Wake Impact Assessment report

Outer Dowsing Wind Farm

P0232-C1751A-CA-REP-001-2.0

REVISION HISTORY

Rev	Date	Description	Author	Checker	Approver
1.0	13/03/2025	Final Version for submission	CCO	MCA	NEL
2.0	03/04/2025	Updated version with Dudgeon Extension correction	CCO	MCA	NEL

LIST OF ACRONYMS

The following table lists some of the acronyms used in this report.

Abbreviations	Definition
AEP	Annual Energy production
BoP	Balance-of-Plant
CFD	Computational Fluid Dynamics
DCO	Development Consent Order
EPA	Energy Production Assessment
ERA5	ECMWF Reanalysis 5th Generation
ECMWF	European Centre for Medium-Range Weather Forecasts
EPSG	European Petroleum Survey Group Geodetic Parameter Database
FL	Floating Lidar
IEC	International Electrotechnical Commission
MM	Meteorological (Met.) Mast
MERRA	Modern-ERA Retrospective analysis for Research and Applications
MoMM	Mean of Monthly Means
CAPEX	Capital Expenditure
EIA	Environment Impact Assessment
O&M	Operation and Maintenance
P50	Exceedance probability: The probability of exceeding the reported P50 value for annual energy production is 50%
P90	Exceedance probability: The probability of exceeding the reported P90 value for annual energy production is 90%
PBE	Production Based Estimate
PC	Power Curve
PPA	Power Purchase Agreement
Q&A	Questions and Answers
SPV	Special Purpose Vehicle
SCADA	Supervisory Control and Data Acquisition
TI	Turbulence Intensity
TSA	Turbine Supply Agreement
WAsP	Wind Atlas Analysis and Application Program
WF	Wind Farm
WRF	Weather Research and Forecasting
WSBE	Wind Speed Based Estimate
WSM	Wind Sector Management
WTG	Wind Turbine Generator
WT	Wood Thilsted

EXECUTIVE SUMMARY

Outer Dowsing Offshore Wind Farm (the “Client”) has retained Wood Thilsted Partners Ltd (WT) to develop an independent wake impact assessment, arising from their proposed Outer Dowsing Offshore Wind farm (the “Project” or “ODOW”) on neighbouring and future projects. The Outer Dowsing project is situated in the UK region of the Southern North Sea, to the south of Dogger Bank.

The Project and the neighbouring projects are all located in an increasingly busy part of the Southern North Sea and there is potential to impact the operational neighbouring wind farms, along with other proposed future wind farms.

The operational wind farms under consideration are Triton Knoll, Westermost Rough, Lincs, Race Bank, Inner Dowsing, Lynn, Dudgeon, Hornsea 1, Hornsea 2, Humber Gateway and Sheringham Shoal. The other proposed future wind farms along with the Project are, Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension.

To assess the additional wakes arising from the Project in combination with other proposed projects given above, several scenarios have been considered. The considered scenarios are: the sole impact of the Project on existing assets, the cumulative impact of all proposed wind farms along with the Project, the cumulative impact of Hornsea 3 and Hornsea 4 with the Project, and finally the cumulative impact of Sheringham Shoal Extension and Dudgeon Extension with the Project. WT has further assessed the impacts from the Project to each of the future projects, Hornsea 3 and Hornsea 4 proposed future projects only, to the Dudgeon Extension and Sheringham Shoal Extension future projects only and finally to all future projects, in combination.

A range of publicly available datasets has been utilised for the assessment of future wind farm parameters, including the development phase, possible turbine configurations, wind farm boundaries, turbine type and hub height. Sources for this include the 4C Offshore Wind Market Intelligence [1], Map Stand Location Intelligence portal [2], and submissions to the National Infrastructure Planning Portal [3], along with correspondence with the Client [4]. It should be noted that due to the early stage of some of the projects, the information compiled for the future projects are not considered final, therefore the impacts will be subject to change – this report should be considered as being based on the best available information at the time of preparation.

This report provides a summary of the data used, along with the methodologies that have a proven track record for assessing the impact of wakes between wind farms. The primary objective of the study is to estimate the comparative loss in energy arising due to wakes caused by the addition of new wind farms including the Project and not estimating the absolute values for energy production and wakes. A short description of wind farm wakes, their effects and methodologies for their modelling is also included in Section 1.2.

WT has assessed the effects of future wind farms by utilising different scenarios. Table 1 below summarises the main scenarios considered and Table 2 summarises the magnitude of additional losses.

Table 1 External Wakes Scenarios

Scenario	Included Wind Farms	Comments / Assumptions
Baseline (Scenario 0a)	Existing Operational Wind Farms [1.]	Existing operational conditions
Baseline + **ODOW** (Scenario 0b)	Baseline + **ODOW** [2]	Sole impact of 1500 MW ODOW project on the operational wind farms, which are expected to be operational in 2030.
Scenario 1a	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2]	Baseline scenario for 1b below, cumulative effect of all future wind farms
Scenario 1b	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Impact of ODOW along with all future development. Sheringham Shoal Extension (345 MW) and Dudgeon Extension (450 MW) will be operational by 2030. Hornsea 3 (3000 MW) will be operational by 2027. Hornsea 4 (2400 MW) will be operational by 2030.
Scenario 1c	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Technically same scenario with 1b above, but here the effect of ODOW on Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 were investigated.
Scenario 2a	Baseline + Hornsea 3 and Hornsea 4 [2]	Baseline scenario for 2b below
Scenario 2b	Baseline + Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Impact of ODOW along with Hornsea 3 and Hornsea 4. Hornsea 3 (3000 MW) will be operational by 2027. Hornsea 4 (2400 MW) will be operational by 2030.
Scenario 2c	Baseline + Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Technically same scenario with 2b above, but here the effect of ODOW on Hornsea 3 and Hornsea 4 were investigated.
Scenario 3a	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2]	Baseline scenario for 3b below
Scenario 3b	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2], with **ODOW** [2]	Impact of ODOW along with Sheringham Shoal Extension and Dudgeon Extension. Sheringham Shoal Extension (345 MW) and Dudgeon Extension (450 MW) expected to be operational by 2030.
Scenario 3c	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2], with **ODOW** [2]	Technically same scenario with 3b above, but here the effect of ODOW on Sheringham Shoal Extension and Dudgeon Extension were investigated.

[1] Triton Knoll, Westermost Rough, Lincs, Race Bank, Inner dowsing, Lynn, Dudgeon, Hornsea 1, Hornsea 2, Humber Gateway and Sheringham Shoal

[2.] Based on discussions held with the Client a 15 MW turbine with 236 m rotor diameter and 158m rotor height were assumed to be used for all future wind farms including ODOW. This assumption for the future wind farms is considered to provide a conservative position impact assessment as part of the DCO application

Based on these scenarios a conservative assessment of the additional wake loss arising from ODOW on the existing operational wind farms is calculated up to a maximum of **-0.88 %** (primarily the effect of ODOW on the Dudgeon Wind Farm).

The average effect of ODOW on all the existing wind farms, with or without the future wind farms varies between **-0.58 %** (the sole effect of ODOW on existing projects) and **-0.51 %** (the effect of ODOW on existing projects, in combination with all future wind farms). The effect of ODOW on individual operational wind farms varies between **-0.03%** and **-0.88%**.

WT has also investigated the effect of ODOW on future developments, including the impact of ODOW on all future developments at once, the impact of ODOW on Hornsea 3 and Hornsea 4 and the impact of ODOW on Sheringham Shoal Extension and Dudgeon Extension. For Hornsea 3 and Hornsea 4, the highest effect is observed is -**0.07%** on Hornsea 4 and for Dudgeon Extension and Sheringham Shoal Extension, the highest effect is observed as **-0.89%** on Dudgeon Extension. The individual results are also provided.

The results summarised above are shown in Table 2 for the effects on operational wind farms and Table 3 for the effects on future wind farms, below. Summary of all the results are normalized to the baseline can be seen in Table 4 below.

Considering the engineering wake model approaches used and distances between the Client assets and proposed neighbouring wind farms, WT considers the assessed additional wake loss numbers to be commensurate with WT's expectations. WT also finds the above results comparable with recent studies conducted by DNV and RWE [8] about cluster wakes and their effects on wind farm annual energy production.

Table 2 Comparison of Scenario 1b and 1a, Scenario 2b and 2a and Scenario 3b and 3a for operational wind farms

Scenario	Additional wake loss on each operational wind farm (%)											
	Triton Knoll	Westermost Rough	Lincs	Race Bank	Inner Dowsing	Lynn	Dudgeon	Hornsea 1	Hornsea 2	Humber Gateway	Sheringham Shoal	Total additional wake loss on all operational wind farms
Scenario 0b vs 0a	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.88%	-0.70%	-0.75%	-0.23%	-0.76%	-0.58%
Scenario 1b vs 1a	-0.77%	-0.08%	-0.17%	-0.52%	-0.05%	-0.03%	-0.58%	-0.68%	-0.70%	-0.23%	-0.41%	-0.51%
Scenario 2b vs 2a	-0.77%	-0.08%	-0.17%	-0.52%	-0.05%	-0.03%	-0.84%	-0.70%	-0.75%	-0.23%	-0.74%	-0.57%
Scenario 3b vs 3a	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.60%	-0.68%	-0.70%	-0.23%	-0.41%	-0.51%

Table 3 Summary of the results of future wind farm scenarios

Scenarios basis	Scenario Name	Additional wake loss on each future wind farm arising from Outer Dowsing (%)			
		Hornsea 3	Hornsea 4	Sheringham Shoal Extension	Dudgeon Extension
Impact of ODOW on all future wind farms	Scenario 1c vs Scenario 1a	-0.01%	-0.06%	-0.27%	-0.87%
Impact of ODOW on Hornsea 3&4	Scenario 2c vs Scenario 2a	-0.01%	-0.07%	-	-
Impact of ODOW on Sheringham & Dudgeon Extensions	Scenario 3c vs Scenario 3a	-	-	-0.30%	-0.89%

Table 4 Summary of the results of all scenarios, normalized to the baseline

Scenarios basis	Scenario Name	Additional wake loss on each operational wind farm (%)										
		Triton Knoll	Westermost Rough	Lincs	Race Bank	Inner Dowsing	Lynn	Dudgeon	Hornsea 1	Hornsea 2	Humber Gateway	Sheringham Shoal
Impact of ODOW on existing farms	Scenario 0a	0	0	0	0	0	0	0	0	0	0	0
	Scenario 0b	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.88%	-0.70%	-0.75%	-0.23%	-0.76%
Impact of all future development s on existing farms	Scenario 1a	-0.66%	-0.18%	-0.27%	-0.50%	-0.13%	-0.18%	-2.79%	-1.09%	-1.44%	-0.10%	-2.39%
	Scenario 1b	-1.43%	-0.26%	-0.45%	-1.02%	-0.18%	-0.21%	-3.37%	-1.76%	-2.14%	-0.34%	-2.80%
Impact of ODOW and Hornsea 3&4 on existing farms	Scenario 2a	-0.22%	-0.17%	-0.01%	-0.02%	0.00%	0.00%	-0.09%	-0.99%	-1.37%	-0.09%	-0.03%
	Scenario 2b	-0.99%	-0.25%	-0.18%	-0.54%	-0.05%	-0.03%	-0.93%	-1.69%	-2.11%	-0.32%	-0.77%
Impact of ODOW and Sheringham & Dudgeon Extensions on existing farms	Scenario 3a	-0.44%	-0.01%	-0.26%	-0.47%	-0.13%	-0.18%	-2.73%	-0.09%	-0.07%	-0.02%	-2.38%
	Scenario 3b	-1.23%	-0.09%	-0.44%	-1.00%	-0.18%	-0.20%	-3.32%	-0.77%	-0.78%	-0.25%	-2.80%

1. INTRODUCTION

1.1. Background to the study

The Client has retained Wood Thilsted Partners Ltd (WT) to develop an independent wake impact assessment, arising from their proposed Outer Dowsing Offshore Wind Farm Project (the "Project" or "ODOW") to the neighbouring projects. The Project and the neighbouring projects, which may potentially be affected are all located in the Southern North Sea.

The neighbouring projects under consideration in the Southern North Sea are:

- Triton Knoll (857 MW, commissioned in 2022)
- Westermost Rough (210 MW, commissioned in 2015)
- Lincs (270 MW, commissioned in 2013)
- Race Bank (573 MW, commissioned in 2017)
- Inner Dowsing (97.2 MW, commissioned in 2008)
- Lynn (97.2 MW, commissioned in 2008)
- Dudgeon (402 MW, commissioned in 2017)
- Hornsea 1 (1218 MW, commissioned in 2020)
- Hornsea 2 (1320 MW, commissioned in 2022)
- Humber Gateway (219 MW, commissioned in 2015)
- Sheringham Shoal (317 MW, commissioned in 2011)

The Client is interested in the potential differences in annual energy production on the operational and future wind farms noted above, driven by the wake effects from the Project in conjunction with the other proposed future wind farms, Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension. These proposed future projects have already received Consent.

In order to assess the additional wakes arising from the Project in combination with other proposed projects given above, a range of scenarios have been considered. The chosen scenarios are;

- the sole impact of the Project on existing assets,
- the cumulative impact of all proposed wind farms along with the Project,
- the cumulative impact of Hornsea 3 and Hornsea 4 with the Project,

- the cumulative impact of Sheringham Shoal Extension, Dudgeon Extension with the Project,
- the impact of Project on the proposed projects Hornsea 3 and Hornsea 4, and
- the impact of Project on the proposed projects Sheringham Shoal Extension and Dudgeon Extension.

It should be noted that due to the physical complexity of wind turbine wake phenomena (as explained in Section 1.2), the cumulative assessments will not be as high as the sum of the impact of each individual wind farm added together. This is to be expected, considering the complexity of flow and interaction & recovery processes of wakes downstream of a wind turbine. Therefore, in order to have a fairer view of the wake impacts, it is considered appropriate to assess their effects on both an individual and cumulative basis.

The project area has a range of proposed and operational wind farms as shown in Figure 1-1.

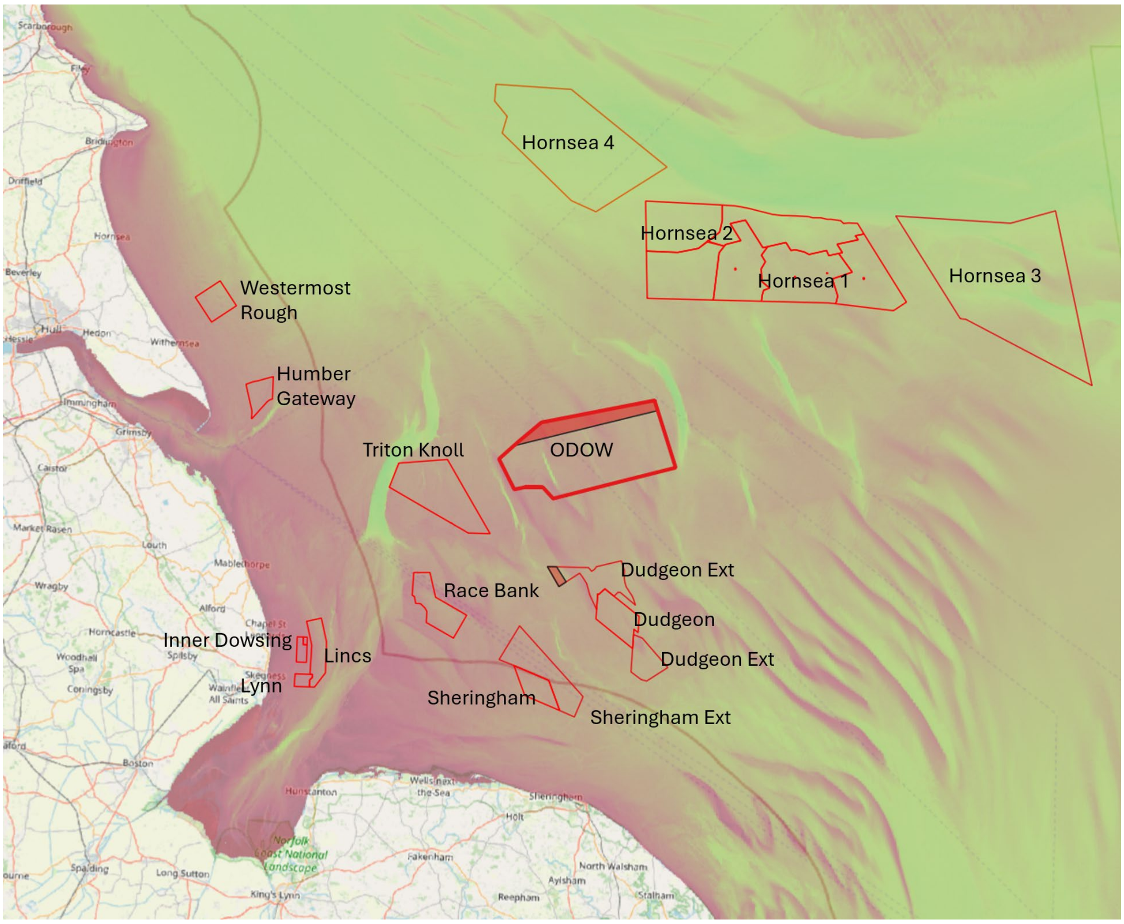

Figure 1-1 Location of the Client's proposed ODOW (shown highlighted in red) in the context of this part of the Southern North Sea.

By way of introduction, WT finds it appropriate to briefly explain the issue of wind farm wakes and industry methodologies to model them.

1.2. Wind Farm Wakes

Wind turbines generate electricity by extracting the useful kinetic energy within the wind. This energy conversion process leaves a slower-moving and highly chaotic, therefore less-useful wind downstream of the wind turbine. This downstream region is characterized by lower wind speeds and higher turbulence and is referred as the wind turbine wake. The turbulence in the wake is driven by tip vortices generated at the turbine blade tips and turbulent eddies just behind the turbine, which is a region with intense swirling motions of air. Wakes both affect the performance of the downstream turbines with respect to energy yield and altered mechanical stress on the structure.

As the flow propagates downstream, the highly chaotic state of the wake recovers gradually to the original airflow state, by mixing of the slower, turbulent air within the wake with the undisturbed air in the surroundings. This recovery is affected by factors such as the ambient turbulence, which is the natural turbulence of the background atmosphere; wind shear, which describes the change in wind speed with height; and the atmospheric stability, which is the resistivity of the atmosphere to the disturbances. The full recovery behind a single turbine usually requires distances such as 10-12 turbine rotor diameters.

As a general rule of thumb, modelling the effects associated with internal wakes and designing the wind farm turbine layouts in such a way to minimize these internal wake effects are essential in the realisation of wind farms. Industry best practices often apply constraints of 4-6 rotor diameters between the turbines in non-significant wind directions and 7-8 rotor diameters between the turbines in prevailing wind directions. It should be noted that this report is focused on investigation of long distance wakes across wind farm clusters.

Recent research studies ([8] [9]) indicate that offshore wind farm wakes can be notable at distances of 30–60 km. Their impact can be observed up to 100 km [9], particularly under specific conditions such as low ambient turbulence intensity (TI) and high atmospheric stability, where wake recovery is low. Based on these studies, the maximal extent for neighbouring projects considered in this study are those sites that fall entirely within the 100 km range suggested by the literature. The details of these neighbouring projects are provided in Section 1.1.

There are several methodologies in the industry for modelling wakes, ranging from simple analytical / empirical models to more advanced CFD based models, which have trade-offs in terms of accuracy and computational cost. As covered in Section 5, WT's typical best practice is to use the WindFarmer: Analyst Eddy Viscosity with large wind farm correction model to estimate offshore wake and turbine interaction effects. This model has been validated by DNV in 2019, and results in lower errors across a number of operational offshore wind farms compared to other wake models [10], [11].

2. DESCRIPTION OF THE ASSESSED PROJECTS

2.1. Location of the client assets & data

The Outer Dowsing project is situated in the Southern North Sea, off the East coast of the UK.

A map showing the available wind climate locations at Outer Dowsing FL, Race Bank MM, Dogger Bank West MM and boundaries of all neighbouring, all future projects as well as the ODOW project are presented in Figure 2-1. Further information related to the wind climate files can be found in Section 3.

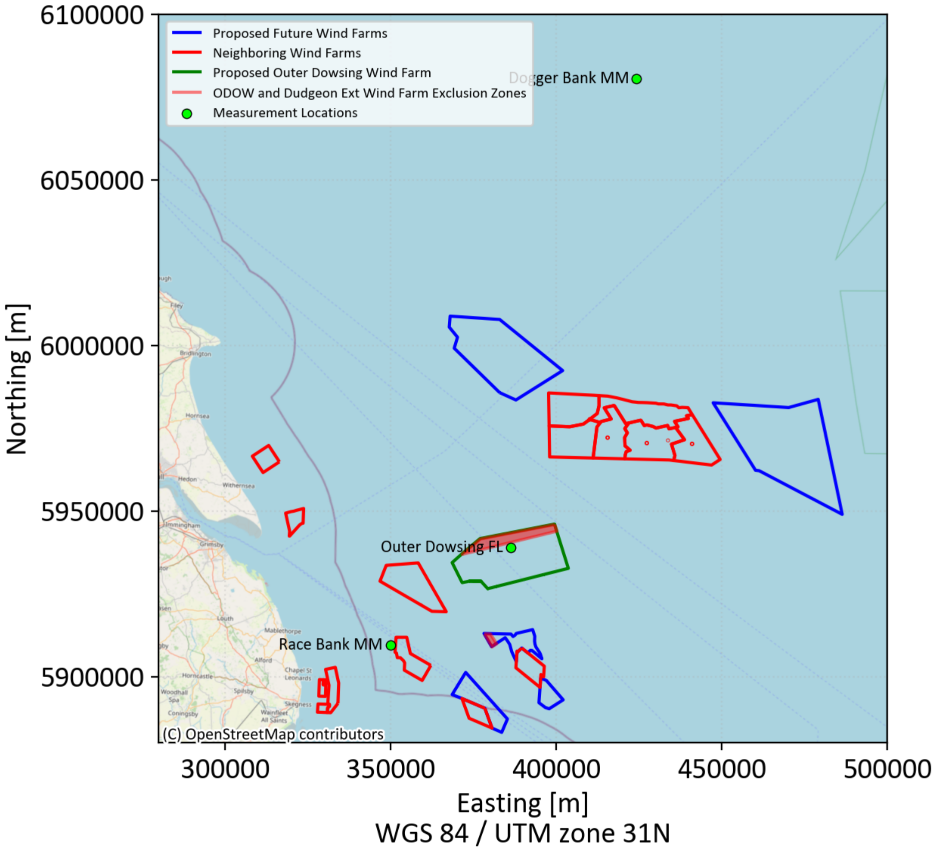

Figure 2-1 Map of the existing projects along with the available measured wind data locations used to derive wind climates. Existing neighbouring farms are shown in red, proposed future farms in blue and ODOW in green. Exclusion zones from the DCO process are shown in red shading.

2.2. Turbine Layouts and Configurations

2.2.1. Power Curves

Turbine configurations for ODOW, operational and other future wind farms, including the turbine model, rated power, hub height, peak power coefficient, number of turbines and total installed capacity, are provided in Table 2-1. The information related to ODOW, and operational wind farms were provided by the Client [4]. For other proposed wind farms, WT has made reasonable assumptions including designing layouts with a set of constraints as described in Section 2.2.2.

It should be noted that for the other proposed wind farms, it has been assumed that the turbine model will be the same as for ODOW, which is a 15.0MW 236m diameter design. Further details regarding this assumption is provided in Section 5.

The general characteristics of all the turbine models under consideration are summarised in Table 2-1. It should be noted that the characteristics and performance data of the operational wind farms are redacted for confidentiality reasons, however it is noted that detailed power curve information has been used in this assessment.

WT has obtained historical pressure and temperature records from eleven nearby meteorological stations within a maximum radial distance of 300 km and maximum elevation difference of 300 m from the site. Using standard lapse rate assumptions, WT has derived air density values between 1.221 kg/m^3 and 1.225 kg/m^3 at an elevation of 158 mMSL. Based on these data, WT has estimated the long-term air density at the site to be 1.224 kg/m^3 at an average elevation of 158 mMSL for all the wind farms.

The supplied power curves used in this analysis have been adjusted to the predicted site air density, in accordance with the recommendations of IEC [12]. This has been undertaken on an individual turbine basis.

2.2.2. Layouts

The layouts related to ODOW, and existing operational wind farms were provided by the Client [4]. For the other future proposed wind farms, WT has designed preliminary wind turbine layouts based on guidelines and constraints described in the project submissions available in the Planning Inspectorate Portal [3], and Development Consent Order (DCO) documents for Hornsea 3 [5], Hornsea 4 [6] Dudgeon Extension and Sheringham Shoal [7], along with general industry practice.

Due to the preliminary nature of the future wind farms, WT did not consider additional constraints while designing the layouts. However, it should be noted that WT has undertaken a high-level review of seabed properties including sea depth, using Emodnet bathymetry data [13] and avoided turbine locations exceeding approximately 50 m, assuming that the project would prefer “shallow” foundation approaches. This has affected Hornsea 3 project in which the northwestern part of the site boundary given in Figure 1-1 remains free of turbines. WT would expect that final layout designed by the respective developer or additional layout considerations would ultimately alter the results, however these are likely to be small in the overall assessment of impact.

As such, WT has designed one layout for each of Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension Wind Farms considering the 15.0MW 236m diameter wind turbine, which is the same wind turbine considered for ODOW.

The allowable number of turbines for each of the Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension Wind Farm sites has been obtained from the available information on proposed farm size from the DCO submissions, using the assumption of the 15.0MW 236m turbines.

Based on the derived wind climate from ODOW FL (see Section 4), WT has estimated the prevailing wind direction at each site in order to define acceptable minimum turbine separation distances in the prevailing and non-prevailing wind directions, and to align the layout grid such that the wake impacts from a row of turbines on the rows behind them are minimised. Typical offshore wind farms currently under development maintain an average inter-turbine spacing of approximately 7-8 rotor diameters in prevailing wind directions, and 4-6 rotor diameters in non-prevailing wind directions.

Given the wind regimes at the wind climate locations, which can be seen in Appendix C-3, WT considers that inter-turbine spacings of 8 rotor diameters in the prevailing wind directions and 6 rotor diameters in the non-prevailing wind directions can be accommodated for the Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension Wind Farm sites.

The grid coordinates of the optimised turbine layouts for the Hornsea 3, Hornsea 4, Dudgeon Extension and Sheringham Shoal Extension wind farms are given in the figures in Appendix A.

Table 2-1 Turbine model parameters and turbine configurations for the neighbouring wind farms.

Wind farm	Associated turbine model	Rated power (kW)	Hub height (mMSL)	Number of turbines	Installed Capacity (MW)
Triton Knoll	Vestas V164-9.5MW	9500	110	90	857
Westermost Rough	Siemens Gamesa SG-6.0-154	6000	110	35	210
Lincs	Siemens Gamesa SWT-3.6-120	3600	85	75	270
Race Bank	Siemens Gamesa SG-6.0-154	6000	110	91	573
Inner dowsing	Siemens Gamesa SWT-3.6-107	3600	80	27	97.2
Lynn	Siemens Gamesa SWT-3.6-107	3600	80	27	97.2
Dudgeon	Siemens Gamesa SG-6.0-154	6000	110	67	402
Hornsea 1	Siemens Gamesa SG-7.0-154	7000	116	174	1218
Hornsea 2	Siemens Gamesa SG DD-8.0-167	8000	116	165	1320
Humber Gateway	Vestas V112-3.0MW	3000	80	73	219
Sheringham Shoal	Siemens Gamesa SWT-3.6-107	3600	80	88	317

Table 2-2 Turbine model parameters and turbine configurations for the proposed future wind farms.

Wind farm	Associated turbine model	Rated power (kW)	Hub height (mMSL)	Number of turbines	Assumed Installed Capacity (MW)
ODOW	Future 15.0MW 236m diameter Turbine	15000	158	100	1500
Hornsea 3	Future 15.0MW 236m diameter Turbine	15000	158	200	3000
Hornsea 4	Future 15.0MW 236m diameter Turbine	15000	158	160	2400
Sheringham Shoal Extension	Future 15.0MW 236m diameter Turbine	15000	158	23	345
Dudgeon Extension	Future 15.0MW 236m diameter Turbine	15000	158	30	450

3. DESCRIPTION OF THE AVAILABLE WIND DATA

3.1. Wind Climate Files

The Client has provided the long-term corrected time series at the hub heights of all the projects, 80.0 m, 85.0 m, 110.0 m, 116.0 m and 158.0 m from the Outer Dowsing FL [4], which is used as the main source of data in the wind flow / wake modelling.

Additionally, to assess TI, WT has obtained cleaned & processed wind measurements from publicly available Race Bank Met. Mast and Dogger Bank West Met. Mast from Marine Data Exchange portal [14].

The input wind time series data are summarised in Table 3-1 below. The locations are shown in Figure 2-1.

Table 3-1 Wind climates summary.

Device	Provided long term time series heights		Period of time series	Location[1]	
	Wind speed (m)	Wind direction (m)		Easting	Northing
Outer Dowsing FL	80.0, 85.0, 110.0, 116.0, 158.0	80.0, 85.0, 110.0, 116.0, 158.0	01/08/2001–31/07/2023	386319.0	5938966.0
Race Bank MM	90.2[2], 89.3[3], 80.0[3], 70.0[3], 60.0[4], 30.0[4]	89.3, 88.1	08/06/2006–17/12/2008	349933.2	5909531.0
Dogger Bank West MM	110.0[5], 104.5[6], 98.4[7], 83.7[6], 68.6[7], 53.5[5], 38.3[5]	104.5, 78.4, 63,4	24/07/2013–19/11/2014	424230.0	6080569.0

1- Coordinate system: WGS 84 / UTM zone 31N (EPSG:32631)
2- Stub mounted anemometer
3- Anemometers orientated to 225 degrees on Race Bank MM.
4- Anemometers orientated to 45 degrees on Race Bank MM.
5- Parallel measurements available orientated to 320 and 140 degrees on Dogger Bank West MM.
6- Anemometers orientated to 320 degrees on Dogger Bank West MM.
7- Anemometers orientated to 140 degrees on Dogger Bank West MM.

Further details of the individual wind climate files provided by the Client, including monthly data statistics at selected heights, can be found in Appendix B. The Outer Dowsing FL is located within the ODOW project boundary.

The Race Bank MM is in the North Sea, approximately 30 km east of Skegness, UK and approximately 1.5- 2 km west of Race Bank Wind Farm project area. WT has obtained cleaned mean wind speed and standard deviation data from 90.2 m (stub mounted), 89.3 m, 80.0, 70.0 m (orientated to 225 degrees), 60.0 m and 30.0 m (orientated to 45 degrees) from the Marine Data Exchange Portal [14], for the 2.3 year period between 08/06/2006– 17/12/2008. Additional checks have been conducted for the handling of stub mounted anemometer data at 90.2 m and consequently WT has decided to extrapolate the TI data calculated from 89.3 m orientated to 225 degrees to the site locations. Additional information from the checks undertaken can be found in Section 4.4. Though WT has not independently verified the steps undertaken for the processing of the data, through comparison with available reference data sets and other measurements, WT considers that this data is of good quality and appropriate for use in deriving a representative TI profile.

The Dogger Bank West Met. Mast is also located in the North Sea, approximately 200 km east of Sunderland and approximately 100 km north of Hornsea 1 and 2 projects. WT has obtained cleaned mean wind speed and standard deviation data from 110.0 m (parallel measurement), 104.5 m (orientated to 320 degrees), 98.4 m (orientated to 140 degrees), 83.7 m (orientated to 320 degrees), 68.6 m (orientated to 140 degrees), 53.5 m and 38.3 m (both parallel measurement), from Marine Data Exchange Portal [14], for the 1.1 year period between 24/07/2013– 19/11/2014. Although, the wind measurements are available at slightly higher measurement level (110 m vs 90.2 m for Race Bank MM), since the location of the Dogger Bank data is further away from the project sites, WT has not incorporated this data in the assessment of TI profile and used only for additional comparison / validation purposes.

It should be noted that the Client has provided the wind climates in the form of long-term corrected hub height time series from the Outer Dowsing FL for the hub heights of 80.0 m, 85.0 m, 110.0 m, 116.0 m and 158.0 m, which are used as the main source of data in this flow / wake modelling study. WT has discussed the process followed by the Client while producing the wind climate file from Outer Dowsing FL and conducted quality checks of this data, including comparisons of WT's assessment of publicly available data from the Race Bank Met. Mast and the Dogger Bank West Met. Mast, as well as Vortex reference data and have deemed this wind climate data acceptable as input for the flow modelling / wake assessment. Further details can be found in Section 4.

3.2. Reference Data

3.2.1. Global Wind Atlas (GWA) and New European Wind Atlas (NEWA)

WT has utilised reference data in the form of wind speed maps for the derivation of horizontal wind speeds across the turbine locations. These include the New European Wind Atlas (NEWA) [15], Global Wind Atlas (GWA) [16] and Vortex proprietary data. Vortex data has been provided by the Client [4] and publicly available data including NEWA and GWA, have been obtained by WT. Further information regarding NEWA and GWA can be found in Appendix D-4.1 and Appendix D-4.2. The resulting wind maps can be found in Figure 3-1 and Figure 3-2 along with the site boundaries.

WT has undertaken checks regarding the variation of wind speeds on those wind speed maps and compared the cross predictions of the wind climate files summarised in Section 3.1. Based on these checks WT has developed an approach for the prediction of the wind conditions at the turbine locations. More detail on the approach can be found in Section 4.3.1.

It should be noted that the Client has provided time series data from Vortex (Vortex SERIES) [4]. WT has compared the frequency distributions predicted by the wind climate files and Vortex SERIES data, to have a better understanding of the wind climate conditions within the site and as further validation tool of the wind climate files.

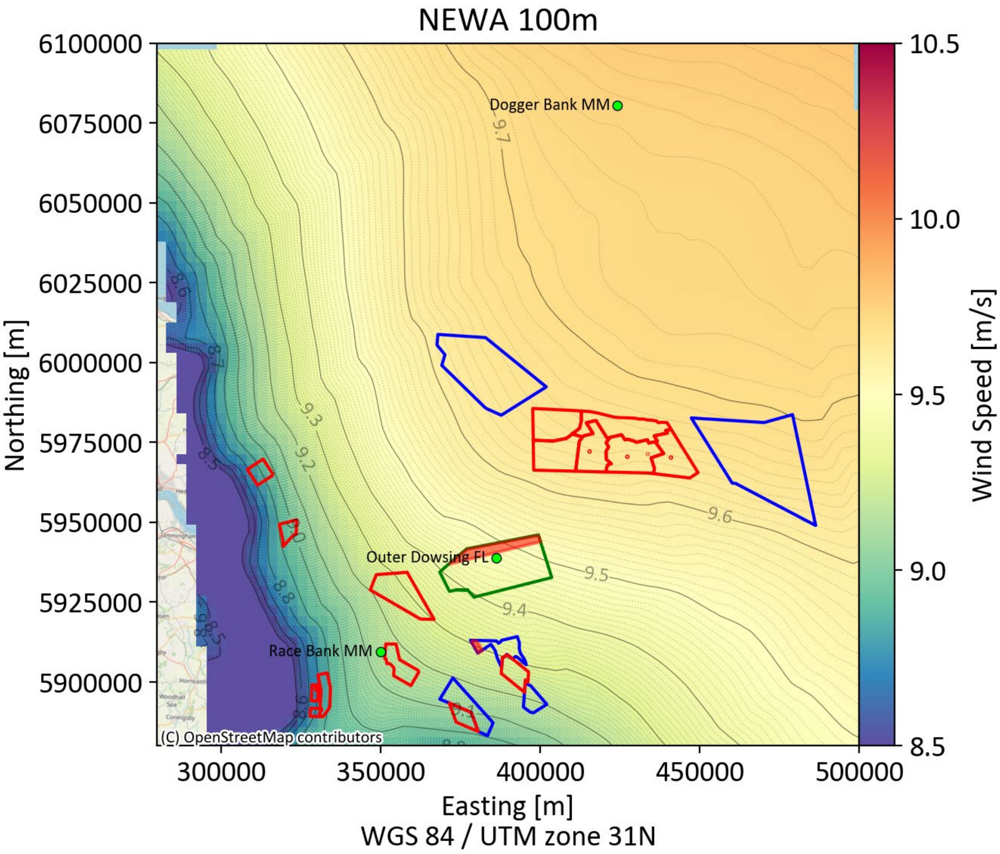

Figure 3-1 New European Wind Atlas (NEWA) 100 m wind map for the site area.

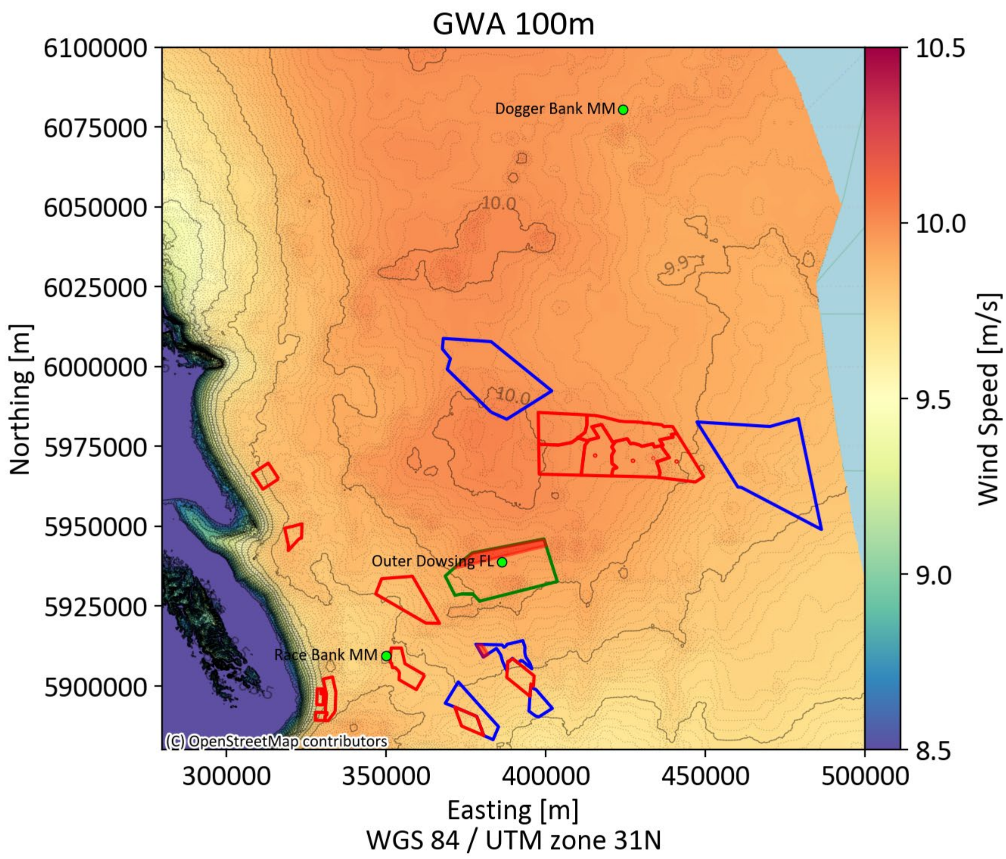

Figure 3-2 Global Wind Atlas (GWA) 100 m wind map for the site area.

3.2.2. Vortex MAP Data

To assess the horizontal wind speed variation across the sites, WT has considered the Vortex MAP product, provided by the Client [4] from Vortex [17]. This has been provided at several heights ranging from 80 m to 160 m and uses the Weather Research and Forecasting (WRF) model forced with ERA5 and downscaled to the site. The wind map at 100 m can be seen in Figure 3-3 along with the site boundaries.

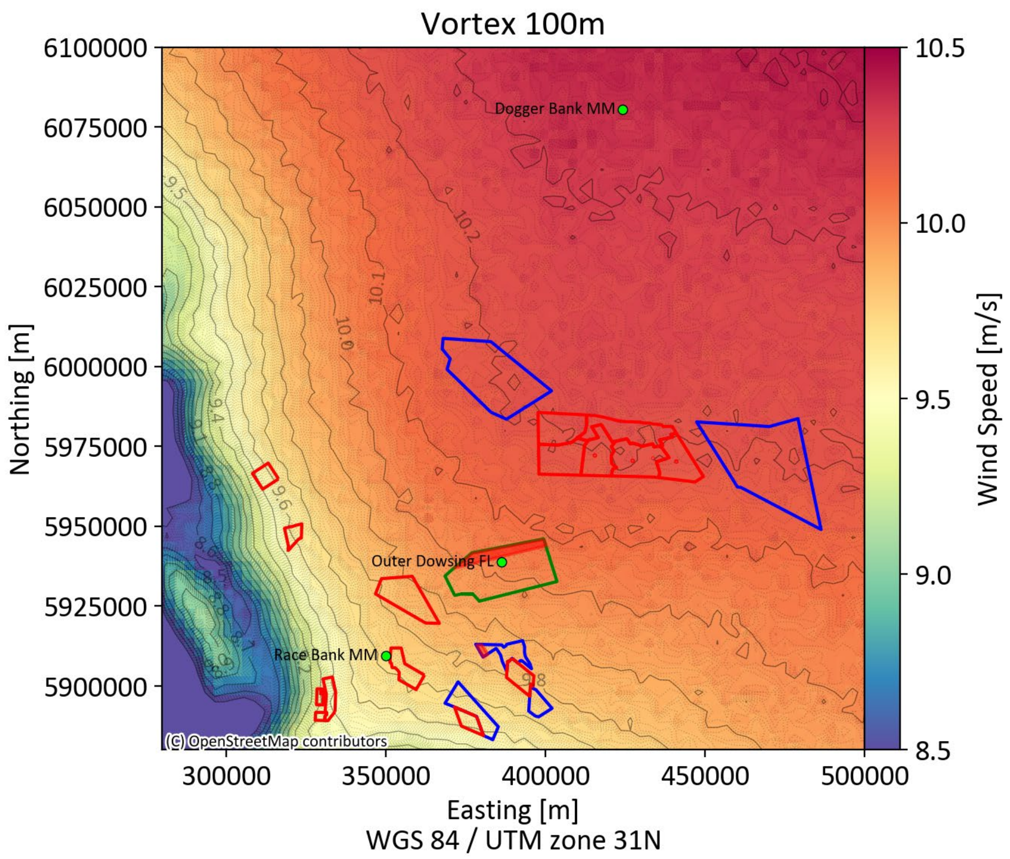

Figure 3-3 Vortex 100 m wind map for the site area.

3.2.3. Vortex SERIES Data

The Client has supplied a 22.6-year dataset from January 2001 to August 2023, derived within ODOW project area, at multiple heights ranging from 100 m to 160 m. This data is from the Vortex SERIES product where the model boundary conditions have come from the ERA5 reanalysis data (will be denoted as "Vortex ERA5 data" throughout the report). The Vortex ERA5 data comes from a WRF-downscaled model with a horizontal resolution of 3 km.

WT has used this data to compare the frequency distributions predicted by the wind climate files to have an improved understanding of the wind climate conditions within the site and as further validation of the wind climate files.

4. LONG-TERM WIND REGIME AT THE SITE

4.1. Validation of wind climate files, specification of the route in predicting turbine location wind speeds

The Outer Dowsing FL data was used as the main source of data in this wake modelling study, along with the wind maps summarised in Section 3.2.

WT has undertaken some further checks using the Race Bank and Dogger Bank West mast data, and developed an approach in predicting the long term mean wind speeds at the turbine locations, that are detailed in the following sections.

4.1.1. Validation of wind climate files

According to the discussions held with the Client [4], the cleaned Outer Dowsing FL data have been generated using a MCP, which WT opines that the methodology is acceptable and follows the industry best practices.

WT has evaluated the provided long-term wind climate data from the Outer Dowsing FL, by visually comparing the frequency distribution created using this data with the frequency distribution from Vortex ERA5 data. WT has also compared the Outer Dowsing frequency distributions with the Race Bank MM and Dogger Bank West MM. The results of the comparisons can be seen in Appendix C-3. According to the comparison between the Vortex ERA5 and Outer Dowsing FL the wind roses fit each other quite well, confirming Client's MCP methodology from Vortex ERA5 data.

WT observed that there is generally acceptable agreement among the wind climates at the Race Bank MM and Dogger Bank West MM with some differences in some non-significant wind direction sectors, which can also be seen in Appendix C-3. The Outer Dowsing wind rose, and Race Bank / Dogger Bank wind roses are also similar in terms of significant wind directions. Considering that the differences in measurement height, location, period and measurement principles of LiDARs and meteorological masts, WT opines that these differences can be within expectations.

4.1.2. Method for predicting the turbine location wind speeds

To spatially extrapolate the wind speeds from the Outer Dowsing FL location to the turbine locations, Vortex MAP product, Global Wind Atlas and New European Wind Atlas data were considered. WT has made consistency checks with these data. Based on these checks, as explained in Section 4.3, WT has used the average predictions from New European Wind Atlas and Vortex MAP product.

In order to do the consistency checks of wind maps explained above, WT has also made high-level long-term correlations in the Dogger Bank West MM and Race Bank MM data, using monthly correlations with Vortex ERA5 data. Further information can be found in Section 4.2.1.

4.2. Long term hub height wind regime at the site

4.2.1. Derivation of long-term wind speed at the Race Bank MM and Dogger Bank MM

As discussed in Section 3, the Outer Dowsing FL wind climate data contain wind time series already adjusted to the long-term wind speed and extrapolated to the hub heights.

To bring the Race Bank MM and Dogger Bank West MM to the same long-term context with Outer Dowsing FL and make meaningful comparisons, WT has made high level monthly correlation analysis using each of the met. mast data and Vortex SERIES data. The methodology is explained in Appendix D-2.1 and Appendix D-2.2.

The results from each Met. Mast is shown in Appendix C-1, which presents the correlations of monthly mean wind speeds at Race Bank MM at 89.3 mMSL and Dogger Bank West MM at 110 mMSL primary measurement heights and the Vortex ERA5 at 160 mMSL. The correlations are of excellent quality, each with a coefficient of determination, R^2, of 0.99 and 0.98 respectively for Race Bank MM and Dogger Bank West MM.

The long-term wind speeds for Race Bank MM and Dogger Bank MM are as given in Table 5 2:

Table 4-1 Long-term wind speed for Race Bank MM and Dogger Bank MM.

Met. Mast	Height [mMSL]	Valid Measurement period [years]	Measured Mean Wind Speed [m/s]	Long-term reference period [years]	Long-term wind speed adjustment [%]	Long-term wind speed at measurement height [m/s]
Race Bank MM	89.3	2.3	9.9	22.6	-3.5	9.5
Dogger Bank West MM	110.0	1.1	10.7	22.6	-3.6	10.3

4.2.2. Vertical wind speed interpolation

The variations in wind speed with height at the wind climate locations have been defined using the power law shear exponents according to the expression given in Appendix D-3.1. The variations are calculated for each wind climate file and have been used to predict the wind resource at the proposed hub heights.

The shear exponents at the wind climate locations have been derived. WT notes that the estimated wind shear exponents are in line with WT's expectations for such offshore locations.

4.2.3. Derivation of the long-term hub height wind speed and direction frequency distribution

As indicated in Section 4.1, the primary measurement device, which is the main source of data in flow / wake modelling is the Outer Dowsing FL data, for the prediction of long-term wind speeds at the turbine locations.

The long term corrected hub height time series for Outer Dowsing FL, provided by the Client [4] has been used to define the wind speed and direction frequency distributions.

For Race Bank MM and Dogger Bank West MM, which are used only in validation of wind maps and the derivation of TI profile, the hub height time series, which are the vertically extrapolated measurement time series, have been used to define the long-term wind speed and direction frequency distributions.

The following procedure was used, to avoid the introduction of bias into the annual mean wind regime prediction from seasonally uneven data coverage:

- The mean wind speed and direction frequency distribution for each month was determined from the valid data recorded in that month over the period. The frequency distribution for each month considered to be representative of the long term for that month thereby assuming the valid data are representative of any missing data.
- The frequency distributions for each of the twelve months were averaged, weighted by the number of days in each month, to determine the long-term annual frequency distribution.

The resulting hub height wind rose and frequency distributions at the wind climate locations at 100 m height can be seen in Appendix C-2, where the wind rose shapes are considered as representative for the sites under consideration.

4.3. Wind regime across the site

4.3.1. Wind flow modelling

To assess the horizontal wind speed variation across the turbine locations at the sites, as explained in Section 3.2, WT has considered use of the Vortex MAP product, New European Wind Atlas and Global Wind Atlas, at 100 m height for reference.

Wind model validation

Given that wind climate files are available at three different locations across the wind farms, WT has undertaken a performance check utilizing all three-wind maps to understand the agreement. The results of this check are given in Table 4-2 below, including the percentage differences with the predicted long term hub height wind speeds. It should be noted that the lighter colours indicate high performance and darker reds / blues shows poor performance.

Table 4-2 Comparison of wind map wind speeds and long-term wind speeds at 100 m height (colouring shows relative performance of map approaches).

Wind Climate File	Wind speed derived on Vortex wind map [%]	Wind speed derived on GWA [%]	Wind speed derived on NEWA [%]
Outer Dowsing FL	4.80%	3.72%	-1.24%
Race Bank MM	0.47%	1.55%	-5.29%
Dogger Bank West MM	1.50%	-2.29%	-4.26%

Whilst WT considers this exercise beneficial to inform the relative performance and agreement of wind maps and measurements, it is acknowledged that there are limitations and elevated uncertainty in performing this validation, because of the nature of measurement devices, as one is floating LiDAR and other two are meteorological masts, in which the measurements may be affected by lattice structure of the mast at certain wind sectors. It should be noted that the difference in measurement periods, differences in data processing approaches (as Outer Dowsing FL data have been processed by the Client), and also modelling inputs & methodology used in generation of the wind maps can play a role in these error margins, which are up to 4.8%, given in Table 4-2.

Notwithstanding the uncertainties discussed above, it is considered that uncertainties in the wind regime across the site have a lower impact on the analysis conducted in Section 5 due to it being a delta on wake impact, which is not as sensitive to wind speed errors as a traditional energy yield analysis.

WT also conducted a cross-prediction check across the measurement devices using the speedups derived from each of the wind speed maps and evaluated the consistency of the wind climate files and performance of wind speed maps. The results are given in Table 4-3, Table 4-4 and Table 4-5.

Table 4-3 Wind speed cross-predictions at 100 m height for Vortex.

Predicted from wind climate file	Predicted from Vortex MAPS at 100 m [%]		
	Outer Dowsing FL	Race Bank MM	Dogger Bank West MM
Outer Dowsing FL	-	4.31%	3.25%
Race Bank MM	-4.13%	-	-1.02%
Dogger Bank West MM	-3.15%	1.03%	-

Table 4-4 Wind speed cross predictions at 100 m height for GWA.

Predicted from wind climate file	Predicted from GWA at 100 m [%]		
	Outer Dowsing FL	**Race Bank MM**	**Dogger Bank West MM**
Outer Dowsing FL	-	2.14%	6.16%
Race Bank MM	-2.10%	-	3.93%
Dogger Bank West MM	-5.80%	-3.78%	-

Table 4-5 Wind speed cross predictions at 100 m height for NEWA.

Predicted from wind climate file	Predicted from NEWA at 100 m [%]		
	Outer Dowsing FL	**Race Bank MM**	**Dogger Bank West MM**
Outer Dowsing FL	-	4.28%	3.16%
Race Bank MM	-4.10%	-	-1.08%
Dogger Bank West MM	-3.06%	1.09%	-

Regarding the selection of wind speed map, considering the inherent uncertainties in the checks made, as explained above, the results did not easily allow WT to select a wind map, and thus it is considered that the wind flow modelling has additional challenges. It is noted that NEWA and Vortex seem promising according to the cross prediction checks when Dogger Bank MM and Race Bank MM were considered, with cross prediction errors around 1.0% - 1.1%.

WT has decided to further consider two averaging options across different wind speed maps, namely average of three wind speed maps and average of Vortex and NEWA. The results of this check are given in Table 4-6, Table 4-7 and Table 4-8 below.

Table 4-6 Comparison of wind map wind speeds and long-term wind speeds at 100 m height.

Wind Climate File	Wind speed derived using average of all three wind maps [%]	Wind speed derived using average of Vortex and NEWA wind maps [%]
Outer Dowsing FL	2.43%	1.78%
Race Bank MM	-1.09%	-2.41%
Dogger Bank West MM	-1.68%	-1.38%

Table 4-7 Wind speed cross-predictions at 100 m height using average of all three wind maps

Predicted from wind climate file	Predicted from average of all the maps at 100 m [%]		
	Outer Dowsing FL	Race Bank MM	Dogger Bank West MM
Outer Dowsing FL	-	3.56%	4.18%
Race Bank MM	-3.44%	-	0.60%
Dogger Bank West MM	-4.01%	-0.60%	-

Table 4-8 Wind speed cross predictions at 100 m height using average of Vortex and NEWA wind maps

Predicted from wind climate file	Predicted from average of NEWA and Vortex at 100 m [%]		
	Outer Dowsing FL	Race Bank MM	Dogger Bank West MM
Outer Dowsing FL	-	4.30%	3.20%
Race Bank MM	-4.12%	-	-1.05%
Dogger Bank West MM	-3.11%	1.06%	-

Looking at these results, averaging across three maps brings the error margin to the order of around 2.5% and cross prediction errors between Race Bank and Dogger Bank West MM around 0.6%, which is considered as favourable for the use of averaging. WT has further calculated the turbine location wind speeds using these maps and the variation in turbine wind speeds in three wind maps is given in Appendix C-4. Looking the plot given in Appendix C-4, WT considered that the turbine location predictions of GWA is inconsistent with NEWA and Vortex, therefore decided to use the average of NEWA and Vortex in the prediction of turbine location wind speeds.

Wind speed variation across the sites

As noted, the Outer Dowsing FL is the primary sources of data for the analysis and therefore have been used to initiate the wind flow model from which the wind speeds at the proposed turbine locations have been predicted, using the average of NEWA and Vortex wind maps, as explained above.

4.4. Turbulence Intensity

It is widely accepted in the wind industry that turbulence intensity measurements from Lidar devices (volume measurements) are not directly comparable to turbulence intensity measurements from meteorological masts using cup anemometers (point measurements), which is currently what the wind industry standards are based on.

In addition to the difference in turbulence intensity measurements from Lidars due to the volume to point measurement issue, floating Lidar systems have the added complication of motion impacting the measurements, which artificially increases the measured turbulence intensity.

Due to these reasons, WT found that Dogger Bank MM and Race Bank MM are good candidates for the sites under consideration, to calculate the turbulence intensity. Therefore, WT has adjusted the turbulence profile measured at the Dogger Bank MM and Race Bank MM to be representative of the expected long-term hub height wind speeds at the Outer Dowsing FL. As standard deviation is assumed constant, the turbulence intensity can be scaled from the met mast location to the turbine locations using the ratio in long-term wind speed between the met mast and the long-term wind speed of the site in question.

Figure 4-1 and Figure 4-2 show the assumed turbulence intensity profile at the Outer Dowsing FL, from Race Bank MM and Dogger Bank MM, respectively, derived at the turbine hub height of 158 m, along with profiles for IEC turbulence subclasses A, B and C [11]. Considering its distance to the site is much closer than Dogger Bank, therefore expected to have more similar conditions to the turbine locations, and having more measured data of 2.3 years than Dogger Bank West, which is 1.1 years, WT deems Race Bank MM is a better candidate than Dogger Bank MM in predicting the ambient TI for the turbine locations at each hub height. WT has considered Dogger Bank MM just for additional comparison / validation purposes.

It should be noted that, as discussed in Section 3.1, the top anemometer installed at 90.2 m is noted as stub mounted in the Race Bank MM documentation, which is possibly installed to a shorter rod compared to a longer boom, which can induce additional flow distortion from the nearby devices and the lattice structure from the mast itself due to the use of shorter rod. WT was unable to confirm the installation, as no picture related to the anemometer at 90.2 m was provided in the documentation. However, WT has made an additional check and compared the TI profiles of 90.2 m and 89.3 m northwest anemometers. This check yielded that the 90.2 m anemometer has a slightly higher TI values, which may possibly confirm the possible additional flow distortion due to the stub mounting. The results of this check can be seen in Appendix C-5. Therefore, WT has decided to use the 89.3 m orientated to 320 degrees anemometer as the primary one, and used the data measured by this device to derive the on-site TI profiles given below.

Table 4-9 shows the tabulated ambient turbulence intensity profiles for the mentioned combinations of sites and hub heights. WT notes that the magnitude of derived turbulence intensity values is in line with WT's experience, considering the expected offshore wind conditions at sites around the UK, with similar hub height.

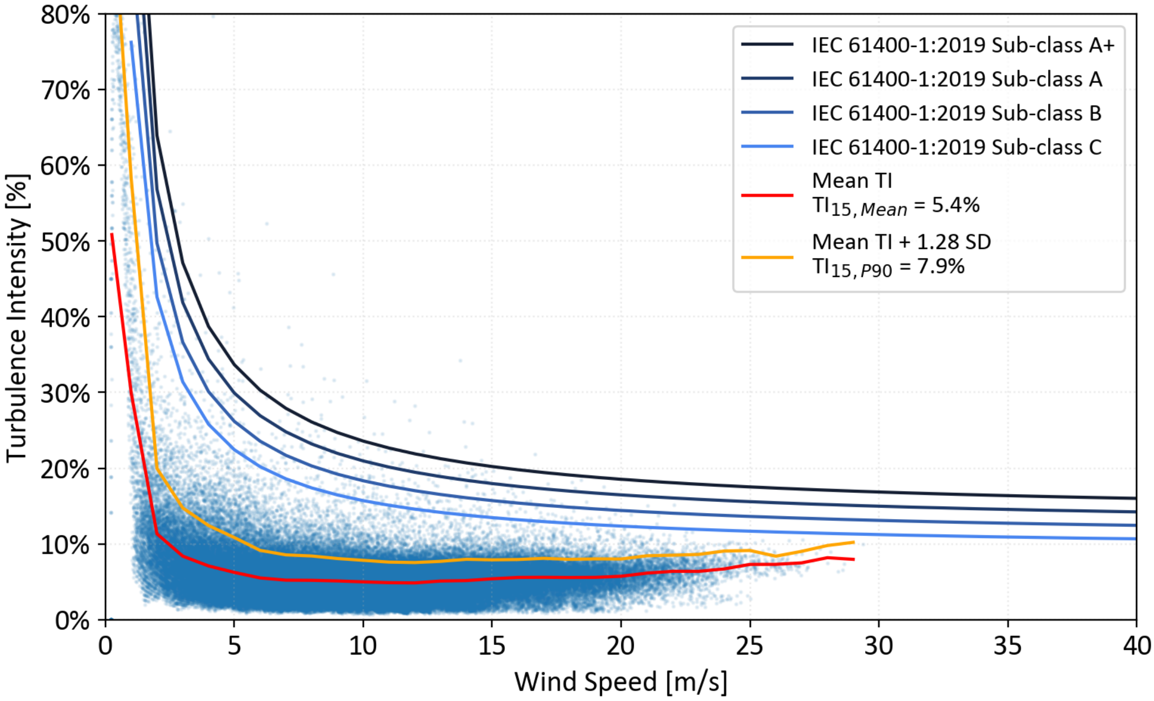

Figure 4-1 Ambient Turbulence Intensity profile assumed at the Outer Dowsing FL location at 158.0 m height, as derived from measurements made at the Race Bank MM.

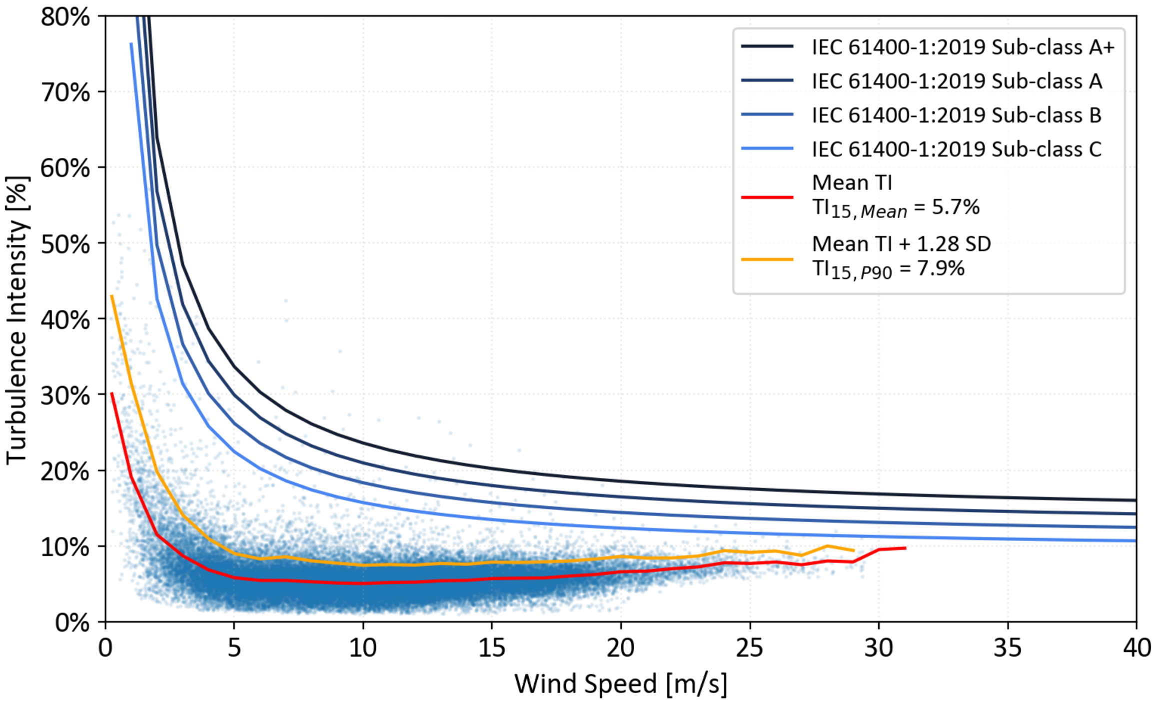

Figure 4-2 Ambient Turbulence Intensity profile assumed at the Outer Dowsing FL location at 158.0 m height, as derived from measurements made at the Dogger Bank MM.

Table 4-9 Ambient Turbulence Intensity profile assumed at Outer Dowsing FL at each hub height.

Wind speed bin centre (m/s)	Mean TI at Outer Dowsing FL at 80 mMSL hub height (%)	Mean TI at Outer Dowsing FL at 85 mMSL hub height (%)	Mean TI at Outer Dowsing FL at 110 mMSL hub height (%)	Mean TI at Outer Dowsing FL at 116 mMSL hub height (%)	Mean TI at Outer Dowsing FL at 158 mMSL hub height (%)
0	57.86%	57.41%	54.34%	54.22%	50.83%
1	27.40%	27.40%	28.51%	28.45%	29.94%
2	11.66%	11.68%	11.55%	11.55%	11.34%
3	8.59%	8.54%	8.45%	8.43%	8.40%
4	7.36%	7.34%	7.21%	7.21%	7.10%
5	6.39%	6.36%	6.33%	6.32%	6.25%
6	5.79%	5.77%	5.65%	5.64%	5.52%
7	5.59%	5.56%	5.41%	5.40%	5.23%
8	5.58%	5.55%	5.37%	5.36%	5.21%
9	5.46%	5.42%	5.30%	5.29%	5.13%
10	5.31%	5.28%	5.15%	5.14%	5.00%
11	5.23%	5.19%	5.05%	5.04%	4.90%
12	5.52%	5.46%	5.16%	5.14%	4.86%
13	5.59%	5.53%	5.37%	5.35%	5.12%
14	5.87%	5.78%	5.47%	5.44%	5.17%
15	6.05%	6.01%	5.76%	5.74%	5.41%
16	5.99%	5.95%	5.76%	5.77%	5.59%
17	6.07%	6.02%	5.84%	5.81%	5.60%
18	6.08%	6.03%	5.77%	5.76%	5.58%
19	6.48%	6.33%	5.92%	5.89%	5.60%
20	6.80%	6.71%	6.31%	6.30%	5.74%
21	6.94%	6.84%	6.57%	6.53%	6.16%
22	7.01%	6.89%	6.69%	6.68%	6.39%
23	7.86%	7.68%	6.93%	6.84%	6.38%
24	7.93%	7.84%	7.46%	7.50%	6.71%
25	8.06%	7.95%	7.65%	7.59%	7.31%
26	8.56%	9.08%	7.80%	7.81%	7.31%
27	9.36%	8.11%	8.51%	8.49%	7.51%
28	-	-	8.28%	8.26%	8.19%
29	-	-	-	-	7.97%

5. METHODOLOGY & RESULTS OF THE WAKE ASSESSMENT

The Energy Yield and the subsequent impact of the wakes produced by the individual wind farms have been calculated using WindFarmer: Analyst software. Of concern in any Energy Yield study is the effect of wake and turbine interaction losses (including blockage effect) from inside the farm and from adjacent farm sites. WT's typical best practice is to use the WindFarmer: Analyst Eddy Viscosity with large wind farm correction model to estimate offshore wake and turbine interaction effects, as validated by DNV in 2019, which results in lower errors across a number of operational offshore wind farms compared to other wake models [9], [10].

As noted in Appendix D-4.1a, the blockage effects have also been calculated using the Blockage Effect Estimator Tool (BEET) implemented within WindFarmer: Analyst software, which is based on a validation study incorporating more than 50 CFD simulations. The wind farm blockage is defined as the slowing-down effect caused by the wind farm itself, as it presents an obstacle to the incoming wind flow. This effect is usually not estimated in many standard industry wake models. According to WT's estimates, the wind farm blockage based on the BEET is found to be around 0.9% for all the scenarios considered and this figure is also inherent in the wake effect estimations given in Table 5-3.

No specific sensitivity assessment of the available range of wake models has been undertaken as the intention is to provide an independent assessment, in line with methodologies that have a proven track record.

A series of scenarios have been established to assess the relative impact of the build out of the Outer Dowsing farm to the proposed future sites. Table 5-1 below summarises the scenarios applied in this assessment.

The Baseline scenario represents the current situation of the project area, such that all existing operational wind farms, as listed in Table 5-2.

Baseline + ODOW scenario assumes the sole impact of ODOW on the existing operational wind farms.

Then, the effect of ODOW along with all the additional future wind farms, Sheringham Shoal, Dudgeon Extension, Hornsea 3 and Hornsea 4 was considered in Scenarios 1a and 1b. The effect of ODOW along with Hornsea 3 and Hornsea 4 only, was considered in Scenarios 2a and 2b and finally the effect of ODOW along with Sheringham Shoal Extension and Dudgeon Extension was considered in Scenarios 3a and 3b.

WT has further investigated the effect of ODOW in the future development, such that impact of ODOW in Hornsea 3 and Hornsea 4 was considered in Scenario 2c and the impact of ODOW in Sheringham Shoal Extension and Dudgeon Extension was considered in Scenario 3c.

For the future wind farms, Sheringham Shoal, Dudgeon Extension, Hornsea 3 and Hornsea 4, it is assumed that the same 15 MW wind turbine as for ODOW, which is a 15.0MW 236m rotor diameter at a hub height of 158 m. This assumption is considered reasonable, given that the project timelines are similar as well as considering current sector trends.

It should be noted that the information compiled for the future projects are not certain at this stage, and the impacts will be subject to change; therefore, this report should be considered as being based on the best available information at the time of preparation.

No changes to the existing wind farms e.g. repowering/ extended maintenance or non-operational turbines were assumed.

The projected decrease in potential energy production due to additional wake and turbine interaction losses from each scenario on each of the Client assets are shown in Table 5-3, Table 5-4 and Table 5-5.

The results of the turbine basis analysis are presented in Appendix C. A definition of turbine interaction loss factors applied to all scenarios is included in Appendix D-4.

Table 5-1 External Wake Main Scenarios

Scenario	Included Wind Farms	Comments / Assumptions
Baseline (Scenario 0a)	Existing Operational Wind Farms [1]	Existing operational conditions
Baseline + **ODOW** (Scenario 0b)	Baseline + **ODOW** [2]	Sole impact of 1500 MW ODOW project on the operational wind farms, which are expected to be operational in 2030.
Scenario 1a	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2]	Baseline scenario for 1b below, cumulative effect of all future wind farms
Scenario 1b	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Impact of ODOW along with all future development. Sheringham Shoal Extension (345 MW) and Dudgeon Extension (450 MW) will be operational by 2030. Hornsea 3 (3000 MW) will be operational by 2027. Hornsea 4 (2400 MW) will be operational by 2030.
Scenario 1c	Baseline + Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Technically same scenario with 1b above, but here the effect of ODOW on Sheringham Shoal Extension, Dudgeon Extension, Hornsea 3 and Hornsea 4 were investigated.
Scenario 2a	Baseline + Hornsea 3 and Hornsea 4 [2]	Baseline scenario for 2b below
Scenario 2b	Baseline + Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Impact of ODOW along with Hornsea 3 and Hornsea 4. Hornsea 3 (3000 MW) will be operational by 2027. Hornsea 4 (2400 MW) will be operational by 2030.
Scenario 2c	Baseline + Hornsea 3 and Hornsea 4 [2] with **ODOW** [2]	Technically same scenario with 2b above, but here the effect of ODOW on Hornsea 3 and Hornsea 4 were investigated.
Scenario 3a	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2]	Baseline scenario for 3b below
Scenario 3b	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2], with **ODOW** [2]	Impact of ODOW along with Sheringham Shoal Extension and Dudgeon Extension. Sheringham Shoal Extension (345 MW) and Dudgeon Extension (450 MW) expected to be operational by 2030.
Scenario 3c	Baseline + Sheringham Shoal Extension, Dudgeon Extension [2], with **ODOW** [2]	Technically same scenario with 3b above, but here the effect of ODOW on Sheringham Shoal Extension and Dudgeon Extension were investigated.

[1] Triton Knoll, Westermost Rough, Lincs, Race Bank, Inner dowsing, Lynn, Dudgeon, Hornsea 1, Hornsea 2, Humber Gateway and Sheringham Shoal

[2] Based on discussions held with the Client a 15 MW turbine with 236 m rotor diameter and 158m rotor height were assumed to be used for all future wind farms including ODOW. This assumption for the future wind farms is considered to provide a conservative position impact assessment as part of the DCO application

Table 5-2 Baseline scenario wind farms included.

Project Name	Ownership details [1]	Turbine	Farm Capacity
Triton Knoll	RWE (59%) J-Power (24%) Kansai Electric Power (16%)	Vestas V164-9.5MW (164 m rotor diameter)	857 MW
Westermost Rough	Ørsted (50%) Green Investment Group (GIG) Equitix Limited	Siemens Gamesa SG-6.0-154 (154 m rotor diameter)	210 MW
Lincs	Ørsted Green Investment Bank Offshore Wind Fund Octopus Renewables Infrastructure Trust plc Equitix Limited	Siemens Gamesa SWT-3.6-120 (120 m rotor diameter)	270 MW
Race Bank	Ørsted Macquarie Capital Group Limited Norges Bank Investment Management	Siemens Gamesa SG-6.0-154 (154 m rotor diameter)	573 MW
Inner dowsing	Green Investment Group (GIG) Equitix Limited	Siemens Gamesa SWT-3.6-107 (107 m rotor diameter)	97.2 MW
Lynn	Green Investment Group (GIG) Equitix Limited	Siemens Gamesa SWT-3.6-107 (107 m rotor diameter)	97.2 MW
Dudgeon	Equinor Masdar Chine Resources Company Limited	Siemens Gamesa SG-6.0-154 (154 m rotor diameter)	402 MW
Hornsea 1	Ørsted Global Infrastructure Partners LLP The Renewables Infrastructure Group Limited (TRIG) Greencoat UK Wind Octopus Energy Generatuin Daiwa Energy & Infrastructure Brookfield Infrastructure Partners	Siemens Gamesa SG-7.0-154 (154 m rotor diameter)	1218 MW

Hornsea 2	Ørsted AXA IM Alts Credit Agricole Assurances Brookfield Infrastructure Partners	Siemens Gamesa SG DD-8.0-167 (167 m rotor diameter)	1320 MW
Humber Gateway	RWE AG Greencoat UK Wind	Vestas V112-3.0MW (112 m rotor diameter)	219 MW
Sheringham Shoal	Equinor Green Investment Group (GIG) Equitix Limited The Renewables Infrastructure Group Limited (TRIG)	Siemens Gamesa SWT-3.6-107 (107 m rotor diameter)	317 MW

1- Publically available datasets were used [1] and [2] for the ownership details.

It should be noted that the scope of work presented in this report has been focused on the potential difference in annual energy production due to wake impacts of each future wind farm scenario. As this is not a complete EPA study, WT did not undertake a comprehensive technical loss assessment, which is typically required in order to estimate a realistic annual energy production for any wind farm, and as such Table 5-3 presents the results of additional effect of addition of ODOW project to the development of all future projects (Scenario 1b vs Scenario 1a), addition of ODOW to the development of Hornsea 3 and Hornsea 4 only (Scenario 2b vs Scenario 2a) and addition of ODOW to the development of Sheringham Shoal Extension and Dudgeon Extension only (Scenario 3b vs Scenario 3a)

Table 5-4. presents the effect of ODOW in the future development, only, such that impact of ODOW in Hornsea 3 and Hornsea 4 and the impact of ODOW in Sheringham Shoal Extension and Dudgeon Extension.

Table 5-5 presents the results as a percentage difference normalised to the baseline.

Table 5-3 Comparison of Scenario 1b and 1a, Scenario 2b and 2a and Scenario 3b and 3a for operational wind farms

Scenario	Additional wake loss on each operational wind farm (%)											
	Triton Knoll	Westermost Rough	Lincs	Race Bank	Inner Dowsing	Lynn	Dudgeon	Hornsea 1	Hornsea 2	Humber Gateway	Sheringham Shoal	Total additional wake loss on all operational wind farms
Scenario 0b vs 0a	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.88%	-0.70%	-0.75%	-0.23%	-0.76%	-0.58%
Scenario 1b vs 1a	-0.77%	-0.08%	-0.17%	-0.52%	-0.05%	-0.03%	-0.58%	-0.68%	-0.70%	-0.23%	-0.41%	-0.51%
Scenario 2b vs 2a	-0.77%	-0.08%	-0.17%	-0.52%	-0.05%	-0.03%	-0.84%	-0.70%	-0.75%	-0.23%	-0.74%	-0.57%
Scenario 3b vs 3a	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.60%	-0.68%	-0.70%	-0.23%	-0.41%	-0.51%

Table 5-4 Summary of the results of the future wind farm scenarios

Scenarios basis	Scenario Name	Additional wake loss on each future wind farm arising from Outer Dowsing (%)			
		Hornsea 3	Hornsea 4	Sheringham Shoal Extension	Dudgeon Extension
Impact of ODOW on all future wind farms	Scenario 1c vs Scenario 1a	-0.01%	-0.06%	-0.27%	-0.87%
Impact of ODOW on Hornsea 3&4	Scenario 2c vs Scenario 2a	-0.01%	-0.07%	-	-
Impact of ODOW on Sheringham & Dudgeon Extensions	Scenario 3c vs Scenario 3a	-	-	-0.30%	-0.89%

Table 5-5 Summary of the results of the scenarios for the impact on existing farm assets, normalized to the baseline

Scenarios basis	Scenario Name	Additional wake loss on each operational wind farm (%)										
		Triton Knoll	Westermost Rough	Lincs	Race Bank	Inner Dowsing	Lynn	Dudgeon	Hornsea 1	Hornsea 2	Humber Gateway	Sheringham Shoal
Impact of ODOW on existing farms	Scenario 0a	0	0	0	0	0	0	0	0	0	0	0
	Scenario 0b	-0.79%	-0.08%	-0.18%	-0.53%	-0.05%	-0.03%	-0.88%	-0.70%	-0.75%	-0.23%	-0.76%
Impact of all future developments on existing farms	Scenario 1a	-0.66%	-0.18%	-0.27%	-0.50%	-0.13%	-0.18%	-2.79%	-1.09%	-1.44%	-0.10%	-2.39%
	Scenario 1b	-1.43%	-0.26%	-0.45%	-1.02%	-0.18%	-0.21%	-3.37%	-1.76%	-2.14%	-0.34%	-2.80%
Impact of ODOW and Hornsea 3&4 on existing farms	Scenario 2a	-0.22%	-0.17%	-0.01%	-0.02%	0.00%	0.00%	-0.09%	-0.99%	-1.37%	-0.09%	-0.03%
	Scenario 2b	-0.99%	-0.25%	-0.18%	-0.54%	-0.05%	-0.03%	-0.93%	-1.69%	-2.11%	-0.32%	-0.77%
Impact of ODOW and Sheringham & Dudgeon Extensions on existing farms	Scenario 3a	-0.44%	-0.01%	-0.26%	-0.47%	-0.13%	-0.18%	-2.73%	-0.09%	-0.07%	-0.02%	-2.38%
	Scenario 3b	-1.23%	-0.09%	-0.44%	-1.00%	-0.18%	-0.20%	-3.32%	-0.77%	-0.78%	-0.25%	-2.80%

6. CONCLUSIONS

A differential energy yield assessment approach has been undertaken using the WindFarmer: Analyst software which has a proven track record, to provide an independent evaluation of the possible external wake losses caused by the Outer Dowsing project.

The following conclusions are noted:

1. Based on the approach detailed in this report, WT has conducted a series of wake model runs according to the selected scenarios given in Table 5-1 and compared the results with a baseline scenario whose details are provided in Table 5-2. Table 5-3 provides the additional wake effect results at all operational neighbouring wind farms for each of the future scenarios. It was assumed that there are no changes to the existing wind farms e.g. repowering/ extended maintenance or non-operational turbines.

2. Based on these scenarios a conservative assessment of the additional wake loss arising from ODOW on the existing operational wind farms is calculated up to a maximum of **-0.88 %** (primarily the effect of ODOW on the Dudgeon Wind Farm).

3. The average effect of ODOW on all the existing wind farms, with or without the future wind farms varies between **-0.58 %** (the sole effect of ODOW on existing projects) and **-0.51 %** (the effect of ODOW on existing projects, in combination with all future wind farms). The effect of individual operational wind farms varies between **-0.03%** and **-0.88%**.

4. WT has also investigated the effect of ODOW on future developments individually, such as the impact of ODOW on all future development at once, the impact of ODOW on Hornsea 3 and Hornsea 4 and the impact of ODOW on Sheringham Shoal Extension and Dudgeon Extension. As seen on Hornsea 3 and Hornsea 4, the highest effect is observed as -**0.07%** on Hornsea 4 and for Dudgeon Extension and Sheringham Shoal Extension, the highest effect is observed as **-0.89%** on Dudgeon Extension.

5. Considering the engineering wake model approaches used and distances between the Client assets and proposed neighbouring wind farms, WT considers the assessed additional wake loss numbers to be commensurate with WT's expectations. WT also finds the above results comparable with recent studies conducted by DNV and RWE [8] about cluster wakes and their effects on wind farm annual energy production.

6. The future wind farms in the vicinity of the operational neighbouring wind farms are at an early stage of development. For the operational wind farms in the vicinity of Client assets, basic turbine and layout parameters are known to WT and summarised in Table 5-2, and as such modelling of these assets

contains reduced uncertainty. For the wind farms at an early stage of development, there is currently limited information available about the turbine types, layouts and hub heights. For the prediction of current status of those future wind farms, including the development phase and possible turbine configurations, a range of publicly available datasets has been utilised including the 4C Offshore Wind Market Intelligence [1], Map Stand Location Intelligence portal [2], and submissions to the National Infrastructure Planning Portal [3], along with correspondence with the Client [4]. As such, as some of the information compiled for the future projects is uncertain at this stage, the impacts will be subject to change – this report should be considered as being based on the best available information at the time of preparation.

7. It should also be noted that WT has utilised WindFarmer: Analyst Eddy Viscosity wake model with large wind farm and blockage correction, which is an engineering wake model having a proven track record in wind energy industry.

7. REFERENCES

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2. Map Stand Location Intelligence Portal, https://mapstand.com/
3. National Infrastructure Planning Portal , https://infrastructure.planninginspectorate.gov.uk/
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5. Infrastructure Planning, The Hornsea Three Offshore Wind Farm Order 2020, https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010080/EN010080-003266-EN010080%20Hornsea%20Three%20-%20Development%20Consent%20Order.pdf
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7. Infrastructure Planning, The Sheringham Shoal and Dudgeon Offshore Wind Farm Order 2024, https://infrastructure.planninginspectorate.gov.uk/wp-content/ipc/uploads/projects/EN010109/EN010109-002390-SADEP%20DCO%20DESNZ%20170424_Redacted.pdf
8. C. Montavon (1), C. Rodaway (2), K. Gunn (2), G. Smith (1), D. Dunsmore (1), M. Del Hoyo (1), K. Sinclair (1). 1:DNV , 2:RWE. Cluster Wakes and their Effect on a Wind Farm Annual Energy Production. Are current models capturing the magnitude of the effects observed in operational data? Whitepape of work Presented at WindEurope Technology Workshop, June 2024
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12. IEC 61400-1 Wind turbines – Part 1: Design requirements, Edition 4, 2019.
13. Emodnet bathymetry data, [redacted]
14. Marine Data Exchange portal, [redacted]
15. New European Wind Atlas, a free, web-based application developed, owned and operated by the NEWA Consortium. For additional information: [redacted]
16. Global Wind Atlas 3.0. For additional information: [redacted]
17. Vortex MAPS data sets. Purchased on behalf of the client for the area [redacted]

APPENDIX A: WIND FARM SITE INFORMATION

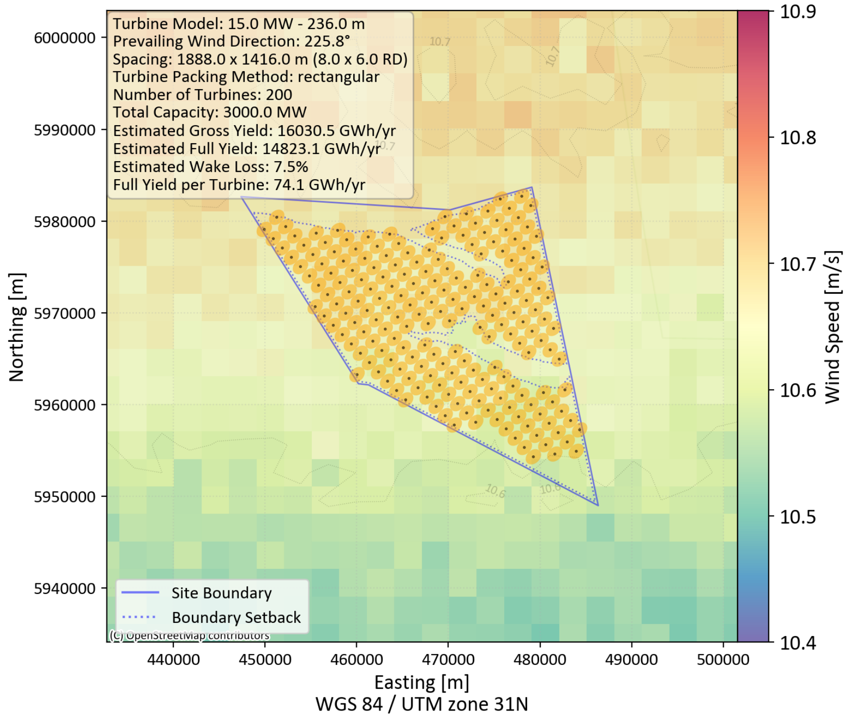


Figure A-1 Optimised turbine layout for Hornsea 3 future wind farm.

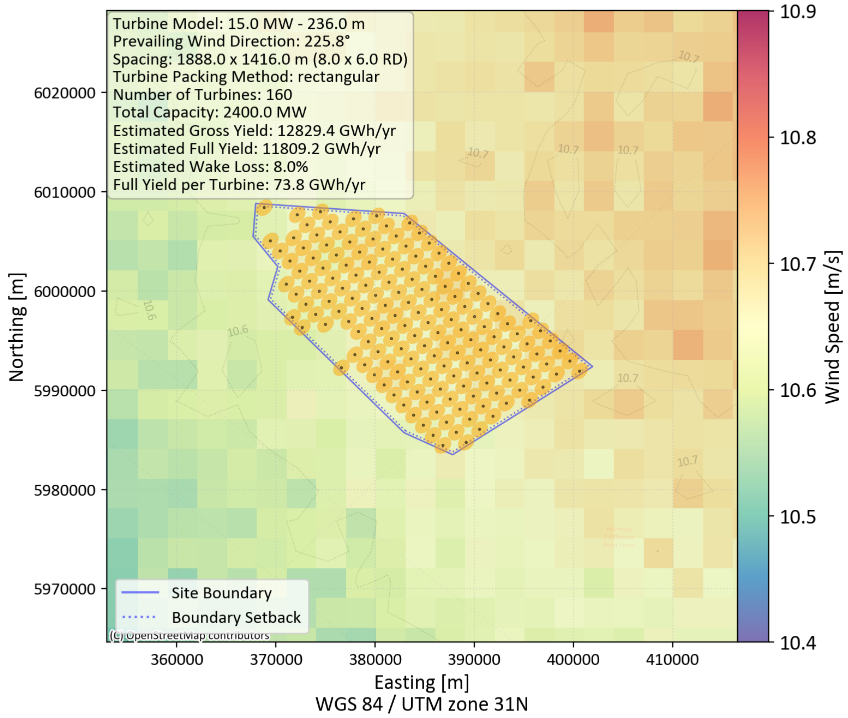


Figure A-2 Optimised turbine layout for Hornsea 4 future wind farm.

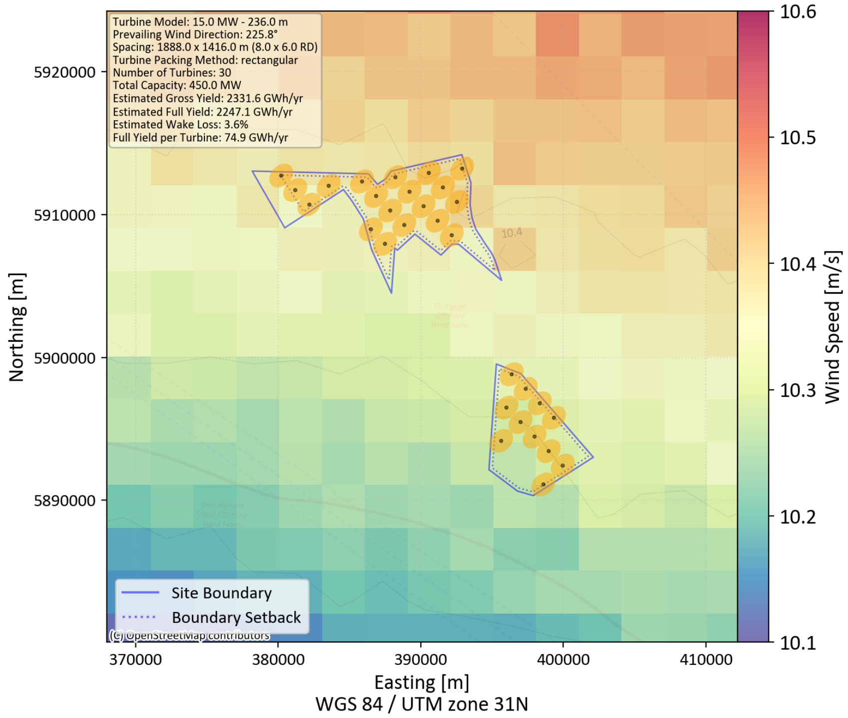


Figure A-3 Optimised turbine layout for Dudgeon Extension future wind farm.

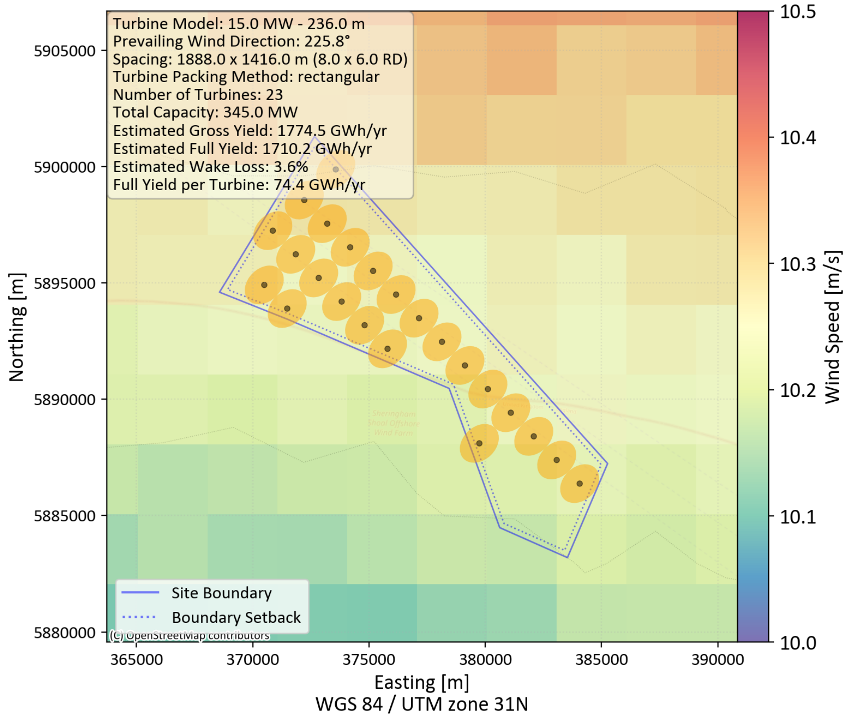


Figure A-4 Optimised turbine layout for Sheringham Shoal future wind farm.

APPENDIX B: WIND DATA

B-1. Outer Dowsing FL

B-2. Race Bank MM

B-3 Dogger Bank West MM

B-1 Outer Dowsing FL

Table C-1 Outer Dowsing FL configuration.

Site name	Outer Dowsing	Elevation (mMSL)	Eastings (m)	Northings (m)	Coordinate system	Datum	Zone
Device name	Outer Dowsing FL	0	386319.0	5938966.0	UTM	WGS 84	31N
Installation date	Unknown*						

* Long term corrected data between 01/08/2001– 31/07/2023 was provided by the Client

B-2 Race Bank MM

Table C-3 Race Bank MM configuration.

Site name	Race Bank	Elevation (mMSL)	Eastings (m)	Northings (m)	Coordinate system	Datum	Zone
Device name	Race Bank MM	0	349933.2	5909531.0	UTM	WGS 84	31N
Installation date	Unknown *						

* Cleaned data between 08/06/2006– 17/12/2008 was utilised by WT

Table C-4 Race Bank MM data summary at selected heights.

Month	Mean wind speed (m/s)					Wind speed data coverage (%)				
	90.2 mMSL[1]	89.3 mMSL[2]	80 mMSL[2]	70 mMSL[2]	60 mMSL[3]	90.2 mMSL[1]	89.3 mMSL[2]	80 mMSL[2]	70 mMSL[2]	60 mMSL[3]
Jun-06	8.0	7.0	7.8	7.6	6.7	74.8	99.5	74.8	74.8	99.5
Jul-06	7.2	7.1	7.1	6.9	6.7	99.9	100.0	99.9	99.9	99.9
Aug-06	8.2	8.3	8.3	8.2	8.0	100.0	100.0	100.0	100.0	100.0
Sep-06	8.8	8.7	8.6	8.4	8.1	100.0	100.0	100.0	100.0	100.0
Oct-06	10.5	10.4	10.3	10.1	9.8	100.0	100.0	100.0	100.0	100.0
Nov-06	12.5	12.4	12.3	12.0	11.4	98.6	98.6	98.6	98.6	98.6
Dec-06	11.5	11.9	11.3	11.0	10.6	99.8	92.5	99.8	99.8	92.4
Jan-07	14.0	13.9	13.7	13.3	12.5	99.7	99.7	99.7	99.7	99.7
Feb-07	9.9	9.9	9.7	9.4	9.1	100.0	100.0	100.0	100.0	100.0
Mar-07	10.9	10.8	10.6	10.4	10.0	100.0	100.0	100.0	100.0	100.0
Apr-07	8.0	8.5	7.7	7.6	8.0	47.3	100.0	48.0	47.3	100.0
May-07	–	8.4	–	–	7.9	0.0	100.0	0.0	0.0	100.0
Jun-07	9.9	7.5	9.5	9.6	7.1	24.3	100.0	25.1	24.3	100.0
Jul-07	8.8	8.7	8.6	8.5	8.1	100.0	100.0	100.0	100.0	100.0
Aug-07	8.4	8.4	8.3	8.2	8.0	100.0	100.0	100.0	100.0	100.0
Sep-07	9.6	9.5	9.4	9.3	9.0	100.0	100.0	100.0	100.0	100.0
Oct-07	7.0	6.9	6.9	6.8	6.6	100.0	100.0	100.0	100.0	100.0
Nov-07	11.1	11.1	11.0	10.9	10.6	99.8	99.8	99.8	99.8	99.8
Dec-07	11.1	11.0	10.8	10.6	10.1	99.2	99.2	99.2	99.2	99.2
Jan-08	13.6	13.4	13.2	12.9	12.2	99.8	99.8	99.8	99.8	99.8
Feb-08	11.3	10.7	11.0	10.7	9.7	90.4	97.3	90.9	90.4	97.3
Mar-08	12.6	12.4	12.3	12.1	11.8	98.7	99.7	98.7	98.7	99.7
Apr-08	9.6	9.2	9.4	9.2	8.6	88.1	98.3	88.2	88.1	98.3
May-08	9.3	9.2	8.9	8.7	8.6	99.4	99.4	99.4	99.4	99.4
Jun-08	7.9	7.8	7.8	7.6	7.3	100.0	100.0	100.0	100.0	100.0
Jul-08	8.8	8.8	8.7	8.5	8.2	97.2	97.2	97.2	97.2	97.2
Aug-08	9.3	9.2	9.1	9.0	8.5	93.9	94.0	93.9	93.9	93.9
Sep-08	8.1	8.0	7.9	7.8	7.6	99.9	99.9	99.9	99.9	99.9
Oct-08	11.1	11.0	10.9	10.7	10.2	99.9	99.9	99.9	99.9	99.9
Nov-08	11.6	11.5	11.3	11.2	10.9	99.7	99.8	99.8	99.8	99.8
Dec-08	10.4	10.4	10.3	10.2	10.0	53.0	53.1	53.0	53.0	53.1

1- Stub mounted anemometer

2- Anemometers orientated to 225 degrees on Race Bank MM.

3- Anemometers orientated to 45 degrees on Race Bank MM.

B-3 Dogger Bank West MM

Table C-4 Dogger Bank West MM configuration.

Site name	Walney	Elevation (mMSL)	Eastings (m)	Northings (m)	Coordinate system	Datum	Zone
Device name	Dogger Bank West MM	0	424230.0	6080569.0	UTM	WGS 84	31N
Installation date	Unknown *						

* Cleaned data between 24/07/2013– 19/11/2014 was utilised by WT

Table C-5 Dogger Bank West MM data summary at selected heights.

Month	Mean wind speed (m/s)					Wind speed data coverage (%)				
	110.0 mMSL[1]	104.5 mMSL[1]	83.7 mMSL[1]	53.5 mMSL[1]	38.3 mMSL[1]	110.0 mMSL[1]	104.5 mMSL[1]	83.7 mMSL[1]	53.5 mMSL[1]	38.3 mMSL[1]
Sep-13	9.5	9.5	10.7	10.3	10.0	14.5	14.9	11.1	11.1	11.1
Oct-13	13.4	13.1	12.8	12.2	11.9	93.5	100.0	87.4	86.9	86.9
Nov-13	10.7	10.6	10.5	10.2	9.9	98.5	100.0	98.9	98.9	98.9
Dec-13	15.3	15.3	14.8	14.1	13.7	100.0	100.0	99.6	99.7	99.7
Jan-14	13.0	12.6	12.3	11.8	11.6	94.8	99.6	86.4	86.7	86.7
Feb-14	15.0	14.9	14.5	13.9	13.5	99.6	100.0	92.1	92.6	92.6
Mar-14	11.7	11.4	11.2	10.6	10.3	84.8	100.0	95.3	96.8	96.8
Apr-14	10.0	9.9	9.6	8.8	8.5	79.8	98.3	91.7	98.3	98.3
May-14	8.4	8.6	8.4	7.8	7.6	89.5	100.0	94.2	100.0	100.0
Jun-14	7.1	7.0	6.9	6.7	6.6	85.3	87.2	81.7	87.1	87.1
Jul-14	7.5	7.5	7.4	7.1	6.9	90.8	100.0	97.9	98.0	98.0
Aug-14	9.8	9.8	9.7	9.3	9.2	98.6	100.0	96.1	96.7	96.7
Sep-14	6.6	6.6	6.5	6.3	6.2	99.8	99.9	98.6	98.6	98.6
Oct-14	12.3	12.1	11.9	11.4	11.2	96.6	99.9	94.0	94.5	94.5
Nov-14	10.9	10.5	10.0	9.6	9.5	55.3	62.0	52.1	51.9	51.9

1- Anemometers orientated to 320 degrees on Dogger Bank West MM.

APPENDIX C: ANALYSIS RESULTS

C-1. Long term correlations for Race Bank and Dogger Bank West MM

C-2. Site long term wind regime

C-3 Long term frequency distribution comparisons

C-4 Plot of turbine predictions of each wind climate file

C-5 Race Bank MM 90.2 mMSL and 89.3 mMSL Ambient Turbulence Intensity Comparisons

C-6 Turbine level wake results

C-1 Long term correlations for Race Bank and Dogger Bank West MM

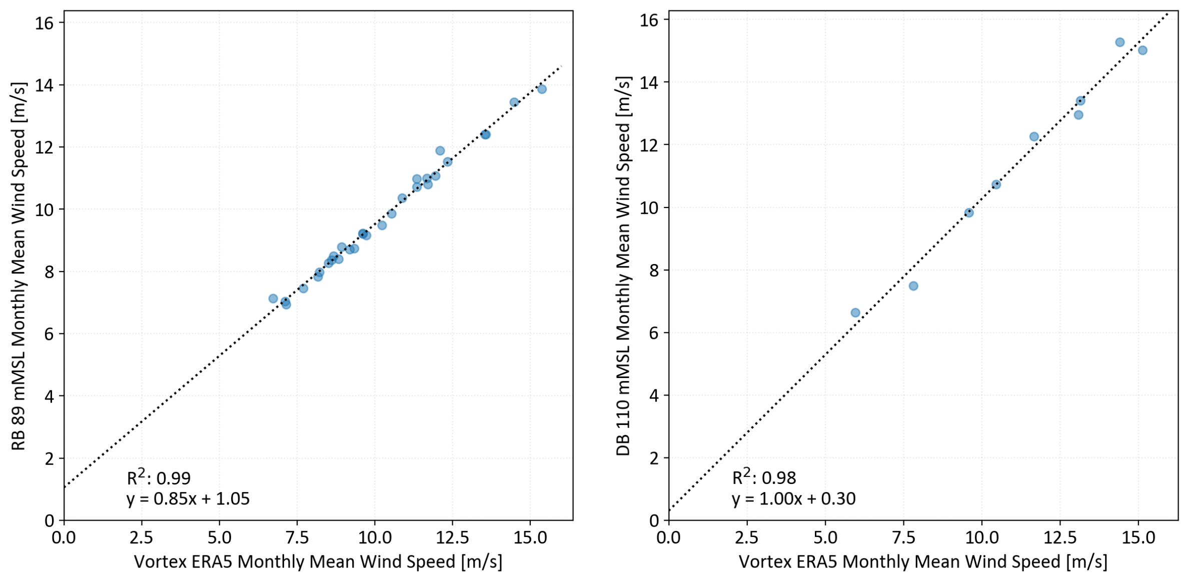
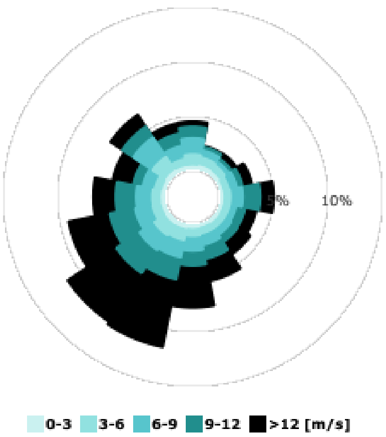


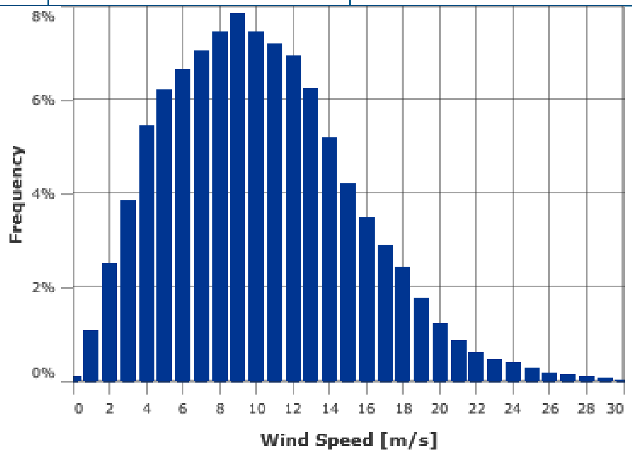
Figure D-1 Long-term correlations – monthly correlations between Race Bank MM - Vortex ERA5 reanalysis data (left) and between Dogger Bank West MM - Vortex ERA5 reanalysis data (right).

C-2 Site long-term wind regimes at 100 m height

Table D-1 Long-term wind regime for Dogger Bank West MM at 100 m

Monthly mean wind speeds			
Month	Wind speed [m/s]	Valid wind speed data [years]	Valid direction data [years]
January	12.2	1.0	1.0
February	14.3	1.0	1.0
March	11.0	1.0	1.0
April	9.6	1.0	1.0
May	8.2	1.0	1.0
June	6.8	0.9	0.9
July	7.2	1.0	1.0
August	9.4	1.0	0.6
September	6.7	1.2	0.5
October	12.1	2.0	2.0
November	10.2	1.6	1.6
December	14.6	1.0	1.0
Annual	10.2		



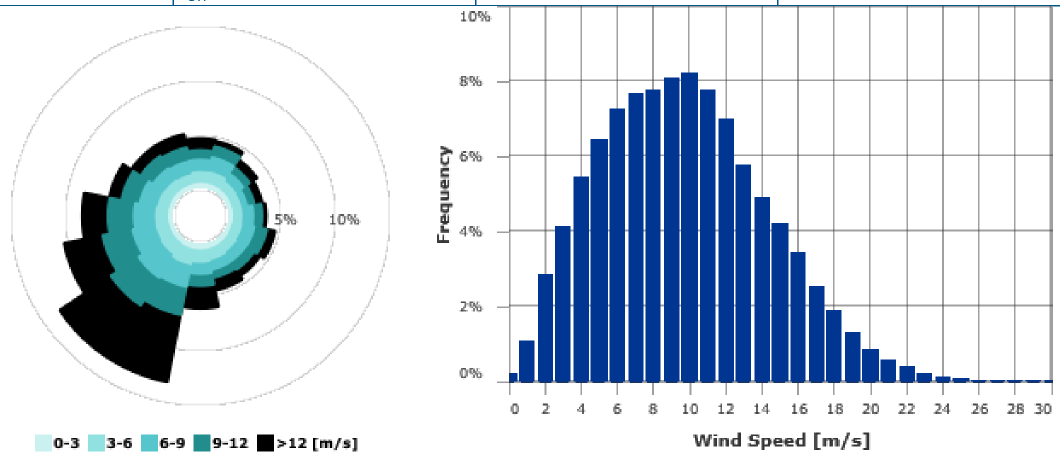


Wind Speed [m/s]	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	No Direc tion	Total [%]
0	+	0.01	0.01	0.01	+	+	+	+	+	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.09
1	0.04	0.05	0.04	0.02	0.04	0.03	0.04	0.03	0.05	0.06	0.07	0.07	0.08	0.06	0.08	0.06	0.23	1.07
2	0.09	0.14	0.14	0.08	0.09	0.09	0.10	0.09	0.12	0.17	0.17	0.15	0.13	0.10	0.17	0.12	0.55	2.50
3	0.22	0.29	0.23	0.15	0.15	0.20	0.25	0.18	0.18	0.20	0.24	0.19	0.19	0.17	0.18	0.20	0.61	3.83
4	0.36	0.24	0.28	0.22	0.25	0.29	0.27	0.27	0.27	0.32	0.40	0.27	0.21	0.24	0.37	0.24	0.93	5.43
5	0.44	0.30	0.25	0.25	0.24	0.25	0.18	0.24	0.28	0.49	0.53	0.32	0.35	0.27	0.71	0.26	0.83	6.19
6	0.48	0.29	0.17	0.24	0.29	0.15	0.17	0.25	0.31	0.56	0.53	0.47	0.45	0.34	0.77	0.33	0.82	6.62
7	0.51	0.22	0.17	0.30	0.32	0.19	0.23	0.30	0.40	0.51	0.60	0.55	0.43	0.40	0.74	0.36	0.85	7.05
8	0.47	0.22	0.12	0.25	0.42	0.22	0.31	0.42	0.53	0.52	0.53	0.53	0.49	0.40	0.72	0.49	0.80	7.43
9	0.51	0.20	0.10	0.23	0.56	0.26	0.25	0.46	0.56	0.61	0.53	0.63	0.66	0.37	0.57	0.47	0.87	7.84
10	0.36	0.14	0.11	0.14	0.60	0.32	0.24	0.46	0.46	0.69	0.77	0.79	0.65	0.27	0.44	0.34	0.67	7.45
11	0.31	0.07	0.12	0.15	0.52	0.30	0.26	0.40	0.41	0.68	1.01	0.87	0.60	0.27	0.36	0.38	0.45	7.17
12	0.25	0.04	0.12	0.26	0.35	0.22	0.33	0.40	0.44	0.77	1.01	0.80	0.60	0.32	0.24	0.41	0.36	6.93
13	0.14	0.03	0.12	0.31	0.37	0.22	0.35	0.36	0.50	0.82	0.76	0.68	0.54	0.40	0.16	0.27	0.22	6.25
14	0.08	0.01	0.11	0.23	0.34	0.30	0.26	0.30	0.43	0.74	0.61	0.64	0.38	0.39	0.12	0.16	0.08	5.19
15	0.03	+	0.11	0.14	0.22	0.22	0.14	0.24	0.37	0.63	0.68	0.61	0.24	0.30	0.13	0.11	0.03	4.21
16	0.02	+	0.08	0.07	0.11	0.10	0.13	0.14	0.38	0.62	0.68	0.52	0.18	0.22	0.12	0.09	0.01	3.47
17	0.01	+	0.04	0.01	0.03	0.05	0.13	0.11	0.40	0.63	0.57	0.39	0.15	0.16	0.12	0.07	+	2.88
18	0.01	+	0.03		0.01	0.02	0.12	0.16	0.42	0.61	0.43	0.25	0.11	0.12	0.09	0.02	+	2.41
19	0.01	0.01	0.01		+	0.01	0.05	0.18	0.30	0.55	0.35	0.10	0.06	0.07	0.07	+		1.77
20	0.02	0.01	+			+	0.02	0.11	0.19	0.46	0.24	0.06	0.03	0.03	0.05	0.01		1.23
21	0.03	+					+	0.07	0.15	0.29	0.16	0.04	0.02	0.02	0.05	0.01		0.84
22	0.02						0.01	0.06	0.13	0.18	0.07	0.05	0.02	0.01	0.05	+		0.61
23	+						+	0.04	0.12	0.13	0.06	0.03	0.01	+	0.04	+		0.44
24	+						+	0.02	0.05	0.14	0.09	0.01	+	+	0.05	+		0.37
25							+	0.02	0.04	0.06	0.09	0.01	+	+	0.05	+		0.29
26							+	0.01	0.03	0.03	0.04	+	+	0.01	0.04			0.16
27								0.01	0.04	0.03	+	+	+	+	0.02			0.11
28								0.01	0.04	0.01	0.01	+	+	+	0.01			0.08
29									0.03	0.01	+	+	+	+				0.04
30									+	0.01	+	0.01		+				0.02
30+																		
Total [%]	**4.42**	**2.28**	**2.34**	**3.06**	**4.91**	**3.44**	**3.85**	**5.35**	**7.63**	**11.51**	**11.24**	**9.08**	**6.61**	**4.99**	**6.54**	**4.38**	**8.34**	**100.0**
Mean Speed	**7.95**	**6.25**	**7.98**	**8.90**	**9.45**	**9.32**	**9.84**	**10.98**	**12.40**	**12.74**	**11.84**	**11.12**	**10.00**	**10.25**	**9.04**	**8.90**	**6.82**	**10.18**

Note: '+' indicates a non-zero frequency <0.005%. Blank cell indicates zero frequency.

Table D-2 Long-term wind regime for Race Bank MM at 100 m

Monthly mean wind speeds			
Month	Wind speed [m/s]	Valid wind speed data [years]	Valid direction data [years]
January	13.4	2.0	2.0
February	10.1	2.0	2.0
March	11.4	2.0	2.0
April	8.7	2.0	2.0
May	8.6	2.0	2.0
June	7.3	3.0	3.0
July	8.0	3.0	3.0
August	8.4	2.9	2.9
September	8.6	3.0	3.0
October	9.2	3.0	3.0
November	11.4	3.0	3.0
December	10.8	2.5	2.4
Annual	9.7		



Wind Speed [m/s]	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	No Direction	Total [%]
0	0.01	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.02	+	0.23
1	0.07	0.08	0.07	0.06	0.07	0.05	0.06	0.08	0.07	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.03	1.06
2	0.19	0.18	0.18	0.17	0.15	0.17	0.18	0.20	0.20	0.22	0.16	0.17	0.15	0.15	0.16	0.18	0.04	2.86
3	0.29	0.26	0.23	0.24	0.23	0.18	0.26	0.25	0.30	0.33	0.30	0.24	0.25	0.25	0.25	0.22	0.03	4.12
4	0.36	0.34	0.33	0.29	0.30	0.27	0.29	0.37	0.40	0.44	0.38	0.33	0.36	0.32	0.31	0.32	0.03	5.42
5	0.37	0.43	0.29	0.29	0.31	0.37	0.37	0.40	0.45	0.58	0.48	0.47	0.44	0.43	0.37	0.33	0.06	6.44
6	0.41	0.49	0.30	0.27	0.29	0.48	0.40	0.41	0.49	0.68	0.62	0.61	0.50	0.43	0.44	0.38	0.04	7.26
7	0.37	0.51	0.36	0.22	0.35	0.41	0.40	0.36	0.37	0.70	0.86	0.71	0.62	0.52	0.43	0.41	0.03	7.64
8	0.38	0.43	0.30	0.19	0.41	0.38	0.33	0.28	0.32	0.71	0.94	0.80	0.73	0.65	0.45	0.46	0.02	7.77
9	0.36	0.43	0.23	0.18	0.39	0.41	0.32	0.26	0.34	0.77	0.96	0.86	0.89	0.69	0.50	0.46	0.02	8.08
10	0.31	0.44	0.24	0.18	0.32	0.46	0.32	0.24	0.37	0.85	1.04	0.92	0.92	0.62	0.50	0.46	0.01	8.19
11	0.28	0.29	0.25	0.28	0.24	0.38	0.32	0.25	0.38	0.93	1.05	0.99	0.74	0.52	0.45	0.43	0.01	7.77
12	0.25	0.18	0.25	0.31	0.15	0.30	0.27	0.27	0.37	0.94	0.99	0.94	0.59	0.45	0.34	0.34	0.01	6.97
13	0.20	0.13	0.19	0.23	0.11	0.25	0.18	0.22	0.39	0.91	0.92	0.77	0.46	0.32	0.22	0.26	0.01	5.77
14	0.17	0.10	0.15	0.14	0.10	0.18	0.11	0.19	0.38	0.88	0.93	0.62	0.38	0.17	0.17	0.23	0.01	4.90
15	0.15	0.08	0.15	0.10	0.06	0.09	0.08	0.18	0.31	0.86	0.88	0.52	0.32	0.12	0.13	0.19	+	4.22
16	0.14	0.05	0.10	0.08	0.03	0.05	0.06	0.15	0.23	0.78	0.75	0.42	0.26	0.10	0.10	0.14		3.43
17	0.11	0.03	0.06	0.03	0.01	0.04	0.03	0.11	0.18	0.65	0.56	0.29	0.20	0.06	0.06	0.09		2.53
18	0.08	0.02	0.03	0.01		0.02	0.02	0.08	0.13	0.59	0.42	0.19	0.14	0.03	0.05	0.07		1.88
19	0.06	0.01	0.01	+		+	0.02	0.04	0.10	0.45	0.29	0.11	0.08	0.02	0.04	0.05		1.28
20	0.03	+	+			+	0.02	0.03	0.08	0.28	0.18	0.07	0.05	0.03	0.04	0.03		0.84
21	0.02	+				+	0.01	0.03	0.06	0.20	0.10	0.05	0.04	0.02	0.04	0.02		0.58
22	0.01	+					+	0.02	0.03	0.12	0.08	0.04	0.04	0.01	0.02	0.01		0.38
23	+							0.01	0.01	0.05	0.04	0.03	0.04	0.01	+	+		0.20
24	+							+	+	0.02	0.03	0.02	0.03	0.01	+	+		0.11
25								+	+	0.02	0.01	0.01	0.01	+				0.06
26									+	0.01	0.01	+	+					0.03
27									+	+	+	+	+					0.01
28										+		+						+
29												+						+
30																		
30+																		
Total [%]	**4.61**	**4.50**	**3.74**	**3.29**	**3.53**	**4.49**	**4.09**	**4.46**	**5.99**	**13.02**	**13.03**	**10.25**	**8.34**	**6.03**	**5.14**	**5.14**	**0.35**	**100.0**
Mean Speed	**8.69**	**7.69**	**8.30**	**8.22**	**7.55**	**8.38**	**8.10**	**8.83**	**9.79**	**11.70**	**11.28**	**10.50**	**9.95**	**8.86**	**8.84**	**9.14**	**5.55**	**9.66**

Note: '+' indicates a non-zero frequency <0.005%. Blank cell indicates zero frequency.

C-3 Long-term frequency distribution comparisons

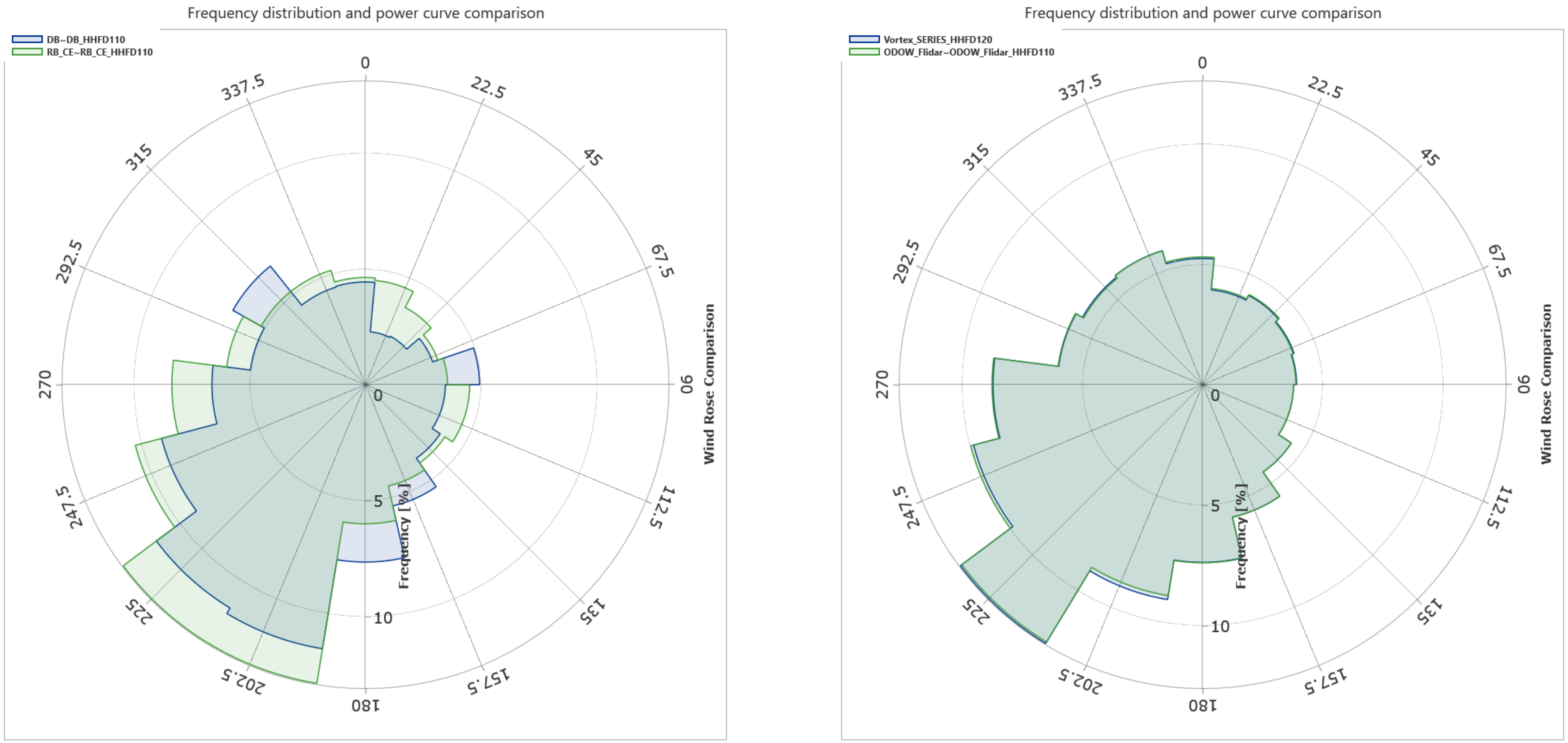


Figure D-2 Comparison of Race Bank MM and Dogger Bank West MM (left) and Race Bank MM and Outer Dowsing FL long-term frequency distributions (right)

C-4 Plot of turbine predictions of reference wind map

Figure D-3 Prediction of turbine wind speeds from each wind climate file using NEWA

C-5 Race Bank MM 90.2 mMSL and 89.3 mMSL Ambient Turbulence Intensity Comparisons

Wind Speed [m/s]	All DirectionTI from 90.2 m [%]	All DirectionTI from 89.3 m [%]
1	31.7	30.1
2	17.4	11.6
3	12	8.6
4	9.7	7.3
5	8.4	6.5
6	7.2	5.8
7	6.7	5.6
8	6.4	5.4
9	6.2	5.4
10	5.9	5.2
11	5.8	5.1
12	5.6	5.1
13	5.6	5.3
14	5.6	5.3
15	5.8	5.5
16	5.9	5.7
17	5.9	5.7
18	5.8	5.7
19	5.8	5.8
20	6	5.9
21	6.3	6.3
22	6.5	6.6
23	6.7	6.4
24+	6.8	7.2

APPENDIX D: ANALYSIS METHODOLOGY

D-1. Wind data analysis process overview

D-2. Hub-height wind speed and direction distributions

D-3. Wind flow modelling

D-4. Gross energy output

D-1 Wind data analysis process overview

The analysis of the wind data involved several steps, which are summarised below:

1. The processed and long-term corrected wind speed data from the wind climate location are processed and evaluated for an estimation of long-term wind speeds extrapolated to hub height using power law wind shear exponent.
2. The on-site mast measurements are correlated with the sources of long-term reference wind data, and the results evaluated, to develop an estimate of reference period wind speeds at measurement height.
3. Long-term hub-height wind speed and direction frequency distribution estimates at each wind climate location are derived from the measured and synthesized data.
4. The wind regime at the turbine locations is assessed using wind flow models and WT experience and judgment.

D-2 Data correlation and prediction

The period of data available at the measurement locations can be extended through establishing relationships between two data sets, using correlations to synthesize the missing data at the measurement location. In this procedure, concurrent wind data from a "target" sensor and a "reference" sensor are compared. The concurrent measured wind data are then used to establish the correlation between the winds at the two locations. This correlation is then used to synthesize data at the "target" location from the "reference" location.

"Monthly synthesis method" and "Mean of monthly means" methods are used in this assessment, to extend the period of record available at a measurement location.

D-2.1 Monthly synthesis method

In the correlation of monthly wind speeds, the concurrent monthly wind speeds are compared to establish a single correlation slope and offset. The slope and offset values are applied to the wind data at the "reference" location, thereby obtaining synthesized monthly wind data for the period of missing data at the "target" location.

The measured and synthesised monthly wind speed time series are combined, with priority given to the measured data. The long-term wind speed is then derived from this combined measured and synthesised monthly time series.

D-2.2 Mean of monthly means

In order to avoid the introduction of seasonal bias into estimates of the annual wind speed as well as wind speed and direction distributions from seasonally uneven data coverage, the following procedure is followed:

- The wind speed or distribution for each month is determined from the average of all valid data recorded in that month over the period. This is taken as the monthly mean, thereby assuming that the valid data are representative of any missing data.
- The mean of the monthly means, weighted by the number of days in a month, is taken to determine the annual mean ("mean of means").

D-3 Hub-height wind speed and direction distributions

D-3.1 Shear power law

The boundary layer power law shear exponents at the measurement locations are derived from the available measurement heights. The power law relates the ratio of measured wind speeds, $\boldsymbol{U_1/U_2}$, to the ratio of the measurement heights, $\boldsymbol{z_1/z_2}$, using the wind shear exponent, $\boldsymbol{\alpha}$, as follows:

$$\frac{\overline{U}(z_1)}{\overline{U}(z_2)} = \left(\frac{z_1}{z_2}\right)^{\alpha}$$

where

α is power law wind shear exponent
$\overline{U}$ is the wind speed
z is the height above mean sea level

The boundary-layer power law shear exponent was derived for each measurement location using the ratios of measured concurrent wind speed data recorded at multiple measurement heights.

D-3.2 Directional shear method

The relationship between two or more heights at a measurement location is established for each of twelve 30° direction sectors, using the technique described in Section D-4.1. These relationships are used to derive the boundary-layer power law shear exponent in each of the twelve direction sectors, which are then used to extrapolate data recorded at the primary measurement height to the target hub height, on a directional basis.

The annual average wind speed frequency and direction distributions at measurement height are determined from the site period wind speed data using the mean of monthly means approach described in Section D-4.4. The resulting distributions in each direction sector are then scaled to the predicted long-term hub height wind speed(s).

D-3.3 Time series method

The boundary-layer power law shear exponent is derived between two measurement heights for each 10 minutes, or hourly, time step. A time series of wind speed at the target hub height is calculated by extrapolating the upper measurement height using the instantaneous boundary-layer power law shear exponent. The Mean of Monthly Means procedure is used to avoid the introduction of bias into the annual wind regime prediction from seasonally uneven data coverage at each mast as discussed in Section D-4.4.

D-3.4 Annual shear method

The relationship between two, or more, heights at a measurement location is established using the concurrent mean of monthly means technique described in Section D-4.4. These relationships are used to derive the boundary-layer power law shear exponent, which is then used to extrapolate data recorded at the upper measurement height to the target hub height.

D-4 Wind flow modelling (offshore)

To calculate the variation of mean wind speed over the site, several techniques are considered:

- For offshore projects, any site-specific downscaled mesoscale map obtained for the site will be considered.
- In addition to the above, any publicly available wind maps (global, regional, national) covering the vicinity of the project is considered.

Unless coastal effects are anticipated, speed-up factors between the proposed turbine locations and wind climate locations are derived on an all-directional basis from the different techniques outlined above and compared. Depending on the results of the comparison, and the quality of the validation if multiple measurement locations are available, the most robust technique for predicting the wind speed variation across the site will be identified. This may be an ensemble approach consisting of results from multiple models.

To determine the long-term mean wind speed at any location, the speed-up factor for each location is applied to the long-term wind speed previously derived for the measurement location.

The following sub-sections describe each of the modelling approaches in further detail.

D-4.1 Global Wind Atlas

The Global Wind Atlas is a combined mesoscale and microscale wind flow model which has been run to produce results for the entire global land mass and coastal areas with a focus on the needs of wind resource and energy assessment. Model outputs are available at elevations of 10, 50, 100, 150 and 200 m above ground/sea at a downscaled horizontal grid spacing of 250 m. Further details of the model can be found at [redacted]

D-4.2 New European Wind Atlas

The New European Wind Atlas (NEWA) uses the Weather Research and Forecasting (WRF) model, forced with ERA5 reanalysis data, to generate a regional map of wind speed variation across Europe and Turkey, including offshore.

Data are available at seven heights between 50 m and 500 m. Both mesoscale and microscale modelling has been performed. The mesoscale data is based on a simulation period of 30 years and has a horizontal grid resolution of 3 km. Further details of the model can be found at [redacted]

D-5 Gross energy output / assessment of wakes

The gross energy production is the energy production of the wind farm obtained by calculating the predicted free stream hub height wind speed distribution at each turbine location and the manufacturer-supplied turbine power curve.

In defining the gross energy output, it is assumed that there are no wake interactions between the turbines and no energy loss factors are applied. The Energy Yield and the subsequent impact of the wakes produced by the individual wind farms have been calculated using WindFarmer Analyst computational model. It includes adjustments to the power curve to account for differences between the predicted long-term annual turbine location air density and the air density to which the power curve is referenced.

Of concern in any Energy Yield study is the effect of wake and turbine interaction losses (including blockage effect) from inside the farm and from adjacent farm sites. WT's typical best practice is to use the WindFarmer: Analyst Eddy Viscosity with large wind farm correction model to estimate offshore wake and turbine interaction effects, as validated by DNV in 2019, which results in lower errors across a number of operational offshore wind farms compared to other wake models.

D-5.1 Turbine interaction effect calculations

Wind turbines extract energy from the wind and downstream from each turbine there is a momentum deficit with respect to free stream conditions, which is equal to the thrust force on the machine, referred to as the wake, where the wind speed is reduced. As the flow proceeds downstream there is a spreading of the wake and the wake recovers towards free stream conditions. Turbulent momentum transfer is important in this process.

The wake effect loss is the aggregated influence on the energy production of the wind farm which results from the changes in wind speed caused by the impact of the turbines on each other. WT uses the WindFarmer: Analyst software – Eddy Viscosity model and implements the Large Wind Farm correction for offshore projects. This software has been developed by DNV and validated using measurements on both full-scale machines and on wind-tunnel models.

The model is employed in a scheme which, taking each wind speed and direction in turn calculates the power production of the wind farm. The important parameters used in this process are:

- array layout
- upstream mean wind speed
- ambient turbulence
- wind turbine thrust characteristic
- wind turbine power characteristic
- rotor speed
- speed-up factors from site wind flow calculations

Any wind speed variations across the site due to coastal or mesoscale effects are accounted for in the model using the speed-up factors calculated by an appropriate wind flow model as described above. The array model is used to calculate the wind speed in the turbine wakes, assuming the terrain is flat, and the wind speed is adjusted by the speed-up factor when the wake reaches a downstream turbine.

D-5.1a Internal wake and blockage effects

This is the effect that the wind turbines within the wind farm being considered have on each other. In addition, the wind farm itself presents an obstacle to the incoming wind flow, which is not accounted for in many standard industry wake models and causes a slow-down effect referred to as wind farm blockage. This effect has also been calculated using the Blockage Effect Estimator Tool (BEET) within WindFarmer:Analyst which is based on more than 50 CFD simulations.

D-5.1b Wake effect external

This is the effect that the wind turbines from neighbouring wind farms (if any) have on the wind farm being considered. These are calculated in the same way as internal wake effects.

D-5.1c Future wake effect

Where future wind farms are to be constructed in the vicinity of the project under consideration, the wake effect of these may be estimated and taken into account if sufficient information is available.