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Advice on future assessment of ecosystem effects from offshore wind farms

Advice for KEC

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Summary

Within Wozep (the Dutch offshore wind ecological programme) research has been started to investigate the potential effects of offshore wind on the ecosystem through changes in the physical functioning of the system. Earlier in 2021 the first results of scenario studies with state-of-the-art combined hydrodynamic-ecological models have been delivered. Although the models still need further development, the results indicate substantial effects on primary production and ecosystem functioning with a large upscaling scenario for offshore wind. This scenario also indicated large differences between different regions in the North Sea.
Within the Framework for the Assessment of Ecological and Cumulative Effects (KEC) (developed to look at how offshore wind in cumulation may affect protected species in the North Sea) Deltares was asked to indicate how the scientific insights yielded by the Wozep study, can currently be used in the KEC procedures taking into account the model uncertainties. This report outlines the application possibilities of these tools in assessing effects and in ascertaining options to mitigate effects.

The Wozep results indicate that different regions in the North Sea have a different sensitivity to ecosystem effects. Despite model uncertainty, these differences are substantial and are supported by underlying knowledge of the system. These preliminary results can therefore with care be used in the current planning process. The Wozep results also indicate that the cumulative effect of many wind farms in relatively close proximity are likely much larger than the sum of effects of individual, isolated farms. With the current projections for windfarm development both parameters (sensitivity of the location and planned density of farms) need to be considered.

The Wozep model results indicate that the central North Sea (with seasonal stratification) and the German Bight are most sensitive to changes due to enhanced mixing and possible destratification of the water column. In the Holland Coast area, a potential effect is identified regarding the transport of fine sediment towards the Wadden Sea. This is an issue that is seen as very sensitive, due to the UNESCO World Heritage status of the Wadden Sea. In the current projections used in KEC 4.0 for development of offshore wind farms, we see that large upscaling is foreseen in the Holland Coast. Most of these developments have already started or tenders will start within the next few years. In the German Bight, there are significant search areas on the Dutch side, as well as large ongoing developments in the German EEZ. The German Bight is physically and ecologically complex and shows a high sensitivity of ecosystem processes to offshore wind. With the large density of wind farms already foreseen in this area, it may be sensible to consider delaying further upscaling until we have more insight in cumulative effects and the consequences of design options in farm layout that can diminish or mitigate effects

Contents

1 Introduction

1.1 KEC

The Framework for the Assessment of Ecological and Cumulative Effects (KEC) was developed to look at how offshore wind may affect protected species in the North Sea. This framework focuses less on the effect of individual wind farms and more on the ecological impact of all the wind farms together. It is intended to assess the cumulative ecological effects of the wind farms that are in place, under construction or planned for the future. The aim of the KEC is to determine whether all the built and planned wind farms, when viewed as a whole, will have 'significant negative effects' on the ecology. The KEC is used to calculate the cumulative effects of offshore wind farms (OWF's) on species with a protected status in nature legislation and to assess whether these effects will stay within defined acceptable limits. This involves looking at both the existing wind farms and the proposed planned wind farms.

Earlier versions of the KEC have focussed on windfarms operational or planned in the period leading up to 2030. In the 'North Sea 2022-2027 Programme', search areas for new offshore wind areas are designated (approx. 27 GW) that will be used for the roadmap beyond 2030. These search areas will have to be incorporated into the calculations of cumulative ecological effects in accordance with the KEC method.
This assignment focuses specifically on the qualitative assessment of ecosystem effects.

The present report is part of the update of the KEC on the new search areas for offshore wind energy until 2040. Other parts estimate effects on bird collisions, bird habitat loss and marine mammals. These subjects were not part of the assignment reported here.

1.2 Wozep ecosystem effects research

Within Wozep (the Dutch offshore wind ecological programme) research has been started to investigate the potential effects of offshore wind on the ecosystem through changes in the physical functioning of the system. An earlier desk study had shown that a possible future large-scale increase in offshore wind farms in the North Sea may have ecosystem effects on the North Sea (Boon et al. 2018). This concerns either effects that are not currently occurring, or that are not yet relevant on the scale of the North Sea ecosystem but may become relevant in the future. To gain timely insight in these processes, Wozep has initiated the first research into these ecosystem effects, which builds on the 2018 desk study. Wozep focuses primarily on the effects of offshore wind on species with protected status. An important question is therefore: to what extent do effects of offshore wind farms affect these species through the physical processes, the growth of algae and further through the food chain?

It will probably never be possible to model all the ecosystem effects from changes in fluid dynamics, sediment dynamics, primary production, secondary production all the way up to the apex predators. Particularly apex predators such as sharks and rays, birds and marine mammals have this protected status. This project therefore followed a two-tier approach: a "bottom-up" deterministic modelling approach to gain insight in the effects on the physics of the system and the base of the food chain, and a "top-down" approach assessing the vulnerability of the species with protected status for changes in their food web and food landscape. The aim of this first modelling exercise was to gain insight into 1) if physical changes due to offshore wind were likely to cause substantial changes in the North Sea ecosystem, 2) which areas were most susceptible to changes and 3) which processes were most relevant.

The results of this first research indicated that ecosystem effects can indeed be very relevant and that there are major differences between different North Sea regions.

The modelling suite as used in the present study is still under development and should not yet be used to precisely quantify potential effects of realistic scenarios for direct policy support. The intention is that these models will be used as such in the near future, and the current assessment is that with the right amount of validation they have the potential to be used as such. This allows us to determine safe upscaling levels and optimal configuration of wind farms, with minimal negative impact on the North Sea.

1.3 Aim of this report

Although the current results from Wozep cannot yet be used at face value, they do already give an indication which areas are more susceptible to changes and which ones are likely to see lower impacts. The first aim of this report is to highlight how the current results can be used in the assessment of future windfarm developments, and what the limitations of their use are. The second aim is to indicate how such models (once further developed) can be used within the KEC to diminish risks to the environment. This will cover factors such as:

- Total level of upscaling
- Location of OWFs
- Size of OWFs
- Orientation of OWFs relative to each other and relative to e.g. tidal currents
- Size and spacing of turbines
- In-farm orientation of turbines relative to prevailing wind and current directions.

1.4 Report outline

Chapter 2 describes the approach of the Wozep research into ecosystem effects. The main results of the project from 2020 are described in Chapter 3. That chapter overlays the Wozep results and the zonation determined in this project with the current development areas and search areas for offshore wind for the North Sea Programme 2022-2027. Chapter 4 describes how this research can be used in the future for the purposes of the KEC and assesses the design factors that are likely to have an impact on ecosystem effects. Chapter 5 describes the phased approach required to develop the current tools into policy support tools and use them in assessments for future scenarios. Conclusions and recommendations are described in Chapter 6.

2 Wozep ecosystem research approach

2.1 Description model approach

For the hydrodynamic modelling, the 3D Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is used, which was developed in recent years as part of Deltares' strategic research. The main purpose of 3D DCSM-FM is to have a versatile model that can be used for studies on the Northwest European Continental Shelf, including the North Sea and adjacent shallow seas, such as the Wadden Sea. It aims to combine state-of-the-art capabilities with respect to modelling of water levels (tide and surge) as well as (residual) transport phenomena. The latter is crucial for application in water quality and ecological modelling. By combining this, the model is ideally suited for this study. The earlier exploratory study (Boon et al. 2018) had indicated that effects on stratification are likely (at least in some parts of the North Sea) in and around wind farms. Such effects can be very far reaching for ecological processes (Ruardij et al. 1997, Große et al. 2016, Flores et al. 2017). The new DCSM-FM model is known to be extremely good at simulating this process (Zijl et al. 2018, Zijl et al. 2020).

Offshore wind turbines interact with tidal flow and cause drag on the flow. This causes the formation of eddies, increases turbulence and slows down the average current speed. With a model grid size of at least 900m, the effects of monopiles (i.e. the eddies and consequent turbulence generation) within the offshore wind OWFs are too small to explicitly include in the model schematization. Therefore, a sub-grid approach is used. In this approach, a quadratic sink term is included in the horizontal momentum equations. The energy extracted from the main flow in this manner is at the same time reintroduced as a source term in the equation for turbulent kinetic energy (k) (Zijl et al. 2021).

The locations of the offshore wind farms are specified in the hydrodynamic model by means of a polygon along its boundaries. In each computational cell within this polygon the appropriate sink and source terms are computed considering the pile density (number of piles per unit of area) and mean pile diameter. Different values for turbine density and monopile diameter are used for areas that are operational, under construction or planned.
Since the wind forcing of the model does not yet include the impact of OWFs on the meteorological conditions, this has been included in a simplified manner by reducing the near surface wind speeds within the wind farms by 10%. Other meteorological forcing parameters, such as air temperature and relative humidity, are left unchanged. Wake effects and directional changes of the wind are not yet considered. Further details about the set-up and the parameterisation of wind farms in the model can be found in Zijl et al. (2021).

Coupled to the hydrodynamic model we have run models to assess the effects of wind farms on fine sediment dynamics and on nutrient transport and primary production. Running the water quality and ecology models at the full resolution of the hydrodynamic model takes about 2 weeks calculation on a 20-core cluster. To carry out tests for both the fine sediment model and the water quality and ecology model, we also constructed a coarser grid on which calculations can be done faster. This also provides a good first impression of results, but experience from the past has taught us that model resolution can be a crucial factor, particularly in fine sediment modelling. The results of the coarser resolution models have to be assessed with caution.

Within the first study, we have not yet managed to include the full set of results from the fine sediment model in the ecological model. The fine-scale ecological runs have therefore used a well-calibrated sediment field from an older model, used to assess the effects of sand mining in the coastal zone (Van der Kaaij et al. 2017). This means that in those runs only the effects of the changes in hydrodynamics (stratification, changes in currents and therefore transports of nutrients) are taken into account, not the concomitant effects of the changes in fine sediment dynamics. To get some first ideas about the combined effects, some extra runs with the coarser models have been carried out in which the sediment fields used in the ecological model were proportionally increased or decreased, according to the results from the fine sediment model.

Three scenario runs have been performed with this model.
1. a reference scenario without any wind farms present
2. a 2020 scenario with the currently operational wind farms present
3. a hypothetical upscaling scenario, based on the outlook of the industry for roughly 2050 (Figure 2.1).

The purpose of the upscaling scenario was to learn as much as possible regarding the sensitivity of the ecosystem in different parts of the North Sea, it was never meant as a realistic future scenario. The full arguments and reasoning for the design of the used scenario can be found in the Wozep reports (Van Duren et al. 2021, Zijl et al. 2021).

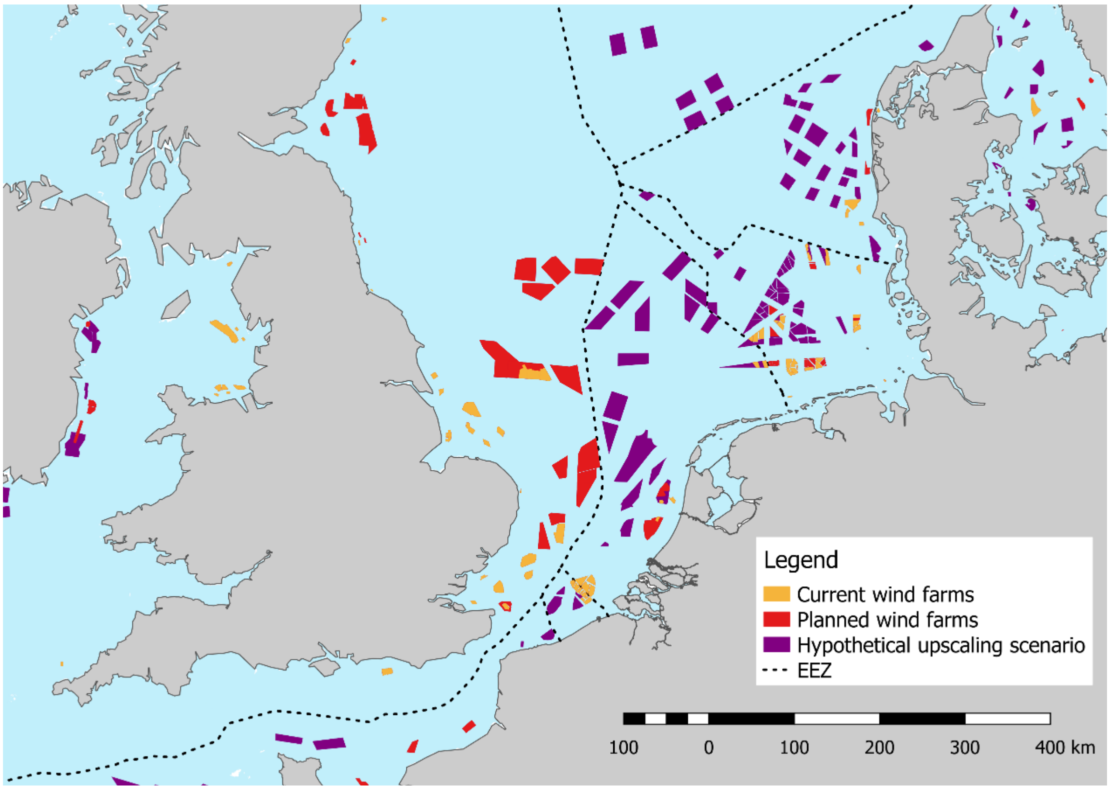

Figure 2.1: Hypothetical upscaling scenario used in the Wozep study. The orange coloured farms represent the "2020" scenario", i.e. the currently operational ones. Red areas are already designated as wind farm in a process of being developed, the purple ones were either defined as "search areas for wind energy" by national governments and others were chosen by us.

2.2 Description of current state of development

The modelling suite as used in the Wozep study (Zijl et al. 2021) is currently in a developmental stage and should in this form not be used for immediate decision support. However, the work has indicated that with certain improvements (inclusion of certain key processes and validation of the wind farm effects) it has the potential to be used in future KEC-scenarios. Below is a discussion of the main sources of uncertainty in the use of the model.

2.2.1 Model development and uncertainties associated with the model

The hydrodynamic part of the model has had a longer history of development and has also been validated more extensively than the other elements (fine sediment modelling and the water quality and ecology modules). Regarding validation on the reference situation (i.e. without wind farms) the model appears to perform very well regarding processes such as stratification (Zijl et al. 2020). Improvements are still desirable regarding the atmosphere – water interaction.

The main issue regarding hydrodynamics is the fact that currently the wind wakes of the windfarms are not incorporated in the models. Wakes can extend for more than 50 km behind farms, depending on processes such as atmospheric stability (Cañadillas et al. 2020). Although in the wakes the reductions in wind speed are significantly less than within the farm itself, this is still an important factor to include for future assessments. Wind drives waves and waves impact processes such as fine sediment dynamics. It seems likely that in deeper areas, where waves rarely or not reach the seabed, this effect is likely less important than in shallower areas. Wind stress acting at the sea surface and acting at the sea bed can also reduce or destroy stratification (Burchard et al. 2002, Carpenter et al. 2016). As stratification is a major driver of ecological processes in the North Sea and this is a process that is affected by wind farms, incorporating this process is essential before this model is used for policy support.

The SPM module in the modelling suite still needs more calibration. Although the process formulations in this model, as well as the SPM fractions used are similar to the older models that were e.g. used for the EIA-sand mining (Van der Kaaij et al. 2017), there is a major difference due to the size of the model domain. The older ZUNO-DD domain was much smaller and covered only the southern part of the North Sea. Sediment concentrations in the water column were quite strongly influenced by the import and export of SPM across the model boundaries. The model was well calibrated for this. The new model covers the full North Sea and part of the Atlantic Ocean. Therefore, concentrations in the southern North Sea are determined by internal dynamics. This requires longer model spin-up times and a different calibration than were initially used in the Wozep project. The model produced patterns in SPM concentration that were very similar to observations, but the absolute values were too low. Meanwhile (in different projects) a large part of this bias has been reduced, but in order to be used in environmental studies and environmental impact assessments it needs further work.

The water quality and ecological module also requires further work. The simulated phytoplankton biomass appears to be very consistent with measurements, and winter nutrient levels were well reproduced by the model. However, it seems that the N:P ratio of nutrient uptake by phytoplankton may be underestimated. In several areas the phosphate (PO_4) stock is depleted and nitrate (NO_3) is overestimated in summer. The largest source of uncertainty is a lack of good validation data on the most important process: primary production. There are data available for phytoplankton biomass. However, as this is a resultant of primary production and mortality, biomass is not a good proxy for production. Getting good, spatially explicit data on primary production is a major step forward to reduce this uncertainty.

The largest adjustment required for the ecological model is the growth of mussels high up in the water column on the monopiles. In the model the mussels died off, which is clearly not the case in the field, where mussels grow very well in the upper 5 metres of the water column on the turbine monopiles (Degraer et al. 2013). This clearly requires further calibration of mussel parameters suitable for this environment.

2.2.2 Uncertainty regarding the knock-on effects on higher trophic levels

The Wozep project results on ecosystem effects indicate clear effects on primary production in the North Sea. In some areas the model predicts a reduction while in other areas an increase of primary production is predicted. A decrease is generally seen as negative. Primary production forms the basis of the food web, less production tends to mean fewer animals. There are clear correlations between levels of primary production and e.g. benthic animals (Reiss et al. 2011) and also fish and fisheries (Chassot et al. 2010, Capuzzo et al. 2018). However, it is not easy to predict how changes at the base of the food web will translate into changes in carrying capacity for individual species. It is likely that the effects may be different for e.g. plaice in comparison to herring and also different for red-throated divers in comparison to seals. This is due to differences in diet, differences in location where they forage, differences in life history, etc. etc. Additions to the current model (e.g. adding zooplankton species) may give indications on how benthic and pelagic carbon flows are likely to change, but to link effects on specific species (e.g. those with high conservation status) will require different research.

Also, an increase in primary production is not always a positive change for all species. Eutrophication has been the cause of harmful algal blooms in the North Sea. Although these have reduced over the past decades due to a marked reduction of nutrient run-off from land (Prins et al. 2012), increased nutrient availability due to reduced stratification could reverse this.

2.2.3 Current scenario

In the Wozep project only one single hypothetical upscaling scenario has been assessed (Van Duren et al. 2021). The main aim of this initial study was to assess 1) if ecosystem effects were likely to be significant enough to expect knock-on effects higher up the food web 2) assess which parts of the North Sea are likely to be more sensitive to change 3) assess if the model was fit for purpose. A striking difference between the scenario for 2020 (only the currently operational wind farms) and the large upscaling scenario was that in the 2020 scenario, effects were restricted to the wind farms and the immediate vicinity, while in the upscaling scenario there were conspicuous effects outside the windfarms. For future assessments it will be important to assess effects of individual wind farms as well as the effect of these farms in conjunction with other wind farms in the vicinity.

3 Future applications of the model to assess effects of design options

3.1 Description of design factors that can affect results

Below a number of factors is listed that will influence the way offshore wind farms affect hydrodynamics and hence the rest of the ecosystem. At present we do not know yet exactly how such factors will affect resulting impacts and to what extent. However, in principle these are variables that can be adjusted to minimise negative impacts on the ecosystem.

3.1.1 Location

The Wozep research has indicated that different parts of the North Sea react differently to the placement of windfarms. This is caused by differences in depth, distance to freshwater discharges in tidal currents and differences in fine sediment concentrations in the seabed. A summary of the differences between different regions can be found in section 4.1.

A small number of large farms or a large number of smaller farms will influence both the local flow velocities as well as the influence the farms have on mixing. As the wind farms exert drag on water, on average water flow inside the farms is slowed down and outside the farms water flow will accelerate. In larger, continuous farms relatively more water will be forced through the farms, likely resulting in higher flow velocities and more mixing inside the farms, compared to a design with a larger number of smaller wind farms (Figure 3.1).

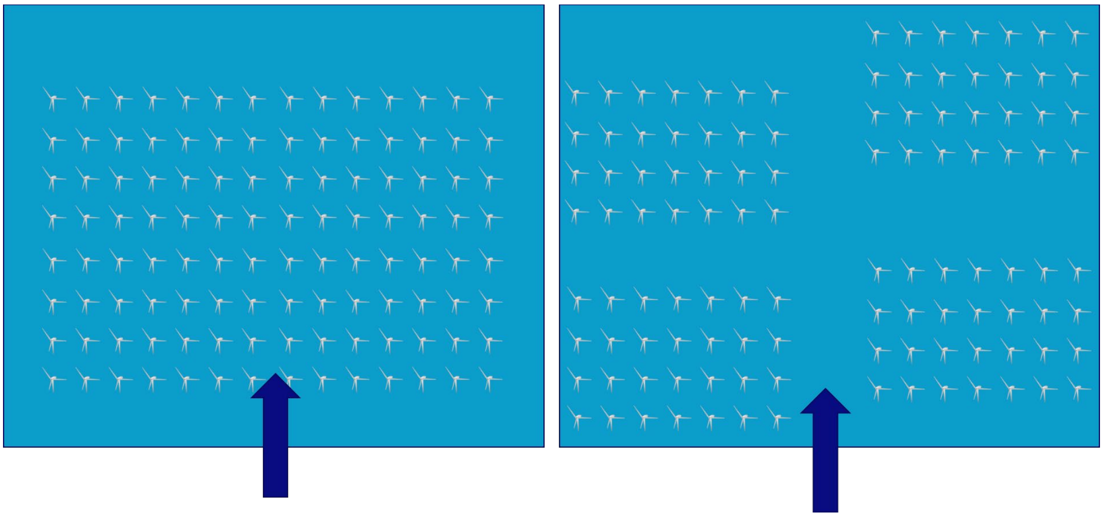

Figure 3.1 Left: Illustration of the tidal current (indicated by the blue arrow) hitting one continuous farm (i.e. being forced through the farm) and Right: the tidal current hitting a patchy farm lay-out, where flow will accelerate between the smaller wind farms.

Also, the shape of farms, relative to the ambient tidal current will change flow and mixing around the farms and also inside the farms. With ‘elongated’ farms that are oriented perpendicular to the current, more water will be forced through the farms, resulting in higher velocities and more turbulence inside the farm, while farms oriented parallel to the main current will likely reduce velocities inside the farms more and increase velocities outside the farms (Figure 3.2). The principles that apply here are similar to those that apply e.g. to flow through patchy vegetation (Temmerman et al. 2010).

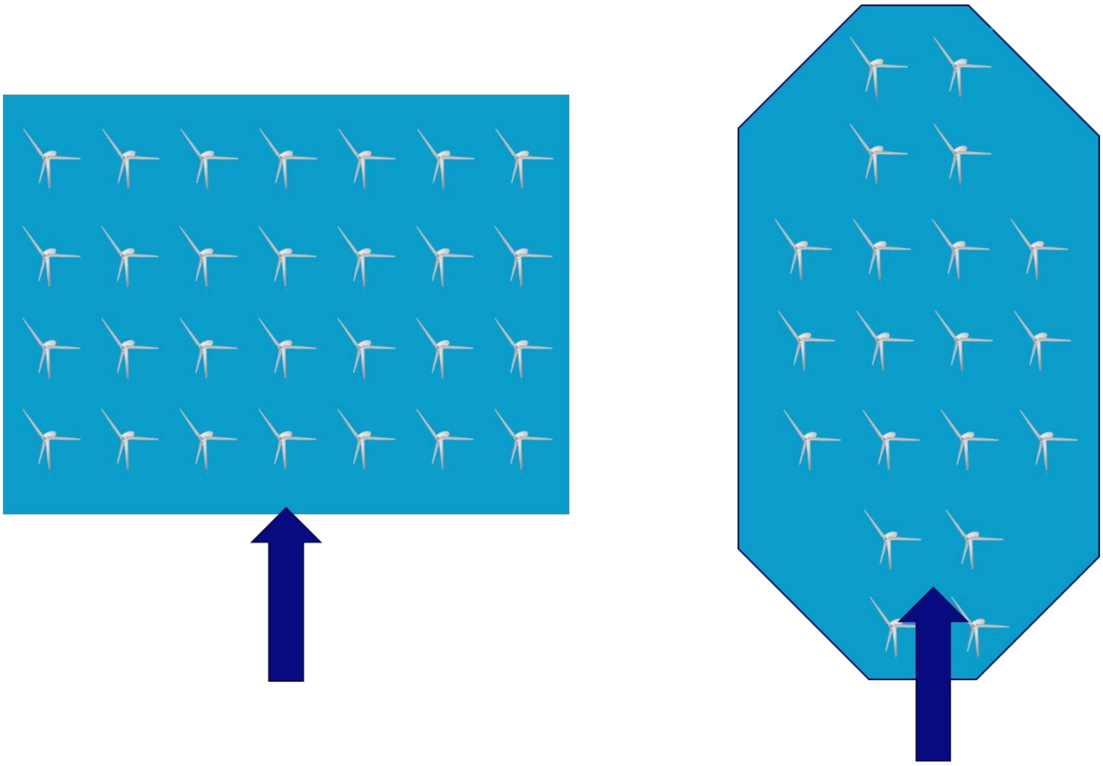

Figure 3.2: Schematic illustration of changing the shape of a wind farm with respect to the current (indicated by the blue arrow). In the left-hand situation, the tidal flow "hits the farm" on the wide edge, forcing more water through the farm; in the right-hand situation water is more diverted around the farm.

Also factors within the offshore wind farms can influence the way the farms interact with currents and waves. First of all, the size of the turbines and the associated spacing. The wake of a turbine scales with its size. In order to achieve a certain capacity density (energy yield per km^2 of wind farm) there is an optimal distance between turbines depending on their size, keeping the distances between turbines as small as possible to limit the length of cables while also limiting reduced power output due to wake effects (Deutsche WindGuard 2018). Larger spacing (i.e. fewer turbines per km^2) will diminish drag on the flow and hence the effects on hydrodynamics. Exactly how wind wake effects from larger turbines affect wave formation in comparison to smaller ones, remains to be investigated.

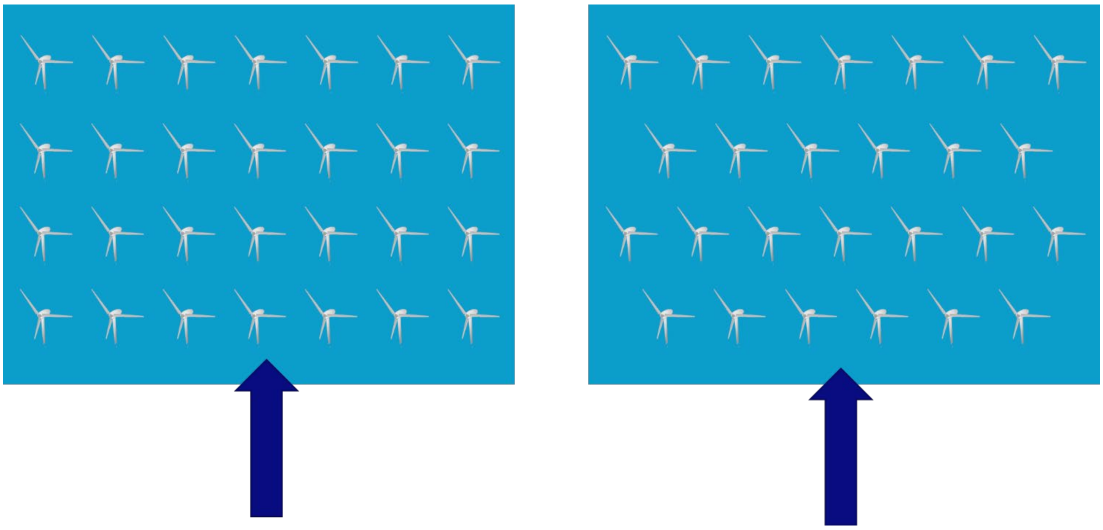

Figure 3.3 Schematic drawing of possible within farm configurations

Another factor that will affect currents and turbulence is how turbines are spaced with respect to the ambient (tidal) current, as illustrated in Figure 3.3. In the situation on the left the turbines are oriented in line with the flow, allowing “channelling” of water through the farm. In the situation on the right this will not occur. How important this factor is, will depend on the length of the wake of the turbine monopile in the water and the spacing of the turbines. Also, turbines may not be spaced homogeneously over the concession area, but more concentrated closer to the edges.

At present it is not known which configuration has fewer effects – this is something that future model studies can explore. Adjusting the configuration of turbines with respect to the ambient current may be an option to reduce effects on hydrodynamics, SPM dynamics and ecosystem functioning. However, this may also mean that turbines are placed less favourably with respect to prevailing wind directions, entailing a reduction in average yield. This and any increase in required cable lengths will need to be weighed against any benefit in reduced ecosystem effects.

3.2 Methodology potential

Using only the hydrodynamic module of the model requires significantly less calculation time. As hydrodynamics is the main driver of SPM dynamics and nutrient transport, running only the hydrodynamic module will already give strong indications whether any ecosystem effects can be expected. The current model, preferably run in conjunction with the SWAN wave module, can give first indications of effects in different areas of the North Sea. It also indicates how the size and shape of wind farms in relation to the main tidal current direction, modulates those effects. To assess the impact of different configurations of wind turbines within the farms, further research on accurate parameterisation is required. This requires a different type of modelling using either CFD or LES models to assess the interaction of wakes under water within the farms.

4 Wozep current results in relation to OWF search areas

4.1 Description of effects per area and associated uncertainties

Note: in this section we describe the effects – the level of uncertainty of the modelled effects (i.e. the model uncertainties) and the uncertainties regarding the interpretation of the effects in terms of impact on the food web.

Figure 4.1 shows a of map how the Dutch and international windfarms currently under consideration in the KEC are located in the various effect zones identified in the Wozep study. Note that in the Wozep study the distribution of wind farms in the upscaling scenario is different from that in the search areas considered in KEC 4.0.

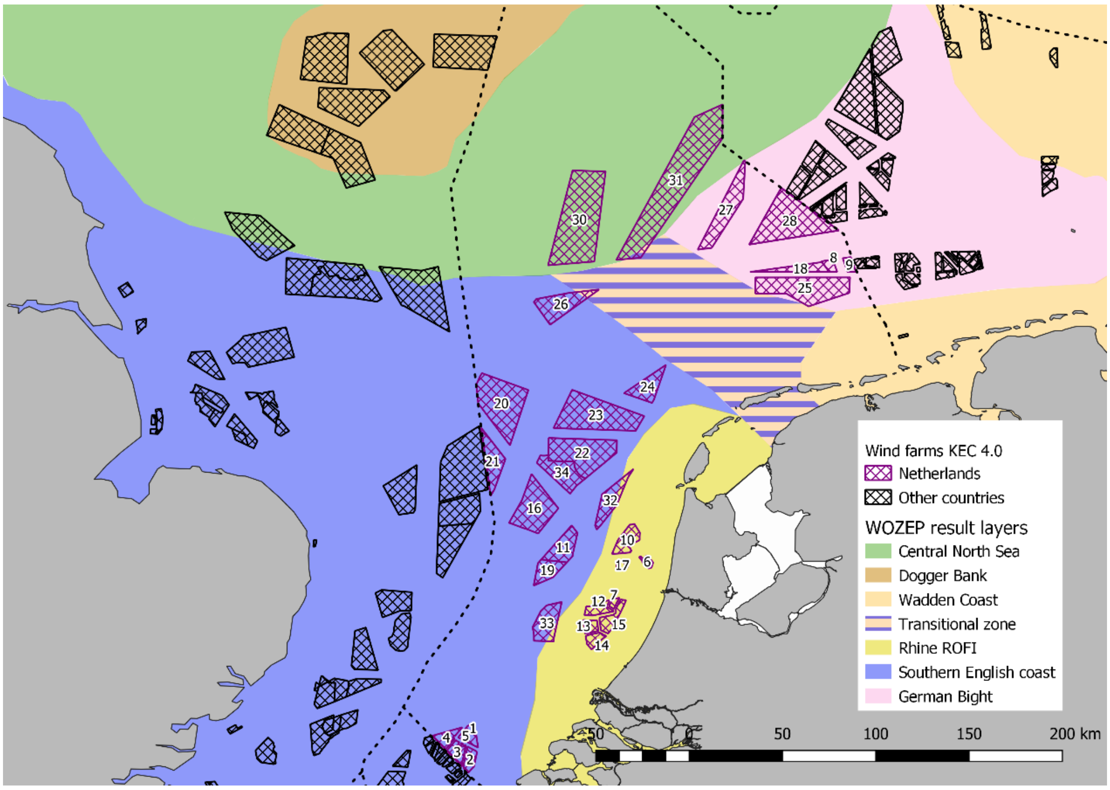

Figure 4.1: wind farm locations considered in KEC-4.0 and the effect areas identified in Wozep. Numbers refer to wind farms and search areas named in Table 4.1and Table 4.2.

4.1.1 Central North Sea

This area is intermittently to seasonally stratified due to temperature. Enhanced mixing in the wind farms has the effect to weaken stratification and enhance vertical exchange of heat, nutrients and suspended matter. This is most expressed in areas with weak or intermittent stratification that can easily be eroded, but even the areas with relatively strong seasonal stratification appear to experience clear effects from wind farms. The effects reach well beyond the immediate wind farm perimeters. The area is low in suspended particulate matter (SPM) concentrations in the upper water layers. Wind farms appear to increase this concentration, but this does not cancel out the effects of increased nutrient availability in the upper layers. In this area the net effect is an increase in primary production. Although there is an overall increase in the primary production, onset of phytoplankton growth in spring appears to be a bit later. Effects in this area are primarily due to changes in stratification.

Uncertainties

The model is relatively well-calibrated for these processes, i.e. confidence level in the model results is relatively high here. The expected increase in primary production may at face value appear to be positive. However, how this translates to higher trophic levels is uncertain.

4.1.2 German Bight

This area is characterised by frequent but not very strong stratification. Temperature stratification is dominant, but also salinity plays a role here. This is an area where there are strongly opposing effects of wind farms. On one hand, increased availability of nutrients can boost primary production; however, increased SPM levels in the upper layers may also reduce it. The model runs with adapted SPM fields suggest that SPM effects are substantial and in some sub-areas dominant. This clearly needs further quantification with the fully coupled model system and well calibrated and validated SPM fields. In this area, the spring bloom is severely delayed due to both the effect of reduced stratification and enhanced fine sediment in the upper layers.

Uncertainties

Due to the complexity of this area and the strongly opposing effects of wind farms on primary production, this is the area with the highest level of uncertainty of model results.

4.1.3 Southern English coast and western part of the Dutch Continental Shelf

These are the areas that are fully mixed. Changes in stratification do not occur here. The main effect of windfarms is the increase in turbidity in the top layers of the water column. In some parts, e.g. close to the Thames estuary, the system without wind farms is extremely turbid and hence very low in productivity. In absolute terms, any increase in SPM in the top layers does not decrease productivity much further, although in relative terms the decrease may be large. Further away from the Thames estuary, increased turbidity due to wind farms reduces production.

Uncertainties

The model uncertainties regarding SPM dynamics (certainly in absolute terms) and the fact that wind wakes are not yet included in the model are the main sources of uncertainty here.

4.1.4 Danish and German Wadden Sea coast

This area is in most ways similar to the UK coastal area. It is generally not stratified, or only very occasionally. It is high in nutrients but due to high SPM concentrations it is light limited and not very productive. Effects of wind farms on SPM concentrations in the upper layers and on productivity are minimal. There is no clear delineation between this zone and the UK Coastal zone, hence the blue/orange hatched area is indicated as “Transition zone”.

Uncertainties

Uncertainties are similar to those in the UK coast and the western part of the DCS.

4.1.5 Rhine ROFI

This is an area with high nutrient availability and without temperature stratification, but some salinity stratification. It is a highly dynamic area with strong tidal currents. In this area primary production is more light-limited than nutrient-limited. Nutrient availability in upper layers is high due to riverine input. The net effect is that higher fine sediment concentrations in the upper layers decrease primary production, but increased mixing does not enhance productivity. The changes in mixing in this area (in horizontal and vertical direction) are likely to have some effect on the transport of fine sediment along the Dutch coast and towards the Wadden Sea. This effect needs further quantification. To what extent this is also influenced by farms further to the west (in the UK coast and the westernmost part of the Dutch EEZ) will need to be investigated.

Uncertainties

The Rhine ROFI is hydrodynamically a very complex area, due to the combination of strong tidal forcing and density effects. Also, fine sediment dynamics is complex in this region due to the high and temporal spatial variability in salinity.

4.1.6 Dogger Bank

This is a relatively isolated shallow area surrounded by the seasonally stratified area. It has a unique composition of ecological communities. Sufficient light penetrates to the bed for primary production, hence this is one of the few areas in the North Sea where microphytobenthos (i.e. microalgae growing on the seabed) occurs. The stratification regime of the Dogger Bank is unclear, some areas occasionally have some (not very strong) temperature stratification, other parts are nearly always fully mixed. The bed consists predominantly of medium sand and coarse-grained material, so even though waves easily reach the bed, resuspension of fine sediment from the bed is limited. The resulting effects of offshore wind farms on the Dogger Bank on primary production are limited and spatially varying. In some areas there is a small net increase, in other areas a small net decrease in primary production.

Uncertainties

The processes of stratification, mixing and SPM dynamics in this area are relatively well understood. In this area the confidence level in the model is fairly high. As this is an area where we expect relatively minor effects on primary production, it is also likely that knock-on effects on higher trophic levels are minor in this part. The main source of uncertainty in this area is caused by the effects of shellfish growth on the turbine supports.

4.2 Location of search areas in relation to effect zones

The Dutch OWFs that are already in the 2030 road map (and those that are already partially operational), most are located in the Holland Coast area – either in the Rhine ROFI area or in the western part of the DCS (Table 4.1). Although these areas see limited effects of destratification (either because they are not stratified or because in the Rhine ROFI nutrient limitation is not an issue) the combined effect of these farms may affect the northward transport of fine sediment. For operational farms, changes in location or the farm layout are no longer an option. However, the impact on transport towards the Wadden Sea by the farms not yet under tender, should have priority.

Table 4.1: Indication of the effect zones in which the wind farms in the 2030 roadmap are located, their associated risk in terms of ecosystem effects and the projected density of farms in the area after completion. All these farms are fully located in one effect area (colours correspond to the effect zones as indicated in Figure 4.1).

Nr	Wind Farm	Wozep effect area	Area sensitivity	Projected density
1	Borssele 1	West DCS-Southern UK	moderate	high
2	Borssele 2	West DCS-Southern UK	moderate	high
3	Borssele 3	West DCS-Southern UK	moderate	high
4	Borssele 4 - Blauwwind	West DCS-Southern UK	moderate	high
5	Borssele Site V -Two towers	West DCS-Southern UK	moderate	high
6	Egmond aan Zee	ROFI	moderate	moderate
7	Eneco Luchterduinen	ROFI	moderate	moderate
8	Gemini Zee energie	German Bight	high	very high
9	Gemini Buitengaats	German Bight	high	very high
10	Hollandse Kust Noord (Tender 2019)	ROFI	moderate	moderate
11	Hollandse Kust West - (Tender 2020/2021)	West DCS-Southern UK	moderate	high
12	Hollandse Kust Zuid Holland I	ROFI	moderate	moderate
13	Hollandse Kust Zuid Holland II	ROFI	moderate	moderate
14	Hollandse Kust Zuid Holland III	ROFI	moderate	moderate
15	Hollandse Kust Zuid Holland IV	ROFI	moderate	moderate
16	IJmuiden Ver	West NCP-Southern UK	moderate	high
17	Prinses Amaliawindpark	ROFI	moderate	moderate
18	Ten noorden van de Waddeneilanden - (Tender 2022)	German Bight	high	very high

For the search areas where wind farms can be developed, two search areas (30 and 31 in figure 4.1) are located in the seasonally stratified areas of the central North Sea (Table 4.2.). In these areas effects of stratification appear to be largest, but effects of increased fine sediments into upper water layers is likely less.

Several more (25, 27, 28 and 29 on the map), are located in the German Bight. The German Bight appears to be sensitive to ecosystem changes. In this area effects on stratification have already been demonstrated on relatively small farms (Floeter et al. 2017). Not only on the Dutch part large-scale developments are foreseen, also in the German EEZ the density of OWFs is already very high and is likely to increase further. It seems likely that in this area the combined effects of the future German and Dutch farms need to be considered carefully.

There are furthermore a number of wind farms planned in the western part of the DCS. Effects of individual farms on e.g. mixing are perhaps less relevant here, but in this case, specific attention should be paid to the cumulative effect on SPM dynamics and northward transport of SPM.

Table 4.2: Indication of the effect zones in which the (variants of) search areas for wind farms extra until 2030 ("acceleration") and until 2040 are located, their associated risk in terms of ecosystem effects and the projected density of farms in the area after completion. All these farms are fully located in one effect area (colours correspond to the effect zones as indicated in Figure 4.1).

	Wind Farm	Wozep effect area	**Area sensitivity**	**Projected density**
19	Hollandse Kust West zuidelijke punt	West DCS-Southern UK	moderate	high
20	Zoekgebied 1 Noord	West DCS-Southern UK	moderate	high
21	Zoekgebied 1 Zuid	West DCS-Southern UK	moderate	high
22	Zoekgebied 2 Zuid	West DCS-Southern UK	moderate	high
23	Zoekgebied 2 Noord	West DCS-Southern UK	moderate	high
24	Zoekgebied 8	West DCS-Southern UK	moderate	high
25	zoekgebied 4	German Bight	high	very high
26	zoekgebied 3	West DCS-Southern UK	moderate	high
27	Zoekgebied 5 middenberm	German Bight	moderate	high
28	Zoekgebied 5 Oost klein	German Bight	high	very high
29	Zoekgebied 5 Oost origineel	German Bight	high	very high
30	Zoekgebied 7	Stratified	very high	moderate
31	Zoekgebied 6	Stratified	very high	moderate
32	Hollandse Kust West Noord	West DCS-Southern UK	moderate	high
33	Hollandse Kust West Zuid	West DCS-Southern UK	moderate	high
34	IJmuiden Ver Noord	West DCS-Southern UK	moderate	high

5 Towards practical application of modelling tools

5.1 Model development

5.1.1 Assessing ecosystem effects

In order to evaluate ecosystem effects of specific scenarios ('rekenvarianten') within the KEC, two issues need to be addressed with respect to the model.

1. The different modules within the model need to be further validated, not just with respect to the reference situation, but also with respect to the effects in wind farms that are already currently visible.
2. A number of processes that are currently not yet or not well enough incorporated in the model, need to be added. The highest priority is the incorporation of the wind wakes from the farms into the model. Although the wind speed decrease in the wake is much less extreme than within the farms itself (wakes of individual turbines), the potential surface area is much larger. These wind wakes may affect both the fine sediment dynamics (e.g. due to reduced resuspension due to lower wave heights) as well as stratification.
3. Furthermore, in certain areas the effects of mussels present in the upper water layers on the turbine poles may be important. Particularly in areas with a high density of wind farms this may affect availability of phytoplankton for zooplankton and in some cases may even affect primary production, although the latter is not certain.

5.1.2 Assessing mitigating design options

The model indicates that different areas of the North Sea have different susceptibilities to ecosystem change (See section 3.1.1). The current single upscaling scenario gives an indication, and after further validation should be suitable to assess ecosystem effects with farms in different densities in different parts of the North Sea.
The ecosystem-scale model should be suitable to assess design options such as large continuous farms vs. smaller, more patchy layout, or different shapes of the farms with respect to the dominant current direction, as described in section 3.1.2. As we know that the factors described in section 3.1.2 have an effect on velocities and mixing, it is likely they will also affect ecosystem effects to some extent. We cannot yet quantify the potential mitigation of ecosystem effects due to design changes, nor can we evaluate whether this differs spatially over de North Sea.

What can be expected with a reasonable level of certainty is that larger, but wider spaced turbines will have less effect than a higher density of smaller turbines. In order to assess the effect of within-farm design features (i.e. effect of orientation of turbines relative to the main current direction, as illustrated in section 3.1.3) it may be necessary to investigate this with a different type of model. With a grid size of at least 900m, the piles of the OWFs are too small to be explicitly included in the model schematisation and a sub-grid approach has been adopted (paragraph 2.1). Using finer scale hydrodynamic models such as computational fluid dynamics (CFD) or large eddy simulation (LES), this parameterisation can be refined to take into account vortex interaction and other processes within the wind farm. A start has been made in the current NWA project "Do wind farms increase or decrease turbidity and under-water light penetration?" led by NIOZ.

5.1.3 Assessing cumulative effects with other human uses

Apart from offshore wind, the expected energy transition on the North Sea may also see the development of technologies such as offshore solar. Effects of such technologies will involve shading and effects on wave propagation. The same basic model set-up can be used to assess ecosystem effects of such techniques.

There is also a drive towards a transition from less fishing towards more aquaculture of seaweed and shellfish, also on the open North Sea. With appropriate parameterisation and the addition of relevant species, the same basic model is also capable of assessing ecosystem effects of seaweed and mussel aquaculture (Vilmin 2020, Vilmin and Van Duren 2021).

Furthermore, there is a drive to restore substantial beds of native oysters (*Ostrea edulis*). This species used to be very widespread in parts of the North Sea (Olsen 1883, Bennema et al. 2020) and had a major impact on the benthic habitat. The WOZEP model can also be used to assess the carrying capacity of the North Sea for this species.

In the future it will therefore be possible to apply this model to study the impacts from offshore wind alone, and in conjunction with other human uses and restoration efforts, to assess cumulative effects.

5.2 Developing criteria

Apart from a model that is sufficiently reliable and fit for purpose, we also require criteria for various ecosystem parameters, to assess whether certain scenarios are acceptable or whether certain mitigation measures are sufficient to reduce effects to acceptable limits. These criteria should include weighing options to evaluate effects from wind farms in cumulation with developments within the Dutch EEZ as well as with farms in the international North Sea.

It makes sense to define criteria for acceptable changes in primary production. In general, a decrease of primary production can be seen as undesirable. How a marked increase should be valued, remains to be discussed. Large increases may pose increased risks for eutrophication effects, e.g. harmful algal blooms.

It also seems appropriate to develop certain criteria regarding changes in fine sediment transport towards sensitive areas such as the Wadden Sea. This needs to be assessed in conjunction with other activities that affect sediment transport such as sand mining, dredging and nourishments.

A significant challenge will be to develop criteria in relation to the effects they have on higher trophic levels. Direct relations between primary productivity and e.g. fish biomass and fisheries yield have been demonstrated (Conti and Scardi 2010, Marshak and Link 2021). However, for individual species relationships may be much less clear. Certain fish species may be more limited by availability of shelter or specific breeding habitat, rather than food availability. As birds and marine mammals generally feed on specific species, we need to get better insight into the relationships between effects at the base of the food web and the species that have a high conservation status. The ‘top-down’ part of the Wozep research has indicated that individual based models (IBMs) are the most suitable approach (Van der Meer and Aarts 2021).

One of the effects that needs to be investigated in the near future is the impact of growth of large amounts of mussels and other filter feeders on the turbine poles high up in the water column. The first (relatively simplistic) modelling exercises indicate that benthic species, such as mussels, may become significant competitors to zooplankton in areas with high densities of wind farms (Slavik et al. 2018). Such shifts are very likely to have impacts on carbon flows through the food web and are likely to impact higher trophic levels. For some species this may be a negative impact, but for others the impact may be beneficial. Determining suitable criteria for potential shifts, is going to be a necessary, but likely complex task.

6 Conclusions and recommendations

6.1 Phasing in choices for search areas

It is clear from the first Wozep results that there are differences between areas in expected ecosystem effects. Although in some areas the impact on primary production appears to be positive, we do not know at present how to interpret such changes in terms of effects on higher trophic levels. Hence, we should, for the time being, consider potentially large changes as large risk. This leads to the conclusion that it would be sensible to phase the tenders in lower-risk search areas before the high-risk ones.

However, we have also seen that a large density of wind farms leads to more interactive effects and effects that go well beyond the limits of the wind farms. The total effect can be more than the sum of the effects of the individual farms. It is therefore also important to assess wide-scale interactive effects in lower-risk areas against perhaps more isolated effects in higher risk areas. This clearly also includes the effects of wind farms outside the Dutch EEZ.

Based on the current information from the 2020 scenario and one upscaling scenario, there are two issues to assess with high priority:

- The German Bight – this area is, according to the model, very sensitive to changes. Alarge number of Dutch and German wind farms are planned in the area. The model results for this area have a relatively high uncertainty due to the physical complexity of the area.
- The Holland Coast, this area is less sensitive to changes in stratification as it is permanently mixed or only intermittently and weakly stratified. However, given the high density of farms in this area, negative effects on primary production due to increased turbidity in the top layers and potential effects on fine sediment transport need to be investigated

Although the search areas 6 and 7 (numbers 30 and 31 in Figure 4.1) are located in the seasonally stratified areas, which may cause substantial ecosystem effects, it appears that decisions regarding the development of these sites will only be taken at a later date. There is a higher degree of confidence in the model regarding the effects in these areas in comparison to the German Bight. The potential effects still require further investigation, but there is more time available for this assessment and for investigating mitigation measures.

6.2 Research methodology

A comprehensive overview of modelling and observation requirements to gain insights into effects of wind farms can be found in the ‘recommendations’ report for Wozep (Van der Molen and Soetaert 2021).

6.2.1 Modelling

Numerical models are basically the only instruments we have to assess impacts in situations that do not exist yet. As described in chapter 2, the current model needs validation and improvement (inclusion of certain processes) before it can be used in policy support. Models will never be able to predict the full range of ecosystem effects as well as the exact effect on each element of the marine food web. However, they can be useful tools in assessing risks and ascertaining marine spatial planning options that carry the lowest risk.

Assuming sufficient effort is geared towards these improvements, it is likely that a sufficiently accurate model can be operational within a few years.

Regarding research into mitigation options, such as referred to in section 5.1.2, a great deal can be done with the hydrodynamic model and the wave model. It is important that the wind wakes are included in such research, but this is a line of research that can be done in parallel to the ecosystem effect studies. For within-farm design factors such as alignment of turbines relative to the flow different modelling approaches are required.

6.2.2 Measurements / monitoring

Model development needs to go hand in hand with measurements. Most important parameter that we need good spatially explicit measurements on is primary production. Phytoplankton biomass or chlorophyll concentrations are currently measured routinely. However, these are a poor indicator of what is happening in aquatic systems and hence are also a poor indicator to validate models with.

Within MONS it is envisaged that primary production will be measured on a more routine basis. This is going to be extremely useful for validation and calibration of the reference situation. What is required for this particular application, is to get data in and around wind farms in different areas of the North Sea.

Particularly for the SPM model we need more measurements at different depths in the water column. Remote sensing images are very useful to get an impression of patterns at the surface area, but measurements near the bed are required to assess if the main processes regarding sedimentation and erosion of fine sediment are parameterised correctly.

Regarding mitigation options, particularly for processes within farms (e.g. alignment of turbines relative to the flow), physical scale model tests would be a good additional method to gain process knowledge. These should be carried out with appropriate observation techniques, such as particle image velocimetry (P.I.V.) (Adrian 2005). Appropriate scaling is going to be a challenge to investigate interaction of wakes behind turbines and such tests should be performed in large enough facilities.

6.2.3 Links with higher trophic levels

As most of the policy targets are geared towards apex predators (marine mammals, birds, sharks and rays) it is important to gain more insight how changes at the base of the food chain impact these higher trophic levels. Approach and focal species have been identified in other parts of the Wozep research (Van der Meer and Aarts 2021, Van Duren et al. 2021).

6.2.4 International aspect

Last but not least, it is important to liaise closely with neighbouring countries as effects of Dutch wind farms are not confined to the Dutch EEZ and interactive effects across marine borders are likely. The latter is particularly important for areas such as the German Bight.

6.3 Conclusions

Due to the sensitivity of the German Bight and the fact that in this area the density of offshore wind farms (Dutch and German) is very high we recommend that decisions regarding development of search areas 4 and 5 (numbers 25, 27 and 28 on the map) are delayed. This allows time for further research, both on the magnitude of ecological impacts and on design options to reduce negative effects.

The same recommendation holds for search areas 6 and 7 (numbers 30 and 31 on the map), however, with less importance than the recommendation for delay for search areas 4 and 5.

We recommend particularly to investigate the potential ecosystem effects for a lower density of farms in this area than what has currently been investigated in the upscaling scenario, and weigh this against the effects of the currently foreseen very high density of farms in the permanently mixed areas (Wester part of the DCS, the blue area in Figure 4.1).

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