REPORT

Quick scan of effects from large upscaling of offshore wind (part B)

Effects on ecosystem processes from the large-scale development of offshore wind in the North Seas

Client: Rijkswaterstaat

Reference: BJ2530-RHD-XX-XX-RP-EO-0001

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1 Introduction

1.1 Background and purpose

Growth of the offshore wind (OW) energy industry must be accelerated to meet global 2050 Net Zero Carbon commitments. The international ambitions to reach these goals include substantial upscaling of OW in the North Sea and Celtic Sea. At the European level, the ambition has been formulated for at least 60 GW offshore wind by 2030 and 300 GW offshore wind by 2050, excluding UK and Norway. The spatial study North Seas 2030 – offshore wind development (Royal HaskoningDHV, 2022) shows that the ambitions of only the member states of the EU already add up to at least 62 GW at the North Seas by 2030. This is already more than the European ambition of 60 GW offshore wind. Together with the ambition of the UK (50 GW) and Norway (4,5 GW), this brings the ambition of OW in the North Seas in 2030 up to at least 117 GW. These results show that up to 2030 and 2050, the North Seas will be changing, as a large increase of OW can be expected.

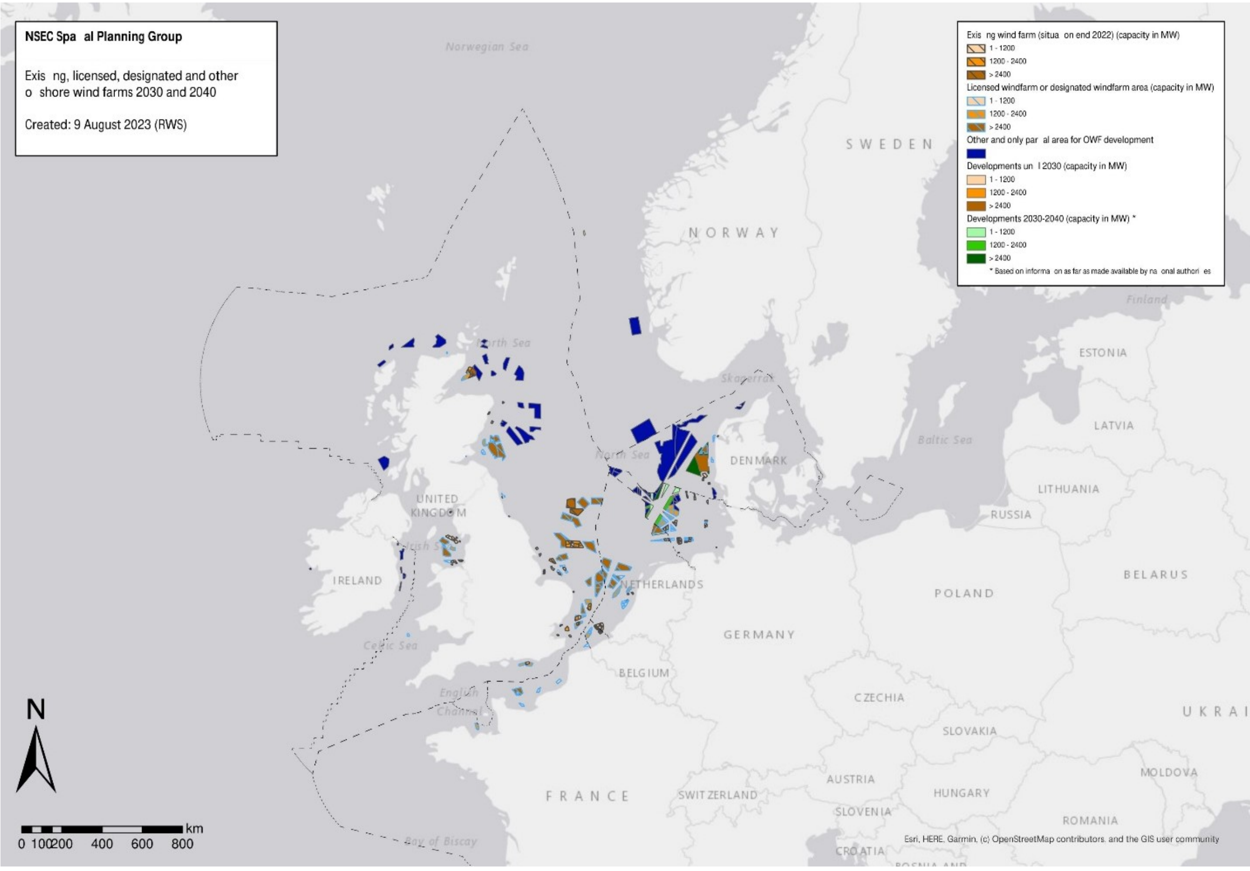

Figure 1. Map of the North Sea and Celtic Sea with an overview of the existing, designated and planned offshore wind park developments (RWS from input from NSEC parties, 2023).

Since the construction of the first windfarms, there have been concerns about their effects on nature The presence of offshore wind farms (OWFs) in the North Seas changes the local environment both above and below water. Impacts of OWFs appear in multiple stages of construction, operation, and decommissioning. The main impacted species groups are birds, bats, marine mammals, fish, and benthic marine organisms. In addition, significant effects are expected on ecosystem processes through the alteration of abiotic processes like stratification and its effect on primary production. However, besides negative impacts, OWFs might also offer opportunities for nature enhancement.

To support international discussion and decision-making around the spatial aspects of future upscaling of offshore wind, a quick scan on the effects from the large upscaling of offshore wind has been commissioned by Rijkswaterstaat as delegate of the North Sea Energy Coalition (NSEC). The spatial area of this study considers the North Sea and the Celtic Sea (OSPAR regions II and III respectively).

The quick scan contains the following components:

A. Cumulative effects from OW developments on species and habitats
B. Cumulative effects from OW developments on ecosystem processes
C. Opportunities from OW developments

This report contains the outcomes of part B from this quick scan and provides a high-level overview of published research on the effects on ecosystem processes from long-term offshore wind energy developments in the North Sea and Celtic Sea (respectively OSPAR regions II and III). These are based on the existing and designated areas for offshore wind development in 2030 as well as an outlook towards the long-term (2030-2050) plans for offshore wind energy production. The other components are described in separate reports. It should be noted that the focus of this study is on the effects on ecosystem processes during the operational phase of OW, not the construction or decomissioning phase.

1.2 Approach and input

This part of the quick scan focuses on the effects from large-scale OW developments on ecosystem processes in the North Sea and Celtic Sea. For this purpose, the client and NSEC partners delivered approximately 20 literature studies on the effects from OW on various ecosystem processes. A synthesis of knowledge from these studies was conducted in order to provide an overview of the main conclusions and recommendations with regards to these potential ecosystem effects from OWF. To consolidate and deepen the insights from this synthesis, two interviews plus additional email conversations were conducted with a leading subject matter expert and scientist on this topic, Dr. L.A. (Luca) van Duren of Deltares[1] (L. A. van Duren, personal communication, 17 April 2023 and 20-04-2023).

It should be noted that this literature review and interviews might not include all available knowledge on this topic and is therefore not fully comprehensive and should be considered a ‘quick scan’.

1.3 Main assumptions

In this synthesis and expert judgment on the potential effects on ecosystem processes from long-term development of OWFs, the below assumptions and disclaimers apply.

- The potential ecosystem effects in this report should not be considered as actual *cumulative* effects, **since other anthropogenic pressures and developments** (like the effects from shipping, fisheries, oil and gas production or other types of energy production) are not included in scientific modelling.
- The potential ecosystem effects from the studies in this report are **focused on *direct* ecosystem effects**, not the potential subsequent *indirect* effects on marine organisms, their habitats and food web interactions. More specifically, the **relationships and feedback mechanisms between ecosystems and species are not taken into account**.
- The potential ecosystem effects from the studies in this report **can often not be defined as positive or negative**, since there is uncertainty regarding the implications and the valuation of these effects depends on the views taken (e.g., the implications of changes to ecosystem processes on food web interactions

[1] *Deltares is an independent Dutch research institute working on innovative solutions in the field of water and subsurface (https://www.deltares.nl/en)*

and indirect effects on higher trophic levels or more fundamentally, comparisons and ambitions regarding historical and desired situations).

- There is a **high level of uncertainty in predicted ecosystem effects, and these vary across regions.** The results from this synthesis are **based on studies that often rely on modelling data to predict effects**. Some studies are based on empirical data and/or have used *in situ* measurements as input for model parameters, however still, extrapolations into the future are based on modelled data (to simulate future situations). The results from these models are influenced by the (number, type and values of) parameters used as input and s**ome of these parameters are based on assumptions and uncertainties in science itself** (e.g., using a constant value for mixing efficiency, using cylindrical foundation structures, not incorporating mussel growth, not incorporating feedback and interaction between OWFs)**.** The level of evidence has been included in conclusions and hypotheses, i.e., whether knowledge is based on empirical (*in-situ*) or simulated (modelled) data. Therefore, all conclusions and hypotheses in this report should be considered with a level of uncertainty. Models have been developed using the best available scientific knowledge to date and as knowledge increases, these models can strengthen or weaken the current hypotheses. More research is being undertaken or planned that will contribute to the currently predicted effects.

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2 Potential ecosystem effects from OW

2.1 Introduction on ecosystem effects

The international ambitions for the upscaling of offshore wind in the North Sea and Celtic Sea demand us to carefully assess its implications for the already pressured ecology in this marine environment. Several studies have indicated that OWFs, when developed at the scales of the current international ambitions, can potentially have a substantial effect on important ecosystem processes. According to scientific literature and subject matter experts, the most important risks from the upscaling of offshore wind in the North Sea and Celtic Sea are 1) the effects on ecosystem processes and their interrelation with the complex food web dynamics and 2) the cumulative effects of offshore wind developments and other anthropogenic pressures (L. A. van Duren, personal communication, 17 April 2023; Vrooman et al., 2019).

This synthesis of knowledge focuses on the effects on ecosystem processes that are most relevant to changes in primary production in the North Sea and Celtic Sea. The effects on ecosystem processes in this context are hydro-morphological changes like changes in currents, spatiotemporal stratification and sedimentation patterns and are hereafter called ecosystem effects. Primary production in the marine context refers to the process by which microscopic algae convert sunlight into organic matter through photosynthesis. Primary production is crucial for the marine food web as it provides the foundation for all other marine organisms, being consumed by zooplankton and subsequently transferring energy to higher trophic levels, including fish, marine mammals, and seabirds. Changes in primary production can ultimately result in fundamental changes to the entire marine ecosystem(Friedrichs et al., 2007).

An important hydrodynamic process that drives primary production is stratification. Stratification refers to the way that a body of water is layered based on its density. The density of water is determined by its temperature and salinity: seawater density is highest at 4°C and decreases with higher temperatures and density increases with higher salinity. The warmer or fresher and hence less dense water tends to stay near the surface, while the colder or more saline and hence denser water sinks to the bottom. This creates different layers of water with different properties, and this layering is important for many aspects of marine life. Solar radiation in summer heats the surface of the water column (often creating temperature differences of 5 to 10°C from the cooler bottom layers) and induces stratification in certain regions of the sea. This seasonal development of stratification is known to have a large influence on the productivity and food web of the North Sea and Celtic Sea, with implications for carbon fixation, oxygen concentrations and food availability for marine life (Carpenter et al., 2016; Cazenave et al., 2016; Dorrell et al., 2022; van Duren et al., 2021).

One way that stratification affects primary production is by limiting the amount of nutrients that are available to photosynthetic organisms, such as phytoplankton. In areas where the water is stratified, the nutrient-rich deep water is separated from the nutrient-poor surface water, which can limit the growth of these organisms. This can have significant impacts on the food web and overall productivity of the marine ecosystem. However, stratification can also create areas of high productivity where the nutrient-rich deep water is brought up to the surface through processes such as upwelling. This can lead to the growth of large blooms of phytoplankton and other organisms, which can support a variety of marine life. Overall, the process of stratification is complex and can have both positive and negative effects on primary production and the marine ecosystem as a whole (Cazenave et al., 2016; Dorrell et al., 2022; van Duren et al., 2021).

So far, much of the offshore wind energy production in Europe has been in well-mixed unstratified, shallow waters near shore. Sector growth, however, is now pushing potential developments further offshore, into deeper, and seasonally stratified waters. The ambitions for large-scale offshore wind production have the potential to significantly impact the process of stratification and introduce a 'new normal' in the hydrodynamics of the North Sea and Celtic Sea. The construction and operation of offshore wind farms involve significant human activity and infrastructure, which can cause changes in the water circulation and mixing in the surrounding ocean. This mixing can disrupt the stratification of the water column and alter the availability and distribution of nutrients, which can impact primary production and the entire marine food web (see Figure 2). For example, the installation of wind turbines and associated infrastructure on the seabed can change the flow of water and create turbulence, which can mix the layers of water and bring nutrient-rich water to the surface. This could lead to increased primary production and support the growth of new marine organisms, but it could also alter the distribution and abundance of existing marine life (Dorrell et al., 2022).

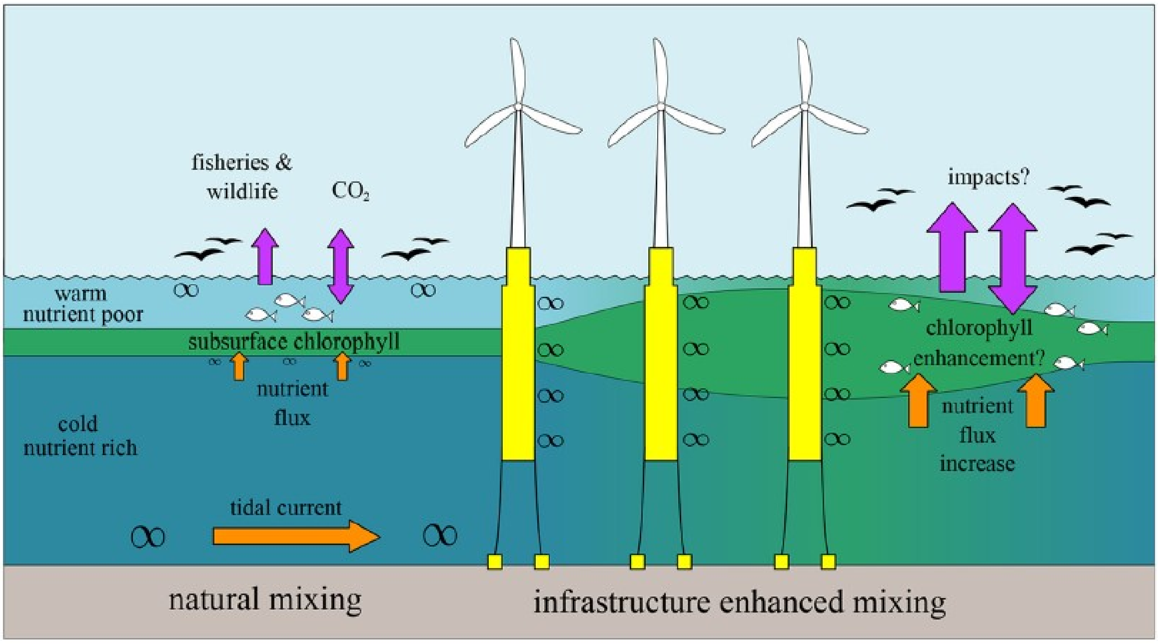

Figure 2. Offshore wind infrastructure adds turbulence throughout the water column within and around an OWF. In seasonally stratified waters, this can lead to destratification and a mixing of the otherwise warm nutrient-poor surface water with colder nutrient-rich deeper water. This in turn can lead to changes in primary production, ecosystem functioning and oceanic carbon sequestration (Dorrell et al., 2022).

Another important limiting factor for primary production is light penetration. Light penetration is affected by the concentration of fine sediments (i.e., silt) in the water column and is driven by the level of turbulence. The turbulent wakes from large OWFs can induce the resuspension of fine sediment (as illustrated in Figure 3 below) and thereby inhibit primary production. It can also affect visual predation for certain marine species. In addition, resuspended sediments can significantly impact sediment transport and downstream sedimentation. This could potentially alter existing morphological processes and bathymetry, particularly in a sediment-dominated sea basin like the North Sea and Celtic Sea. The specific effects are dependent on water depth and sediment type as well as the OWF design (e.g., scour protection, etc.) (Vanhellemont & Ruddick, 2014).

Other ecosystem effects from OWFs are the decrease of wind velocity within and downwind from the turbines (wind-wake effect). This leads to a disturbance of wave height and the diffraction of waves potentially favoring stratification (Boon et al., 2018). Other effects are changes in current velocity leading to local vertical upwelling and downwelling, resulting in the mixing of nutrients between stratified water layers. The effects and extent of these changes are highly dependent on atmospheric conditions, however several data-modelling studies have provided evidence through that the ongoing OWF developments can

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have a substantial impact on the structuring of coastal marine ecosystems on basin scales (Akhtar et al., 2021; Daewel et al., 2022; Djath & Schulz-Stellenfleth, 2019; Platis et al., 2020).

Finally, it should be noted that climate change also modifies marine ecosystem processes like increasing seawater temperatures with potential effects on stratification. These changes are likely different from changes from large-scale OWFs and are potentially contradicting (i.e., increasing surface water temperatures from climate change effects versus decreasing surface water temperatures from increased turbulence from OWFs) (Friedland et al., 2022). Altogether, the effects on ecosystem processes from climate change or OW developments have only recently been subject to science and to a limited extent.

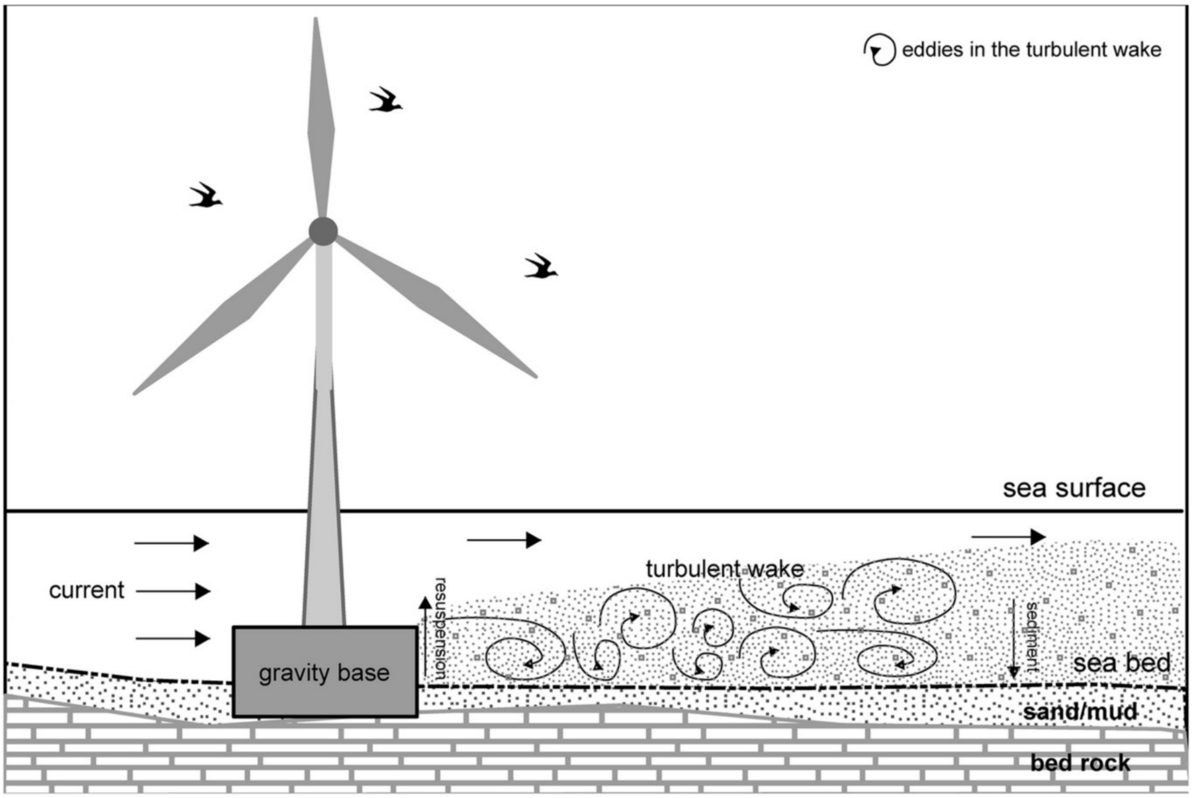

Figure 3. Illustrated effects from offshore wind turbines on the resuspension of sediment in the water column (Huang, 2022).

2.2 Main effects

The research on the effects from OWFs on abiotic ecosystem processes and primary production in the North Sea and Celtic Sea is sparse due to its relatively recent introduction as a solution for offshore energy production in this region. A few studies have focused on the effects in existing OWFs in the North Seas through in situ measurements providing empirical data. Other research has used data-modelling to study the effects for which in some cases input for model parameters is validated by in situ measurements alongside other variables.

It is important to note that the studies that have used data-modelling to predict changes to ecosystem processes are based on specific OW production scenarios using national plans and hypothetical scenarios towards 2050. The scenarios used in these models are not fully accurate aligned since national plans for OW production is a continuously moving target and science is hence often based on outdated information. Figure 4 below illustrates the changes from current OW plans and designations in relation to the scenarios as included in the study referenced below (van Duren et al., 2021). Updating these models with the latest plans for OW production will change the results from these studies, however it is expected that this will not lead to different conclusions and recommendations as are described below (L. A. van Duren, personal communication, 17 April 2023).

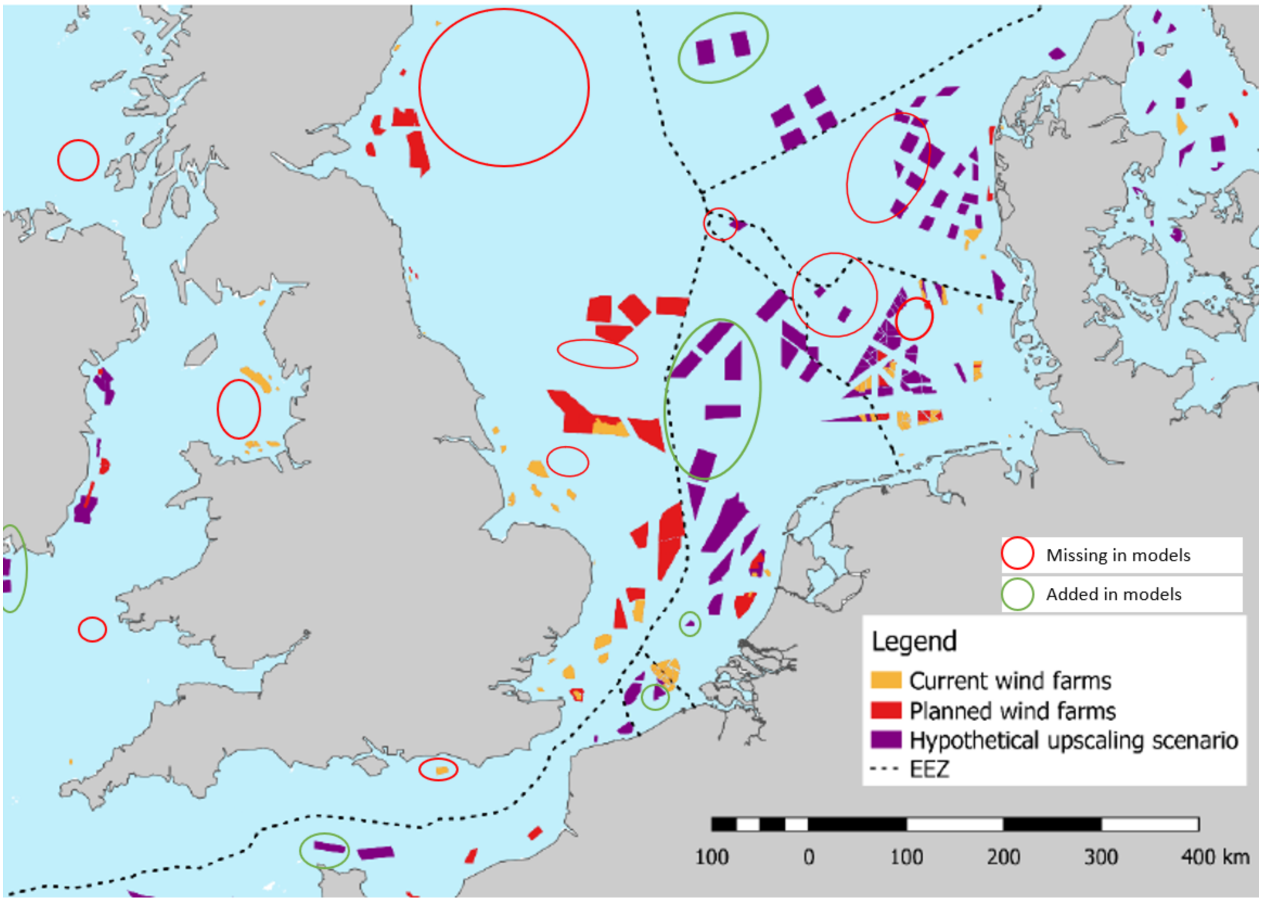

Figure 4. Map of North Sea and Celtic Sea displaying the differences between the most recent plans for upscaling of OW compared to the plans as applied in the modelling conducted by van Duren et al. (2021).

Following is a concise summary of the main findings from the supplied scientific literature and interviews with subject matter experts on this topic.

- Wind-wake effects: The effects from altered wind speeds in and downwind from OWF clusters, also called wind-wake effects, have been simulated through several data-modelling studies for the North Sea. These effects are more pronounced under stable atmospheric conditions and can extend more than 50 kilometers downwind from OWF clusters (Figure 5). (Akhtar et al., 2021; Christiansen et al., 2022; Daewel et al., 2022; Djath & Schulz-Stellenfleth, 2019; Platis et al., 2020).

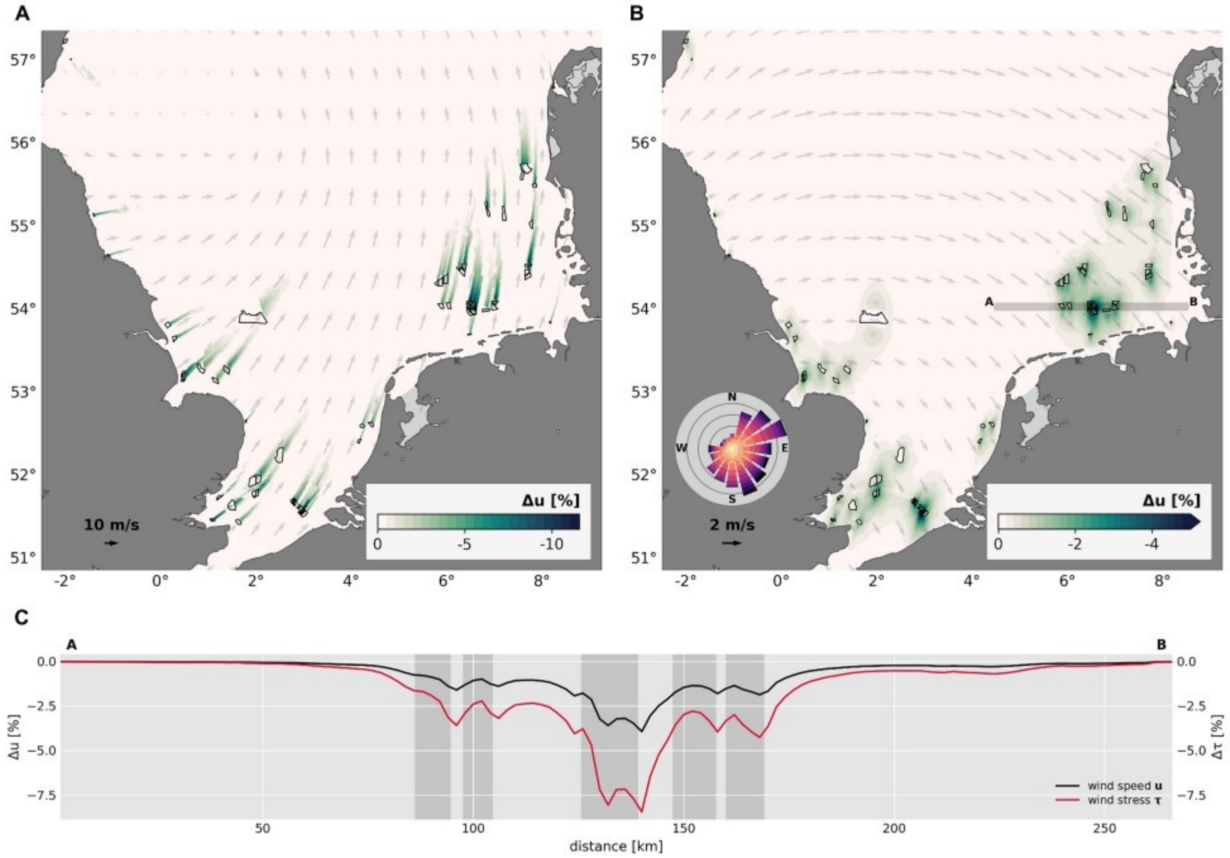

*Figure 5. Simulated changes in mean wind speed during a strong wind event in May 2013 (**A**) and mean wind speed changes over the period of May – September 2013 (**B**). Grey arrows indicate the mean wind direction. The wind rose indicates the wind direction and intensity. **C** displays the relative changes in wind speed and wind stress along a transect from A to B with OWFs being situated along the grey sections (Christiansen et al., 2022) (i.e., displaying substantial decreases).*

- <u>Effects on stratification (from wind-wake effects)</u>: The above-mentioned wind-wake effects can lead to substantial effects on stratification in certain areas of the North Sea. Changes are minor in shallow mixed waters but can be severe in areas with regular and stronger stratification regimes. Stable atmospheric conditions further amplify the effects, which are most frequent during spring and summer months, coinciding with the timing of seasonal stratification and blooms in phytoplankton production. Cascading effects on stratification have been simulated particularly in areas with clustered OWFs (Figure 6) (Christiansen et al., 2022). In areas with limited hydrodynamics, from for instance the tidal regime, stratification can be increased. In areas with more complex hydrodynamics the interaction of tidal currents with turbine foundations are expected to be more dominant and can result in contradicting effects (i.e., decreased stratification) (L. A. van Duren, personal communication, 17 April 2023).

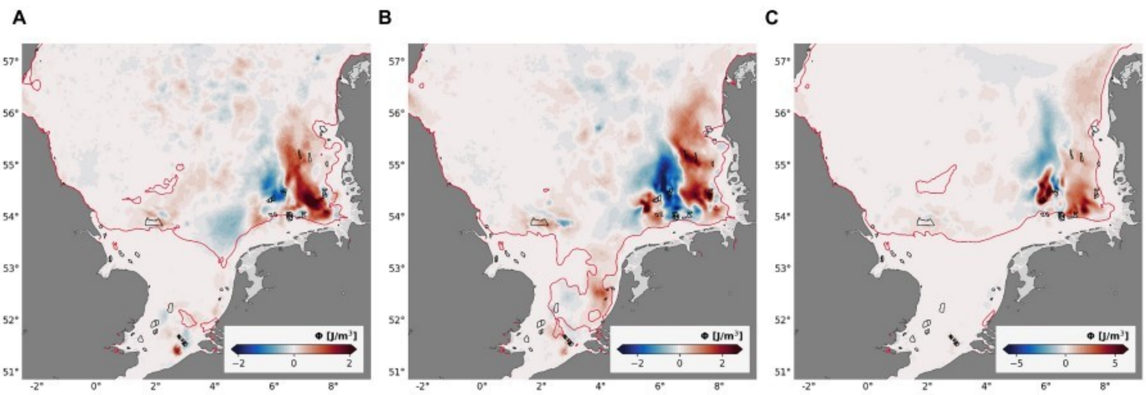

*Figure 6. Monthly mean changes in stratification for the months of June (**A**), July (**B**), and August (**C**). The red lines indicate the location of the mean tidal mixing fronts within the respective months. Black polygons indicate OWFs. (Christiansen et al., 2022)*

- <u>Effects on stratification (from interaction between currents and OWF foundations)</u>: As currents move past OWF foundation structures they generate a turbulent wake that contributes to a mixing of stratified water columns (Carpenter et al., 2016; Cazenave et al., 2016; Floeter et al., 2017; van Duren et al., 2021). Substantial effects have been demonstrated through in situ measurements and data-modelling on temperature stratification, and to a lesser degree on salinity stratification (Figure 7), particularly in areas with seasonal stratification. This effect has been shown to occur within OWFs and extend well beyond the footprint of turbines (Cazenave et al., 2016; Floeter et al., 2017; van Duren et al., 2021).

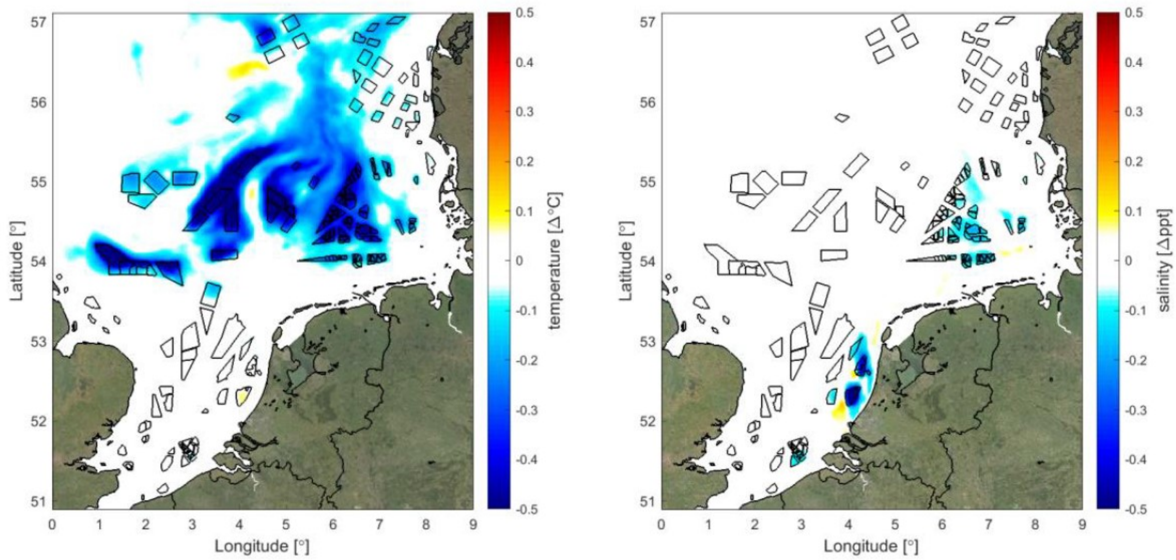

Figure 7. Simulated changes in (annual mean) stratification of surface temperature (left) and salinity (right). Both figures display the percentage difference between a reference and upscaling scenario. The central southern North Sea and German Bight have pronounced seasonal temperature stratification resulting in the most significant changes (blue areas) (van Duren et al., 2021).

- <u>Effects on fine sediment (silt) concentrations</u>: Substantial effects have been simulated through data-modelling on currents and stratification in certain regions with effects on the transport of fine sediment concentrations and nutrients (Figure 8). A slight reduction in tidal amplitude is expected in the 'corner' of the German Bight. An increase in silt concentrations in surface layers has been observed inside and immediately around OWFs. The near-bed concentrations of silt are predicted to decrease in many

OWFs, however in others, particularly in some of the English OWFs south-west of the Dogger Bank, an increase in silt concentrations is also expected near the sea bottom. These effects are affected by the season, with higher increases fine sediment concentrations in surface layers in spring and summer than in other times of the year (Carpenter et al., 2016; van Duren et al., 2021).

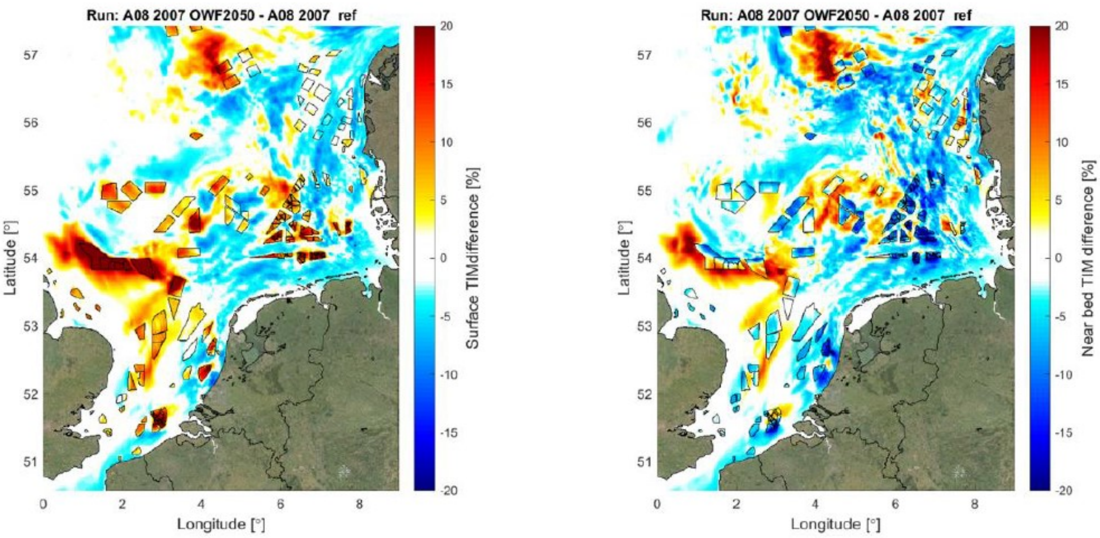

Figure 8. Left: simulated changes in fine sediment concentrations near the surface. Right: simulated changes in fine sediment concentrations near the seabed. Both figures display the percentage difference between a reference and upscaling scenario. (van Duren et al., 2021)

- <u>Effects on primary production</u>: Through simulations in several data-modelling studies it is expected that the upscaling of OW will lead to changes in stratification in certain regions of the North Sea and Celtic Sea. This has shown to lead to an increase in primary production in these areas due to enhanced vertical mixing and nutrient-input (Figure 9). These effects occur in and around OWFs and are more pronounced and extend well beyond the vicinity of OWFs in spring during the spring bloom (Figure 10). In certain areas, a delay in the onset of stratification and primary production is amplified by an increase in silt concentrations in surface layers. These changes are expected to result in substantial effects on the marine ecology in specific regions (Dorrell et al., 2022; Floeter et al., 2017; van Duren et al., 2021). Other studies have also demonstrated decreased dissolved oxygen concentrations inside areas with existing low concentrations potentially resulting in substantial impact on the structuring of the marine ecosystem (Daewel et al., 2022). See below for details on 2.4 Region-specific effects.

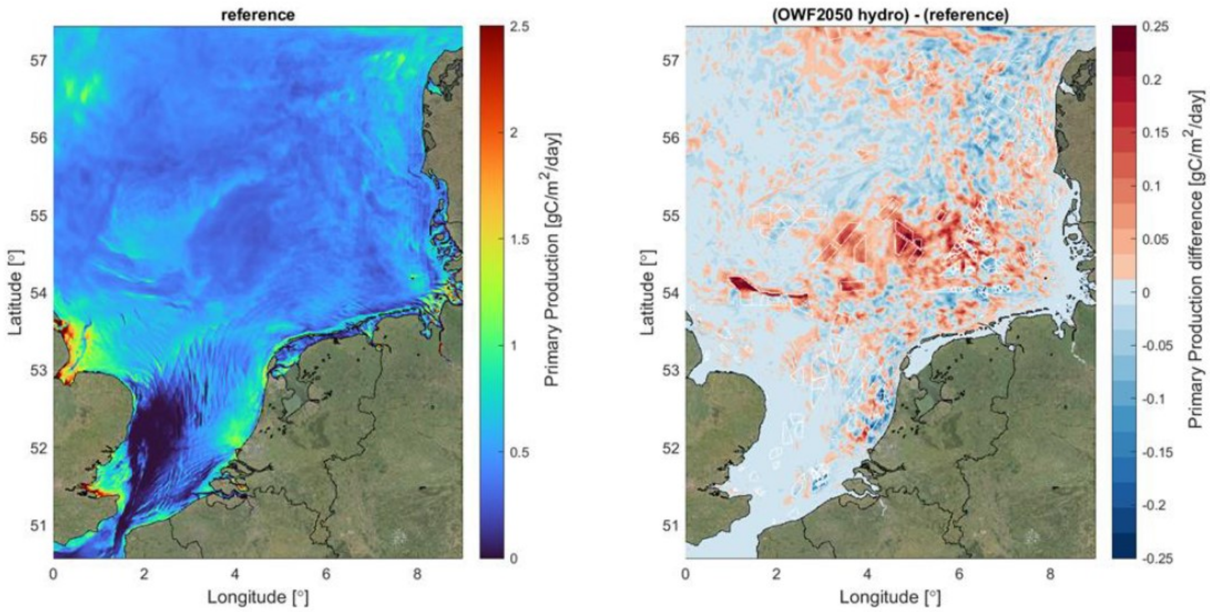

Figure 9. Left: annual average primary production in the North Sea (reference scenario). Right: simulated changes in annual average primary production from an upscaling scenario. (van Duren et al., 2021)

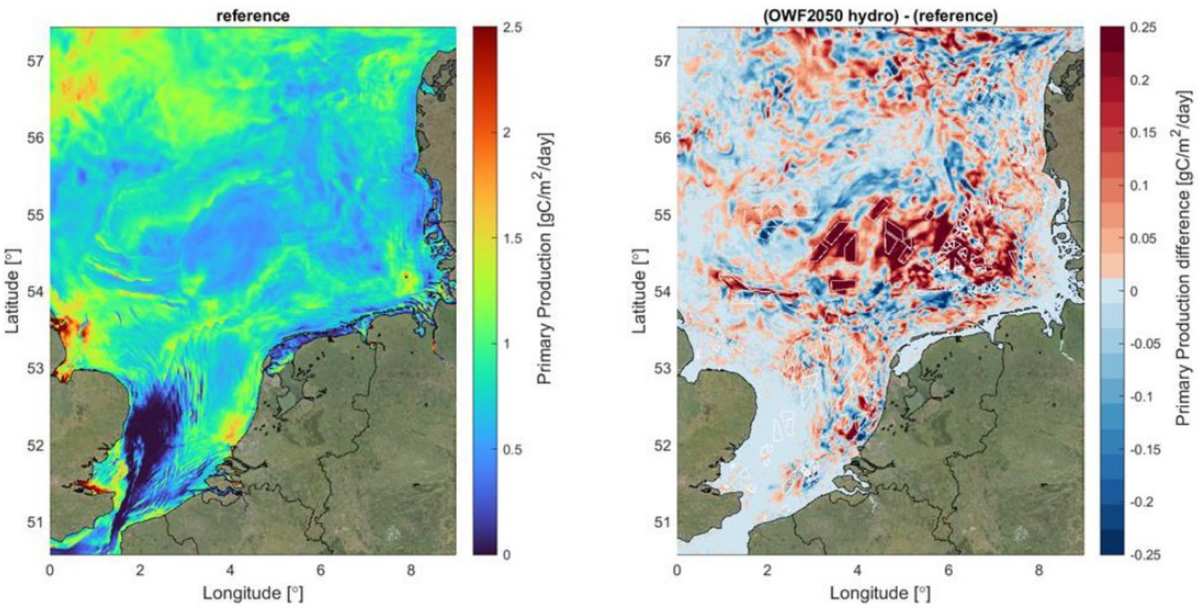

Figure 10. Left: average spring primary production in the North Sea (reference scenario). Right: simulated changes in average spring primary production from an upscaling scenario. (van Duren et al., 2021)

- Effects on turbid wakes: Extensive turbid wakes (sediment plumes) from OWFs in the Southern North Sea have been observed by remote sensing (Figure 11). The impact from this (re)suspended fine sediment is still unclear, but their spatial extent underline the need for further study, since resuspended fine sediment affects light penetration and subsequent primary production, and potentially other marine species (e.g., visual predation), as well as sediment transport and downstream sedimentation and potentially alter bathymetry (Vanhellemont & Ruddick, 2014).

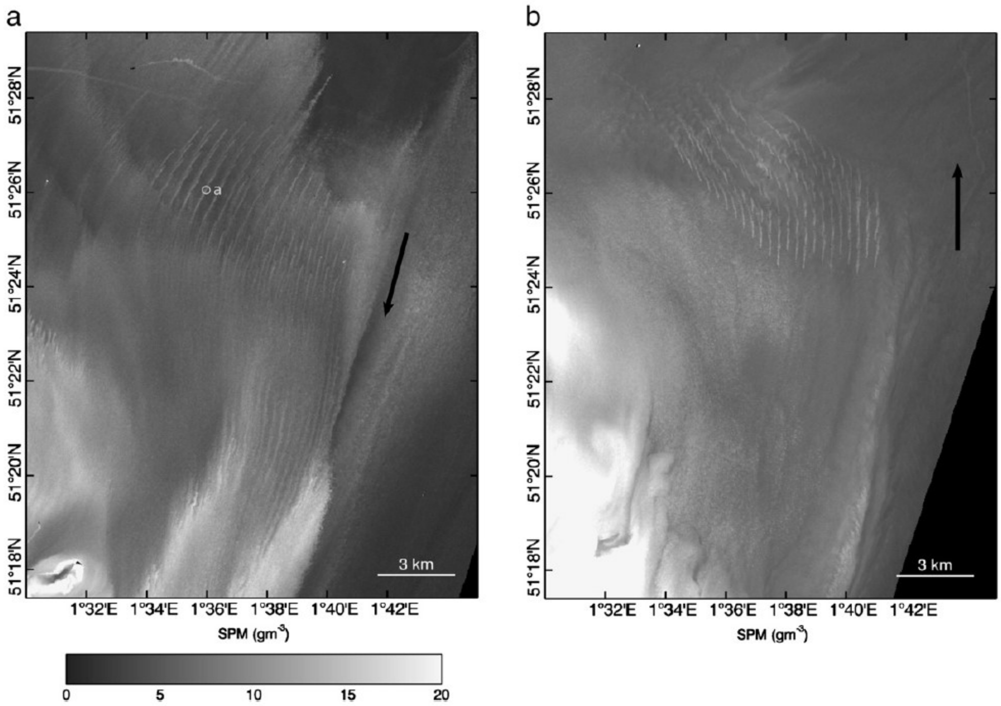

Figure 11. Turbid wakes from the two largest operational OWFs in the world in the Southern North Sea as seen from Landsat-8 imagery. The arrows depict the tidal stream direction at the time. (Vanhellemont & Ruddick, 2014)

- Additional effects on nutrient dispersal and marine food web: Changes in marine ecosystem processes can lead to substantial changes in the marine food web. For instance, several studies have demonstrated that changes in temperature can lead to changes in the dispersal of phytoplankton and zooplankton, altering the nutrient availability for higher trophic levels and thereby impacting the entire marine food web (Friedland et al., 2018, 2022).
- Additional (bottom-up) effects on marine ecology: The upscaling of offshore wind will likely lead to a substantial increase of epibenthic communities that attach themselves to submarine turbine foundations, like the blue mussel (*Mytilus edulis*).
    - Blue mussels can induce extensive ecological change through filtration of the water column and providing functional structure and nutrients for other marine species, hence increasing local biodiversity (Slavik et al., 2018).
    - OWFs that inhabit large communities of filter feeders like the blue mussel may locally remove phytoplankton from the water column through filtration, which could impact local ecosystem functioning (Slavik et al., 2018).

2.4 Region-specific effects

Van Duren et al. (2021) has distinguished different regions in the North Sea basin based on their predicted ecosystem effects from the large upscaling of offshore wind (Figure 12). A description of the most relevant areas and their specific effects on ecosystem processes is provided below.

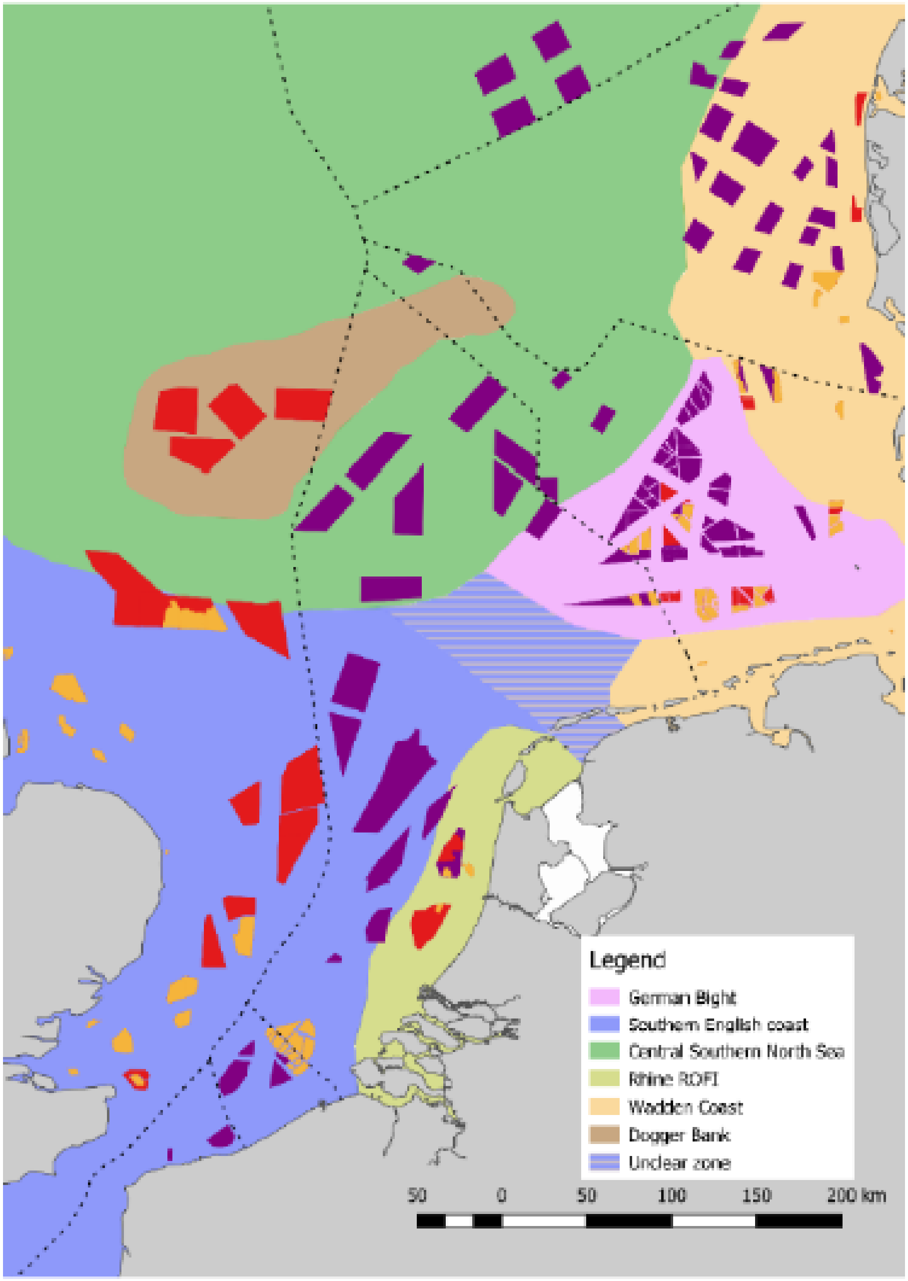

Figure 12. Areas in the North Sea with different ecosystem effects from the upscaling of offshore wind (van Duren et al., 2021)

- **Central German Bight**: Substantial changes to ecosystem processes are expected from the upscaling of offshore wind in this area. This area is characterized by regular but not strong stratification and the main predicted changes here are destratification and increased suspended particulate matter (i.e., fine sediment concentrations) in the surface water layers, with opposing effects on primary production. This is expected to result in a significant delay in the onset of the spring bloom in primary production (Carpenter et al., 2016; L. A. van Duren, personal communication, 17 April 2023; van Duren et al., 2021). Wind-wake effects in this area are predicted to result in a decrease in primary production in the center of large OWF clusters in the inner German Bight (Daewel et al., 2022).

- **Central southern North Sea, particularly south of the Dogger Bank** (around the Oyster Grounds): Substantial changes to ecosystem processes are expected from the upscaling of offshore wind in this area. This region contains areas with regular seasonal stratification. The main predicted changes here are a delay in stratification and mixing of nutrients. The effects on the resuspension of fine sediment concentrations are limited in this region, which in combination with the above is expected to lead to a significant increase in primary production. This effect is amplified during spring and leads to a delay in the onset of the spring bloom. Effects extend well beyond the immediate OWF perimeters. It is assumed that the increased nutrient input will benefit benthic fauna and associated species, but may be detrimental for others, however this should be studied further (L. A. van Duren, personal communication, 17 April 2023; van Duren et al., 2021). Wind-wake effects in this area are predicted to result in a decrease in primary production in the center of large OWF clusters at the Dogger Bank, and an increase southeast of the Dogger Bank at the Oyster Grounds (Daewel et al., 2022).
- **Rhine ROFI (Region Of Fresh water Influence) along the Dutch coastline**: Changes to fine sediment concentrations are expected this region. These are predicted to reduce primary production and increase the transport of sediment and nutrients downstream. This area generally has higher rates of primary production, so the effects on primary production are potentially less impactful. However, the transport of fine sediment along this highly dynamic region with strong currents warrants caution around future plans for upscaling of OW (van Duren et al., 2021).
- **German, Danish and English coastal areas, western Dutch Continental Shelf and on the Dogger Bank**: Limited ecosystem effects are expected from the upscaling of offshore wind in this area. These areas are relatively shallow and have limited stratification (i.e., the water column is fully mixed). Therefore, OWFs will not lead to changes in stratification in these areas. Due to the existing turbidity in these regions, OWFs are not likely to affect productivity here. Further off the coast, particularly away from the Thames estuary, the increased turbidity from large-scale OWFs could potentially lead to reduced primary production (van Duren et al., 2021).
- **Celtic Sea**: Large-scale expansion of offshore wind in this area can lead to a change in the amplitude of tides at the coasts with significant impact on intertidal areas (e.g., bird habitats). It will also lead to a decrease in stratification in offshore areas where seasonal stratification occurs (Cazenave et al., 2016). Since limited studies have been conducted on the potential ecosystem effects from the large upscaling of offshore wind in the Celtic Sea, the predictions for this region are highly uncertain at this stage.

2.5 Conclusion

In summary, based on the plans for large upscaling of offshore wind the North Seas and Celtic Sea, significant changes can be expected to ecosystem processes like stratification, currents, tidal amplitude, fine sediment concentrations, nutrient mixing and primary production, as demonstrated through several scientific studies. These changes are likely to cause knock-on effects on other trophic levels in the marine environment. Based on the extent and spatial planning as used in the studies and modelling of these ecosystem effects, the largest changes can be expected in the southern North Sea and Central German Bight, with direct and significant effects on primary production in this region. The specific areas of highest concern should be studied and modelled further to assess the location and design of OWFs with the least expected impact on marine ecosystem processes (see also the next chapter).

3 Recommendations

This chapter contains the most important knowledge gaps and recommendations based on the synthesis of literature and interviews with subject matter experts.

3.1 Prevention and mitigation

- Due to the uncertainties around the actual impact from the upscaling of offshore wind in the North Sea and Celtic Sea on ecosystem processes and its interrelation to the complex food chain dynamics, it is recommended to minimize potential effects as much as possible (Carpenter et al., 2016; L. A. van Duren, personal communication, 17 April 2023; van Duren et al., 2021).
- The design of offshore wind farms provides important mitigation measures to minimize ecosystem effects. Note that in general, the effect of mitigation measures on hydrodynamic processes is predicted more easily than the effects on ecological processes. Some examples of potential preventive and mitigation measures for OWF design are (L. A. van Duren, personal communication, 17 April 2023):
    - Consider reduction of OWF development in areas with potential large impacts.
    - Current models have demonstrated that a larger spacing between turbines in an OWF reduces the mixing of the water column and decreases the wind-wake effects (Platis et al., 2020), both with positive effects on turbidity and stratification. In other research, this design in addition with higher turbines has also shown to be beneficial for certain seabird species by allowing them more space to fly through OWFs.
    - Ecosystem effects are dependent on the positioning and formation of individual turbines within an OWF, i.e., positioning the groups of monopiles parallel to predominant current directions will be more favorable compared to positioning them across currents. Wind-wake effects also differ depending on the direction-based layout of OWFs, therefore it is recommended to further model the effects from different layouts (Platis et al., 2020).
    - Ecosystem effects are expected to be different with contiguous OWFs, dependent on the size of OWFs, and predicted effects should be modelled to confirm this.
- Effects can be minimized by limiting the size of OWFs or by using floating or semi-submerged OWF platforms in certain regions (Carpenter et al., 2016). Floating or semi-submerged OWF platforms will result in fewer effects on turbidity through the resuspension of fine sediment concentrations. However, this technique is not suitable in the relatively shallow regions of the North Sea (i.e., <60 meters), but could be a good and viable solution for energy production in deeper waters like in the more northern regions of the North Sea and Celtic Sea (L. A. van Duren, personal communication, 17 April 2023).

3.2 Region-specific recommendations

The specific areas of highest concern should be subject to further research to assess the most appropriate location and design of OWFs. Below are some region-specific recommendations from the perspective of preventing potential effects on ecosystem processes for particular areas of concern.

- **Central German Bight**: Due to the sensitivity of this region to changes in ecosystem processes, its complex situation, and the fact that this area is likely to see a very high density of OWFs in the future it is advised to proceed here with caution. For The Netherlands it is advisable to develop in other areas first. This will allow time for further research on the effectiveness of mitigating options in terms of OWF design and layout.
- **Central Southern North Sea**: It is advised that further studies are conducted prior to large-scale development of OW in this region due to the sensitivity of this region to changes in ecosystem

processes, especially during the spring bloom in primary production, the uncertainty around its implications (being positive or negative), and the fact that the effects extend well beyond the immediate vicinity of planned OWFs in this region.

- **Rhine ROFI along the Dutch coastline:** Large-scale offshore wind developments in this region should be considered with caution due to the predicted changes on the transport of fine sediment concentrations. This is a highly dynamic area and is subject to potential changes in bathymetry and morphology, which is of particular relevance to coastal protection and the intertidal Wadden Sea.
- **German, Danish and English coastal areas, western Dutch Continental Shelf:** These regions are less likely to be affected by changes to ecosystem processes from OW. If other ecological effects are also limited, these areas could be further explored for the development of OW. Note that further off the coast, particularly away from the Thames estuary, increased turbidity from large-scale OWFs could potentially lead to reduced primary production and should be considered with caution.
- **Celtic Sea:** This region has not been subject to extensive studies from the large upscaling of OW. The studies that have taken place have modelled a potential significant impact on intertidal areas. Therefore, it is advised that more research is undertaken prior to the large-scale development of OW in this region.

3.3 Further research and updated effect forecasts

The results from this synthesis are based on studies that have relied on modelling data to predict effects. Some of these studies have used *in situ* measurements as input for model parameters, however still, extrapolations into the future are based on modelled data (to predict future situations). The results from these models are influenced by the (number, type, and values) of parameters used as input and some of these parameters are based on assumptions and uncertainties in science itself. E.g., using a constant value for mixing efficiency, using cylindrical foundation structures, not incorporating mussel growth and not incorporating feedback and interaction between OWFs**.** Models have been developed using the best available scientific knowledge to date but require further fine-tuning. Below are recommendations to update these.

- There is a large knowledge gap in the understanding of the interrelation between ecosystem effects, primary production and how these affect specific species in higher trophic levels in the North Sea and Celtic Sea (Carpenter et al., 2016; Floeter et al., 2017; van Duren et al., 2021). To understand this better, the following recommendations are made:
  - Conduct field and modelling studies on phytoplankton composition, biomass and production around OWFs in relation to destratification, nutrient mixing and SPM concentrations (similar to studies such as (Floeter et al., 2017).
  - Conduct field and modelling studies on how changes in primary production from changes in stratification affect secondary production (particularly zooplankton and shellfish).
  - Study the effects on stratification and primary production from the turbulence created by the accumulation of epistructural communities.
  - Study and further quantify the effects on primary production through the filtering capacity of phytoplankton by epistructural species (e.g., blue mussels) that inhabit OWFs (Slavik et al., 2018).
  - Study the epistructural species in combination with hydrodynamic modelling to assess the risks and spatial extent of the spread of non-endemic (invasive) species.

There is a knowledge gap in the wind-wake effects on the regional ecosystem scale including the cumulative effects from the interaction between OWF clusters in modelling. It is recommended that future research addresses this knowledge gap (Carpenter et al., 2016; Floeter et al., 2017; van Duren et al., 2021).

- A better understanding is required of the turbulence and induced mixing from different OWF foundation structures in order to determine the most appropriate OWF design (Carpenter et al., 2016).
- It is recommended to further study the effects from turbid wakes (sediment plumes) from OWFs, since resuspended fine sediment affects light penetration and subsequent primary production, and potentially other marine species, as well as sediment transport and downstream sedimentation (Vanhellemont & Ruddick, 2014).
- It is recommended to assess the effects from OW for each ecosystem component in cumulation with other anthropogenic pressures, preferably incorporating the effects from climate change. This should enable the assessment of the actual cumulative effects of all anthropogenic pressures on the various ecosystem components and its impact on the ecology in the North Sea and Celtic Sea. This assessment should include the level of impact from each anthropogenic pressure in order to prioritize measures and mitigations.
- As mentioned in paragraph 2.2, models have been run using outdated plans for OW development and hypothetical scenarios, that were designed for research purposes – not to simulate realistic scenarios, and plans are continually changing. Figure 4 illustrates these differences. To assess the actual effects from the most recent and accurate plans for OW development, these models need to be updated, rerun and reanalysed.
- It is important to apply an adaptive management approach to the decision-making around OWF designations, i.e., to base decisions on the most recent and best available information.
- It is important that the international collaboration on the effects from OWF on marine ecology is strengthened. Particularly the collaboration and knowledge sharing in research and mitigating measures and the collaboration in marine spatial planning by governments can be improved. It is recommended that an international research program is developed where cross-boundary research topics are jointly funded and coordinated by governments and knowledge gaps are addressed by a collaborating team of international scientists (pers. comm. Luca van Duren, 2023).
- It is recommended to follow and where possible collaborate on the most recent and current developments and (research) programs on this topic. Below are the main programs to keep track of (L. A. van Duren, personal communication, 17 April 2023):
  - National research programs (like WOZEP in The Netherlands)
  - Effects of windfarms on fine sediment dynamics (program by the NIOZ)
  - NWA Wind at Sea research program
  - ECOAMARE[2] (EU awarded project to research the upscaling of OW and multi-use)
  - Offshore Wind Evidence and Change[3]
  - Insite[4]
  - eMSP[5] Community of Practice
  - Offshore Coalition for Energy and Nature (OCEAN)[6]

[2] https://www.nwo.nl/en/news/new-nwa-funding-eu25-million-nwa-research-energy-transition-and-ecology-north-sea
[3] https://www.thecrownestate.co.uk/en-gb/what-we-do/on-the-seabed/offshore-wind-evidence-and-change-programme/
[4] https://insitenorthsea.org/
[5] https://www.emspproject.eu/
[6] https://offshore-coalition.eu/

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