of 420 A, whereas Prinses Amalia has an expected design current of 280 A. As the magnetic field is dependent on the current divided by the square of the distance, compared to Gemini, the total area within the 5 nT contour will in turn be the square root of the current factor (e.g. the square root of 420 A / 560 A for OWEZ and Luchterduinen). This would result in approximately 87 % of the area percentage as calculated in section 2.1.4 for OWEZ and Luchterduinen, and approximately 71 % of the area percentage for Prinses Amalia.

Of the four wind farms using a 66 kV operating voltage for their cables, Borssele has the biggest (expected) design current of 665 A. Hollandse Kust (west) has an expected design current of 612 A, and Hollandse Kust (zuid) and Hollandse Kust (noord) have a design current of 577 A. Following the same calculations as shown above, the affected area in Hollandse Kust (west) would be approximately 96 % of the area percentage of Borssele. For Hollandse Kust (zuid) and Hollandse Kust (noord) this would be approximately 93 %.

3

PROTECTED SPECIES AND RATE OF ENCOUNTER

3.1 Protected species Dutch North Sea

In table 3.1, the relevant protected species in the Dutch North Sea are listed. Species occurring in the Dutch North Sea and protected under the Environment and Planning Act (EPA), in offshore Natura 2000 areas [6], and/or protected under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) [7] have been taken under consideration.

Table 3.1 Relevant protected species in the Dutch North Sea. The current conservation status is based on the 'Bouwstenen ten behoeve van het Strategisch Plan Natura 2000' and for OSPAR species, on the latest Quality Status Report [8]. If the 'bouwsteen' is not (yet) available, information from [9] has been used

Group	Species	Species (NL)	Protection regime	Conservation status in Dutch North Sea
Marine mammals	harbour porpoise (<i>Phocoena phocoena</i>)	bruinvis	EPA, Natura 2000, OSPAR	favourable (national conservation status), not good (OSPAR)
	common seal (<i>Phoca vitulina</i>)	gewone zeehond	EPA, Natura 2000	favourable (NCS)
	grey seal (<i>Halichoerus grypus</i>)	grijze zeehond	EPA, Natura 2000	favourable (NCS)
	white-beaked dolphin (<i>Lagenorhynchus albirostris</i>)	witsnuitdolfijn	EPA	not assessed
	minke whale (<i>Balaenoptera acutorostrata</i>)	dwergvinvis	EPA	not assessed
Migratory fish	houting (<i>Coregonus oxyrinchus</i>)	noordzeehouting	EPA, Natura 2000, OSPAR	moderately unfavourable (NCS)
	european sea sturgeon (<i>Acipenser sturio</i>)	europese steur	EPA, OSPAR	poor (OSPAR)
	allis shad (<i>Alosa alosa</i>)	elft	OSPAR, Natura 2000	not assessed (NCS), poor (OSPAR)
	twaite shad (<i>Alosa fallax</i>)	fint	Natura 2000	very unfavourable (NCS)
	salmon (<i>Salmo salar</i>)	zalm	Natura 2000, OSPAR	very unfavourable (NCS), poor (OSPAR)
	sea lamprey (<i>Petromyzon marinus</i>)	zeeprik	Natura 2000, OSPAR	very unfavourable (NCS), poor (OSPAR)
	river lamprey (<i>Lampetra fluviatilis</i>)	rivierprik	Natura 2000	moderately unfavourable (NCS)
	european eel (<i>Anguilla anguilla</i>)	paling	OSPAR	poor (OSPAR)

Group	Species	Species (NL)	Protection regime	Conservation status in Dutch North Sea
Elasmobranchs	basking shark (<i>Cetorhinus maximus</i>)	reuzenhaai	OSPAR	poor (OSPAR)
	thornback ray (<i>Raja clavata</i>)	stekelrog	OSPAR	good (OSPAR)
	spotted ray (<i>Raja montagui</i>)	gevelkte rog	OSPAR	good (OSPAR)
	spurdog (<i>Squalus acanthias</i>)	doornhaai	OSPAR	poor (OSPAR)
Benthic species and habitats	flat oyster and flat oyster reefs (<i>Ostrea edulis</i>)	platte oester en platte oesterriffen	OSPAR	poor (OSPAR)
	ocean quahog (<i>Arctica islandica</i>)	noordkromp	OSPAR	not assessed
	ross worm reefs (<i>Sabellaria spinulosa</i>)	zandkokerwormriffen	OSPAR	not assessed
other	atlantic cod (<i>Gadus morhua</i>)	kabeljauw	OSPAR	not assessed but threatened/in decline

For the selection of species protected under OSPAR, the overview in Bos & Tamis [7] has been used. This overview is complemented with the basking shark, which based on recent research, can also occur in Dutch wind farms [10]. The selection of Natura 2000 species is based on the conservation objectives of all marine and coastal Natura 2000 areas. For the selection of species protected under the Environment and Planning Act, the Naturalis Species Register has been analysed, filtered on species occurring more than ‘incidentally/periodically’ in the Dutch North Sea [11]. For marine mammals, this information has been complemented with the latest survey results of marine mammals in the Dutch North Sea, by Geelhoed et al. (2024) [12].

3.2 First ranking

3.2.1 Methods

The potential risk of species encountering EMF and experiencing associated effects, can be assessed with a risk assessment often used in ecological research [13], [14]. These risk assessments are based on an assessment of the *severity* of expected effects when exposed to the risk, and the *rate of encounter* with the risk (in this case, EMF).

3.2.2 Severity

The severity of expected effects is based on species’ sensitivity to EMF and their protection and conservation status (table 3.2). Species known to be able to detect electric and/or magnetic fields from offshore cables are attributed with a scoring of 3; species insensitive with 1, and species possibly sensitive with 2. The scoring of 2 applies to species that have been researched, but for which either results are inconclusive, or very limited with realistic EMF strengths. The conservation status and protection status show the relevance of the species in a policy context (table 3.1). If there are multiple assessments of the species (for instance both in the OSPAR context as well as in the national conservation status context), the average environmental status (rounded down, for a worst-case perspective) has been used.

To calculate the severity score, the average of the three categories has been calculated, with *sensitivity to EMF* weighted by a factor of 2 as EMF sensitivity is the most determining factor for expected effects. This leads to a severity score between 1-3. The severity scoring is summarised in table 3.2.

Table 3.2 Severity score

Severity score	1	2	3
sensitivity to EMF	insensitive to electric or magnetic fields from cables, or highly unlikely	possibly sensitive to electric or magnetic fields from cables (research has been done, but is inconclusive)	sensitive to electric or magnetic fields from cables, or unknown (worst-case approach)
current conservation status	good environmental status	moderate environmental status	poor environmental status
protection regimes	1 protection regime	2 protection regimes	3 protection regimes
severity score (weighted average)	$= (2 * \text{score sensitivity to EMF} + \text{score current conservation status} + \text{score protection regimes}) / 4$		

3.2.3 Rate of encounter

The rate of encounter is based on development and reproduction strategy, depth range, and seasonality (table 3.3) [2]. If development and reproduction occur in fresh water (away from wind farms), the score of 1 has been attributed. These species are not exposed to EMF from infield cables during embryonic development. Marine benthic eggs on the other hand, are at risk of developing fully within an EMF zone from a cable (score of 3). In between (score of 2) are the species that have a chance of being exposed to EMF during embryonic development, but if this happens, this would be brief: either pelagic eggs pass over a cable, or embryo-carrying adults pass the cables. Similar considerations apply to addressing depth range: pelagic species are likely to be exposed to low EMF levels (in the water column) (score of 1), and benthic species are likely to be exposed to high(er) EMF levels (score of 3). Lastly, the rate of encounter depends on the occurrence of the species in the North Sea, which is further elaborated on in chapter 4. Some species migrate and spend part of their life in fresh water. Others are present year-round, with higher risks of exposure.

To calculate the rate of encounter score, the average of the three categories has been calculated. This leads to a severity score between 1-3. The severity scoring is summarised in table 3.3.

Table 3.3 Rate of encounter score

Rate of encounter score	1	2	3
development and reproduction	takes place in fresh water or elsewhere	pelagic eggs, embryos in the belly or live birth	marine benthic eggs
depth range	pelagic species	benthopelagic	benthic species
seasonality	present <2 seasons/year	present 2-3 seasons/year or year-round for a portion of their life cycle	present year-round
rate of encounter score	$(\text{score development and reproduction} + \text{score depth range} + \text{score seasonality}) / 3$		

3.2.4 Risk

The risk is calculated from the severity and rate of encounters score, following the formula below:

$$\text{risk} = \sqrt{(\text{severity}^2 + \text{rate of encounter}^2)}$$

Instead of using the simpler and perhaps more intuitive approach of multiplying severity by the rate of encounter, we chose to use the 'Euclidean distance' formula to calculate risk. In ecological research, this makes sense because it ensures that an increase in either factor, severity or rate of encounter, will always result in a higher overall risk, regardless of the value of the other factor. This method also makes combinations of both high severity and high encounter rate stand out more, as high-risk situations.

Applying this formula to our categories of severity and rate of encounter, gives *possible* risk scores between 1.41 (if all aspects are score '1') and 4.24 (if all aspects are scored '3'). Assuming all combinations of scoring are possible, these risk scores can be divided into the lower third (score of < 2.65), middle third (score of 2.65 < R < 3.24) and higher third (score of > 3.24). These can be translated to low risk, medium risk, and high risk species, following similar research to the impact of fisheries on benthic habitats [14] and impacts of offshore developments on sharks and rays [13].

Table 3.4 shows a filled-in risk matrix based on the categories described above. This is followed by figure 3.1, which depicts the resulting risk levels. In the paragraphs below, the substantiation of the scoring is described in more detail for each assessed species.

Table 3.4 Risk score for the assessed species. Substantiation of the scoring is included in paragraph 3.3

Severity	harbour porpoise	common seal	grey seal	white-beaked dolphin	minke whale	houting	European sea sturgeon	allis shad	twaitte shad	salmon	sea lamprey	river lamprey	European eel	basking shark	thornback ray	spotted ray	spurdog	flat oyster	ocean quahog	ross worm reefs	atlantic cod	
sensitivity to EMF	2	1	1	2	2	3	2	3	3	3	3	3	2	3	3	3	3	3	3	3	3	2
conservation status	2	1	1	2	2	2	3	3	3	3	3	2	3	3	1	1	3	3	2	2	2	2
protection status	3	2	2	1	1	3	2	2	1	2	2	1	1	1	1	1	1	1	1	1	1	1
severity score	2.25	1.25	1.25	1.75	1.75	2.75	2.25	2.75	2.50	2.75	2.75	2.25	2.00	2.50	2.00	2.00	2.50	2.50	2.25	2.25	2.25	1.75
Rate of encounter																						
reproduction and development	2	2	2	2	2	1	1	1	1	1	1	1	1	2	3	3	2	3	2	2	2	2
depth range	2	2	2	2	2	1	3	1	2	1	2	2	1	1	3	3	2	3	3	3	3	2
seasonality	3	3	3	3	2	1	3	2	2	3	3	3	1	3	3	3	3	3	3	3	3	3
RoE score	2.33	2.33	2.33	2.33	2.00	1.00	2.33	1.33	1.67	1.67	2.00	2.00	1.00	2.00	3.00	3.00	2.33	3.00	2.67	2.67	2.67	2.33
overall risk score	3.24	2.65	2.65	2.92	2.66	2.93	3.24	3.06	3.00	3.22	3.40	3.01	2.24	3.20	3.61	3.61	3.42	3.91	3.49	3.49	3.49	2.92

Figure 3.1 Risk score based on the severity and rate of encounter



3.3 Species

In the following paragraphs, the substantiation of the scoring is described from high-risk species to lower-risk species.

3.3.1 High risk species (score >3.24)

Flat oyster and flat oyster reefs (*Ostrea edulis*)

Severity

So far, electroreception with specialized receptor cells has only been observed in vertebrates [15]. No specific research to sensitivity of flat oysters to EMF exists [1], [16]. Research to other bivalves (including North Sea species like the blue mussel (*Mytilus edulis*), and Baltic clam (*Limecola balthica*)) does not show effects of EMF on mortality, but there are several studies which show effects of exposure to (high) AC-fields on physiology (cellular processes) and development [1], [16]. As such, the flat oyster has been attributed a score of 3.

Rate of encounter

The flat oyster is a benthic species, settling on hard substrates on the seabed (score of 3). Larvae of this species are free-floating (pelagic), which would lead to a score of 2. However, the flat oyster is known to exhibit 'parental care' - the first days of larval development take place inside the female oyster shell, after which the larvae are released into the water column [17].

As part of the early development of these larvae takes place at the seabed, a score of 3 is attributed to *reproduction and development*. The species is present in the North Sea year-round (score of 3).

Thornback ray (*Raja clavata*)

Severity

Thornback rays are known to be sensitive to electromagnetic fields (score of 3), already at one-third of the duration of their embryonic development [18]. Field research to EMF effects on this species did not find predictable effects of EMF (50 HZ, AC cable) on behaviour, but did indicate subtle behavioural changes [19], [20]. Exposure of embryos to AC-fields in a laboratory setting did lead to increased activity in the embryos, which might lead to an increased predation risk [21].

Rate of encounter

Like most elasmobranchs, thornback rays deposit their egg cases at (or close to) the seabed, in coastal waters [21] (score of 3). The egg cases are sessile and are not likely to move during embryogenesis. Thornback rays are benthic species, living, resting and foraging close to the seabed [22] (score of 3). They are present in the North Sea year-round (score of 3), and are thought to be the most common elasmobranch species in offshore wind farms in the Netherlands [10].

Spotted ray (*Raja montagui*)

Severity

Spotted rays are elasmobranchs and sensitive to electromagnetic fields, although no specific field research to the species exists. Assuming their sensitivity to EMF is similar to sensitivity of related ray-species (e.g. [18] or [21]), they have been attributed a score of 3.

Rate of encounter

Spotted rays also deposit their egg cases at (or close to) the seabed, in coastal waters (score of 3), and they are benthic species which live, rest and forage close to the seabed (score of 3). The species is less common in the North Sea than the thornback ray, but it can be assumed they are present year-round (score of 3) (although in wind farms researched in [10] they have only been observed in summer and autumn).

Ocean quahog (*Arctica islandica*)

Severity

The ocean quahog is, like the flat oyster, a benthic bivalve to which no research to EMF effects exists. Following the line of reasoning as presented above, the ocean quahog has been attributed a score of 3.

Rate of encounter

The ocean quahog is a benthic species (score of 3) but unlike the flat oyster, it is not known to exhibit parental care. Larvae of the ocean quahog are free-floating (pelagic) and therefore attributed a score of 2. The species is present in the North Sea year-round (score of 3).

Ross worm (*Sabellaria spinulosa*)

Severity

Research to EMF effects on worms is limited [1], and research to *Sabellaria* is lacking. There are some indications that exposure to AC (or DC) EMF could have behavioural or physiological effects in worms, but studies are inconclusive [23], [24]. Since this is unknown for *Sabellaria*, the species has been attributed a score of 3.

Rate of encounter

Sabellaria forms tubes (made of sand) and as such, can form reefs at the seabed (score of 3). *Sabellaria* undergo free spawning, eggs are released into the water column and develop as free-floating larvae (score of 2) [25]. The species is present in the North Sea year-round (score of 3).

Spurdog (*Squalus acanthias*)

Severity

The spurdog, or spiny dogfish, is a shark species which can sense electric and magnetic fields like all elasmobranchs [26]. Whether EMF from power cables could affect the species, is not entirely clear: in a mesocosm experiment, no behavioural response was found when exposed to EMF from a 36 kV AC cable [19], [27], but this was done with a limited number of fish. From a precautionary point of view regarding their sensitivity to EMF from power cables, they have been attributed a score of 3.

Rate of encounter

The spurdog gives birth to live young (score of 2) and is a species which exhibits both benthic as well as pelagic behaviour (score of 2) [lit. 46]. Spurdogs undertake seasonal migrations [28] but are expected to be present in the North Sea year-round (score of 3).

Sea lamprey (*Petromyzon marinus*)

Severity

Lampreys are known to be electro-sensitive, but there is no evidence that lampreys also have the ability to detect magnetic fields [29]. There is no field research into this species group, so no research is available to specifically the effects of offshore cables and associated EMFs from these cables (score of 3).

Rate of encounter

Adult sea lampreys migrate to coastal areas after spending several years as larvae inhabiting (sandy) mud in freshwater regions [29]. They spend a few years at sea before returning to fresh water to spawn (score of 1). As such, for a portion of their life they are present at sea year-round (score of 3). Their depth range is complicated to assess, as field work to the species is sparse, and the depth range depends on the species they prey on. In [30], almost half of the host species of sea lampreys at sea seem to be demersal fish. Therefore, sea lampreys have been attributed a score of 2 (partially pelagic, partially benthic behaviour).

Harbour porpoise (*Phocoena phocoena*)

Severity

Harbour porpoises are possibly sensitive to electromagnetic fields (scoring of 2). A first behavioural study (laboratory study) with one individual did not show any significant behavioural effects of exposure to an AC-field with realistic field strengths (in the μT -range) [3]. In addition, a study in Dutch offshore wind farm Borssele found no correlation between proximity to cables and porpoise acoustic activity [31], and as hearing is considered the primary sense, effects are considered unlikely [1]. Nevertheless, as related species show sensitivity to the Earth's magnetic field (for navigation) [32], [33] and the knowledge base is still limited, the species is still considered possibly sensitive for EMF.

Rate of encounter

Harbour porpoises carry their young during pregnancy, and give birth to live offspring (scoring of 2). Harbour porpoises feed on pelagic fish, but also on benthopelagic or benthic fish (e.g. sandeel) and crustaceans [34], [35]. Therefore, their behaviour can be considered partially pelagic, partially benthic (scoring of 2). Although sometimes in slightly different densities, harbour porpoises are present in the North Sea year-round (scoring of 3) [36], [37].

European sea sturgeon (*Acipenser sturio*)

Severity

Although no research has been done to specifically the European sturgeon, it is known the family of sturgeons (Acipenseridae) can sense both magnetic and electric fields [29]. Research to the green sturgeon, Atlantic sturgeon and pallid sturgeon has not found negative effects of DC cables on sturgeon migration [29], [38]. Effects of AC cables have not been researched in the field, but a laboratory study to effects of AC EMFs did not find any behavioural effects [39].

All studies to date suggest sturgeon seem to be able to detect EMF, but their response is likely subtle and it is unclear whether specifically EMF from infield-cables affects the species. Therefore, this species has been attributed a score of 2.

Rate of encounter

Sturgeons spawn in fresh water (score of 1) and is a benthic species, which feeds on benthic animals such as worms and crustaceans [40] (score of 3). European sturgeons have a complex life cycle, growing up in fresh water, moving downstream to the estuaries during the first few years of the juvenile stage, spending time at sea until they become adults (10 - 16 years old) and from then, returning to freshwater each year to spawn [41]. Since in some life stages the species could be present in the North Sea year-round, they have been attributed a score of 3.

3.3.2 Medium-risk species

Salmon (*Salmo salar*)

Severity

Salmons are known to be especially sensitive to electric and magnetic fields, using these senses for large-scale migrations [29]. As such, most studies have been conducted to sensitivity to the Earth's magnetic field (DC). A study that has looked into effects of EMF from DC cables on salmon migration [42], demonstrated some individuals showing avoidance and some showing attraction toward the cable. To our knowledge, no research on the potential effects of AC-cables has been conducted (score of 3).

Rate of encounter

Also the salmon spawns in freshwater (score of 1) and spends most of their adult life at sea [43]. For this portion of their life, they are considered pelagic species [44], [45] (score of 1), which are present at sea year-round for several years (score of 3) [43].

Basking shark (*Cetorhinus maximus*)

Severity

Basking sharks are elasmobranchs, which are known to be sensitive to both electric fields and magnetic fields (score of 3). It is however not known how sensitive they specifically are [46], nor whether they respond to EMF from power cables [47].

Rate of encounter

Contrary to most elasmobranch species, basking sharks give birth to live young (score of 2) and are pelagic, feeding on zooplankton in the water column (score of 1). Their presence in the (Dutch) North Sea is not fully known. Based on recent eDNA research, the species can be present in Dutch waters during winter [10], although previous research suggested presence in mainly the summer months [48], [49]. From a worst-case perspective, the species is assumed to be present year-round (score of 3).

Allis shad (*Alosa alosa*)

Severity

There are no studies to the sensitivity of allis shads to EMF, likely because the species is highly sensitive to handling and stress [29]. Allis shads undertake long-distance migrations, but it is unknown whether they use the Earth's magnetic field (magneto-sensitivity) for these migrations. As such, the allis shad has been attributed a score of 3.

Rate of encounter

The allis shad spawns in freshwater (score of 1) and grows up at sea and in the lower reaches of estuaries. It is a pelagic species which feeds on plankton [50] (score of 1) and each year, this species migrates between fresh and salt water, and vice versa (score of 2).

River lamprey (*Lampetra fluviatilis*)

Severity

See paragraph 'sea lamprey'.

Rate of encounter

Compared to the sea lamprey, the river lamprey is more of a predatory fish as opposed to a parasite [65]. Similar to the sea lamprey, almost half of their prey species are demersal fish [30]. Based on this, and their prey species as listed in [66], their depth range is considered to be partially benthic and partially pelagic in marine waters (score of 2) (as opposed to their benthic larval development in fresh water). Like sea lampreys, adult river lampreys migrate to coastal areas after spending several years as larvae inhabiting (sandy) mud in freshwater regions [29]. They spend a few years at sea before returning to fresh water to spawn (score of 1). As such, for a portion of their life they are present at sea year-round (score of 3).

Twaite shad (*Alosa fallax*)

Severity

For the twaite shad there are no studies to the sensitivity of the species to EMF [29], and it is also unknown whether the species uses the Earth's magnetic field for migrations (score of 3). Research in the Western Scheldt has shown that the Borssele export cable does not seem to negatively impact twaite shad migration, at least not on a large scale [51], [52].

Rate of encounter

The twaite shad spawns in freshwater (score of 1) and grows up in the lower reaches of estuaries and at sea. It is a pelagic species which feeds mainly on plankton, but also on shrimp (a more benthic species). From a precautionary point of view regarding their depth range, they have been attributed a score of 2 [53]. Each year, this species migrates between fresh and salt water, and vice versa (score of 2).

Houting (*Coregonus oxyrinchus*)

Severity

The houting is a salmonid, and as a group they are known to be sensitive to electric and magnetic fields [29]. This particular species has never been researched specifically, and nothing is known about their specific sensitivity and potential effects of power cables on the species (score of 3).

Rate of encounter

The houting was thought to be extinct in the Netherlands, but after reintroduction efforts in 1996 - 2006 there has been a stable population in rivers and lakes in the Netherlands (mainly Lake IJssel) [54]. Houting is a pelagic species, as it mainly feeds on zooplankton and smaller fish [55]. It is a migrating species which reproduces in fresh water (score of 1), but based on latest knowledge, at least a part of the population even fulfils their entire life cycle in fresh water [54]. Therefore, it is assumed that the species occurs in the North Sea <2 seasons/year (score of 1).

White-beaked dolphin (*Lagenorhynchus albirostris*)

Severity

White-beaked dolphins are, like all dolphins, assumed to be sensitive to electric fields. While this has not been specifically researched for this species, research to the related Guiana dolphin and bottlenose dolphin has shown sensitivity to low AC electric fields [32], [56], [57]. Dolphins are highly sensitive to electric fields, as low as $2.4 \mu\text{V cm}^{-1}$ [32], where sensitivity for AC fields decreased with increasing frequency (tested for frequencies up to 25 Hz). As such, it remains the question whether they are sensitive to EMF from 50 Hz AC power cables (scoring of 2).

Rate of encounter

Like all dolphins, the white-beaked dolphin carries their young during pregnancy, and gives birth to live offspring (scoring of 2). The white-beaked dolphin feed on pelagic and benthic fish (such as sandeel), and they spend most of their time diving and foraging in either the water column or close to the seabed (scoring of 2) [58]. According to Geelhoed (2024) it can be assumed that reproduction of this species takes place in the Dutch North Sea, although at low rate [12]. Specific abundance estimates are not available for the Dutch North Sea, but it is known the species is present year-round [12] (scoring of 3).

Atlantic cod (*Gadus morhua*)

Severity

Research to the potential effects of EMF on Atlantic cod has been focused on the effects of magnetic DC-fields on cod larvae [59]. During exposure to DC-fields (22 - 156 uT, 10 minutes) the majority of cod larvae showed decreased swimming speeds. It is not clear to which extent these results also apply to AC-fields. Field research so far has shown no adverse effects of wind farms on Atlantic cods and do not point towards EMF effects inside wind farms [60], [61]. Therefore, they have been attributed a score of 2: they are possibly sensitive to electric or magnetic fields from cables, and research has been done, but is inconclusive.

Rate of encounter

Atlantic cods are present in the North Sea year-round (score of 3), although their distribution is shifting northward and abundance is decreasing in the Southern North Sea [62]. They are a benthopelagic species, foraging mainly just above the seafloor. In juvenile life stages, they also exhibit (more) pelagic behaviour (score of 2) [63]. Regarding reproduction, Atlantic cods spawn close to the seabed, in coarse sand areas, after which the planktonic eggs are dispersed over large distances (score of 2) [64].

Minke whale (*Balaenoptera acutorostrata*)

Severity

Whether the minke whale specifically is sensitive to EMF is unknown, but seeing their large-scale migration and likely dependence on the Earth's magnetic field for these migrations, they can be considered possibly sensitive to electromagnetic fields from cables (scoring of 2).

Rate of encounter

Minke whales give birth to live offspring (scoring of 2). One of their most important food sources is sandeel, which occurs partially buried in the seabed, complemented by several pelagic fish species [67]. This leads to a depth range scoring of 2. The seasonal occurrence of the minke whale is not entirely clear in the Dutch North Sea; it is present at least from May until September [12] and are known to undertake seasonal migrations [67] (scoring of 2).

3.3.3 Low-risk species

Common seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*)

Severity

Like discussed in [1], pinnipeds, like the harbour seal and grey seal are not known to be electro- or magneto-sensitive [68]. They do not have electroreceptors, and the Earth's magnetic field does not seem to play any role in orientation and navigation [69]. Therefore, it is likely that there is no significant effect of EMF on this species group.

Rate of encounter

Seals occur in offshore wind farms and give birth to live young on intertidal flats (score of 2). They exhibit partially pelagic, partially benthic behaviour as they forage on both pelagic and benthic species (score of 2) [70], [71]. They are present in the North Sea year round (score of 3), although their densities are higher close to shore, in the Delta, and in the Wadden Sea [72], [73].

European eel (*Anguilla anguilla*)

Severity

Research to the sensitivity of the European eel to AC-fields has been summarized in [1]: *'While the magneto-sensitivity of European eels was already known [74] latest findings suggest magnetic map orientation of the European eel to the Gulf Stream System [75], 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 [76]. 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 [76]. Field research along an offshore cable trace in Denmark (HVAC) also did not find any indication the emitted EMF had effect on the (migratory) behaviour of eel, drawing similar conclusions [77]. Correspondingly, eels did not display differences in movement or swimming activity when exposed to a 9.6 μ T 50 Hz AC field in laboratory settings [78].'* As such, European eels are sensitive to EMF, but might not be affected by AC-EMF from subsea power cables. Therefore, they have been attributed a scoring of 2.

Rate of encounter

The European eel is estimated to spend only a brief time in the North Sea, once when migrating as larvae/juveniles from the Sargasso Sea to fresh water, and once as adults on their return-migration. As reproduction only takes place in the Sargasso Sea, they have been attributed a score of 1. Eels exhibit both benthic and pelagic behaviour, although during migration (so when they occur in the North Sea), they are assumed to be pelagic as the sole goal is to migrate, and they don't feed during this migration (score of 1). They have a wide range in migration speed (6.8 - 45.2 km/day) and are therefore expected to be present in the North Sea <2 seasons/year (score of 1) [79].

4

ANALYSIS

In chapter 3, species occurring in the North Sea have been attributed a general scoring based on their sensitivity to EMF and their expected rate of encounter with EMF from infield-cables. As the scoring of their potential rate of encounter has been based on life-history traits, this leads to one general scoring for each species, for the entire Dutch North Sea.

The actual distribution of the analysed species in the North Sea (and with that, in different wind farms in the North Sea) also depends on other habitat preferences such as average temperatures, salinity, substrate type, and current speed. Some species are specifically bound to certain spawning grounds, only settle on certain substrate types, or are known to avoid certain habitats. Because of this, for some species a general 'North Sea-scoring' might not provide the necessary level of detail to properly formulate recommendations for future research or mitigating measures on a wind farm scale. In paragraph 4.1, the distribution data of the assessed species is presented, and paragraph 4.2 describes the consequences of this for the risk scoring.

4.1 Species distribution

Information on distribution in the Dutch North Sea is based on MarLIN data (the Marine Life Information Network) and additional sources for cetaceans [36]¹, [80], seals [81], benthos (with an emphasis on priority areas regarding conservation targets) [82], [83], [84], cod [64], salmon [85], [86], and sharks and rays [28]. For migrating fish species. No full coverage distribution data is available for the Dutch North Sea. In Appendix I, notes on the distribution of the assessed species are summarised and where available, shown on maps.

4.2 Considerations for risk scoring

Based on these distribution data, for some wind farms there are considerations to deviate from the general risk scoring presented in chapter 3. These considerations are summarized in table 4.2.

Table 4.1 Considerations for risk scoring, regarding general distribution of species

Wind farm	Considerations for risk scoring
Luchterduinen	ocean quahog not present, no known occurrence of <i>Sabellaria</i>
OWEZ	ocean quahog not present, some limited overlap with areas that are considered potentially suitable for flat oyster restoration, no known occurrence of <i>Sabellaria</i>
Prinses Amalia	ocean quahog not present, some limited overlap with areas that are considered potentially suitable for flat oyster restoration, no known occurrence of <i>Sabellaria</i>
Borssele	ocean quahog not present, some overlap with areas that are considered suitable for <i>Sabellaria</i> , slightly higher abundance of thornback ray

¹ From Gilles et al. (2023) more recent distribution data is available, but the 'survey blocks' this data is reported in, does not allow for making a distinction between different wind farms in the Dutch North Sea.

Wind farm	Considerations for risk scoring
Hollandse Kust (zuid)	ocean quahog not present, no known occurrence of <i>Sabellaria</i>
Hollandse Kust (noord)	ocean quahog not present, no known occurrence of <i>Sabellaria</i>
Hollandse Kust (west)	ocean quahog not present, no known occurrence of <i>Sabellaria</i>
Ten Noorden van de Wadden	ocean quahog not present, some limited overlap with areas that are considered potentially suitable for flat oyster restoration, recurrent spawning area for cod, no known occurrence of <i>Sabellaria</i>
IJmuiden Ver	ocean quahog not present, some overlap with areas that are considered suitable for <i>Sabellaria</i>
Nederwiek	limited presence of the ocean quahog, some overlap with areas that are considered suitable for <i>Sabellaria</i> , slightly higher abundance of thornback ray and spotted ray
Doordewind	ocean quahog not present, high overlap with areas that are considered potentially suitable for flat oyster restoration, relatively high occurrence of the white-beaked dolphin, recurrent spawning area for cod, no known occurrence of <i>Sabellaria</i>

In many wind farms, the ocean quahog (which inhabits silty sediments) does not occur, because in the Dutch North Sea, these silty sediments are limited to the former Oyster Grounds. For *Sabellaria* reefs and flat oyster reefs on the other hand, the presence of wind farms leads to availability of suitable settlement substrate (hard substrates) in areas where previously, only soft sediments were available. Because of this, even though these species have not been found yet in certain locations, this might change over the years. This is not the case for the ocean quahog.

Wind farm Doordewind stands out for its especially high potential for flat oyster restoration (high habitat suitability), recurrent cod spawning occurs here, and also 'northern' species like the white-beaked dolphin occur in higher densities here, than in the other Dutch wind farms of the 2030 Routekaart.

Regarding fish species, in wind farms located in the western part of the North Sea towards the UK border, the thornback ray (Borssele, Nederwiek) and spotted ray (Nederwiek) are expected to be present in slightly higher densities than in the other wind farms. Distribution data of the other migrating fish and marine mammals do not lead to an alternative risk scoring, since their presence can be assumed everywhere in similar abundance (sometimes approaching zero, as for the allis shad, houting, and European sturgeon).

5

FINDINGS AND RECOMMENDATIONS

5.1 Main findings

The main factors determining the EMF around infield cables in Dutch North Sea wind farms are the amount of electrical current flowing through the cables, the distance from the cable, the cable's physical design (arrangement and spacing of the cable cores, cross-sectional area, and the lay-length of the cables), and the burial depth. Newer wind farms use higher voltages and larger turbines, which result in higher currents and generally larger areas of the seabed being influenced by EMF, especially during periods of high wind (occurring more in winter).

For many wind farms however, information especially about the lay length of the cables and the actual operational currents is missing or not (publicly) available. These gaps make it difficult to model EMF precisely and assess its potential effects on protected marine species. Still, based on species' conservation status, protection status, sensitivity to EMF, method and location of reproduction, depth range, and occurrence in the North Sea, a risk assessment could be made. This has resulted in an overview of species at high, moderate, and low risks of EMF exposure as summarised in table 5.1. For the policy-relevant benthos, the flat oyster has the highest risk score; for migrating fish, this is the sea lamprey. For elasmobranchs, the thornback ray and spotted ray are at highest risk, and for marine mammals it is the harbour porpoise.

Table 5.1 Summary of findings, risk score and notes on specific wind farms. Species at high risk (red), medium risk (yellow) and low risk (green)

Species	Score	Notes on specific wind farms	Species	Score	Notes on specific wind farms
flat oyster	3.91	high potential in Doordewind	salmon	3.22	-
thornback ray	3.61	slightly higher abundance in Borssele and Nederwiek	basking shark	3.20	-
spotted ray	3.61	slightly higher abundance in Nederwiek	allis shad	3.06	extremely rare
ocean quahog	3.49	only possibly occurs (in a limited area) within Nederwiek	river lamprey	3.01	-
ross worm (<i>Sabellaria</i>)	3.49	suitable habitat in especially Ijmuiden Ver , Nederwiek and Borssele , currently not present elsewhere	twaite shad	3.00	-
spurdog	3.42	-	houting	2.93	extremely rare
sea lamprey	3.40	-	white-beaked dolphin	2.92	slightly higher abundance in Doordewind
harbour porpoise	3.24	-	atlantic cod	2.92	Doordewind recurrent spawning area
sturgeon	3.24	extremely rare	minke whale	2.66	-
			common seal	2.65	-
			grey seal	2.65	-
			european eel	2.24	-

Calculations indicate that the surface area potentially impacted by EMF exposure is maximum of 13 %, which may appear limited. However, this estimate does not account for several important factors. EMFs extend vertically into the water column, creating a three-dimensional exposure zone. EMF emissions from turbine structures themselves are not included in this calculation. Furthermore, organisms may experience repeated exposure over time, and there is currently no data available on the effects of cumulative or repeated exposure, nor on potential habituation processes.

5.2 Recommendations

5.2.1 Research and monitoring recommendations

There is a lack of in-field measurements of EMF in offshore wind farms, which limits the extent to which existing research to effects of AC-cables on marine species can be used to predict actual effects in the Dutch North Sea. Where there currently is a standard monitoring and research requirement for installing and using export cables, this is not yet the standard for infield-cables. Also applying this monitoring and research requirement for wind farms, is a research recommendation closely related to the policy recommendations described below (paragraph 5.2.2).

Regarding specific species, for several high-risk species knowledge of potential EMF effects is lacking (flat oyster, *Sabellaria*, ocean quahog, sea lamprey). As ocean quahogs currently (and in the near future) do not occur within the expected extend of the EMF from infield cables, especially research to the high-risk species flat oyster and *Sabellaria* is recommended, followed by research to the sea lamprey, a species with a lower risk of exposure. Research into the effects of EMF on flat oysters (*Ostrea edulis*) and *Sabellaria* can be undertaken under controlled laboratory conditions, applying the exposure values presented in this report.

As neither species falls under animal welfare legislation, and given that flat oysters are routinely maintained under ex situ conditions, the proposed research can feasibly be completed within a limited timeframe (<1 year) and budget (<€ 100,000). To safeguard both the technical integrity and ecological validity of the study, it is recommended that the work is carried out by an experienced research institute with demonstrated expertise in EMF exposure studies.

Research into the magneto- and electrosensitive rays remains a priority, and research to migratory fish could, from a risk perspective, focus on the sea lamprey. Other migrating fish either have a lower protection status, and/or have a lower occurrence in the Dutch North Sea, and/or spend less time in vicinity of EMF (more pelagic species). For marine mammals, research could focus on the harbour porpoise seeing their high occurrence, high protection status and possible sensitivity to EMF.

5.2.2 Policy recommendations

In an EMF workplan developed in 2024 [92], suggestions have been made on how to advance knowledge development on the topic of EMF effects on marine species, which possible mitigating measures exist, and how precautionary principle¹ could be interpreted and applied.

One of the recommendations in this workplan was to investigate the potential effects of infield-cables further, for which this study provides the first steps.

A possible approach to the precautionary principle as suggested in [92], is to work with certain threshold values (e.g. a maximum percentage of the Dutch continental shelf (NCP) which may be affected by EMF). The calculations in this report show that it is possible to calculate the affected area in different wind farms based on cable characteristics, but that the most important piece of information that is missing, is information about the lay length. Seeing the large impact the lay length has on the extend of the EMF (see paragraph 2.1.2, and specifically figure 2.3), gaining knowledge on this is crucial. This will eventually result in realistic modelled scenarios, improving the quality of the risk assessment for EMF-sensitive species. As also suggested in [91], a policy measure should be to include the requirement to document infield-cable properties (including but not limited to burial depth, cable diameter, materials used and especially lay-length) in site decisions.

¹ The precautionary principle is a concept within environmental policy, which holds that action should be taken to prevent potential environmental harm, even if there is scientific uncertainty about the effects of the activity. For background information on this topic in relation to potential EMF effects, we refer to the EMF workplan [92] and Appendix I of this workplan.

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Appendices

SPECIES DISTRIBUTIONS

I.1 Species distributions in the North Sea

Table I.1 summarises the main differences in species distribution within the Dutch North Sea, which could be relevant for the risk assessment.

Table I.1 Remarks regarding distribution of species in the Dutch North Sea

Group	Species	Remarks regarding distribution
Marine mammals	harbour porpoise (<i>Phocoena phocoena</i>)	depending on the source, slightly higher densities towards Noord-Holland [36] and towards Germany, where they are known to reproduce [80]
	common seal (<i>Phoca vitulina</i>)	occur in high densities in and around the Wadden Sea and Delta, with in the North Sea highest densities close to shore [81]
	grey seal (<i>Halichoerus grypus</i>)	
	white-beaked dolphin (<i>Lagenorhynchus albirostris</i>)	low occurrence Southern North Sea, higher occurrence towards the north of the North Sea [80]
	minke whale (<i>Balaenoptera acutorostrata</i>)	in general, low occurrence in the Dutch North Sea [80]
Migratory fish	houting (<i>Coregonus oxyrinchus</i>)	(very) rare, these species occur in very low densities in the Dutch North Sea
	european sea sturgeon (<i>Acipenser sturio</i>)	
	allis shad (<i>Alosa alosa</i>)	distribution and habitat range at sea is not well known for shads [52], but the allis shad is considered virtually extinct in the Netherlands
	twait shad (<i>Alosa fallax</i>)	distribution and habitat range at sea is not well known for shads [52]
	salmon (<i>Salmo salar</i>)	higher densities are expected in proximity to Rhine and Meuse deltas [85], [86], after which migration is mainly northwards [87]
	sea lamprey (<i>Petromyzon marinus</i>)	distribution and habitat range at sea is not well known for lampreys [29]
	river lamprey (<i>Lampetra fluviatilis</i>)	
	european eel (<i>Anguilla Anguilla</i>)	spends limited time in the Dutch North Sea as the area is mainly used as migratory route between fresh water and the Sargasso Sea [88]
Elasmobranchs	basking shark (<i>Cetorhinus maximus</i>)	occurs in the Dutch North Sea in, but is mainly seen in UK waters (MarLIN)
	thornback ray (<i>Raja clavata</i>)	occurs in low densities in the entire Dutch North Sea, with higher densities towards UK waters [28]
	spotted ray (<i>Raja montagui</i>)	occurs in low densities in the entire Dutch North Sea, with higher densities towards UK waters [28]
	spurdog (<i>Squalus acanthias</i>)	occurs in low densities in the entire Dutch North Sea [28]

Group	Species	Remarks regarding distribution
Benthic species and habitats	flat oyster and flat oyster reefs (<i>Ostrea edulis</i>)	restoration projects ongoing, present in the Voordelta, potentially suitable habitat in and around the former Oyster Grounds [83]
	ocean quahog (<i>Arctica islandica</i>)	higher densities in and around the former Oyster Grounds [89]
	ross worm reefs (<i>Sabellaria spinulosa</i>)	higher densities in sandy sediments and around areas with sand waves [84], [90], towards the UK and the Frysian Front [83]
other	atlantic cod (<i>Gadus morhua</i>)	occurs in the entire North Sea, distribution shifting northwards, and recurrent spawning areas are located north of the Wadden Islands [91]

Distribution maps

In the figures below, distribution data of the selected species (when publicly available) is shown. For the harbour porpoise, two distribution maps are shown. One from Waggit et al. (2020) and one from Gilles et al. (2020). The Waggit et al. (2020) maps are based on several different types of surveys and species distribution models; Gilles et al. (2020) is based on aerial surveys, and this reference is normally used in Dutch policy documents. For the migratory fish, no distribution data covering the North Sea are available. For the flat oyster (*Ostrea edulis*) and the Ross worm (*Sabellaria spinulosa*), occurrence maps as well as habitat suitability maps have been shown.

Figure I.1 Harbour porpoise distribution in the North Sea from Waggit et al. (2020) [80] (left) and Gilles et al. (2020) (right) [36]. For underlying assumptions and methodology, see the cited sources

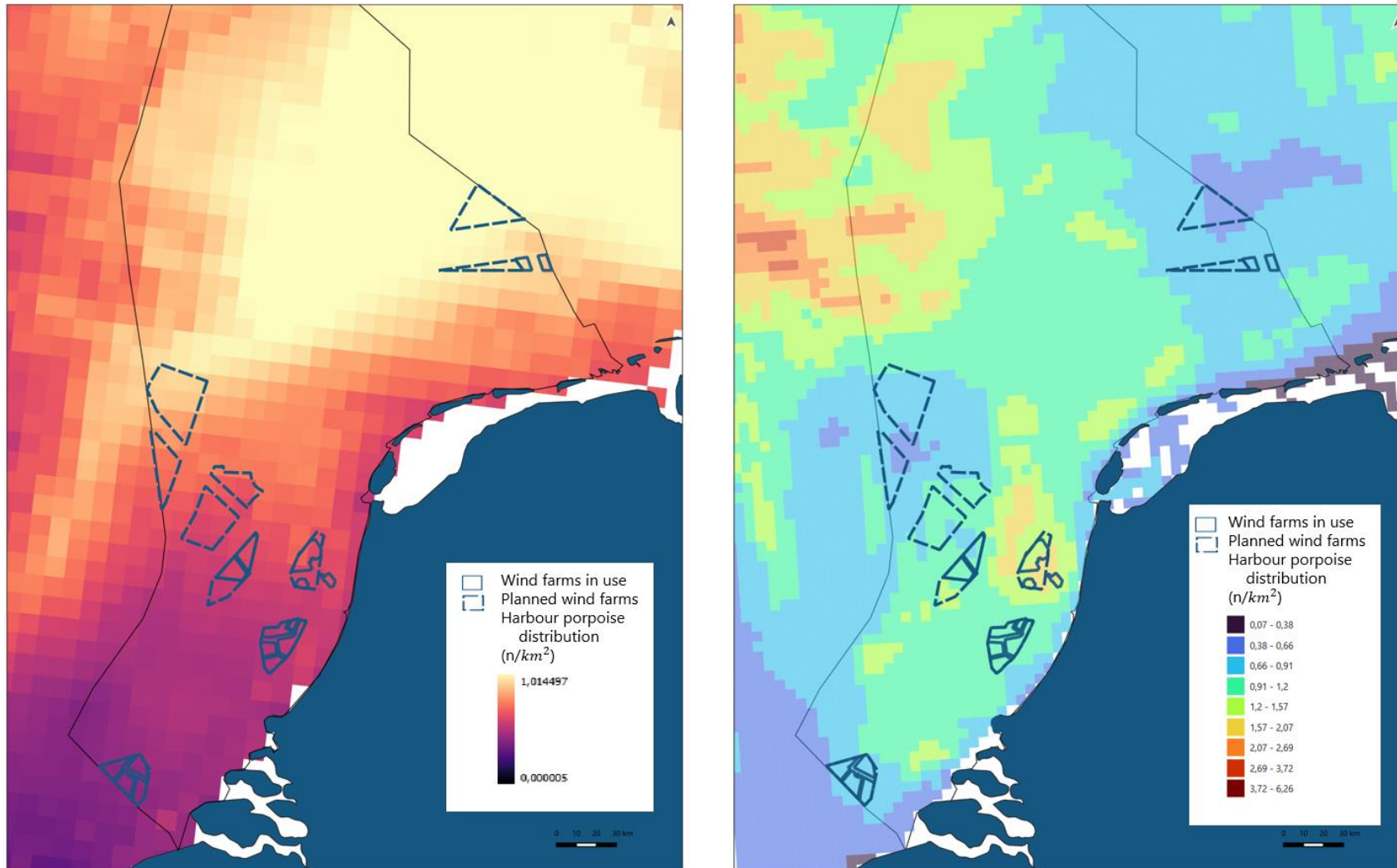


Figure I.2 Common seal (left) and grey seal (right) distribution in the North Sea [81]. For underlying assumptions and methodology, see the cited sources

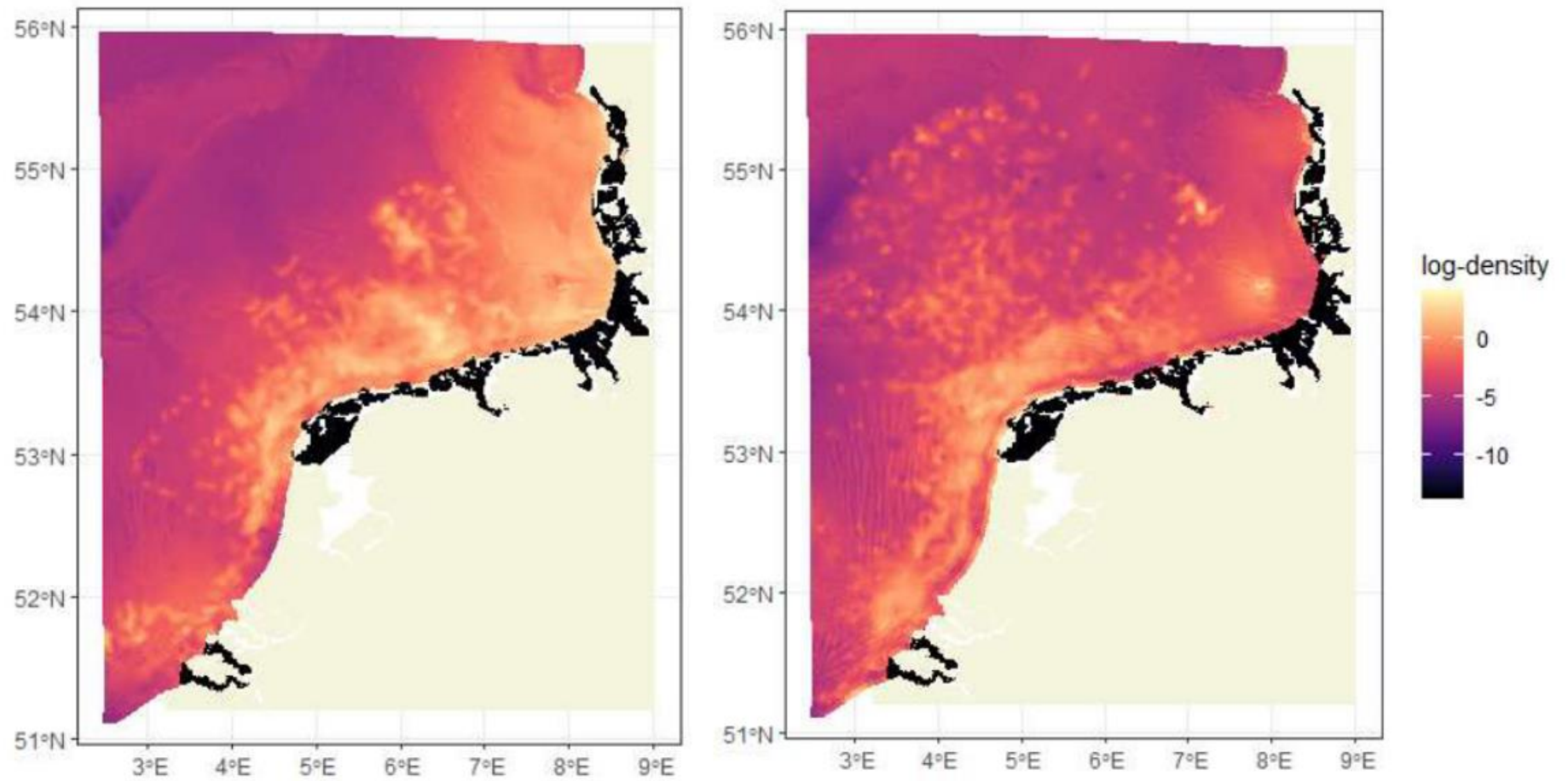


Figure I.3 Minke whale (left) and white-beaked dolphin (right) distribution in the North Sea from Waggit et al. (2020) [80]. For underlying assumptions and methodology, see the cited sources

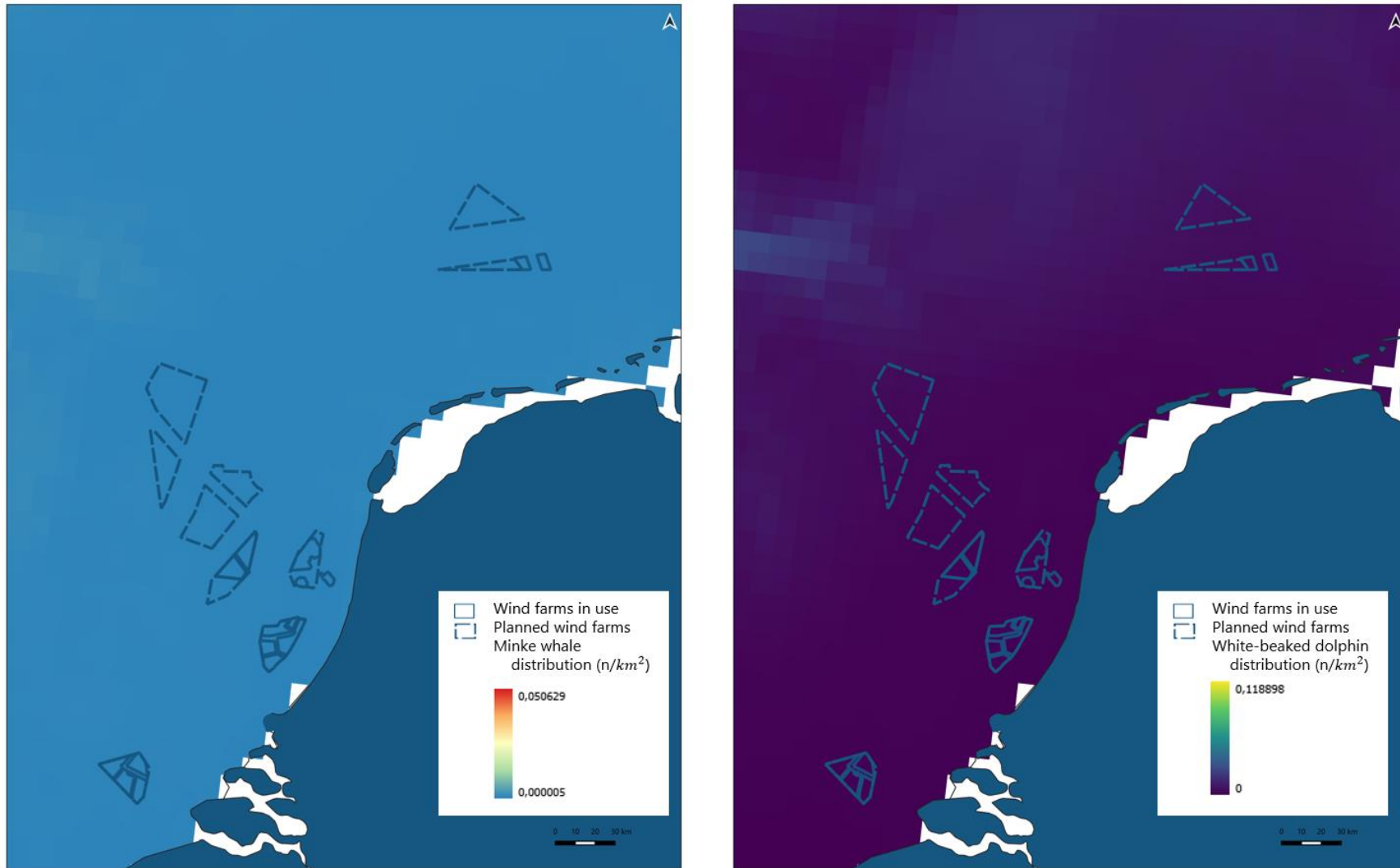


Figure I.4 Sabellaria occurrence (left) and predicted habitat suitability (right) in the North Sea from Herman & van Rees (2022) and MONS monitoring, retrieved from Informatiehuis Marien

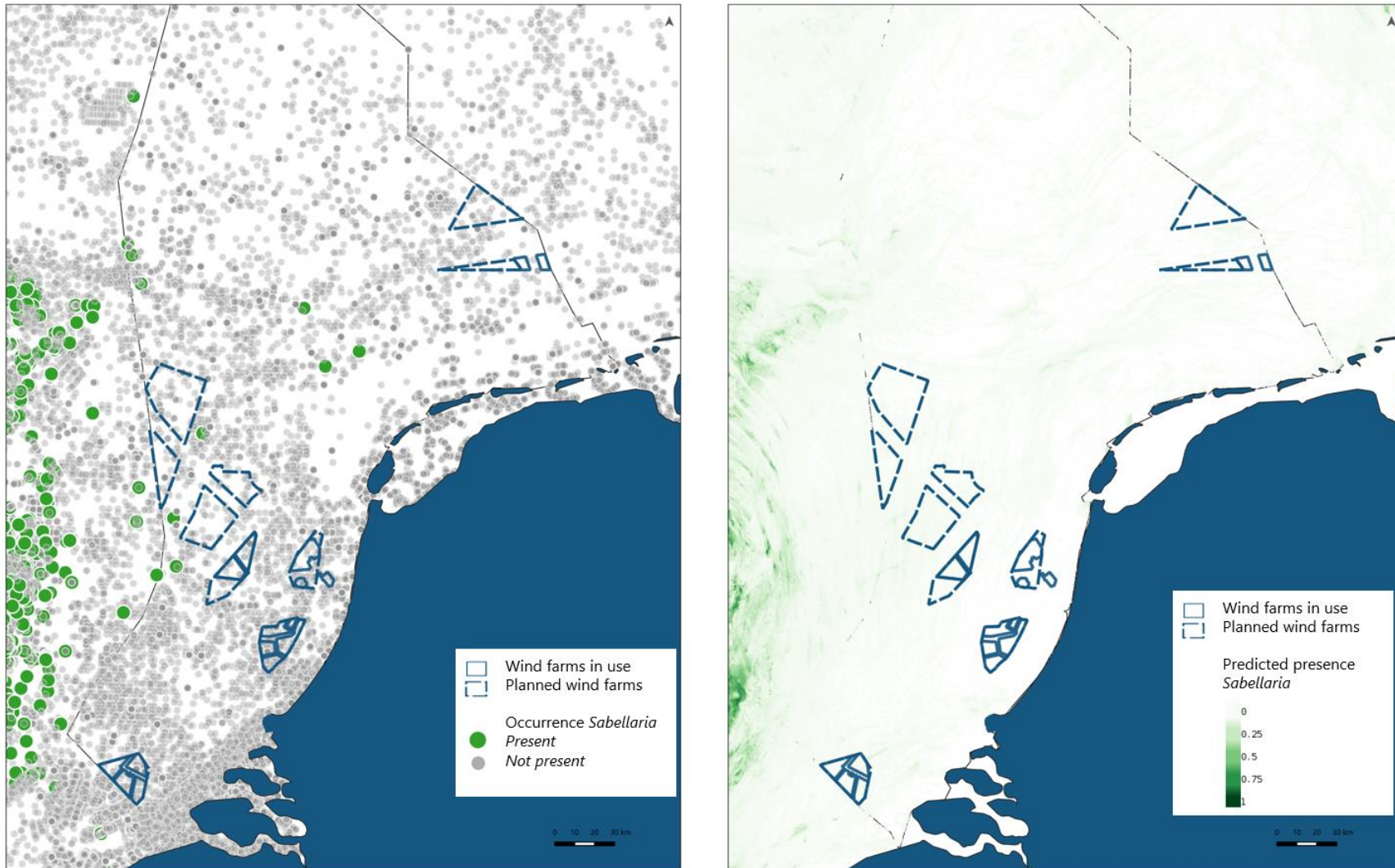


Figure I.5 Flat oyster occurrence (left) and predicted habitat suitability (right) in the North Sea from Herman & van Rees (2022) and MONS monitoring, retrieved from Informatiehuis Marien

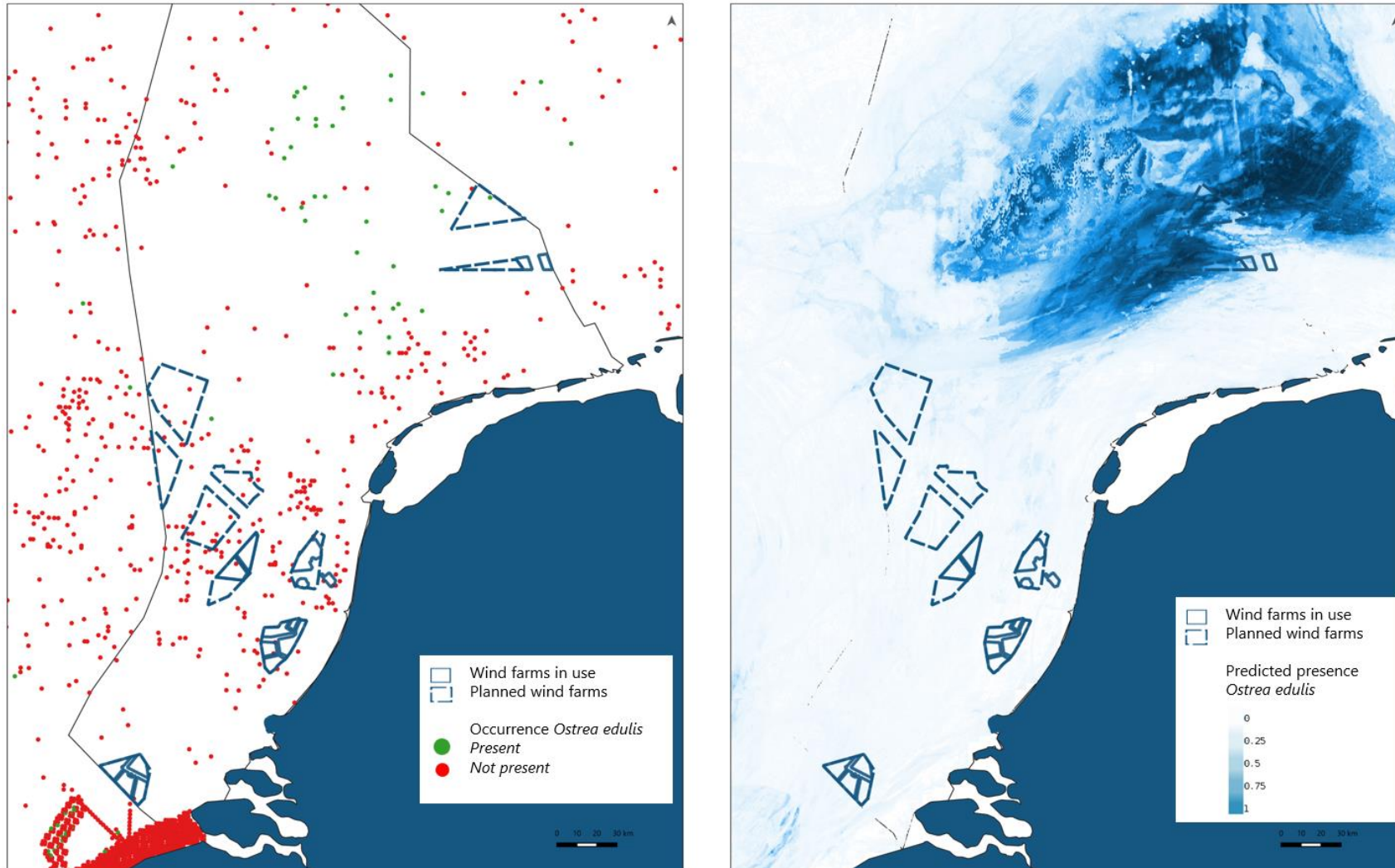


Figure I.6 Distribution of the thornback ray (left), spotted ray (middle) and spurdog (right) from Sguotti et al. (2016) [28]

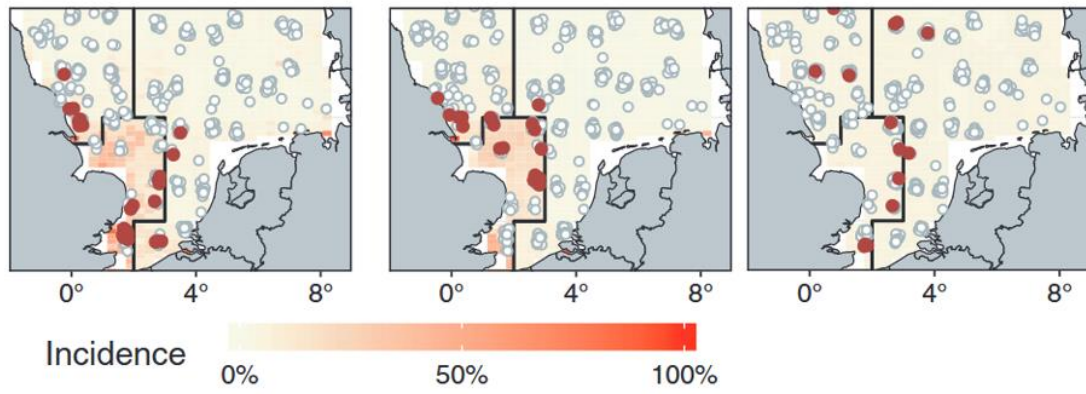


Figure I.7 Distribution of Atlantic cod spawning grounds from Gonzalez-Irusta et al., 2016 [64]

