DBS Offshore Wind

RWE Renewables UK Dogger Bank South (West) Limited

RWE Renewables UK Dogger Bank South (East) Limited

Dogger Bank South Offshore Wind Farms

Review of Flamborough Front Submission for Deadline 4

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Glossary

Term	Definition
Array Areas	The DBS East and DBS West offshore Array Areas, where the wind turbines, offshore platforms and array cables would be located. The Array Areas do not include the Offshore Export Cable Corridor or the Inter-Platform Cable Corridor within which no wind turbines are proposed. Each area is referred to separately as an Array Area.
Array Cables	Offshore cables which link the wind turbines to the Offshore Converter Platform(s).
Astronomical Tide	The predicted tide levels and character that would result from the gravitational effects of the earth, sun, and moon without any atmospheric influences.
Climate Change	A change in global or regional climate patterns. Within this chapter this usually relates to any long-term trend in mean sea level, wave height, wind speed etc, due to climate change.
Coastal Processes	Collective term covering the action of natural forces on the shoreline and nearshore seabed.
Cohesive Sediment	Sediment containing a significant proportion of clays, the electromagnetic properties of which causes the particles to bind together.
Cumulative Effects	The combined effect of the Projects in combination with the effects of a number of different (defined cumulative) schemes, on the same single receptor / resource.
Cumulative Effects Assessment (CEA)	The assessment of the combined effect of the Projects in combination with the effects of a number of different (defined cumulative) schemes, on the same single receptor/resource.
Current	Flow of water generated by a variety of forcing mechanisms (e.g. waves, tides, wind).
Dogger Bank South (DBS) offshore wind farms	The collective name for the two Projects, DBS East and DBS West.
Effect	Term used to express the consequence of an impact. The significance of an effect is determined by correlating the magnitude of the impact with the value, or sensitivity, of the receptor or resource in accordance with defined significance criteria.

Term	Definition
Hydrodynamic	The process and science associated with the flow and motion in water produced by applied forces.
Inter-Platform Cable Corridor	The area where Inter-Platform Cables would route between platforms within the DBS East and DBS West Array Areas, should both Projects be constructed.
Inter-Platform Cables	Buried offshore cables which link offshore platforms.
Intertidal	Area on a shore that lies between Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS).
Long-Term	Refers to a time period of decades to centuries.
Mean Sea Level	The average level of the sea surface over a defined period (usually a year or longer), taking account of all tidal effects and surge events.
Nearshore	The zone which extends from the swash zone to the position marking the start of the offshore zone (~20m).
Numerical Modelling	Refers to the analysis of coastal processes using computational models.
Offshore	Area seaward of nearshore in which the transport of sediment is not caused by wave activity.
Offshore Export Cable Corridor	This is the area which will contain the offshore export cables (and potentially the ESP) between the Offshore Converter Platforms and Transition Joint Bays at the landfall.
Offshore Export Cables	The cables which would bring electricity from the offshore platforms to the Transition Joint Bays (TJBs).
Scour Protection	Protective materials to avoid sediment erosion from the base of the wind turbine foundations and offshore substation platform foundations due to water flow.
Sea Level	Generally, refers to 'still water level' (excluding wave influences) averaged over a period of time such that periodic changes in level (e.g. due to the tides) are averaged out.
Sediment	Particulate matter derived from rock, minerals or bioclastic matter.
Shore Platform	A platform of exposed rock or cohesive sediment exposed within the intertidal and subtidal zones.

Term	Definition
Short Term	Refers to a time period of months to years.
Surge	Changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and the astronomical tide predicted using harmonic analysis.
Suspended Sediment	The sediment moving in suspension in a fluid kept up by the upward components of the turbulent currents or by the colloidal suspension.
The Applicants	The Applicants for the Projects are RWE Renewables UK Dogger Bank South (East) Limited and RWE Renewables UK Dogger Bank South (West) Limited. The Applicants are themselves jointly owned by the RWE Group of companies (51% stake) and Masdar (49% stake).
The Projects	DBS East and DBS West (collectively referred to as the Dogger Bank South Offshore Wind Farms).
Wave Height	The vertical distance between the crest and the trough.
Wind Turbine	Power generating device that is driven by the kinetic energy of the wind.

Acronyms

Acronym	Definition
ADCP	Acoustic Doppler Current Profiler
BAC	Background Assessment Concentration
CEA	Cumulative Effects Assessment
Cefas	Centre for Environment, Fisheries and Aquaculture
DBS	Dogger Bank South
DCO	Development Consent Order
EAC	European Assessment Criteria
EIA	Environmental Impact Assessment

Acronym	Definition
EPA	Environmental Protection Agency
EQS	Environmental Quality Standard
ERL	Effects Range-Low
ES	Environmental Statement
ExA	Examining Authority
EU	European Union
GBS	Gravity Base Structures
ICES	International Council for the Exploration of the Sea
LAT	Lowest astronomical tide
MLD	Mixed Layer Depth
MMO	Marine Management Organisation
OD	Ordnance datum
OWF(s)	Offshore Wind farm(s)
PINS	Planning Inspectorate
SCAPE	Soft Cliff and Platform Erosion
SCI	Sites of Community Importance
SPA	Special Protection Area
Term	Definition

1 Introduction

1. RWE Renewables UK Dogger Bank South (East) Limited and RWE Renewables UK Dogger Bank South (West) Limited (hereafter referred to as 'The Applicants'). are proposing to develop the Dogger Bank South (DBS) offshore wind farms (DBS) (hereafter referred to as 'the Projects') comprising Dogger Bank South East and Dogger Bank South West in the southern North Sea, approximately 100-120km off the Yorkshire coast **(Figure 1-1**).

2. The Array Areas are within a waterbody that is typically well mixed for the majority of the year. However, during spring and summer months, an oceanographic front known as the Flamborough Front develops in the North Sea separating stratified water in the north from well mixed water in the south. The front is ephemeral in nature and its location and strength varies on a seasonal and yearly basis. However, observational satellite data suggests it may be present within the Array Areas for <40 days of the year (van Leeuwen *et al*. 2015).

3. This technical note provides supplementary information to address comments and questions from Natural England (NE), the Marine Management Organisation (MMO) and the Examining Authority (ExA) (as summarised in **Table 2-1**) related to Flamborough Front as a marine physical processes receptor and the assessment of changes in water circulation due to the presence of infrastructure as presented in **Chapter 8 Marine Physical Environment** [APP-080].

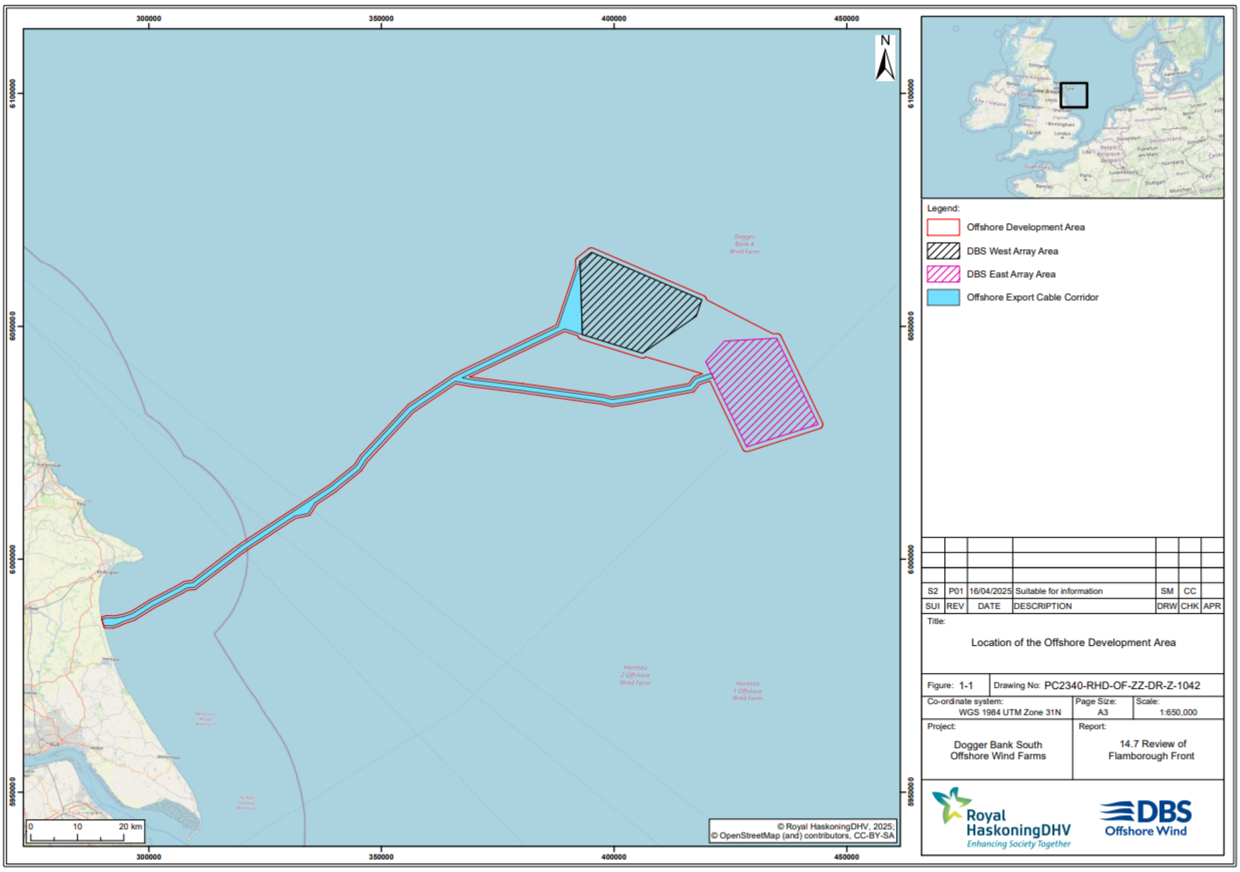

Figure 1-1 Dogger Bank South Offshore Wind Farm Order limits

2 Comments and Questions

4. The Applicants have been consulting with Interested Parties during the examination period. A record of comments and questions, and the Applicants' responses has been collated in **Table 2-1**. The key points raised are summarised below:

- The impact of offshore wind farms (OWFs) on water circulation, stratification, mixing and primary productivity has become increasingly more apparent through ongoing research. However, there remains an evidence gap in current baseline understanding and predicted changes due to offshore wind developments. There is a need to improve the evidence base to support the conclusions of the Environmental Statement.
- NE disagree with the conclusion of the cumulative assessment of changes to water circulation (Flamborough Front) due to the presence of infrastructure (wind turbines and offshore platforms) presented **in Chapter 8 Marine Physical Environment** [APP-080].
- NE and MMO recommend monitoring potential changes in stratification and primary productivity pre- and post-construction. The proposed monitoring plan

should consider the monitoring approach agreed the Hornsea Project 4 development.

5. Supplementary information and assessment to address each of these points is addressed in detail in **Sections 3, 4 and 5**.

Table 2-1 Comments and responses to date

ID	Comment	Response
Natural England		
RR-039: NE5	The presence of the Dogger Bank South Arrays (alone and in combination with other nearby offshore wind farms) could impact circulation, stratification, mixing, and sediment resuspension in the water column. This could in turn, cause changes to the Flamborough Front which could have far-reaching and long-term consequences for the wider marine ecosystem	As noted in section 8.7.4.3 (Changes to Water Circulation (Flamborough Front) due to the Presence of Infrastructure (Wind Turbines and Offshore Platforms) of **Chapter 8 Marine Physical Environment** [APP-080], the structures could potentially create turbulent wakes at a local foundation scale which could locally change tidal mixing processes which may locally perturb the Flamborough Front and across the width of the array areas. However, the Flamborough Front is a strongly stratified regional feature in spring and summer and the high buoyancy forces associated with the stratification would not be destabilised by the local and relatively small turbulent wakes generated in the near field of each foundation. The North Sea within and around the array areas is stratified for less than 40 days a year and they are within a region categorised as intermittently stratified. The nearest seasonally stratified region (stratified for greater than 120 days) is located 17km west of the array areas. The Flamborough Front may be present occasionally at the array areas, but for most of the time the water is well-mixed.

ID	Comment	Response
		With minimum spacings of 830m between foundations across the array, it is unlikely that wake to wake interactions would occur, and individual wakes would remain independent of each other and quickly dissipate away from each foundation (in the order of minutes and tens to hundreds of metres). Given that the Flamborough Front is highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations, especially if the strength of stratification (due to buoyancy forces) was sufficient to overcome any increased mixing. Based on this, no monitoring is proposed to be undertaken for changes to stratification, currents, and primary productivity.
RR-039: B5	Natural England is concerned that the presence of structures in the Dogger Bank South (DBS) Arrays (alone and in combination with other nearby offshore wind farms) could cause turbulent current wakes which impact circulation, stratification, mixing, and sediment resuspension. In turn, changes to the Flamborough Front could have far-reaching and long-term consequences for the wider marine ecosystem.	As noted in section 8.7.4.3 (Changes to Water Circulation (Flamborough Front) Due to the Presence of Infrastructure (Wind Turbines and Offshore Platforms)) of **Chapter 8 Marine Physical Environment** [APP-080], the structures could potentially create turbulent wakes at a local foundation scale which could locally change tidal mixing processes which may locally perturb the Flamborough Front and across the width of the array areas. However, the Flamborough Front is a

ID	Comment	Response
		strongly stratified regional feature in spring and summer and the high buoyancy forces associated with the stratification would not be destabilised by the local and relatively small turbulent wakes generated in the near field of each foundation. The North Sea within and around the Array Areas is stratified for less than 40 days a year and they are within a region categorised as intermittently stratified. The nearest seasonally stratified region (stratified for greater than 120 days) is located 17km west of the array areas. The Flamborough Front may be present occasionally at the Array Areas, but for most of the time the water is well-mixed. With minimum spacings of 830m between monopile foundations across the array, it is unlikely that wake to wake interactions would occur, and individual wakes would remain independent of each other and quickly dissipate away from each foundation (in the order of minutes and tens to hundreds of metres). Given that the Flamborough Front is highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations, especially if the strength of stratification (due to buoyancy forces) was sufficient to overcome any increased mixing.

ID	Comment	Response
		Based on this, no monitoring is proposed to be undertaken for changes to stratification, currents, and primary productivity.
RR-039: B33	Potential Cumulative Effects During Operation and Maintenance – Stratification/Flamborough Front Natural England highlights that the magnitude of impact (for cumulative effects on the Flamborough Front) is considered LOW in close proximity to structure[s], and negligible at the regional scale. This, coupled with a NEGLIGIBLE sensitivity of the Front, has resulted in the cumulative significance of effect being assessed as NEGLIGIBLE. We are unable to agree with this conclusion. As stated in Section 8.8.4, both "Dogger Bank A and Dogger Bank B schemes, and the Projects Array Areas are located in a region of the North Sea where there is the potential for seasonal stratification to occur as the Flamborough Front develops and migrates." Recent studies (e.g. Daewel *et al*., 2022) show that the presence of large OWF clusters (e.g. Dogger Bank) could provoke large-scale hydrodynamic changes that impact marine primary production and the wider marine ecosystem. Therefore, we are concerned that structures in the DBS Arrays, such as foundations and piles, could cause turbulent current wakes which impact circulation, stratification, mixing, and sediment resuspension. In turn, changes to the Flamborough Front could have far-reaching and long-term consequences	The cumulative significance of effect is assessed as negligible because any effects caused by the Projects structures would only interact with other offshore wind farms at a regional scale. The Projects-alone significance at a regional scale is negligible. There would be no interaction at a local scale. Hence, the overall cumulative negligible effect. Monitoring of the Flamborough Front can only be undertaken using remote sensing techniques. This is because, when the Flamborough Front is present, it is a 320 km-long zone separating the well-mixed cooler waters to the south from the warmer stratified waters to the north. The discontinuity in temperature is typically visible in satellite infrared imagery and this is the best method to investigate its location and structure. Trying to monitor the feature using deployment of Acoustic Doppler Current Profilers or other instruments located on the seabed or in the water column would only provide local-scale information which could not be reliably associated with any effects induced by the Projects structures.

ID	Comment	Response
	since the frontal system gives rise to nutrient-rich waters which create a biodiversity hotspot attracting seabirds and marine mammals to the area each year. Given the number of developments of offshore windfarms in the proximity of the Flamborough Front we advise that monitoring of potential change in stratification and productivity from the DBS development is needed to improve the evidence base and conclusions from the ES.	
RR-039: B41	Flamborough Front Natural England notes that the Applicant states that the "*front becomes nutrient rich and is considered to be ecologically important."* Yet, the value of the Flamborough Front has been assessed as MEDIUM. We advise that the Flamborough Front is of HIGH value owing to its colocation with particularly high primary production and ecological importance. However, there is an evidence gap regarding current and predicted future levels of primary production in the vicinity of the DBS Arrays. The sensitivity of the Front has also been assessed as NEGLIGIBLE. However, there is insufficient evidence regarding the future location of the Flamborough Front relative to the DBS Arrays over the lifetime of the Projects. We note that in Section 8.5.12 the Applicant suggests that "*it may be present in the Array Areas, Inter-Platform Cable Corridor and the Offshore Export Cable Corridor during summer 70-90% of the time (Miller & Christodoulou, 2014). During autumn and spring, the front may*	The Applicants agree that the value of the Flamborough Front is high due to the reasons indicated. However, the sensitivity is considered negligible. This is because although the feature may be present in the array areas in summer between 70% and 90% of the time and in autumn and spring, between 30% and 50% of the time, it does not commonly stratify in the vicinity of the Projects' Array Areas on a seasonal basis. Natural England is referred to the Applicants response to RR-039: B5 for a view on potential changes to turbulent mixing due to the interaction of tidal flows with the Projects' structures.

ID	Comment	Response
	be present in the Array Areas and Inter Platform Cable Corridor between 30-50% of the time (Miller & Christodoulou, 2014). There is also a lack of evidence regarding potential changes in turbulent mixing due to the interaction of tidal flows with the DBS Array Areas infrastructure. We are, therefore, unable to agree with the EIA conclusions	
Marine Management Organisation		
REP1-074:1.9.12	1.9.12 The MMO notes NE's concerns regarding Flamborough Front and that the Applicant should monitor potential changes to stratification, currents and primary productivity during pre-construction, post construction and the lifetime of the projects.	Please see the Applicants response to NE stated in the **Response to Natural England's Relevant Representations** [AS-048] (RR-039: NE5) below: *'As noted in section 8.7.4.3 (Changes to Water Circulation (Flamborough Front) due to the Presence of Infrastructure (Wind Turbines and Offshore Platforms)) of* ***Chapter 8 Marine Physical Environment*** *[APP-080], the structures could potentially create turbulent wakes at a local foundation scale which could locally change tidal mixing processes which may locally perturb the Flamborough Front and across the width of the array areas. However, the Flamborough Front is a strongly stratified regional feature in spring and summer and the high buoyancy forces associated with the stratification would not be destabilised by the local and relatively small turbulent wakes generated in the near field of each foundation.*

ID	Comment	Response
		The North Sea within and around the array areas is stratified for less than 40 days a year and they are within a region categorised as intermittently stratified. The nearest seasonally stratified region (stratified for greater than 120 days) is located 17km west of the Array Areas. The Flamborough Front may be present occasionally at the array areas, but for most of the time the water is well-mixed. *With minimum spacings of 830m between monopile foundations across the array, it is unlikely that wake to wake interactions would occur, and individual wakes would remain independent of each other and quickly dissipate away from each foundation (in the order of minutes and tens to hundreds of metres).* *Given that the Flamborough Front is highly dynamic and ephemeral landscape-scale feature, it would not be affected by localised, small-scale changes in water column turbulence induced by individual near-field wakes at foundation locations, especially if the strength of stratification (due to buoyancy forces) was sufficient to overcome any increased mixing.* *Based on this, no monitoring is proposed to be undertaken for changes to stratification, currents, and primary productivity.'*

MCP.1.10	**Applicants:** Your response to NE's RR [AS-048] is noted, however: 1. Can you justify why monitoring of potential changes to the stratification, currents and primary productivity of the Flamborough Front would not be required? 2. Why do you consider there would be a disadvantage to using remote sensing techniques? 3. Can you explain how the Proposed Development would differ from Hornsea 4 OWF, where a detailed monitoring programme was agreed between the Applicant, MMO and NE? 4. How do you seek to address the concerns raised by NE if monitoring was not agreed? **NE:** Has the submission of Change Request 1 altered your position in relation to a requirement for a monitoring programme? If so, how? In addition, do you agree with the Applicants' assessment that the Proposed Development would only result in localised changes, while the Front is considered to be of regional importance and would therefore not be affected?	1. As outlined in section 8.5.12 of Chapter 8 Marine Physical Environment [APP-080], the water column in the Array Areas is categorised as being intermittently stratified and the Flamborough Front may be present for up to 40 days of the year. As this is an ephemeral feature, it would be difficult to predict the position of the front at any given time to inform the deployment of monitoring equipment (e.g. Acoustic Doppler Current Profilers). The monitoring results could therefore be misinterpreted e.g. if no front is detected at a specific location (or water depth) it does not mean the front was not present (or vice versa). There is also a high degree of variability in the existing baseline oceanographic conditions which has not been fully parameterised due to limited data availability (in part due to the difficulty capturing data from a feature that is rarely present and constantly moving). Therefore, there is no academic agreement on the definition of thresholds of change that would set the trigger points for intervention/remediation. The early outputs from highly complex oceanographic modelling of the effects of wind farms on ocean stratification (see presentations delivered in the Marine Physical Processes session of the 7th ScotMER Symposium March 2025) show localised changes in the near field (similar to that presented in section 8.7.4.3 of Chapter 8 Marine Physical Environment [APP-080]) and while far-field effects cover much greater

ID	Comment	Response
		distances, the magnitude of the change is very small and within the range of natural variability. Therefore, it is not clear if a monitoring program would be able to detect change and also if it would be able to distinguish between the effects of the wind turbine structure and those oceanographic changes occurring due to climate change. 2. The existing baseline understanding of the location and duration of the Flamborough Front is based on remote sensing. The Applicants do not believe it would be a disadvantage to use remote sensing and state the following in response to RR-039:B33: *'Monitoring of the Flamborough Front can only be undertaken using remote sensing techniques. This is because, when the Flamborough Front is present, it is a 320 km-long zone separating the well-mixed cooler waters to the south from the warmer stratified waters to the north. The discontinuity in temperature is typically visible in satellite infrared imagery and this is the best method to investigate its location and structure. Trying to monitor the feature using deployment of Acoustic Doppler Current Profilers or other instruments located on the seabed or in the water column would only provide local-scale information which could not be reliably associated with any effects induced by the Projects structures.'*

ID	Comment	Response
		3. The proposed Development differs from Hornsea 4 as Gravity Base Structures (GBS) are not being considered for any structures. The proposed monitoring approach for the Flamborough Front is discussed in the Hornsea Project 4 Clarification Note on Marine Processes Mitigation and Monitoring . In Table 7 of this document the following text is included, which suggests monitoring will only be undertaken if GBS foundations are used: "If Hornsea Four adopts any other consented foundations rather than GBS then this monitoring requirement does not apply, noting the previous remarks offered by Natural England, MMO and Cefas related to monopiles (see 4.4.1.2)." However, the Outline Marine Monitoring Plan does not make specific reference to GBS foundations. As the Applicants have committed to not using GBS foundations, it is not clear how the monitoring proposal for Hornsea 4 is comparable. 4. The Applicants will continue to consult with Natural England through the examination process to reach agreement on this matter. In addition, this technical note summarises the potential effects of the Projects on the Flamborough Front and how other offshore wind farm projects have assessed their potential impacts on the feature will be provided at Deadline 4 of examination.

3 Evidence gap

6. There is concern that there is not a sufficient evidence base to support the assessment of changes to water circulation, stratification, mixing, sediment resuspension and primary productivity created by turbulent wakes due to the presence of infrastructure in the water column. This is an industry wide concern and is not solely applicable to the Projects. The points raised by Interested Parties (see section 2) broadly align with the knowledge gaps highlighted by recent research and publications. To support understanding of the evidence gap, a literature review of key research and publications is presented here.

3.1 Tidal wake

7. Research by Carpenter *et al*. (2016) has shown how OWF foundations in the German Bight region of the North Sea generate a turbulent wake, contributing to mixing of the stratified water column. The significance of this impact on the large-scale stratification within the region is assessed, considering the widespread nature of existing and planned OWFs. This research used a combination of idealised modelling and in situ measurements.

8. The results of Carpenter *et al*. (2016) have shown the effect OWFs have on mixing stratified water is largely dependent on the overall footprint and type of foundations characterising an OWF. The key factor when considering impact due to these parameters is the underlying natural stratified-mixed behaviours of the water body.

9. Notably, Carpenter *et al*. (2016) highlighted the limitations of the current research. These limitations are focused on a lack of knowledge in relation to the structure of an OWFs' foundations (to determine the overall drag induced). As well as limitations in knowledge related to the effect enhanced mixing will induce on the natural stratified-mixed behaviours of a water body. These factors are both key components in determining an OWFs' impact.

10. Overall, Carpenter *et al*. (2016) concluded "OWFs could impact the large-scale stratification, but only when they occupy extensive shelf regions" and "They are expected to have very little impact on large-scale stratification at the current capacity in the North Sea." Although continued large scale development may lead to significant impacts on the natural balances of mixing and stratification in the future.

11. Dorell *et al*. (2022) outlines the potential impacts OWFs could have on stratification by introducing enhanced mixing to seasonally stratified shelf seas. Highlighting the risks of altering shelf sea dynamics through both potentially large local impacts and more widespread system level change. Mainly by altering the natural temporal balance of stratified-mixed water, and subsequent knock-on effects of this.

12. Dorell *at al.* (2022) outlines how management and mitigation of the potential impact can be achieved through the EIA process. Including baseline surveys of the natural cycle of water column stratification, biogeochemical fluxes, and primary production, measured against site, array and design specific observations.

13. This paper concludes with consideration of the limitations in existing research. There is a lack of understating of how the theoretical impacts of enhanced mixing scales from a single monopile, to an OWF array, to an entire shelf sea region with multiple OWFs. There is an appreciation of the challenge of validating regional ecosystem modelling with in situ before-and-after observations, and these are needed to truly assess the direct and indirect impacts of anthropogenic mixing.

14. Isaksson *et al*. (2023) sets out a strategy to enhance our understanding of OWFs potential impacts on shelf seas, using experiences to date in the North Sea as a case study. Key target areas for future research include establishing the extent to which OWFs may change levels of primary production, through enhanced mixing. Additionally, there is a need to determine if wind wakes will have knock-on effects on the natural mixing-stratification balance which supports existing ecosystems.

15. The spatial and temporal scales physical and biological marine processes operate at are provided within this research. This gives an indication as to the requirements for recommended data collection efforts. These findings are presented in **Figure 3-1**.

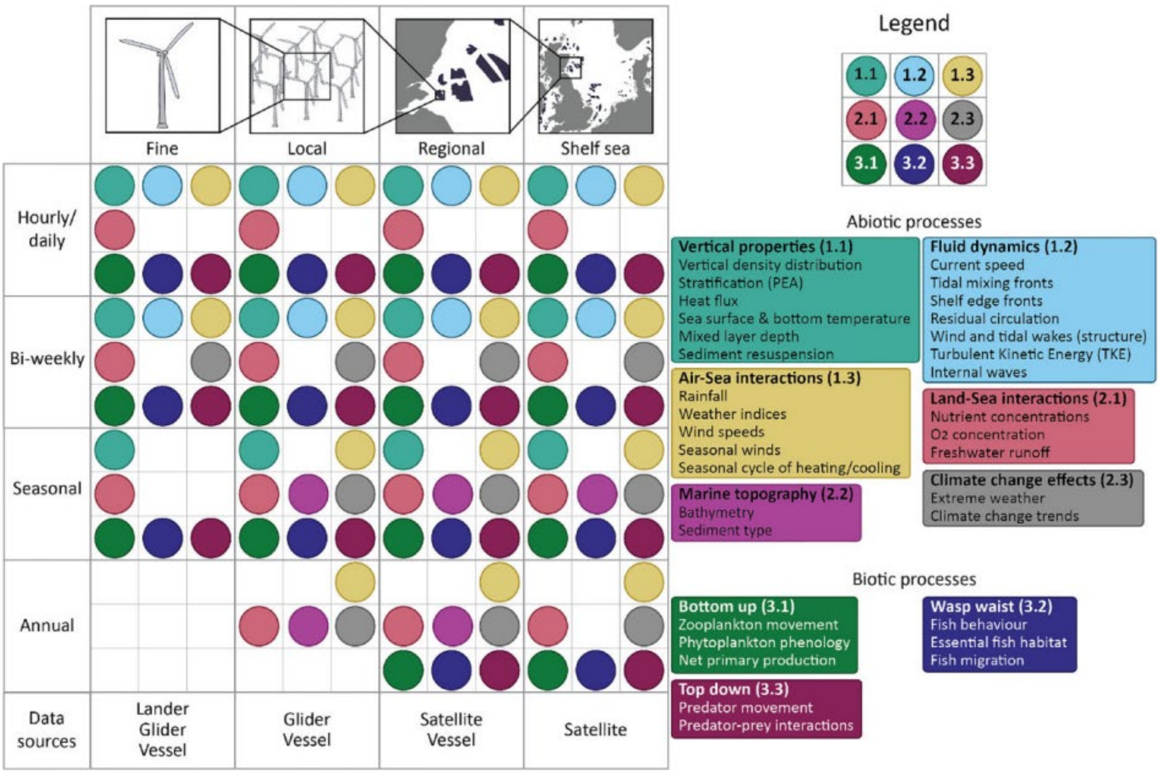

Figure 3-1 Shelf sea biophysical processes and the principal space and time scales at which they operate, including recommendations for how experimental data can be collected. Each circle in the table represents

the full range of the process in question (although specific subprocesses, zooplankton movement, may operate within fewer grid squares). PEA = Potential Energy Anomaly. (Isaksson *et al*.,2023)

16. Enhanced bed shear stress and mixing in the tidal wake of an offshore wind turbine monopile has been observed from novel hydrodynamic data collected 40m from a monopile within the Rhyl Flats offshore wind farm (Austin *et al*., 2025). The increase in bed shear stress within the wake will theoretically increase sediment mobility potentially leading to greater seabed heterogeneity. However, scour protection with a diameter of 20m from the monopile was present. This protection is assumed to be effective as the research does not report increased suspended sediment concentrations.

17. This research acknowledges the potential ecological impacts spanning multiple trophic levels. However, the wake mixing dynamics are poorly understood and further modelling is required to parametrise the broader implications.

3.2 Wind wake

18. Akhtar *et al*. (2021) investigated the alterations to power generation efficiency of OWFs in the North Sea. The target of this issue being potential variations in natural wind conditions resulting from OWF wake effects and increasing OWF clustering.

19. The key findings from Akhtar *et al*. (2021) were that the annual mean wind speed within an OWF may be 2 to 2.5 ms^{-1} lower than the natural speed, depending on the OWFs array structure. This effect may have an impact up to 35 to 40 km downwind during the correct weather conditions and time period.

20. This research provides an indication as to the extent of influence OWFs could have on sea surface atmospheric conditions, although in reality the true magnitude of this potential impact is likely different as these are simulated predications.

21. Christiansen *et al*. (2022) links the influence OWFs have on atmospheric conditions (decreasing sea surface wind speed) to large scale ocean dynamics in the North Sea. The wake effect of OWFs, lowering the energy transferred into the seas surface, may alter the natural seasonal stratification conditions. This may induce a change in stratification strength throughout the North Sea's physical structure. Most notably the depth of the mixed layer during stratified periods may shift, impacting on marine ecosystem processes. This was reported as most noticeable during the decline of stratification in the summer-autumn months in the German Bight.

22. Christiansen *et al*. (2022) concludes that although the implications of increasing wind wake effects from OWFs was mainly evidenced in the German Bight, future developments would continue to increase the magnitude of this impact across larger areas of the North Sea. Growing installations in the Southern Bight and especially near the Dogger Bank are noted as key areas for this effect to be induced. However, the actual effect will likely be different from the outputs reported, as the simulation was limited to the summer season of 2013.

23. Daewel *et al*. (2022) builds on and reinforces the findings of Christiansen *et al*. (2022) through further numerical modelling of North Sea wind wake effects. Although Daewel *et al*. (2022) focuses on the implications of wind wake effects for large scale and local primary productivity.

24. Most notably, annual primary productivity local to OWFs and at a larger scale is reported as up to ±10% different compared to excepted natural conditions, from the modelling results in Daewel *et al*. (2022). Additionally, the depths of the seasonally mixed layer were estimated to be, on average, 1 to 2 m shallower in and around the OWF clusters (**Figure 3-2**). Although, again, the actual effect will likely be different from the outputs reported, as the simulation was limited to the year of 2010.

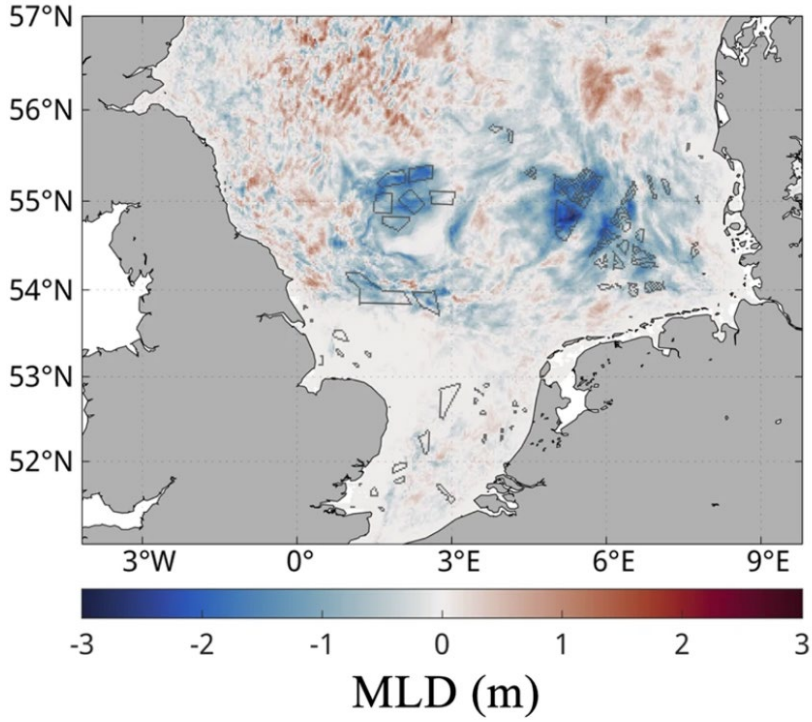

Figure 3-2 Estimated change in mixed layer depth (MLD). (Daewel *et al.*, 2022)

3.3 Ongoing Research

25. There are a number of research projects in progress which focus on the effects of OWFs on stratification and associated ecosystem responses, including ECOWind and eSWEETS3

26. The outputs of this research will contribute to filling the evidence gap and support environmental impact assessments across the renewables industry. The outcomes of these research projects are currently in progress and will be publicised online via the project websites in due course.

4 Review of ES conclusions

4.1 DBS East and DBS West Together

27. An assessment of changes to water circulation (Flamborough Front) due to the presence of Infrastructure (turbines and offshore platforms) was undertaken in **Chapter 8 Marine Physical Environment** [APP-080]. The worst case would be if both DBS East and DBS West were developed together. Here, the Applicants consider the research presented in **Section 3**, alongside the existing assessment to determine if any changes or updates are required.

4.1.1 Sensitivity of the receptor

28. The sensitivity of a marine physical processes receptor is dependent on:

- Tolerance, the extent to which it is adversely affected by an effect;
- Recoverability, which is a measure of a receptors ability to return to state at or close to that which existed before the change; and,
- Value, which considers if the receptor is rare, protected or threatened.

29. The sensitivity of Flamborough Front was defined as negligible according to the criteria outlined in **Table 4-1** and **Table 4-2**. Considering the scale of the Flamborough Front is of the order of hundreds of kilometres and that the wake effects are spatially restricted to the immediate vicinity of individual turbines (see Carpenter *et al*. 2016 and Schultze *et al*. 2020), and that overlapping wake effects are not expected based on hydrodynamic modelling (**Marine Physical Processes Modelling Technical Report (Revision 3)** [REP2-017]), Flamborough Front was considered to have high tolerance .

Table 4-1 Definition of sensitivity

Sensitivity	Definition
High	Tolerance: None, receptor has very limited tolerance of effect. Recoverability: Receptor unable to recover resulting in permanent or long-term (>10 years) change.
Medium	Tolerance: Receptor has limited tolerance of effect. Recoverability: Receptor able to recover to an acceptable status over the medium term (5-10 years).
Low	Tolerance: Receptor has some tolerance of effect. Recoverability: Receptor able to recover to an acceptable status over the short term (1-5 years).
Negligible	Tolerance: Receptor highly tolerant of effect.

Sensitivity	Definition
	Recoverability: Receptor able to recover to an acceptable status near instantaneously (<1 year).

Table 4-2 Definition of value

Value	Definition
High	Value: Receptor is designated and / or of national or international importance for marine geology, oceanography or physical processes and designation status relies on passing water EQS. Receptor is likely to be rare with minimal potential for substitution and may also be of significant wider-scale, functional or strategic importance.
Medium	Value: Receptor is not designated but is of local to regional importance for marine geology, oceanography or physical processes (including water quality).
Low	Value: Receptor is not designated but is of local importance for marine geology, oceanography or physical processes (including water quality).

30. The recoverability of the feature was defined as high as once the turbines are removed the wake effects will cease to exist so will not affect water circulation. The value of the receptor was considered medium according to the criteria outlined in **Table 4-2** (also Table 8-9 of **Chapter 8 Marine Physical Environment** [APP-080] as the receptor is not designated but is regionally important for oceanography. This resulted in the Flamborough Front being assigned a negligible sensitivity (see **Table 4-3**).

Table 4-3 Sensitivity and value of the Flamborough Front as a receptor as defined in Chapter 8 Marine Physical Processes [APP-080]

Receptor	Tolerance	Recoverability	Value	Sensitivity
Flamborough Front	High (Negligible)	High (Negligible)	Medium	Negligible

31. Natural England advise that the value of the Flamborough Front be assessed as high owing to its colocation with particularly high primary production and ecological importance (see **Table 2-1**). However, the Flamborough Front is not designated and is a regional feature that is ephemeral and restricted to the area off the coast of Flamborough Head. It is not a national scale feature and therefore cannot be assigned high value according to the criteria in **Table 4-2** . These criteria were defined to remove subjectivity and ensure consistency in the assessment approach.

32. In the response to RR-039: B41 (see **Table 2-1**), the Applicants outlined they agreed the value of Flamborough Front was high. This statement was made in error without consideration of the value criteria defined in **Table 4-2**. As outlined above, the Applicants consider the value of Flamborough Front to be medium.

33. Natural England state that they do not agree with the conclusions of the assessment as the sensitivity is defined as negligible. The conclusions of the recent research presented in section **3** do not significantly change the assessment criteria (e.g. the feature remains tolerant, can recover quickly and is of medium value as it hasn't been designated). However, considering the advice of Natural England and taking a precautionary approach, its tolerance has been changed to low (the receptor has some tolerance to effect, see **Table 4-1**) which results in the sensitivity being changed from negligible to low (see **Table 4-4**).

Table 4-4 Updated assessment of sensitivity and value of the Flamborough Front as a receptor

Receptor	Tolerance	Recoverability	Value	Sensitivity
Flamborough Front	Some (Low)	High (Negligible)	Medium	Low

4.1.2 Magnitude of impact

34. In **Chapter 8 Marine Physical Processes** [APP-080] the magnitude of impact for near-field (<1km from each foundation) and far-field impacts was assessed according to the criteria defined in **Table 4-5.** (also Table 8-10 of **Chapter 8 Marine Physical Processes** [APP-080]). A low magnitude of impact was defined for the near-field and a negligible magnitude of impact for far-field impacts (**Table 4-6**).

Table 4-5 Definition of magnitude of impacts

Magnitude	Definition
High	Scale: A change which would extend beyond the natural variations in background conditions. Duration: Change persists for more than ten years. Frequency: The effect would always occur. Reversibility: The effect is irreversible.
Medium	Scale: A change which would be noticeable from monitoring but remains within the range of natural variations in background conditions. Duration: Change persists for 5-10 years. Frequency: The effect would occur regularly but not all the time. Reversibility: The effect is very slowly reversible (5-10 years).

Magnitude	Definition
Low	Scale: A change which would barely be noticeable from monitoring and is small compared to natural variations in background conditions. Duration: Change persists for 1-5 years. Frequency: The effect would occur occasionally but not all the time. Reversibility: The effect is slowly reversible (1-5 years).
Negligible	Scale: A change which would not be noticeable from monitoring and is extremely small compared to natural variations in background conditions. Duration: Change persists for less than one year. Frequency: The effect would occur highly infrequently. Reversibility: The effect is quickly reversible (less than one year).

Table 4-6 Magnitude of Impact on Water Circulation as defined in Chapter 8 Marine Physical Processes [APP-080]

Location	Scale	Duration	Frequency	Reversibility	Magnitude of Impact
Near-field	Low	High	Medium	Negligible	Low
Far-field	Negligible	High	Medium	Negligible	Negligible

35. Natural England have advised that they do not agree with the conclusion of the assessment (see **Table 2-1**). After reviewing recent research (presented in **Section 3**), the assessment of magnitude of impact has been reconsidered here.

36. One of the key outcomes of the recent research is that the magnitude of the changes is unknown, partly because the modelling undertaken represents a specific time period (Akhtar *et al*. 2021; Christiansen *et al*. 2022) or the impact of individual turbines that haven't been scaled up to whole wind farm or multiple wind farms scale (Austin *et al*. 2025).

37. There is also uncertainty in defining the range of natural variability in water circulation and primary productivity due to limited observation data. This is needed to understand what the thresholds for change are to be able to distinguish between natural variability, including changes to the natural system due to climate change, and change induced due to the presence of infrastructure.

38. Considering the above, definition of the scale (e.g. size, extent or intensity) of the impact carries some uncertainty. However, recent research is showing that changes are detectable through monitoring in both the near-field (due to tidal wake) and far-field (due to wind wake). Therefore, the scale of impact likely ranges from medium to high and as such, the magnitude of impact has been changed from negligible to low in the initial assessment, to medium (**Table 4-7**).

Table 4-7 Updated assessment of magnitude of Impact on Water Circulation

Location	Scale	Duration	Frequency	Reversibility	Magnitude of Impact
Near-field	Medium-high	High	Medium	Negligible	Medium
Far-field	Medium-high	High	Medium	Negligible	Medium

4.1.3 Significance of effect

39. The assessment of significance of an effect is informed by the sensitivity of the receptor and the magnitude of the impact. A review of recent research on the impact of offshore wind farm infrastructure on water circulation, stratification, mixing, sediment resuspension and primary productivity has resulted in changes to the definition of receptor sensitivity (see **Section 4.1.1**) and magnitude of impact (see **Section 4.1.2**). Therefore, changes to water circulation (Flamborough Front) due to infrastructure (wind turbines and offshore platforms) will have a **minor adverse** significance of effect due to the low sensitivity of Flamborough Front and a medium magnitude of impact. This is not significant in EIA terms.

4.2 Cumulative Effects Assessment

40. The assessment of cumulative effects on water circulation (Flamborough Front) due to the presence DBS infrastructure alongside other offshore wind farms in the southern North Sea concluded the significance of effect is likely negligible (see section 8.8.4 of **Chapter 8 Marine Physical Environment** [APP-080]. This was based on a low magnitude of impact in the near-field and a negligible magnitude of impact at the regional scale (far-field), and a negligible receptor sensitivity. The assessment considered the spatial extent of tidal wake effects to be spatially restricted to the near-field and as the nearest OWF was located 7.5km away (Dogger Bank A), it was concluded there would be no overlapping effects.

41. Natural England advise that they do not agree with this conclusion (see **Table 2-1**) as the recent study of Daewel *et al*. (2022) shows that the presence of large OWF clusters could provoke large-scale hydrodynamic changes that impact marine primary production and the wider marine ecosystem. A review of other recent studies undertaken here (see **Section 3**) provides further evidence that the presence of clusters of wind farms has a greater effect on wind wake which can in turn alter stratification and associated ecological function (e.g. Akhtar *et al*. 2021; Christiansen *et al*. 2022). Based on these findings, the cumulative assessment of changes to water circulation (Flamborough Front) due to the presence of DBS infrastructure alongside other offshore wind farms in the southern North Sea has been updated below.

4.2.1 Sensitivity of the receptor

42. The sensitivity of Flamborough Front is defined as being low according to the criteria discussed in section 4.1.1 and shown in **Table 4-4**.

4.2.2 Magnitude of impact

43. The criteria for defining magnitude of impact is outlined in **Section 4.1.2**. Research suggests that the impact of large clusters of offshore wind farms is greater than the impact from a single wind farm (Akhtar *et al*. 2021; Christiansen *et al*. 2022; Daewel *et al*. 2022). However, there is still uncertainty in understanding the scale of impact relative to natural variability, but as it is considered measurable through monitoring, scale has been defined as medium-high for cumulative effects (see **Table 4-5**).

44. The duration of the impact is high considering the operational lifetime of offshore wind projects and reversibility is negligible as the impact will no longer exist once the turbine structures are removed. Considering the ephemeral nature of the Flamborough Front, a greater number of wind farms and structures will increase the frequency of interactions with the front. However, as the front is temporally restricted and will not be present at all times, the frequency of the impact will be medium according to the criteria defined in **Table 4-8**. Overall, the magnitude of impact on the Flamborough Front receptor due to the cumulative effect of multiple OWFs will be medium.

Table 4-8 Magnitude of Impact on Water Circulation due to the cumulative effect of DBS alongside other offshore wind farms in the southern North Sea

Location	Scale	Duration	Frequency	Reversibility	Magnitude of Impact
Near-field	Medium-high	High	Medium	Negligible	Medium
Far-field	Medium-high	High	Medium	Negligible	Medium

4.2.3 Significance of effect

45. Construction of DBS East and DBS West Together (as a worse case) alongside other offshore wind farms in the southern North Sea will have a likely **minor adverse** significance of effect due to the low sensitivity of the Flamborough Front and a medium magnitude of impact. This is not significant in EIA terms.

5 Monitoring Approaches

46. The initial assessment of changes to water circulation (Flamborough Front) due to the presence of infrastructure (wind turbines and offshore platform foundations) undertaken in **Chapter 8 Marine Physical Processes** [PP-080] concluded the significance of effect was likely **negligible** which is not significant in EIA terms. Therefore, no mitigation was proposed.

47. Following the advice of Natural England, recent research has been reviewed (see **Section 3**) and the ES conclusions were re-evaluated (see **Section 4**). This has resulted in a change to the conclusions of the assessment in relation to the Flamborough Front which will be updated in the ES chapter. The likely significance of effect is **minor adverse** for the development of DBS East and West Together (as a worse case) and **minor adverse** for cumulative effects due to the development of DBS Projects alongside other offshore wind farms in the southern North Sea. This conclusion is also not significant in EIA terms and typically no mitigation would be proposed.

48. However, questions have been raised by the Examining Authority to investigate why monitoring has not been proposed considering Hornsea Project Four have agreed a detailed monitoring programme with NE and the MMO.

5.1 Review of monitoring plans from other OWFS

49. Monitoring as a form of mitigation against uncertainty of impacts on the Flamborough Front has not been routinely proposed for OWFs in the southern North Sea as previously the impact has either been scoped out (e.g. Dogger Bank A, Dogger Bank B and Dogger Bank C) or has been found to be negligible (e.g. Hornsea Project Three).

50. Hornsea Project Four assessed the impact of Flamborough Front and found the sensitivity of this receptor to be medium with negligible magnitude of impact and significance of effect. The front was considered important for giving rise to nutrient rich waters, but Hornsea Project Four was predicted to likely be too spatially distant for resulting turbulent flow wakes to influence Flamborough Front (Orsted, 2021).

51. During the examination period for Hornsea Project Four, the MMO and NE advised the Applicants to undertake monitoring of changes to water circulation should GBS type foundations be installed (see F2.7: Outline Marine Monitoring Plan Revision 02). Following further consultation, an agreement was reached to undertake monitoring regardless of the foundations to be installed (see F2.7: Outline Marine Monitoring Plan Revision 03). The objective of the proposed monitoring is to determine the scale and intensity of near and far field wake-related effects from large foundations. This was justified because the evidence related to wake effects created by offshore wind farm foundations are considered to be an industry-wide knowledge gap.

52. The monitoring approach proposed for Hornsea Project Four is summarised below in **Table 5-1** with full details provided in Table 3 of F2.7: Outline Marine Monitoring Plan Revision 03.

Table 5-1 Summary of Flamborough Front monitoring proposed for Hornsea Project Four

Location	Monitoring approach and objectives
Near-field monitoring	Deployment of towed thermistor chains and ADCPs during a period of summer stratification on a peak (flood or ebb) tide in the lee of three foundations in the Hornsea Four array. To determine if/when the Flamborough Front is present within the Hornsea Project Four array, near-real time satellite observations of sea surface temperature (Sentinel3) will be reviewed and a monthly summary of the location of the front will be developed for the summer period. If the front is consistently found to be north of the offshore array area after three consecutive summer periods then the near-field survey will no longer be required and all associated obligations related to conducting this survey will be considered as fully met.
Far-field monitoring	Assessment of relevant satellite imagery (e.g. Sentinel 3 sea surface temperature and chlorophyll concentrations) to determine array scale effects. *Hornsea Four is open to coordinate monitoring with other projects that may be subject to similar provisions (e.g. Dogger Bank South).* A standalone report will be prepared covering a pre-construction baseline characterisation (1 year), construction (1 year) and a post-construction/operational (5 years) comparison. This will monitor the location of the front via satellite data for five years post-construction covering Spring-Autumn to determine if the Flamborough Front falls within the array area.

5.2 DBS monitoring requirements

53. The conclusions of the assessment of changes in water circulation (Flamborough Front) due to the presence of infrastructure (wind turbines and offshore platforms) presented in section 4 concluded that there would be a likely minor adverse significance of effect which is not significant in EIA terms. Therefore, no mitigation is recommended.

54. In examination, following the advice of Natural England and the MMO, Hornsea Project Four committed to a monitoring plan to assess changes to the Flamborough Front to address industry-wide uncertainty in understanding of offshore wind turbine structures on water stratification. This is an exceptional case that does not follow standard EIA methodological approaches, i.e. mitigation is only proposed for moderate and major adverse effects to lower the residual impact.

55. Based on review presented in Section 3 it is acknowledged that there are gaps in the evidence base used to underpin the assessment, the specific gaps identified here are:

- Defining the scale of the impact. Understanding thresholds of change to distinguish between natural variability, including changes to the natural system due to climate change, and change induced due to the presence of infrastructure.
- Frequency of impact. Defining when and where the Flamborough Front is present.
- The scale of cumulative effects. Understanding the changes due to multiple offshore wind farms (resulting from wind wake effects).
- The significance of changes in water circulation and primary productivity on ecosystems at multiple trophic levels.

56. Addressing these gaps needs a strategic and sector-wide approach that maximises collaboration and engagement with academic and other research organisations. In light of these evidence gaps the Applicants have committed to monitoring the Flamborough Front as outlined in the **In Principle Monitoring Plan (Revision 3)** [document reference: 8.23]. This plan will be developed further in consultation with the MMO and Natural England at prior to construction.

6 Conclusions

57. Based on the advice of Interested Parties during the examination period of the Projects, a detailed review of published research on the potential effects of offshore wind farm infrastructure on water circulation has been undertaken (section 3) and used to update the assessment of changes in water circulation (Flamborough Front) due to the presence of infrastructure as presented in **Chapter 8 Marine Physical Environment** [APP-080].

58. Considering the advice of Natural England and taking a precautionary approach, the following updates to the assessment of significance have been made for the scenario where DBS East and DBS West are built together, and for the cumulative effects assessment:

- The sensitivity of the receptor has been updated from negligible to low as the Flamborough Front as a receptor has some tolerance to the effect (previous assessment considered receptor tolerance to be high).
- The magnitude of impact has been changed from negligible (far-field) and low (near-field) to medium for both near- and far-field. This is due to a change in the scale of the impact which is now considered to be medium to high (previously defined as being low to negligible).
- Changes to receptor sensitivity and magnitude of impact have resulted in a change in the assessment of significance has changed from negligible to minor adverse. However, there is no material change as minor adverse significance of effects is not significant in EIA terms.

59. Based on the updates to the ES conclusions, no mitigation is proposed. However, the Hornsea Project Four assessment did not predict any significant effects yet Natural England, the MMO and Cefas advised monitoring of the Flamborough Front should be undertaken post construction and this was secured in the DCO and DML. Considering the Projects have received similar advice, a commitment will be made to include monitoring of the Flamborough Front within the **In Principle Monitoring Plan (Revision 3)** [document reference: 8.23].

7 References

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RWE Renewables UK Dogger Bank
South (West) Limited

RWE Renewables UK Dogger Bank
South (East) Limited

Windmill Business Park
Whitehill Way
Swindon
Wiltshire, SN5 6PB

RWE MASDAR