Netherlands Enterprise Agency

Wind Resource Assessment

Ten noorden van de Waddeneilanden Wind Farm Zone

Update June 2022 based on 24 months of metocean data

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Netherlands Enterprise Agency

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Behzad Aziz	Project Manager RVO Offshore Wind Energy
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TEN NOORDEN VAN DE WADDENEILANDEN (TNW) WIND FARM ZONE

Certification Report Site Conditions Wind

Netherlands Enterprise Agency

Report No.: CR-SC-DNV-SE-0190-06281-2_Wind
Date: 2022-06-13

DNV

Project name:	Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone	DNV Energy Systems Renewables Certification
Report title:	Certification Report Site Conditions Wind	DNV Denmark A/S Tuborg Parkvej 8
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Date of issue:	2022-06-13	
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Applicable contract(s) governing the provision of this Report:

Objective: To confirm that the wind speed at Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone has been derived in line with the requirements as stated in section 2.3.2 of the DNV-SE-0190:2021 for site conditions. The wind speeds are to be used for design for Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone.

Prepared by:	Verified by:	Approved by:
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0	2021-07-22	First issue	HEHU	IPL	PR
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2	2022-06-13	Update for inclusion of 24 month timeseries and inclusion of the final MetOcean Desktop Study	HEHU	IPL	PR

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DNV

1 EXECUTIVE SUMMARY

The Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone is located in the Dutch Sector of the North Sea, approximately 51 km from the coastline. As part of the tender preparations, the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO) has requested a wind resource assessment of the Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone.

DNV was assigned to validate this wind study and its use within a Design Basis for Offshore Wind Turbine Structures in accordance with DNVGL-ST-0437 and DNVGL-ST-0126.

2 CERTIFICATION SCHEME

Document No.	Title
DNV-SE-0190:2021-09	Project certification of wind power plants

3 SCOPE OF EVALUATION

The scope and interface of the evaluation covered by the report is the Wind Resource Assessment part of the Site Conditions Assessment phase of the Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone project.

The Appendix to this report comprises the detailed DNV evaluation which include references to standards, list of documentation and the conclusion of the DNV evaluation.

4 CONDITIONS

No conditions have been identified.

5 OUTSTANDING ISSUES

No outstanding issues have been identified.

6 CONCLUSION

DNV finds that the wind properties as defined in the documents listed in section A4 are derived in line with the requirements following section 2.3.2 of the DNV-SE-0190:2021 for establishing site assessment.

The properties estimated are:

- Annual average wind speed (at 140 m MSL) at Node 4: 10.30 m/s
- Wind roses
- Wind distributions:
    - Weibull A-parameter (at 140 m MSL) at Node 4: 11.70 m/s
    - Weibull k-parameter (at 140 m MSL) at Node 4: 2.283

APPENDIX A
Wind Resource Assessment

Evaluation of Wind Resource Assessment for Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone

A1 Description of verified component/system

Within the Wind Farm Zone the wind conditions have been estimated. The results and the site conditions are documented by the customer and build the basis for the verification described in the current report.

A2 Interface to other systems/components:

No interfaces to other systems/components are present.

A3 Basis for the evaluation

Applied codes and standards:

Document No.	Revision	Title
DNVGL-ST-0437	2016-11	Loads and site conditions for wind turbines

The evaluation has been based on the following loads, design basis as well as other specific criteria:

Document No.	Revision	Title
N/A		

A4 Documentation from customer

List of reports:

Document No.	Revision	Title
/1/ TNW_20220310_ GHPC_WRA_ Report_V6_F	V06_F 2022-03-10	Ten Noorden van de Waddeneilanden Wind Farm Zone Wind Resource Assessment

List of drawings:

Document No.	Revision	Title
N/A		

List of specifications/manuals/instructions:

Document No.	Revision	Title
N/A		

List of documents taken for information only:

Document No.	Revision	Title
/A/	V06_F	TNW_20211202_GHPC_WRA_NodesTimeSeries_V06-F
/B/ 202007170 / WOZ2210266	Final 1.0	Ten noorden van de Waddeneilanden (TNW) Wind Farm Zone MetOcean Desk Study

A5 Evaluation work

/1/ presents the wind resource assessment for the planned Ten Noorden van de Waddeneilanden (TNW) Offshore Wind Farm Zone. The assessment has been based on combined use of offshore wind measurements and mesoscale model data.

The main outcome of /1/: The long-term mean wind speed at a hub height of 140 m MSL at Node 4 has been determined to be 10.30 m/s with a total associated uncertainty of 4.3 %.

A wake effects and blockage analysis has been undertaken which is not part of the certification of this report. However, the report /1/ concludes that the stated losses are uncertain and that the inclusion of wake loss is left open to the designers. DNV agree to this conclusion.

The wind speed was measured in an on-site floating vertical scanning LiDAR campaign at two independent lidars TNWA and TNWB at measurement heights of 30, 40, 60, 80, 100, 120, 140, 160, 180, 200 and 250 m MSL. Data from the period 19/06/2019-24/06/2020 was used in the assessment. The on-site measurements are supported by the following other Dutch North Sea offshore wind measurements taken at

- Fino1 offshore met mast
- Offshore Wind Farm Egmond aan Zee (OWEZ) met mast
- Ijmuiden offshore met mast (MMIJ)
- Floating LiDAR HKNA within HKN Wind Farm Zone
- Floating LiDAR HKNB within HKN Wind Farm Zone

In /1/ long-term data assessment from different reanalysis datasets have been considered.

- EMD-WRF Europe+
- DOWA mesoscale data
- NEWA mesoscale data
- KNW mesoscale data
- ERA5 mesoscale data
- MERRA-2 mesoscale data

It was found that ERA5 was the best data source and therefore chosen to be used as long-term reference data source for the Measure Correlate Predict (MCP) routine.

For the spatial analysis assessment data from five mesoscale models have been considered.

- GHPC tailor-made WRF model mesoscale data
- DOWA mesoscale data
- NEWA mesoscale data
- KNW mesoscale data
- EMD-WRF-E+ mesoscale data

It was found that GHPC tailor-made WRF model was the best data source and therefore chosen to be used for the spatial analysis at the site.

DNV has reviewed

- Measurements
- Long-term correction
- Spatial analysis
- The results of the wind climate calculation including
  - Air temperature
  - Air pressure
  - Relative humidity
  - Air density Correction
  - Time Series presented in /A/

and has found the documentation to be correct.

Furthermore, DNV has compared the wind speeds presented in /1/ with in-house knowledge about the 'Design' and 'Measured Wind' on existing Belgian and Dutch offshore wind farms and has found that 10.30 m/s long-term mean wind speed including with a total associated uncertainty of 4.3 % can be agreed on.

The wind speeds are to be used for design of future the Ten Noorden van de Waddeneilanden offshore wind farm.

Alignment checks between the 'wind distribution and wind roses' used in the metocean desk study presented in /B/ with the ones presented in /1/ have been performed.

A 6 Conditions to be considered in other certification phases

No conditions have been identified.

A7 Outstanding issues

No outstanding issues have been identified.

A8 Conclusion

DNV finds that the wind properties as defined in the documents listed in section A4 are derived in line with the requirements following section 2.3.2 of the DNV-SE-0190:2021 for establishing site assessment.

The properties estimated are:

- Annual average wind speed (at 140 m MSL) at Node 4: 10.30 m/s
- Wind roses
- Wind distributions:
  - Weibull A-parameter (at 140 m MSL) at Node 4: 11.70 m/s
  - Weibull k-parameter (at 140 m MSL) at Node 4: 2.283.

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Ten noorden van de Waddeneilanden Wind Farm Zone

Wind Resource Assessment

Prepared for:

Rijksdienst voor Ondernemend Nederland (RVO)

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Wind Farm Zone Ten noorden van de Waddeneilanden

Wind Resource Assessment

Prepared for:

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Wind Farm Zone Ten noorden van de Waddeneilanden

Wind Resource Assessment

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1.0.a	23.03.2021	Ditto	Updates to first draft, following Client comments
1.0.b	30.03.2021	Ditto	Internal review
2.0	31.03.2021	Ditto	Second draft for Client, with refined outputs and layout results
3.0	21.04.2021	Ditto	Third draft for Client, addressing comments
3.0_F	29.04.2021	Ditto	Accepted final report to be submitted for certification.
4.0_F	06.07.2021	Ditto	Minor clarifications requested by the certification body are added to the report.
5.0_D	08.12.2021	Ditto	Report updated with additional 12 months of measured wind data.
6.0_F	10.03.2022	Ditto	Updates to draft report, following Client comments; Comparison with Metocean study updated and Metocean alignment document added in Appendix K.

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Acronyms

CLT-MM	Final calibrated and long-term adjusted mesoscale model
CLT-ts	Calibrated and long-term synthesised time series
DOWA	Dutch Offshore Wind Atlas
ECMWF	European Center for Medium-Range Weather Forecasts
EPSG	European Petroleum Survey Group Geodesy
ERA5	ECMWF Reanalysis 5th Generation
ETRS	European Terrestrial Reference System
FINO	Forschungsplattformen in Nord- und Ostsee
FuE Kiel	Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH
GEOS-5	Goddard Earth Observing System Model Version 5
GHPC	Consortium of Guidehouse, ProPlanEn and Arcvera
ID	Identifier
IEC	International Electrotechnical Commission
IFS	Integrated Forecast System
KNW	Koninklijk Nederlands Meteorologisch (Royal Netherlands Meteorological Institute)
LAT	Lowest Astronomical Tide
LOS	Line of Sight
LLS	Linear Least Squares
LT	Long-Term
MBE	Mean bias error
MCP	Measure Correlate Predict
MERRA-2	Modern Era Retrospective Reanalysis (version 2)
Met	Meteorological
MM	Meteorological Mast / Met Mast
MMIJ	Met Mast IJmuiden
MYNN	Mellor-Yamada-Nakanishi-Niino
NASA	National Aeronautics and Space Administration
NCEP	National Center for Environmental Prediction
MM OWEZ	Met Mast at Offshore Wind Farm Egmond aan Zee
RSD	Remote Sensing Device
RVO	Rijksdienst voor Ondernemend Nederland

SRTM	Shuttle Radar Topography Mission
SSL	Sea Surface Levelling
ST	Short-Term
TEMF	Total energy mass flux
TLS	Total Least Squares
TNWWFS	Ten noordern van de Waddeneilanden Wind Farm Site
TNWWFZ	Ten noordern van de Waddeneilanden Wind Farm Zone
TP	Transformer Platform
TS	Time Series
WRF	Weather Research & Forecasting Model
YSU	Yonsie University

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Executive Summary

The Guidehouse Project Consortium (GHPC, the Consortium) has performed an assessment of the wind resource across Ten noorden van de Waddeneilanden Wind Farm Zone (TNWWFZ, Project site), located approximately 80 km from the northern coast of the Netherlands mainland. The Consortium is a collaboration between Guidehouse WTTS B.V, ProPlanEn GmbH, Arcvera and OWC (Aqualis) GmbH.

TNWWFZ has been identified by of Rijksdienst voor Ondernemend Nederland (RVO, "Client") as an area of potential wind energy development. The site is located in the Dutch Exclusive Economic Zone in the Dutch shelf in the North Sea.

The aim of the study was to assess the wind resource across the TNWWFZ to inform possible future investment in offshore wind development. The long-term ambient wind conditions for the development area were analysed on behalf RVO.

This study is based on a combination of onsite and off-site wind measured data. Measurements were gathered onsite by two floating vertical scanning lidars, labelled as TNWA and TNWB, which are located approximately 500 m apart. TNWA gathered data for approximately 18 months, after which it was relocated further east for a further six months. This second location was denoted as TNWA-2. TNWB gathered data for 24 months. These datasets were supported by measurements from the FINO 1 offshore met mast, Offshore Windpark Egmond aan Zee (OWEZ) offshore met mast (OWEZ MM), IJmuiden offshore met mast (MMIJ) and the vertical scanning lidar measurements taken at the Hollandse Kust Noord (HKN) offshore site by two floating lidar systems (HKNA and HKNB). These measurement locations can be observed in Figure 1-1.

The data from TNWA, TNWA-2 and TNWB were gathered, screened and post-processed by Fugro for both measurement locations. GHPC has analysed the screened and post-processed datasets and found the data to be of good quality for TNWA, TNWA-2 and TNWB. It is noted that the data gathered by the TNW lidars were marginally impacted by wakes from the neighbouring Gemini wind farms. Corrections were applied to remove these effects.

Following wake corrections at the onsite locations, the onsite datasets were aggregated to compile a wake-free single dataset, consisting of TNWA and TNWA-2 data as the primary datasets and TNWB as the backup dataset, filling in any gaps in TNWA and TNWA-2. The resulting dataset is representative of the short-term measurements within TNWWFZ and called TNW.

The TNW dataset and FINO 1 data were considered to be the most suitable for long-term correction to derive the final wind speed gradient across TNWWFZ. The TNW and FINO 1 datasets were corrected to the long-term by means of an MCP procedure. The data was corrected with the ERA5 modelled reference dataset using the period from 01 November 2005 to 31 October 2020 for FINO 1 and 01 July 2005 to 30 June 2021 for TNW. The long-term wind speed at TNW at a height of 140 m was found to be 10.30 m/s with a total associated uncertainty of 4.3%, Meanwhile the long-term wind speed at FINO 1 was found to be 9.94 m/s with a total associated uncertainty of 4.0%.

Following the long-term correction, an optimised mesoscale model was developed to assess the wind potential across the TNWWFZ. The first step was to select the most appropriate modelled dataset for the spatial analysis to evaluate the wind distribution across the site. The selected modelled dataset was then calibrated using the short-term measured dataset at the TNW. Following the calibration, the mesoscale model was corrected to the long-term by applying long-term climates the TNW and FINO 1 locations. A distance-inverse squared weighted wind resource grid was developed based on this. The wind resource grid defines the long-term wind gradient and wind distribution across the site.

Based on the calibrated mesoscale model, the short-term calibrated model output was post-processed to obtain synthetic long-term timeseries at five (5) selected nodes were observed. The long-term wind speed at the central node within the TNWWFZ was found to be 10.30 m/s at a height of 140 m, with prevailing direction in the south west (240°) and west directions (270°).

In addition to the long-term wind resource assessment optimised layouts were designed for an identified site within the TNWWFZ. RVO has identified one (1) possible wind farm site (WFS) within TNWWFZ, and designated as Ten noorden van de Waddeneilanden wind farm site I (TNWWFS I), with 70.6 km^2 out of a total area of 120 km^2.

Preliminary example layouts for the TNWWFS I were designed based on 13 MW and 15 MW generic turbine models. The wake impact of these designed wind farms was modelled, and the associated energy yield was calculated.

Layout 1 consist of 47 wind turbines with 15 MW rated power or 705 MW total capacity. The inter turbine spacing is 7 x 4.5 RD and wake losses (internal and external) for the layout are calculated as 10.3%.

Layout 2 consist of 54 wind turbines with 13 MW rated power or 702 MW total capacity. The inter turbine spacing is 7 x 4.5 RD and wake losses (internal and external) for the layout are calculated as 11.1%.

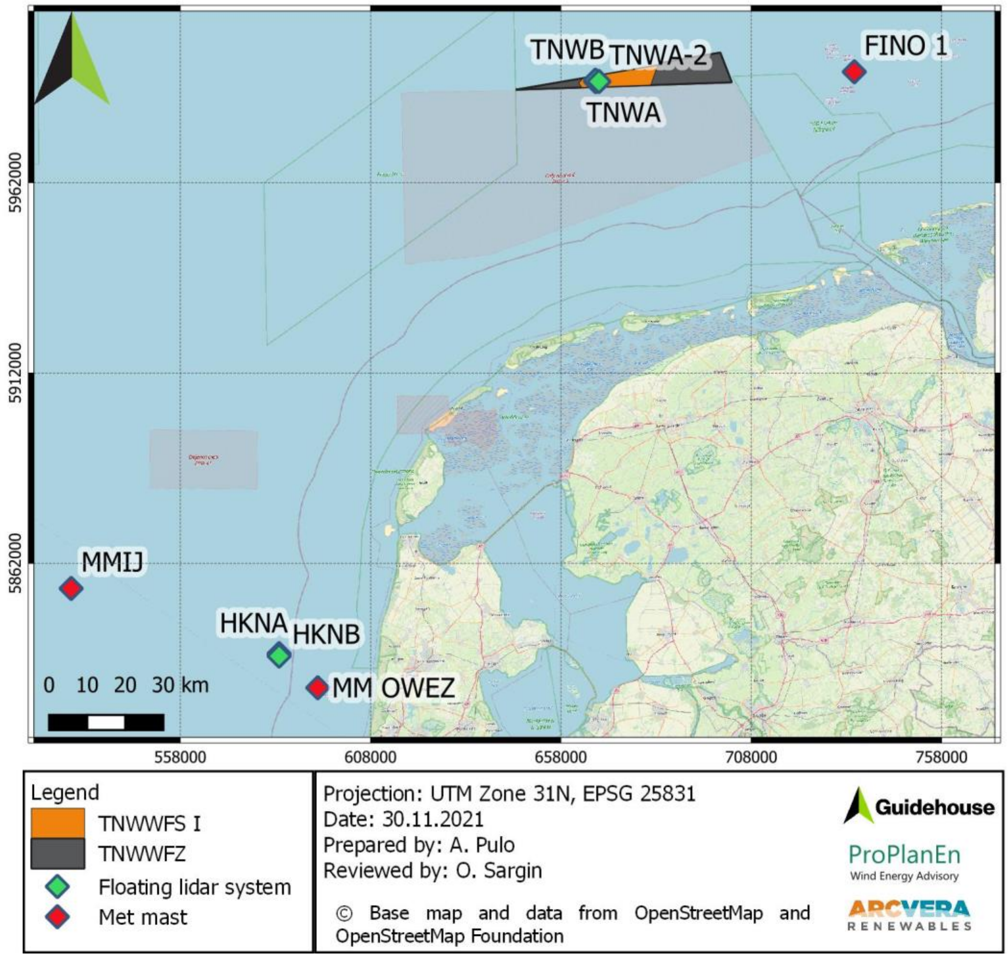

Figure 1-1. TNWWFZ: Locations of measurement locations in relation to the site

It is noted that in addition to the wind resource assessment presented in this report, a metocean desk study (MDS, or metocean study database) has also been undertaken by DHI covering the TNWWFZ. The MDS presents information on the feasibility level on both the meteorological (wind) and the oceanographic (wave/current) climate at the TNWWFZ in order to assist in the wind farm (structural) design process. A metocean report for TNW (and the MDS together cover the normal and extreme wind conditions to be used for design. This includes wind speed turbulence intensity, extreme wind speeds and wind shear, all of which are intended for wind farm design. Meanwhile the study presented in this report is intended to assist in wind farm modelling, energy yield assessment and business case calculations.

Samenvatting

Het Guidehouse Projectconsortium (GHPC, het Consortium) heeft een beoordeling uitgevoerd van de windbron in het windpark Ten noorden van de Waddeneilanden (TNWWFZ, projectlocatie), gelegen op ongeveer 80 km van de noordkust van het Nederlandse vasteland. Het Consortium is een samenwerking tussen Guidehouse WTTS B.V, ProPlanEn GmbH, Arcvera en OWC (Aqualis) GmbH.

TNWWFZ is door de Rijksdienst voor Ondernemend Nederland (RVO, "Klant") aangemerkt als een gebied voor potentiële ontwikkeling van windenergie. De locatie is gelegen in de Nederlandse Exclusieve Economische Zone in het Nederlandse plat in de Noordzee.

Het doel van de studie was om het windaanbod in de TNWWFZ te beoordelen met het oog op mogelijke toekomstige investeringen in offshore windontwikkeling. In opdracht van RVO zijn de omgevingswindcondities op de lange termijn voor het ontwikkelingsgebied geanalyseerd.

Deze studie is gebaseerd op een combinatie van onsite en off-site windmeetgegevens. Metingen werden ter plaatse verzameld door twee drijvende verticale scan-lidars, gelabeld als TNWA en TNWB, die ongeveer 500 m van elkaar verwijderd waren. Deze werden ondersteund door metingen van de FINO 1 offshore met mast, Offshore Windpark Egmond aan Zee (OWEZ) offshore met mast (OWEZ MM), IJmuiden offshore met mast (MMIJ) en de verticale scanning lidar metingen uitgevoerd op de Hollandse Kust Noord (HKN) offshore-site door twee drijvende lidarsystemen (HKNA en HKNB). Deze meetlocaties zijn te zien in figuur 1.

Voor beide meetlocaties zijn de gegevens van TNWA en TNWB verzameld, gescreend en bewerkt door Fugro. GHPC heeft de gescreende en bewerkte datasets geanalyseerd en vond de data van goede kwaliteit voor TNWA en TNWB. Opgemerkt wordt dat de gegevens die door de TNW-lidars zijn verzameld, marginaal werden beïnvloed door zogeffecten van de naburige Gemini-windparken. Om deze effecten te verwijderen zijn correcties aangebracht.

Na zogcorrecties op de onsite locaties, werden de onsite datasets geaggregeerd om een wake-free single dataset samen te stellen, bestaande uit TNWA-data als de primaire dataset en TNWB als de back-updataset, om eventuele hiaten in TNWA op te vullen. De resulterende dataset is representatief voor de korte termijn metingen binnen TNWWFZ en heet TNW.

De TNW-dataset en FINO 1-gegevens werden als het meest geschikt beschouwd voor lange-termijncorrectie om de uiteindelijke windsnelheidsgradiënt over TNWWFZ af te leiden. De datasets van TNW en FINO 1 zijn gecorrigeerd naar de lange termijn door middel van een MCP-procedure. De gegevens zijn gecorrigeerd met de ERA5 gemodelleerde referentiedataset met de periode van 1 juli 2005 tot 30 juni 2021. De lange termijn windsnelheid bij TNW op 140 m hoogte bleek 10,30 m / s te zijn met een totale bijbehorende onzekerheid van 4,3%. Tevens bleek de windsnelheid op lange termijn bij FINO 1 9,94 m / s te zijn met een totale bijbehorende onzekerheid van 4,0%.

Na de langetermijncorrectie is een gekalibreerd mesoschaalmodel ontwikkeld om het windpotentieel in de TNWWFZ te beoordelen. De eerste stap was het selecteren van de meest geschikte gemodelleerde dataset voor de ruimtelijke analyse om de windverdeling over de site te evalueren. De geselecteerde gemodelleerde dataset is vervolgens gekalibreerd met behulp van de korte termijn gemeten dataset bij de TNW. Na de kalibratie is het mesoschaalmodel gecorrigeerd naar de lange termijn door langetermijnklimaten toe te passen op de locaties TNW en FINO 1. Op basis hiervan is een inverse afstandskwadraat gewogen windhulpmiddelraster ontwikkeld. Het windhulpmiddelraster definieert de windgradiënt op lange termijn en de windverdeling over de site.

Op basis van het gekalibreerde mesoschaalmodel werd de kortetermijn-gekalibreerde modeloutput nabewerkt om synthetische lange-termijn tijdreeksen te verkrijgen op vijf (5)

geselecteerde knooppunten. De lange termijn windsnelheid op het centrale knooppunt binnen de TNWWFZ bleek 10,30 m / s te zijn op een hoogte van 140 m, met overheersende richting in het zuidwesten (240 °) en westelijke richting (270 °).

Naast de beoordeling van de windbronnen op lange termijn werden geoptimaliseerde lay-outs ontworpen voor een geïdentificeerde locatie binnen de TNWWFZ. RVO heeft één (1) mogelijke windparklocatie (WFS) geïdentificeerd binnen TNWWFZ, en aangewezen als Ten noorden van de Waddeneilanden windparksite I (TNWWFS I), met 70,6 km2 op een totale oppervlakte van 120 km^2.

Voorlopige voorbeeldlay-outs voor de TNWWFS I zijn ontworpen op basis van generieke turbinemodellen van 13 MW en 15 MW. De zogimpact van deze ontworpen windparken is gemodelleerd en de bijbehorende energieopbrengst is berekend.

Lay-out 1 bestaat uit 47 windturbines met 15 MW nominaal vermogen of 705 MW totaal vermogen. De onderlinge afstand tussen de turbines is 7 x 4,5 RD en zogverliezen (intern en extern) voor de lay-out worden berekend op 10,3%.

Lay-out 2 bestaat uit 54 windturbines met 13 MW nominaal vermogen of 702 MW totaal vermogen. De onderlinge afstand tussen de turbines is 7 x 4,5 RD en zogverliezen (intern en extern) voor de lay-out worden berekend op 11,1%.

Naast de windopbrengst analyse gepresenteerd in dit rapport, heeft DHI een metocean desk studie (MDS) uitgevoerd welke het gebied TNWWFZ beslaat. In deze MDS wordt informatie gepresenteerd over het meteorologische (wind) en oceanografische (stroming en golven) klimaat in het TNWWFZ gebied, met het doel om het windpark ontwerpproces te informeren. Een toekomstig metocean rapport voor TNW (genaamd Metocean campaign final report 24 months) en het MDS tezamen bevatten de normale en extreme windcondities die gebruikt kunnen worden voor het ontwerp. Dit ovat de windsnelheid turbulentie intensiteit, extreme windsnelheden, en windschering (in het Engels wind shear genoemd). De resultaten uit dit rapport daarentegen zijn bedoeld ten behoeve van windpark modellering, energieopbrengst analyse en business case berekeningen.

Methodology

The analysis was based on short-term data measured onsite and long-term data representative for the location. The already cleaned short-term data was quality checked and the influence of pre-existing wind farms considered.

Different independent sources of long-term data were considered and correlated to the short-term measurements. The data was correlated to the short-term measurement and scaled to obtain a site specific long-term ". The long-term data ERA5 was selected as the one that best represents the conditions in the site and leads to the lowest possible uncertainty. GHPC also analysed the meteorological conditions for the site based on the long-term data.

The detailed process is described in this report and the data made available in the corresponding data package.

Key Findings

The ambient long-term mean wind speed at a representative central location (node 5) within the TNWWFZ was found to have been 10.30 m/s at a height of 140 m with a combined final uncertainty of ±0.35 m/s. It is noted that this associated uncertainty is the combined uncertainty of all the separate uncertainty categories and measurement campaigns considered in this study. It is assumed that the reference period is representative for the long-term and thus for the projected development and operational period. The variation over the site is moderate with a maximum variation of 0.05 m/s across the whole site.

Table 1. Key LT wind characteristics at 140 m for node 5 in TNWWFZ

Parameter	Value	Description
Mean wind speed	10.30 m/s	Long-term average
Wind speed uncertainty	3.4%	For 25 years period
Inter-annual variability	5.5%	For 1 year
Weibull A	11.62 m/s	Fitted Weibull distribution
Weibull k	2.281	Fitted Weibull distribution
Mean temperature	10.3°C	Ambient (modelled)
Mean air density	1.219 kg/m³	Ambient (modelled)

Other Considerations

There are several wind farms existing or planned in the vicinity of the target area. This report is not supposed to represent an energy assessment of wind farms future or past. The analysis considers and corrects for the impact of existing wind farms on the local measurements. The aim is to present the best possible representation of current ambient wind conditions as if no wind farms were existing within the target area. Developers of the area are advised to consider the effects of all existing or future wind farms impacting and relevant for and specific to their planned development.

1.0 Introduction

The Dutch government has developed a Routekaart Wind op Zee, which sets out the development of offshore wind energy up to a total capacity of approximately 11 GW by 2030, enough to supply 8.5% of all the energy in the Netherlands.

Ten noorden van de Waddeneilanden Wind Farm Zone (TNWWFZ, Project site) has been identified by RVO as an area of potential wind energy development. The site is located in the Dutch Exclusive Economic Zone in the Dutch shelf in the North Sea. It lies approximately 80 km from the the north mainland coast of the Netherlands, located in water depths ranging from 29 m to 45 m. Exact information on the location and shape of TNWWFZ can be found through the online map viewer service of the Directorate General for Public Works and Water management[1].

The operational offshore wind farms Gemini 1 and Gemini 2 lie to the east of the TNWWFZ, see Figure 1-1.

1.1 Goal of the study

As part of the strategy in offshore wind energy, RVO has requested an independent investigation into the wind and meteorological conditions at TNWWFZ. The investigation is based on a number of short-term and long-term measurements.

The scope of this report is to assess the wind resource across TNWWFZ in which will form part of the information package that informs potential offshore wind developers with an interest in TNWWFZ. In addition to this, two (2) example layout for an identified wind farm site within TNWWFZ were designed based on 13 MW and 15 MW turbine type models. The wake impact of these designed wind farms were modelled and the associated energy yield was calculated.

The reference vertical datum lowest astronomical tide (LAT) being the reference for vertical heights unless noted otherwise. It is noted that LAT is defined as the lower tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions. LAT is approximately 1 m below the mean sea level (MSL) [1].

The reference coordinate system is ETRS 89 UTM 31N with the ESPG Code 25832.

English Style Guide of the European Commission [2] is applicable throughout the document. Point is used as a decimal separator in this study. It is noted that no thousand grouping was used in this study deviating from the same guideline.

This study has been developed by the Guidehouse Project Consortium (GHPC, the Consortium). The Consortium is a collaboration between Guidehouse WTTS B.V., ProPlanEn GmbH, Arcvera and OWC (Aqualis) GmbH. Appendix A gives a brief introduction to the Consortium participants.

1.2 Methodology Overview

Several data sources were analysed for this assessment with onsite short-term measurements and near-site long-term measurements.

Datasets gathered in the Dutch North Sea by measurement devices at several locations were available for analysis and considered in this study. It is noted that one dataset (FINO 1) in the German North Sea was used in the analysis. The primary measurements consist of two

[1] https://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fgeoservices.rijkswaterstaat.nl%2Farcgis2%2Frest%2Fservices%2FGDR%2Fwindenergiegebieden%2FFeatureServer&source=sd

floating lidar systems, labelled as TNWA and TNWB, measuring at multiple heights on the site and a number of additional measurements located off-site. The last six months of data from TNWA were gathered further east and denoted as location TNWA-2. The onsite measured datasets were considered suitable for determining the wind potential across the Project site.

GHPC used FINO 1 data from the FINO database. The data was made available by the FINO initiative (research platforms in the North Sea and Baltic Sea), which was organized by the Federal Ministry for Economic Affairs and Energy (BMWi) on the basis of a resolution by the German Bundestag, the Jülich project management organization (PTJ).[2]

The short-term datasets TNWA, TNWA-2 and TNWB were analysed, corrected and aggregated to compile a single wake-free combined measurement dataset – TNW – which representative of TNWWFZ. The aggregated TNW and FINO 1 datasets were corrected to the long-term.

In order to assess the wind potential across the Project site a wind gradient model was developed following spatial analysis. The model was built based on ERA5 reference reanalysis data, downscaled to TNWWFZ to create a high spatial-resolution mesoscale model. Prior to this selection, various reference dataset sources were considered for the wind gradient model. The final selection was based on the accuracy, validation results, reliability, and robustness of the model. The final wind gradient model was calibrated with measured data at TNW and FINO 1 and long-term adjusted in accordance with the long-term corrected wind data derived in this study. The calibrated and long-term adjusted wind gradient model was used to inform the horizontal and vertical extrapolation of the wind potential across the area of interest.

Figure 1-1 below presents in a flowchart the wind resource assessment methodology employed in this study.

[2] Original text in German: „Die Daten wurden von der Initiative FINO (Forschungsplattformen in Nord- und Ostsee) zur Verfügung gestellt, die vom Bundesministerium für Wirtschaft und Energie (BMWi) auf Grundlage eines Beschlusses des Deutschen Bundestages, vom Projektträger Jülich (PTJ) organisiert und vom BSH koordiniert wurde.“

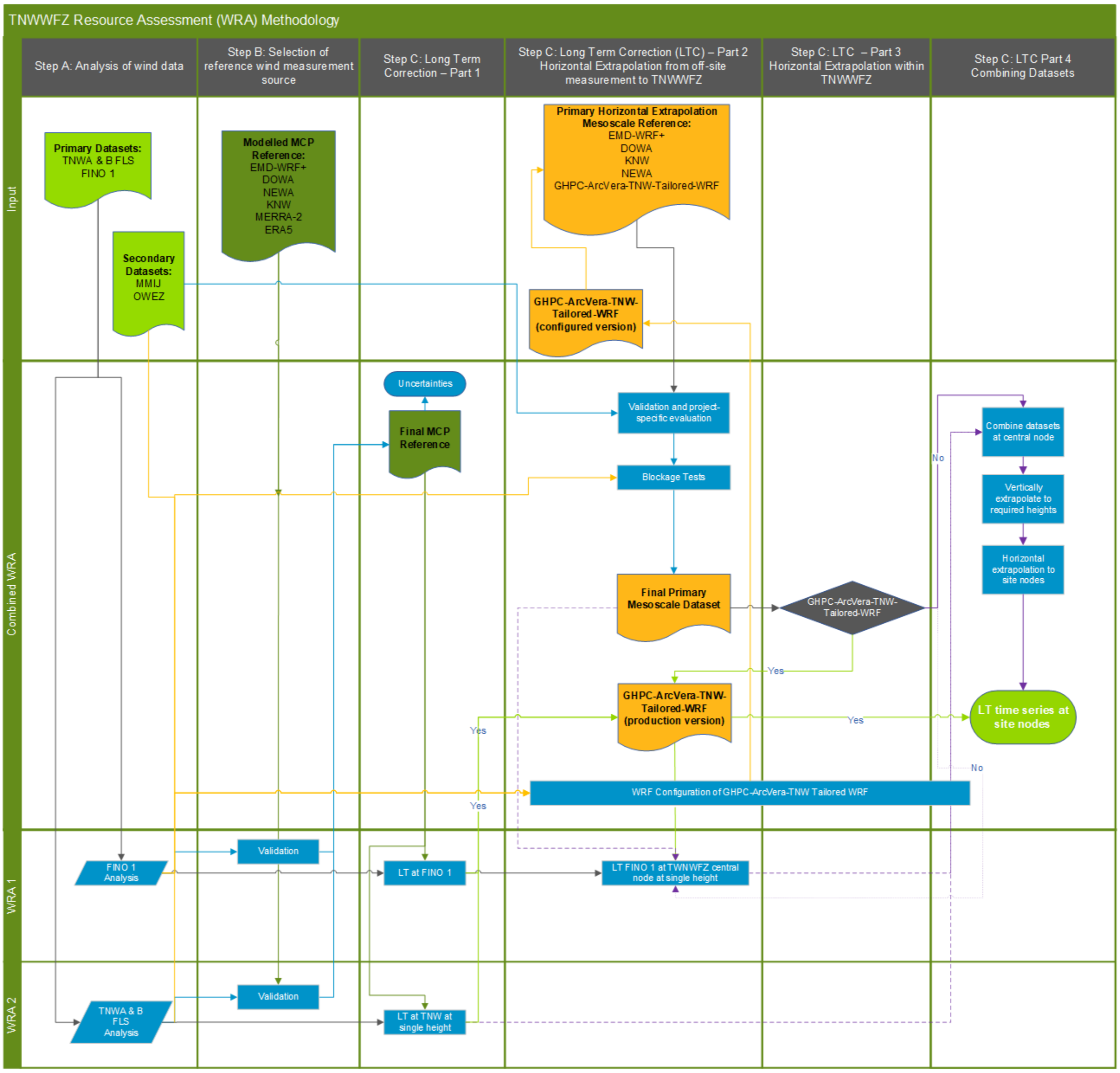

Figure 1-1. Flowchart of wind resource assessment methodology

1.3 Structure of the Report

The report is structured in the following manner:

Section 2.0: Presents the measured datasets considered in this assessment. It provides descriptions of each measurement location, gives insight into the data quality and screening processes applied. This is followed by a quantification of the uncertainty associated with each measurement campaign.

Section 3.0: Presents the selection of the hub height of interest, followed by an investigation of wake impact from neighbouring wind farms on the measured data and the corrections applied. This is followed by a description of the datasets selected for long-term corrections and any adjustment applied prior to conducting an MCP. Finally, the long-term correction of the measured data is presented along with its associated methodology and uncertainty.

Section 4.0: Gives a detailed description of the selected calibrated and long-term adjusted mesoscale model that represents the long-term wind distribution across the site. This is supported by a detailed spatial analysis of different sources and methodologies. The justification for the selected model is presented here along with the optimisation of the model and the final extrapolation across the Project site. This is followed by a comparison with the metocean study at TNWWFZ, an alignment exercise with previous wind resource assessment studies commissioned by RVO and finally, a comparison of the selected mesoscale model with other mesoscale model sources.

Section 5.0: Presents the long-term results from the mesoscale model, including various parameters associated with the long-term wind speed and wind direction and, where possible, compared with the short-term measured corresponding values. Other climatic parameters observed are also presented in this section.

Section 6.0: Presents examples of optimised layouts within the preliminary defined area of TNWWFS I in the TNWWFZ. The layouts consider a number of site constraints and both internal and external wake effects and blockage. An energy yield assessment for the designed layouts is also presented.

Section 7.0: Presents concluding remarks on the study performed and associated recommendations.

2.0 Wind Measurements

GHPC has analysed data gathered by the measurement devices deployed at offshore locations in the Dutch North Sea and a measurement campaign associated with TNWWFZ. Moreover, GHPC has analysed supporting data gathered from the FINO 1 offshore met mast, located in the German North Sea, approximately 61 km east from TNWWFZ.

The following sections give a detailed description of each measurement location and associated data quality. Every dataset is assessed for usability, and an uncertainty assessment is performed.

2.1 Wind Measurement Campaigns Overview

The primary measurement devices which were used for the measurement campaigns are two floating vertical scanning lidars, labelled as TNWA and TNWB. These were also supported by measurements from the FINO 1 offshore met mast, Offshore Windpark Egmond aan Zee (OWEZ) offshore met mast (OWEZ MM), IJmuiden offshore met mast (MMIJ) and the vertical scanning lidar measurements taken at the Hollandse Kust Noord (HKN) offshore site by two floating lidar systems (HKNA and HKNB).

The onsite TNWA and TNWB floating lidar systems were located towards the west side of the TNWWFZ. The FINO 1 offshore met mast is located offsite in the German North Sea, approximately 61 km from the TNWWFZ. Although the FINO 1 is off-site, its dataset is considered to be of excellent quality and has gathered data for more than four years and is therefore an important secondary dataset in this study The other measurement locations lie more than 150 km away from the TNWWFZ and are therefore considered to be supporting tertiary measurements. The high-level characteristics of the measurement devices are presented in Table 2-1.

It is noted that for the majority of the measurement campaign TNWA and TNWB were approximately 500 m apart. In the last six months of the measurement campaign TNWA was re-deployed further east from its initial location. This measurement location will henceforth be referred to as TNWA-2. The TNWA-2 location was selected as the mooring system at TNWA was no longer fully functional. TNWA-2 and TNWB were approximately 950 m apart.

GHPC has kept the same acronyms to have consistent terminology.

Table 2-1. Overview of measurement device locations

Measurement device designation	Measurement device location and type	Onsite/off-site	Type of dataset (short/long-term)
TNWA, TNWA-2	floating lidar system, Fugro Seawatch buoys	onsite	short-term
TNWB	floating lidar system, Fugro Seawatch buoys	onsite	short-term
FINO1	offshore met mast	off-site	short-term
OWEZ	offshore met mast	off-site	short-term
MMIJ	offshore met mast	off-site	short-term
HKNA HKNB (collectively as HKN)	floating lidar system	off-site	short-term

Table 2-2 gives an overview of the wind measured datasets considered in this study and it is noted that the measurement duration in the ‘Measurement duration’ column is noting the data duration used in this study and not necessarily the length of the measurement period. The measurement data and corresponding measurement periods considered in this study are presented in Table 2-2.

Figure 2-2 shows the measurement locations relative to TNWWFZ.

Table 2-2. Characteristics of measurement locations

Measure-ment location	Measure-ment type	Distance from coast [km]	Distance from TNWWFZ centre [km]	Measure-ment duration [years]	Measured variable	Location UTM ETRS89 Zone 31N
TNWA	floating lidar system	80	6	1.5	Wind speed, wind direction	667077 E, 5988551 N
TNWA-2	floating lidar system	80	5	0.5	Wind speed, wind direction	667968 E, 5988591 N
TNWB	floating lidar system	80	6	2	Wind speed, wind direction	667040 E, 5988949 N
FINO 1	offshore met mast	60	61	5	Wind speed, wind direction and other meteorological parameters	735037 E, 5991133 N
OWEZ MM	offshore met mast	15	180	1	Wind speed, wind direction and other meteorological parameters	594102 E, 5829389 N
MMIJ	offshore met mast	82	200	4	Wind speed, wind direction and other meteorological parameters	529340 E, 5855469 N
HKNA HKNB	floating lidar system	26	180	2	Wind speed, wind direction	583963 E, 5838212 N; 583958 E, 5837731 N

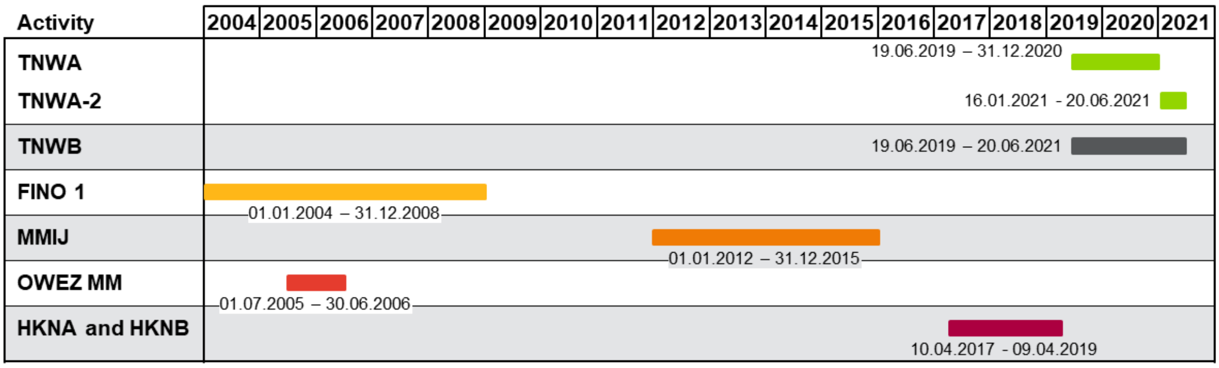

Figure 2-1. Gantt chart of measurement campaigns

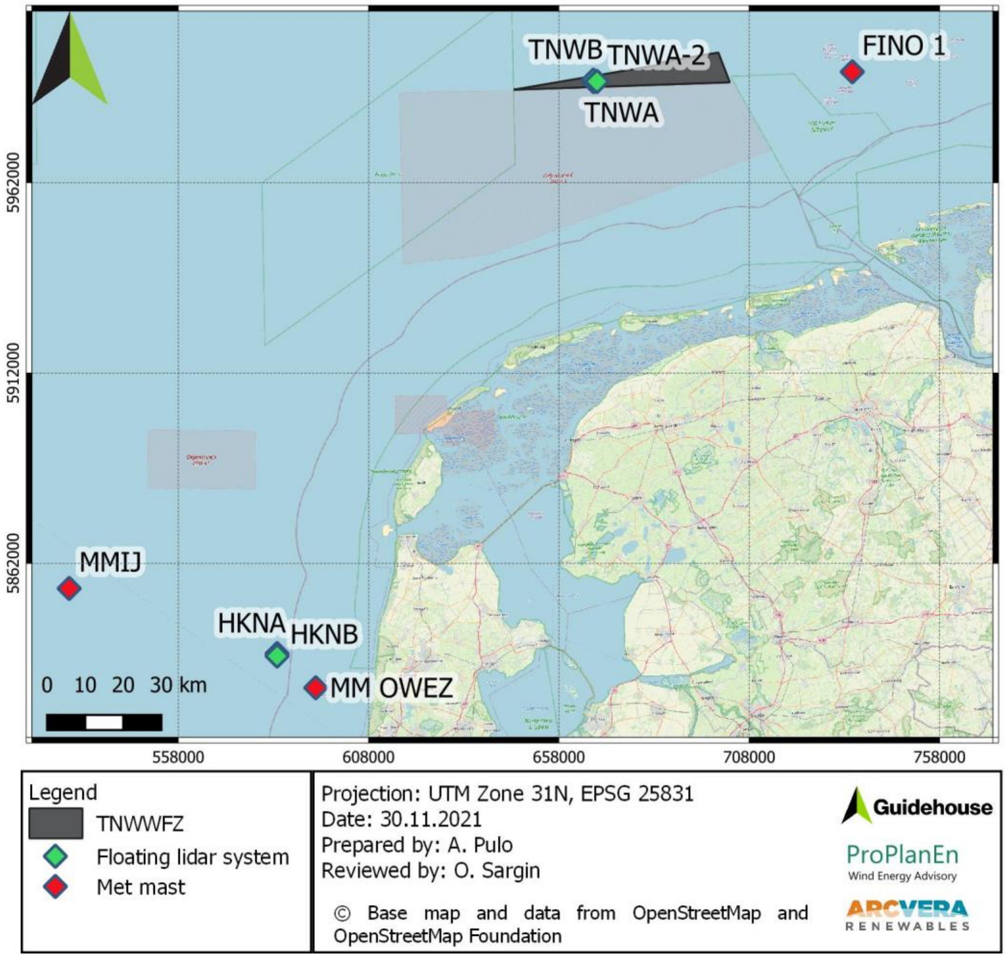

Figure 2-2. TNWWFZ: Locations of measurement locations in relation to the site

2.2 TNWA Floating Lidar System

2.2.1 TNWA and TNWA-2 Measurement Campaign Description

The measurement campaign at TNWA and TNWA-2 was conducted with a Seawatch wind lidar buoy (SWLB) floating lidar system (FLS). A number of different SWLB systems were installed sequentially. The measurement campaign was for a period of 24 months, from 19 June 2019 to 20 June 2021.

The measurement locations are specified in Table 2-2 and depicted in Figure 2-3. It is noted that the measurement location indicated in Table 2-2 is the installation locations of the buoys; the floating motion of the buoy causes the location to change slightly within a 350 m radius. Figure 2-3 depicts the installation location within TNWWFZ.

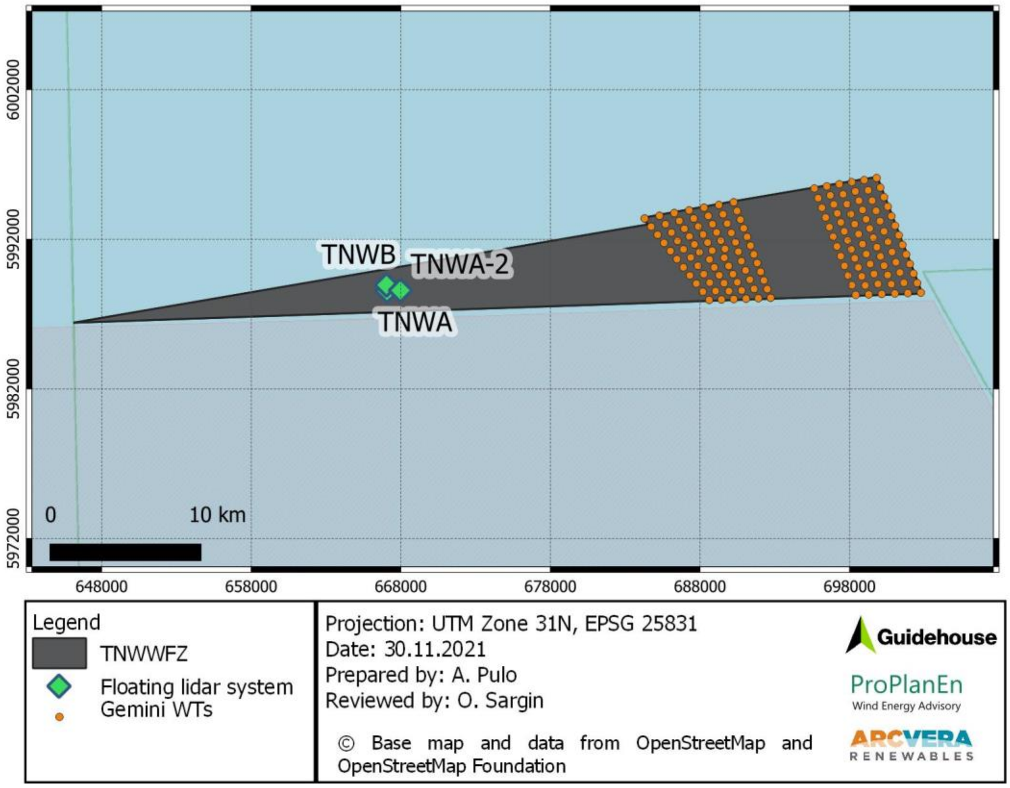

Figure 2-3. Installed TNWA and TNWA-2 floating lidar system within TNWWFZ

The first installed SWLB was with serial number WS190 and was deployed onsite at the TNWWFS I on 19 June 2019 as part of the meteorological and oceanographic measurement campaign commissioned from Fugro by RVO [3]. The WS190 SWLB was installed at TNWA by Fugro Norway AS (Fugro) which was equipped with a number of sensors [3]. The main sensor used to analyse the onsite wind resource is a ZephIR ZX300 CW vertical scanning lidar, which is a marinized version of the ZX300 lidar type. Prior to deployment onsite, the WS190 buoy was validated together with an uncertainty assessment by DNV next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has assessed the pre-deployment validation conducted and concluded that the WS190 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions [4].

In December 2019, the communication between the lidar and the FLS data logger was malfunctioning at intermittent intervals with frequent data gaps. From 28 December 2019 no more data was received from the lidar [5]. To mitigate this, on 22 January 2020, the WS190 buoy was recovered to be taken into service and was replaced with a spare buoy WS170. It is noted that the WS170 has previously been used as a spare buoy for the Hollandse Kust West project as well [6]. Following it's deployment to the Hollandse Kust West project, the WS170 buoy underwent an independent performance verification against a reference lidar at the LEG offshore platform, conducted by DNV. DNV concluded that the WS170 buoy has demonstrated its capability to produce accurate wind speed and direction data across a range of sea states and meteorological conditions [7]. Therefore, GHPC attributes high confidence in the measurements gathered by WS170. Further details on this are presented in 2.4.

On 09 February 2020 at 16:30 UTC an extreme wave event occurred. This also coincides with the time when the air temperature and humidity measurements disappeared. Other measurement are gathered as usual after this event, however only one of the four fuel cells were working after this date [8]. Due to this lack of fuel, there are no more measurements form 26 March 2020 until the FLS is replaced on 11 April 2020 [9]. On 11 April 2020, WS170 is recovered for service and replaced by the original FLS WS190 [10]. It is noted that the described events have impacted the data coverage in the winter months.

The FLS WS190 stopped working on 15 July 2020 due to a laser fault that has been building up since 13 July 2020 which caused some loss of data. Therefore the WS190 buoy was recovered to be taken into service on 22 July 2020. A replacement WS191 buoy was installed at TNWA on 22 July 2020. The WS191 buoy was initially installed at TNWB and underwent a validation process prior to installation [11] there and also underwent refurbishment after deinstallation from TNWB (Further details in section 2.3). The WS191 buoy starting drifting due to a storm on 30 December 2020 at 11:30 UTC and was recovered in an emergency operation from TNWA on 31 December 2020. It is noted that the TNWA station became unusable after this event due to parts of the mooring left on the seafloor.

Buoy WS199 was installed at TNWA-2 (east of TNWA) on 16 January 2021 and was recovered at the end of the measurement campaign on 20 June 2021. Prior to deployment onsite, the WS199 buoy was validated together with an uncertainty assessment by DNV next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has assessed the pre-deployment validation conducted and concluded that the WS199 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions [12].

The key details on this measurement campaign summarised below in Table 2-3**Error! Reference source not found.**. Further details are provided in Appendix B. Figure 2-4 below depicts a timeline for the events occurring during the measurement campaign at TNWA.

Table 2-3. TNWA and TNWA-2 campaign overview

Parameter	Description
Measurement type	ZephIR ZX300 CW lidar
TNWA location [UTM ETRS89, Zone 31]	667077 E, 5988551 N
TNWA measurement period available for analysis	19.06.2019 to 31.12.2020
TNWA-2 location [UTM ETRS89, Zone 31]	667968 E, 5988591 N
TNWA-2 measurement period available for analysis	16.01.2021 to 20.06.2021
Measurement averaging interval	10 minutes
Measurement heights	250 m, 200 m, 180 m, 160 m, 140 m, 120 m, 100 m, 80 m, 60 m, 40 m, 30 m
Distance from coast [km]	Approximately 80 km
Distance from TNWWFZ centre [km]	6 km west

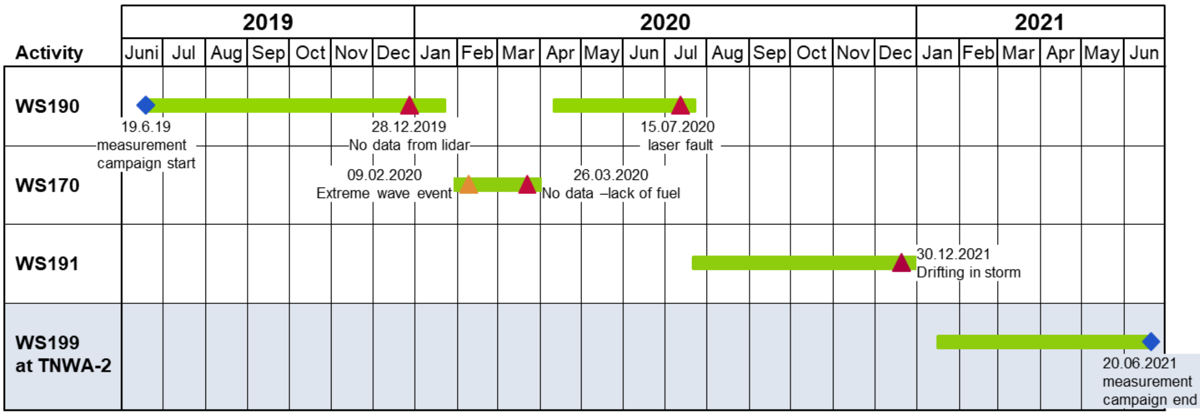

Figure 2-4. TNWA and TNWA-2 measurement campaign timeline

The wind measurement campaign was monitored and executed by Fugro who also compiled monthly reports on the measurement campaign and the data quality. The information on the measurement campaigns presented in this section is based on these monthly reports. The WS190 buoy installation setup and measurement protocols were documented in [3] for the first month of measurements.

2.2.2 TNWA and TNWA-2 Data Handling and Quality Checks

The data validation and post-processing of the measurement campaign was performed each month by third parties. It is noted that the data used in this post-processing was sourced directly from the floating lidar systems which had a higher data coverage than the satellite-transmitted data.

Deltares, which was commissioned by Fugro, conducted the data validation and produced monthly reports based on the assessments conducted. The post-processing was conducted by Fugro which is detailed in the monthly reports issued by Fugro as part of the monitoring process. The validated and post-processed data was then provided to RVO. The data received by GHPC from RVO for the purpose of this study is this aforementioned dataset that has been post-processed and screened.

The validation was performed by comparing the measurements between the two floating lidar systems at TNWA and TNWB and TNWA-2 and TNWB by quantifying the agreement between the two. This was an indication of correct functioning of the different sensors without loss of accuracy. The measurements were also validated against reference stations [1]. Furthermore, the data coverage and plausibility of the data were assessed.

The post processing conducted on the data consisted of

- Marking any missing timesteps with NaN
- Removing any values that are:
  - outside the times that the system is deployed
  - duplicated transmission values
  - out of range values which are replaced by NaN
  - spikes
- Checking the 180-degree wind direction ambiguity on the lidar wind data
- Manual inspection and assessment [3]

Based on the post-processing described above, quality flags were assigned to each datapoint, as indicated in Table 2-4 below.

Table 2-4. TNWA - quality flag descriptions

Quality Flag	Description	Excluded from analysis [yes/no]
MissedTransmission	Satellite transmission not received, row of NaNs	yes
DuplicateToNaN	Duplicated set of values from 1 sensor found and removed	yes
OutOfBounds	Value out of valid range found and removed	yes
OutlierFound	Spike/outlier found and removed	yes
Flipped180Degrees	180° ambiguity found and wind direction flipped 180°	yes
Low signal strength	Signal strength below threshold and value removed	yes

It is noted that during the deployment of the WS170 buoy, the validation analysis between the two floating lidar systems was not possible as the TNWB buoy was removed for a few months for urgent servicing (see section 2.3). GHPC has observed the data provided and checked it for plausibility and double-checked the screening of data conducted.

It is noted that GHPC conducted checks against ERA5 reference data to assist in identifying any notable errors in the measured data. The data was found to be of very good quality and no further filtering of data was conducted by GHPC. Once all data checks were conducted, the data coverage of the dataset at each measurement height was determined. Table 2-5 shows the data coverage and the mean values of the wind speed and wind direction for the measurement heights between 80 m and 180 m while Table 2-6 presents the monthly mean wind speed and data coverage for the representative height of 140 m[3]. Appendix C presents the mean monthly values and associated data coverage for the duration of the measurement period for all measurement heights.

It can be observed that the wind speed data at the measurement height of 140 m has a reasonable data coverage of 84% for the measurement period from 19 June 2019 to 31 December 2020 and a data coverage of 95% for the measurement period from 16 January 2021 to 20 June 2021. The data coverage is for the most part reduced due to issues with the measurement buoy caused either by natural phenomena or fault in the system in the winter months of the year 2020, in July 2020 and January 2021, which can be observed in Table 2-6.

Table 2-5. TNWA and TNWA-2 mean values and data coverage

Height above LAT [m]	Data Type	TNWA		TNWA-2	
		Mean value wind speed [m/s] wind direction* [°]	Data Coverage [%]*	Mean value wind speed [m/s] wind direction**[°]	Data Coverage [%]**
250	Wind speed	10.87	83	10.62	93

[3] It is noted that the height of 140 m has been selected as a representative height based on a high level investigation into recent hub height installations, the increase in turbine rotor diameters and the measurement heights available in this study. More information is presented on this in section 3.1.

Height above LAT [m]	Data Type	TNWA		TNWA-2	
		Mean value wind speed [m/s] wind direction* [°]	Data Coverage [%]*	Mean value wind speed [m/s] wind direction**[°]	Data Coverage [%]**
200	Wind speed	10.67	83	10.44	94
180	Wind speed	10.58	84	10.34	94
160	Wind speed	10.47	84	10.24	94
140	Wind speed	10.35	84	10.10	95
120	Wind speed	10.22	84	9.94	95
100	Wind speed	10.06	84	9.75	95
80	Wind speed	9.88	85	9.52	96
250	Wind direction	239	83	299	93
200	Wind direction	237	83	298	94
180	Wind direction	237	84	298	94
160	Wind direction	236	84	298	94
140	Wind direction	236	84	297	95
120	Wind direction	235	84	296	95
100	Wind direction	235	85	296	95
80	Wind direction	235	85	295	96

*from 19.06.2019 to 31.12.2020
**from 16.01.2021 to 20.06.2021

Table 2-6. TNWA and TNWA-2 monthly mean wind speed and data coverage at 140 m

Month	TNWA		TNWA-2	
	140 m wind speed [m/s]	140 m wind speed data coverage [%]	140 m wind speed [m/s]	140 m wind speed data coverage [%]
Jun.19*	8.25	35	-	-
Jul.19	8.96	91	-	-
Aug.19	9.20	99	-	-
Sep.19	9.91	97	-	-
Oct.19	11.09	97	-	-
Nov.19	9.72	93	-	-
Dec.19	12.84	74	-	-
Jan.20	13.51	25	-	-
Feb.20	15.60	84	-	-
Mar.20	11.43	61	-	-
Apr.20	9.10	66	-	-
May.20	8.15	94	-	-
Jun.20*	8.43	95	-	-
Jul-20	9.51	71	-	-
Aug-20	9.45	98	-	-
Sep-20	8.92	100	-	-
Oct-20	12.00	99	-	-

Month	TNWA		TNWA-2	
	140 m wind speed [m/s]	140 m wind speed data coverage [%]	140 m wind speed [m/s]	140 m wind speed data coverage [%]
Nov-20	11.99	88	-	-
Dec-20	10.97	80	-	-
Jan-21	-	-	10.95	50
Feb-21	-	-	13.51	93
Mar-21	-	-	11.02	92
Apr-21	-	-	8.95	99
May-21	-	-	8.75	97
Jun-21*	-	-	7.09	59
Total*	**10.4**	**81**	**10.10**	**82**

*as a percentage of whole months

2.2.3 Remarks on Data Usability of TNWA and TNWA-2

- The data gathered at TNWA and TNWA-2 was found to be of excellent quality with good data coverage.
- The overall wind speed data coverage at the representative height of 140 m is 81% for the measurement duration from 19 June 2019 to 31 December 2020 and 86% from 01 January 2021 to 20 June 2021.
- The combined TNWA and TNWA-2 data was found to be suitable for long-term correction to determine the onsite long-term climate.
- It is noted that TNWA and TNWA-2 lie approximately 20 km west from the operational Gemini wind farm. The wake impact of the neighbouring wind farm on the measured data was studied and is described in section 3.2. It is noted that the wake impact on TNWA and TNWA-2 was investigated separately.

2.3 TNWB Floating Lidar System

2.3.1 TNWB Measurement Campaign Description

The measurement campaign at TNWB was conducted with a Seawatch wind lidar buoy (SWLB) floating lidar system (FLS). A number of different SWLB systems were installed sequentially. The measurement campaign was for a period of 24 months, from 19 June 2019 to 20 June 2021.

It is noted that the measurement location indicated in Table 2-2 is the installation location of the buoy; the floating motion of the buoy causes the location to change slightly within a 350 m radius. Figure 2-5 depicts the installation location within TNWWFZ. The measurement location is specified in Table 2-2 and depicted in Figure 2-5.

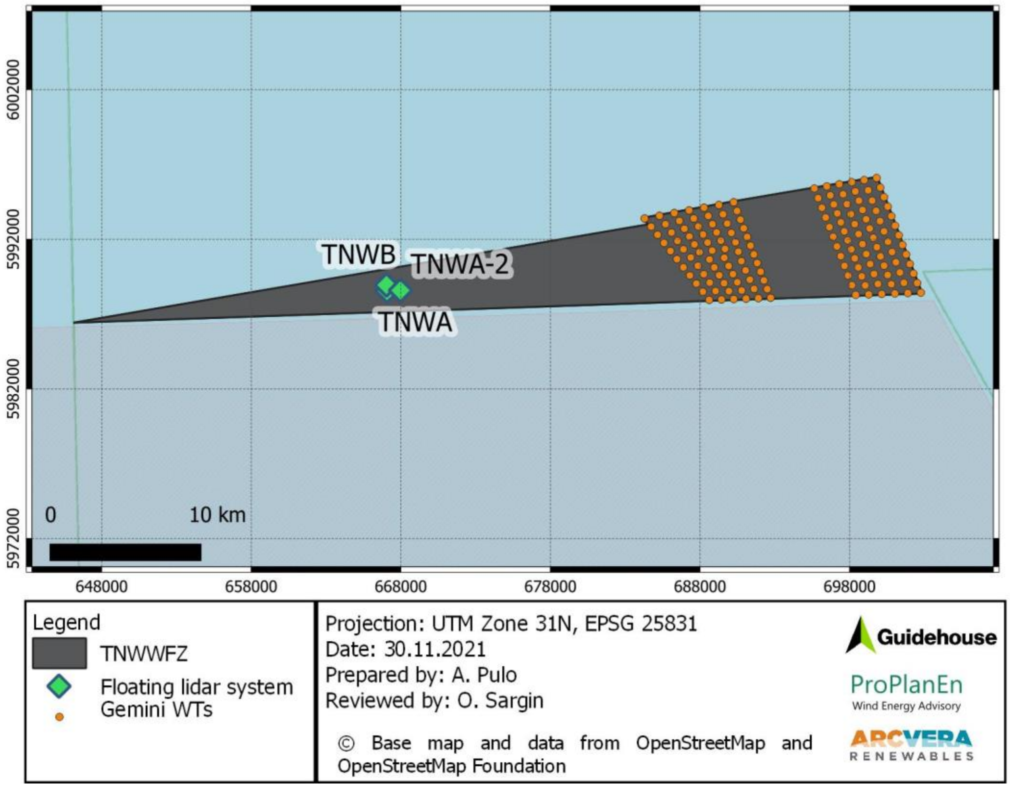

Figure 2-5. Installed TNWB floating lidar system within TNWWFZ

The first installed SWLB was with serial number WS191 and was deployed onsite at the TNWWFZ on 19 June 2019 as part of the meteorological and oceanographic measurement campaign commissioned from Fugro by RVO [3]. The WS191 SWLB was installed at TNWB by Fugro and which was equipped with a number of sensors [3]. The main sensor used to analyse the onsite wind resource is a ZephIR ZX300 CW vertical scanning lidar, which is a marinized version of the ZX300 lidar type. Prior to deployment onsite, the WS191 buoy was validated together with an uncertainty assessment by DNV next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has assessed the pre-deployment validation conducted and concluded that the WS191 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions that were exhibited during the validation [11].

On 12 September 2019 the communication between the lidar and the floating buoy data logger stopped working and the data was stored internally in the FLS and was downloaded at a later date. However, in December 2019, the FLS was working intermittently until it stopped functioning on 22 December 2019. The WS191 was recovered for service on 22 January 2020. No replacement buoy was available. The WS191 was re-deployed onsite after service on 11 April 2020. It is noted that the described events have impacted the data coverage in the winter months.

The WS191 was recovered from site on 24 June 2020 for service. It was replaced by buoy WS170 for the period 24 June 2020 to 14 September 2020. The WS170 was replaced by WS190 on 14 September 2020. On 25 October 2020 the WS190 at TNWB began to drift during a storm and was recovered with an emergency operation on the same day. It is noted that the WS170 and WS190 buoys was previously deployed at TNWA. The reliability of WS170 and WS190 is described in section 2.2.1.

On 10 November 2020 the buoy WS156 was installed at the TNWB location. The WS156 buoy is a first generation SWLB without DGPS heading and was designated as a spare buoy for this Project. In the year 2015 the WS156 buoy was validated together with an uncertainty assessment by DNV next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has assessed the pre-deployment validation conducted and concluded that the WS156 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions that were exhibited during the validation [13]. However, it is noted that the pre-deployment validation was conducted in the year 2015, approximately five year prior to deployment at TNWB. Additionally, the ZX lidar mounted on the WS156 buoy, ZX501, also underwent a validation process in 2019 against a well-known high quality standard cup anemometer at a UK Remote Sensing Test Site [14]. The validation was conducted by DNV. The validation was conducted at four wind speed measurement heights and two wind direction heights. The validation campaign indicated that the ZX501 is able to reproduce cup anemometer wind speeds and wind directions at an accurate and acceptable level. DNV considered the lidar unit to be suitable for formal wind potential and long-term wind resource assessments. The buoy WS156 was also serviced prior to deployment. Therefore, GHPC attributes high confidence in the measurements gathered by WS156.

The WS156 buoy was recovered on 25 January 2021 and replaced by buoy WS187. The WS187 buoy buoy was validated together with an uncertainty assessment by DNV next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has assessed the pre-deployment validation conducted and concluded that the WS187 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions that were exhibited during the validation [15]. The WS187 had also been deployed at the Hollandse Kust West wind measurement campaign and was serviced prior to installation at TNWB.

On 15 February 2021, WS187 started drifting after likely coming in contact with a vessel and was recovered on 16 February 2021. The WS187 was redeployed at TNWB on 3 March 2021, approximately 132m east from the original location as the floater from the mooring was not found. On 05 April 2021, WS187 stopped working due to insufficient power supply. The WS187 was recovered on 03 May 2021 and replaced by WS181. The issued experienced by the WS187 are reflected in a lower data coverage in the months of February to April 2021.

The WS181 buoy underwent a pre-deployment validation and uncertainty assessment by DNV in 2021 next to the Island of Frøya in the Norwegian Sea against a fixed/land based industry accepted lidar. DNV has concluded that the WS181 buoy has demonstrated the capability to accurate measure wind speed and direction across a range of sea states and meteorological conditions that were exhibited during the validation [16]. It is noted that the maximum measurement height was set at 240 m for WS181.

The WS181 was recovered on 20 June 2021 at the end of the measurement campaign. The wind measurement campaign was monitored and executed by Fugro who also compiled monthly reports on the measurement campaign and the data quality. The information on the

measurement campaigns presented in this section is based on these monthly reports. The WS191 buoy installation setup and measurement protocols were documented in [3] for the first month of measurements. Similar reports were reproduced for each month of the measurement campaign.
The key details on this measurement campaign summarised below in Table 2-7. Further details are provided in Appendix B.

Table 2-7. TNWA campaign overview

Parameter	Description
Measurement type	ZephIR ZX300 CW lidar
Location [UTM ETRS89, Zone 31]	667040 E, 5988949 N
Measurement period available for analysis	19.06.2019 to 20.06.2021
Measurement averaging interval	10 minutes
Measurement heights	250 m*, 200 m, 180 m, 160 m, 140 m, 120 m, 100 m, 80 m, 60 m, 40 m, 30 m
Distance from coast [km]	Approximately 80 km
Distance from TNWWFZ centre [km]	6 km west

*with the exception of the data gathered by WS181 which has a maximum height of 240 m

Figure 2-6 below depicts a timeline for the events occurring during the measurement campaign at TNWA.

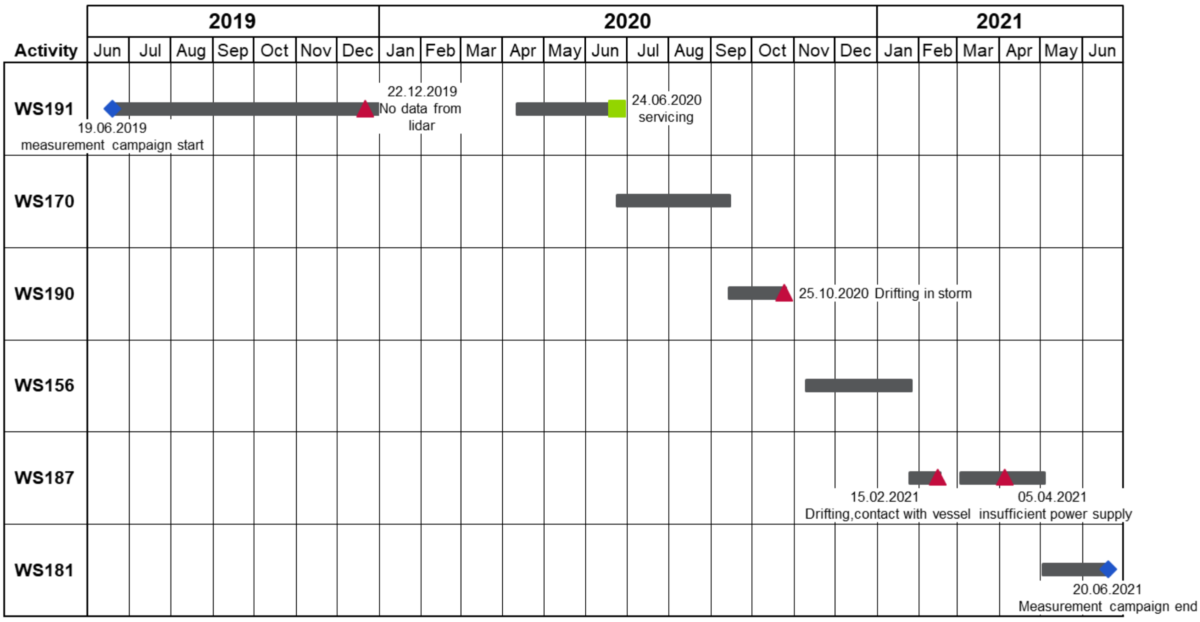

Figure 2-6. TNWB measurement campaign timeline

2.3.2 TNWB Data Handling and Quality Checks

The data validation and post-processing of the measurement campaign was performed each month by third parties. Deltares, which was commissioned by Fugro, conducted the data validation and produced monthly reports based on the assessments conducted. The post-processing was conducted by Fugro which is detailed in the monthly reports issued by Fugro as part of the monitoring process. The validated and post-processed data was then provided to RVO. The data received by GHPC from RVO for the purpose of this study is this aforementioned dataset that has been post-processed and screened.

The validation was performed by comparing the measurements between the two floating lidar systems at TNWA and TNWB by quantifying the agreement between the two. This was an indication of correct functioning of the different sensors without loss of accuracy. The measurements were also validated against reference stations [1]. Furthermore, the data coverage and plausibility of the data were assessed.

The post processing conducted on the data consisted of

- Marking any missing timesteps with NaN
- Removing any values that are:
  - outside the times that the system is deployed
  - duplicated transmission values
  - out of range values which are replaced by NaN
  - spikes
- Checking the 180-degree wind direction ambiguity on the lidar wind data
- Manual inspection and assessment [3]

Based on the post-processing described above, quality flags were assigned to each datapoint, as indicated in Table 2-8 below. GHPC has observed the data provided and checked it for plausibility and double-checked the screening of data conducted. It is noted that GHPC conducted checks against ERA5 reference data to assist in identifying any notable errors in the measured data. The data was found to be of very good quality and no further filtering of data was conducted by GHPC.

Table 2-8. TNWB - quality flag descriptions

Quality Flag	Description	Excluded from analysis [yes/no]
MissedTransmission	Satellite transmission not received, row of NaNs	yes
DuplicateToNaN	Duplicated set of values from 1 sensor found and removed	yes
OutOfBounds	Value out of valid range found and removed	yes
OutlierFound	Spike/outlier found and removed	yes
Flipped180Degrees	180° ambiguity found and wind direction flipped 180°	yes
Low signal strength	Signal strength below threshold and value removed	yes

Once all data checks were conducted, the data coverage of the dataset at each measurement height was determined. Table 2-9 shows the data coverage and the mean values of the wind speed and wind direction for the measurement heights between 80 m and 180 m while Table 2-10 presents the monthly mean wind speed and data coverage for the representative height of 140 m. Appendix C presents the mean monthly values and associated data coverage for the duration of the measurement period for all measurement heights.

It can be observed that the wind speed data at the measurement height of 140 m has a low data coverage of 71% for the measurement period from 19 June 2019 to 20 June 2021. The data coverage is for the most part reduced due to having no instrumentation at TNWB in the winter months, as can be observed in Table 2-10.

Table 2-9. TNWB mean values and data coverage

Height above LAT [m]	Data Type	Mean value wind speed [m/s] wind direction [°]	Data Coverage [%]*
250	Wind speed	10.45	63
240	Wind speed	8.51	6
200	Wind speed	10.12	70
180	Wind speed	10.04	70
160	Wind speed	9.95	70
140	Wind speed	9.84	71
120	Wind speed	9.72	71
100	Wind speed	9.58	71
80	Wind speed	9.41	71
250	Wind direction	247	63
240	Wind direction	254	6
200	Wind direction	247	69
180	Wind direction	247	69
160	Wind direction	247	70
140	Wind direction	246	70
120	Wind direction	245	70
100	Wind direction	245	70
80	Wind direction	244	70

*from 19.06.2019 to 20.06.2021

Table 2-10. TNWB monthly mean wind speed and data coverage at 140 m

Month	140 m wind speed [m/s]	140 m wind speed data coverage [%]
Jun.19*	8.46	36
Jul.19	8.98	90
Aug.19	9.13	97
Sep.19	9.76	92
Oct.19	10.90	85
Nov.19	10.08	69
Dec.19	14.05	50
Jan.20	-	0

Month	140 m wind speed [m/s]	140 m wind speed data coverage [%]
Feb.20	-	0
Mar.20	-	0
Apr.20	9.04	66
May.20	8.14	93
Jun.20*	8.85	73
Jul-20	8.31	100
Aug-20	9.39	100
Sep-20	8.96	99
Oct-20	11.58	79
Nov-20	12.07	68
Dec-20	10.81	99
Jan-21	10.35	98
Feb-21	12.63	52
Mar-21	11.12	90
Apr-21	11.35	13
May-21	8.80	90
Jun-21	7.09	58
Total*	**9.84**	**68**

*as a percentage of whole months

2.3.3 Remarks on Data Usability of TNWB

- The data gathered at TNWB was found to be of excellent quality with reasonable data coverage.
- The overall wind speed data coverage at the representative height of 140 m is 71% for the measurement duration from 19 June 2019 to 20 June 2021.
- The TNWB data was found to have a lower data coverage than required for a reliable long-term correction. Therefore the TNWB data was used to support the TNWA data. This is described in further detail in Section 3.3.1.
- It is noted that TNWB lies approximately 20 km west from the operational Gemini wind farm. The wake impact of the neighbouring wind farm on the measured data was studied and is described in section 3.2.

2.4 TNWA and TNWB Deviations from Best Practices

The information presented in this section has been extracted from [3].

The SWLB is a 3rd party type buoy which was validated by DNV(an accredited institution). The SWLB underwent a six (6) month trial in 2014 and was found to be in accordance to the Carbon Trust requirements [17]. The best practice criteria for the Key Performance Indicators (KPIs) for the “Mean Wind Speed – Slope and Coefficient of Determination” and “Mean Wind Direction – Slope, Coefficient of Determination and Offset” were passed which indicates that the SWLB is capable of capturing wind directions at high accuracy.

Similarly, a six (6) months trial was also conducted at the East Anglia One met mast in 2015 as part of the Carbon Trust programme. The performance was independently verified by a third party [18]. All wind speed KPIs exceeded best-practice limits, as well as most wind direction KPIs.

Moreover, as previously noted, the floating lidars systems of buoy WS190, WS191, WS199, WS156, WS187 and WS181 deployed at TNWA, TNWA-2 and TNWB were independently validated and found to be in good working order [4]; [11];[12], [13], [15], [16].

The WS170 buoy was validated against a land-based lidar system in 2017 [19] and was then validated in-situ during the Hollandse Kust West measurement campaign in 2019 against another floating lidar system, buoy WS188, as described in [20] . It is considered best-practice to validate a floating lidar not more than 12 months prior to its deployment on site, therefore the validation of WS170 in 2019 falls within this recommended timeframe prior to its installation at TNWWFZ. This gives good confidence in the data gathered by WS170 buoy during the TNWWFZ measurement campaign, over and above the checks conducted by GHPC. Moreover, a post-deployment validation of the WS170 buoy was conductedand the WS170 buoy was found to be capable to produce accurate wind speed and wind direction data [7].

It is noted that the pre-deployment validations conducted for WS199, and WS187 were conducted in the year 2019. This means that the units were validated earlier than the recommended 12 month period prior to deployment. However WS187 was serviced before deployment and WS199 was deployed for the first time at TNWA-2. Therefore high confidence is attributed to the data gathered by these buoys.

It is also noted that WS156 underwent a pre-deployment validation in the year 2015, which is outwith the recommended 12 month period prior to deployment. However, the ZX lidar mounted on the WS156 buoy also underwent a validation process in 2019 and the WS156 buoy was serviced before deployment at TNWB. Therefore, GHPC attributes high confidence in the measurements gathered by WS156.

Based on the above, GHPC has observed that the use of WS170 buoy constitutes a minor deviation from industry best practice due to the points mentioned above in relation to the buoy validation. No major deviations from best practice were observed, insofar as could be investigated.

It is noted that the KPIs defined in [17] are meant as guidelines for floating lidars to become commercially accepted as a reliable source of data. Therefore, [17] does not provide direct recommendations for wind resource assessments but present useful input in assessing the performance and quality of a floating lidar system measurement campaign. GHPC considered the performance and quality of the units used in the TNW measurement campaign in the uncertainty assessment.

2.5 FINO 1 Met Mast

As part of the German government's effort towards the expansion of offshore wind energy, during the 2000's three (3) met masts have been erected on offshore research platforms, called "Forschungsplattformen in Nord- und Ostsee" (FINO). The met mast erected at FINO 1 is of interest for the wind potential at TNWWFZ. FINO 1 was deployed in 2003, approximately 61 km from TNWWFZ and has been gathering data ever since.

2.5.1 FINO 1 Measurement Campaign Description

The FINO 1 met mast is equipped with anemometers, wind vanes, ultrasonic anemometer, thermometers, barometers, hygrometer, precipitation sensors, pyranometers and a radiometer.

FINO 1 is the first platform erected within the FINO project. It is located in the German North Sea, approximately 61 km east from TNWWFZ.

Figure 2-7. Installed FINO 1 met mast [Source: Martina Nolte[4]]

The FINO 1 setup, measurement protocols, met mast configuration and monitoring are documented in [21]. Some key details are summarised below in Table 2-11. It is noted that anemometer pairs of cup anemometers and ultrasonic anemometers were mounted at the wind speed measurement heights of 82 m, 62 m and 42 m.

Table 2-11. FINO 1 campaign overview

Parameter	Description
Measurement type	Lattice mast
Location [UTM ETRS89, Zone 31]	735037 E, 5991133 N
Measurement period considered in analysis	01.01.2004 – 31.12.2008
Wind speed measurement heights above LAT [m]	102.5 m, 91.6, 82.1 m, 81.6 m, 71.6 m, 62.1 m, 61.6 m, 51.6 m, 42.1 m, 41.6 m, 34.1 m
Measurement interval	10 minutes
Distance from coast [km]	Approximately 60 km
Distance from TNWWFZ centre [km]	Approximately 61 km

The present operator of the met mast is Forschungs- und Entwicklungszentrum Fachhochschule Kiel GmbH (FuE Kiel) while UL International GmbH (UL) is responsible for the measurements. The anemometers mounted on the met mast are all calibrated in accordance with MEASNET standards and are changed every year. The dismounted anemometers are recalibrated and serviced for further use.

[4] Photo: Martina Nolte, Licence: https://creativecommons.org/licenses/by-sa/3.0/de/legalcode

The wind speed data is affected by flow effects around the mast, neighbouring sensors mounted on the same met mast and other obstacles. Therefore, measurements from FINO met masts are taken only from certain wind direction and corrections applied, if possible [21].

The mast corrected data for this work scope was sourced by GHPC from the Bundesamt für Seeschifffahrt und Hydrographie (BSH) portal which is the marine and hydrographic authority in Germany. The methodology undertaken is described in [21].

It is noted that FINO 1 is located just west of the offshore wind farm Alpha Ventus and is surrounded by other offshore wind farms in the other directions. The construction of the Alpha Ventus offshore wind farm started in 2009 while the other offshore wind farms were built from 2015 onwards. Therefore, in order to avoid the inclusion of wake-impacted data in the assessment, the FINO 1 wind data considered in this study is for the period 01 January 2004 to 31 December 2008, covering a period of five (5) years.

2.5.2 FINO 1 Data Handling and Quality Checks

The FINO 1 met mast data was sourced by GHPC from the BSH portal. The data sourced was monitored by UL and post-processed by a consortium of partners together with Deutscher Wetterdienst (DWD) which issued the final results. The quality checks and post-processing done were documented in [21].

Quality flags were associated with data collected at each timestamp, indicating the quality of the data point and if it was screened with automatic filters or manually. Guidehouse has filtered the data in accordance with the provided data quality flags. Minimal further screening was conducted manually by Guidehouse. A description of the quality flags provided and applied by Guidehouse are presented in Table 2-12.

Table 2-12. FINO 1 quality flag descriptions

Quality Flag	Description	Remark	Excluded from analysis [yes/no]
9	Missing	No data available	Yes
0	Not checked	Not subject to validation	No
2	Formally pass, climatological pass	Data within sensor limits and climatological limits	No
3	Time consistency pass, internal consistency pass	Time series is continuous, good agreement between adjacent sensors	No
4	Manual pass	Manual override of automatic flags	No
1	Manual questionable	Manual check – value considered questionable	Yes
5	Formal fail	Data exceeds sensor limits	Yes
6	Time consistency fail	Time series is discontinuous	Yes
7	Internal consistency fail	Large discrepancy between adjacent sensors	Yes
8	Manual fail	Sensor faulty – value known to be wrong	Yes

Once all data checks were conducted the data coverage of the dataset at each measurement height and instrumentation was observed. These are presented in Table 2-13 together with mean values. Appendix B presents the mean monthly values and associated data coverage for the duration of the measurement period. It is noted that the mean wind speeds and wind directions presented are those measured by cup anemometers and wind vanes, respectively.

Table 2-13. FINO 1 mean values and data coverage

Height above LAT [m]	Data Type	Mean value	Data Coverage [%]
102.5	Wind speed	9.93 m/s	96
92	Wind speed	9.85 m/s	96
82	Wind speed	9.72 m/s	95
72	Wind speed	9.60 m/s	97
62	Wind speed	9.30 m/s	89
52	Wind speed	9.18 m/s	91
42	Wind speed	9.02 m/s	90
34	Wind speed	-	-
92	Wind direction	241°	92
72	Wind direction	235°	79
52	Wind direction	238°	78
34	Wind direction	246°	85

2.5.3 Ambient Turbulence Intensity at FINO 1

The FINO 1 dataset covers a period of five (5) consecutive years and was found to be of very good quality. Based on these considerations, the ambient turbulence intensity (TI) at FINO 1 was assessed and used in the wake modelling conducted at a later stage in the study (section 3.2.1, 6.0). It is noted that the measurement period selected for FINO 1 is not impacted by wakes from neighbouring wind farm and is freestream.

The FINO 1 location exhibits an ambient TI of 0.05 at 15 m/s at a height of 102.5 m. This is in line with the expected TI at offshore locations. Table 2-14 and Figure 2-8 present the ambient TI, binned by wind speed, at a height of 102.5 m.

Table 2-14. FINO 1 ambient TI at 102.5 m

Bin [m/s]	Bin Endpoints [m/s]		Mean TI
	Lower	Upper	
1	0	0.5	0.33
2	0.5	1.5	0.21
3	1.5	2.5	0.13
4	2.5	3.5	0.09
5	3.5	4.5	0.08
6	4.5	5.5	0.07
7	5.5	6.5	0.06
8	6.5	7.5	0.06
9	7.5	8.5	0.05
10	8.5	9.5	0.05
11	9.5	10.5	0.05
12	10.5	11.5	0.05
13	11.5	12.5	0.05
14	12.5	13.5	0.05
15	13.5	14.5	0.05
16	14.5	15.5	0.05

Bin [m/s]	Bin Endpoints [m/s] Lower	Upper	Mean TI
17	15.5	16.5	0.05
18	16.5	17.5	0.05
19	17.5	18.5	0.06
20	18.5	19.5	0.06
21	19.5	20.5	0.06
22	20.5	21.5	0.06
23	21.5	22.5	0.07
24	22.5	23.5	0.07
25	23.5	24.5	0.07
26	24.5	25.5	0.07
27	25.5	26.5	0.07
28	26.5	27.5	0.07
29	27.5	28.5	0.06
30	28.5	29.5	0.08
31	29.5	30.5	0.08
32	30.5	31.5	0.08
33	31.5	32.5	0.09
34	32.5	33.5	0.08
35	33.5	34.5	0.09

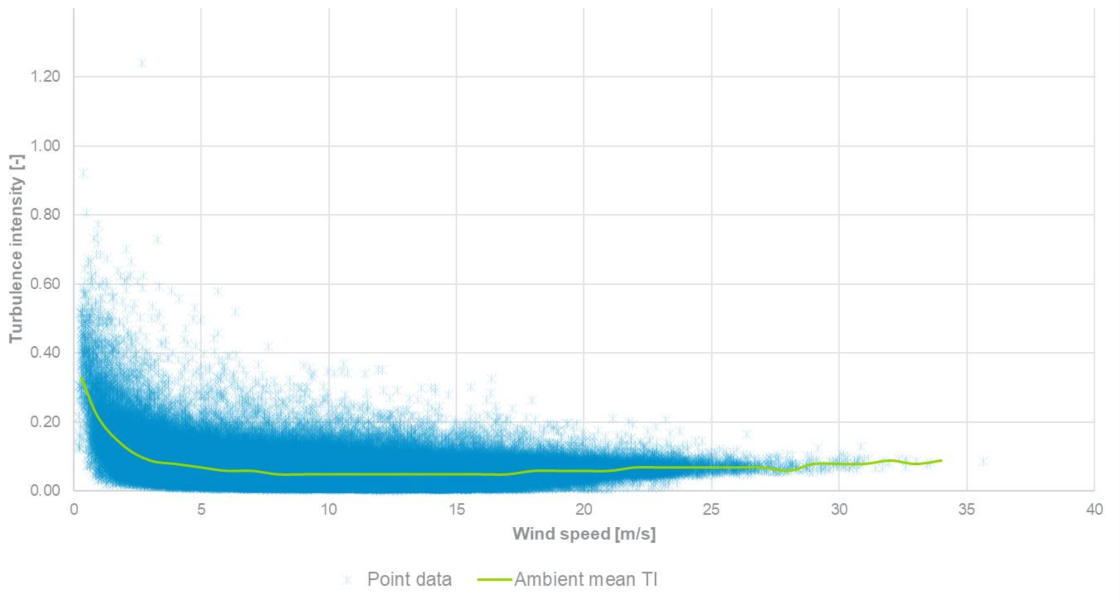

Figure 2-8. FINO 1 ambient TI at 102.5 m

2.5.4 Remarks on Data Usability of FINO 1

- FINO 1 is currently located just west of the offshore wind farm Alpha Ventus. The construction of this offshore wind farm started in 2009. Therefore, in order to avoid the inclusion of wake-impacted data in the assessment, the FINO 1 wind data considered in this study is for the period 01 January 2004 to 31 December 2008, covering a period of five (5) years.
- The data quality of FINO 1 was found to be of excellent quality, with data coverage being excellent, exceeding 96% at the top measurement height for the measurement period being considered.

- The measurement location of FINO 1 is off-site, therefore the dataset has limitations in its representation of the wind conditions at TNWWFZ. However due to the quality of the data and the length of the dataset, the FINO 1 dataset was considered suitable for long-term correction and the final calibration and verification of the spatial gradient model.

2.6 Met Mast OWEZ

The OWEZ met mast was erected in mid-2005 at the site of the OWEZ wind farm. Instrumentation were mounted at three heights above mean sea level (m.s.l). The OWEZ met mast was equipped with: anemometers, wind vanes, ultrasonic anemometer, thermometers, barometers, hygrometer and precipitation sensors. The OWEZ met mast is considered to be in close alignment to IEC standards. Three booms were configured at each measurement height with an anemometer mounted at each boom, with the aim of selecting relatively undisturbed instruments.

It is noted that the OWEZ wind farm was constructed just one year after the erection of the OWEZ met mast. Therefore, only the first year of measurements are considered in the assessment as later years are disturbed by the constructed wind farm.

The recorded data by the OWEZ met mast was processed by Mierij Meteo and ECN was responsible for checking and publishing the data. ECN checked the data for consistency, quality and any out of range numbers and to finally derive a single undisturbed wind speed form the three measurements at each height [22], [23]. GHPC has reproduced the single processed time series for each measurement height, with small adjustments to the ECN-defined filters, in order to increase data availability [24].

Key details of the OWEZ met mast measurement campaign are summarized below in Table 2-15.

Table 2-15. OWEZ MM measurement campaign parameters

Parameter	Description
Measurement type	Lattice Mast
Location [UTM ETRS89, Zone 31]	594102 E, 5829389 N
Measurement period considered in analysis	01.07.2005 – 30.06.2006
Wind speed measurement heights above m.s.l. [m]	116 m, 70 m, 21 m
Measurement interval	10 minutes
Distance from coast [km]	Approximately 15 km
Distance from TNWWFZ centre [km]	Approximately 180 km

Following post-processing the final wind speed values for the top measurement height for the measurement period indicated in Table 2-15 are shown in Table 2-16.

Table 2-16. OWEZ MM mean wind speed and data coverage at 116 m

Parameter	Value
Height above m.s.l.	116 m
Wind speed [m/s]	9.00 m/s
Data coverage (01.07.2005 – 30.06.2006)	86%

2.6.1 Remarks on Data Usability of MM OWEZ

- The OWEZ MM is located just west of the OWEZ offshore wind farm. The construction of this offshore wind farm started in 2006. Therefore, in order to avoid the inclusion of wake-impacted data in the assessment, the OWEZ MM wind data considered in this study is for the period 01 July 2005 to 30 June 2006.06.2006, covering a period of one (1) year.
- The data quality of OWEZ MM was found to be good, with data coverage being very good at 86% at the top measurement height for the measurement period being considered.
- The measurement location of OWEZ MM is more than 150 km off-site, therefore, the dataset has very restricted application in its representation of the wind conditions directly at the TNWWFZ. Nonetheless, the OWEZ MM dataset was considered suitable to assist in the verification the final wind spatial gradient model.

2.7 Met Mast IJmuiden

The IJmuiden met mast (MMIJ) was erected in 2011, approximately 87 km west of the IJmuiden harbour. Instrumentation were mounted at three measurement heights above LAT. The MMIJ was equipped with: anemometers, wind vanes, ultrasonic anemometer, thermometers, barometers, hygrometer and precipitation sensors.

The design of the met mast and data processing techniques were designed such as to ensure high data quality [24]. Flow distortion due to the tower was minimized by installing anemometers on three booms mounted at each height; two anemometers were installed at the top height [25].

The met mast was decommissioned in the year 2016. Therefore, the measurement period considered covers a duration of four (4) whole years from 2012 to 2016.

ECN was responsible for checking the data and did this in several ways. The measurement computer checked the sensor connection and if recordings exceeded minimum and maximum thresholds. Subsequently the data was checked manually. Only valid data was kept in the provided raw data files. Missing values were indicated with blanks.

A single undisturbed wind speed form the measurements at each height were derived based on the methodology defined by ECN [25], , with a slight modification by GHPC to include period with only a single undisturbed wind vane. This methodology was applied to the measurement heights with three anemometers.

No information regarding recommended filters for the top measurement height were defined by ECN, where there are two anemometers. GHPC defined its own method by interpolating based on disturbed sectors. An intercomparison of the two measured wind speeds confirmed the flow disturbances in the expected sectors, based on the mast configuration. The directional filters were then defined based on these sectors [24].

Key details of the IJmuiden met mast measurement campaign are summarized below in Table 2-17.

Table 2-17. MMIJ measurement campaign parameters

Parameter	Description
Measurement type	Lattice Mast
Location [UTM ETRS89, Zone 31]	529340 E, 5855469 N
Measurement period considered in analysis	01.01.2012 – 31.12.2015

Parameter	Description
Wind speed measurement heights above LAT [m]	92 m, 85 m, 58 m, and 27 m
Measurement interval	10 minutes
Distance from coast [km]	Approximately 82 km
Distance from TNWWFZ centre [km]	Approximately 200 km

Following post-processing the final wind speed values for the top measurement height of 92 m for the measurement period indicated in Table 2-17 are shown in Table 2-18.

Table 2-18. MMIJ mean wind speed and data coverage at 92 m

Parameter	Value
Height above LAT	92 m
Wind speed [m/s	9.93 m/s
Data coverage (01.01.2012 – 31.12.2015)	99%

2.7.1 Remarks on Data Usability of MMIJ

- The MMIJ was installed in 2011 and decommissioned in 2016. For the purpose of this study full years were considered, therefore the data period considered in this study is from 01 January 2012 to 31 December 2015, covering a period of four (4) whole calendar years. 2006.
- The data quality of MMIJ was found to be good, with data coverage being excellent at 99% at the top measurement height for the measurement period being considered.
- The measurement location of MMIJ is more than 150 km off-site, therefore, the dataset has very restricted application in its representation of the wind conditions directly at the TNWWFZ. Nonetheless, the MMIJ dataset was considered suitable to assist in the verification the final wind spatial gradient model.

2.8 HKN Floating Lidar System

The HKN A and B floating lidar systems were installed as part of the wind measurement campaign of the offshore wind farm site Hollandse Kust Noord. It is noted that all the information presented in this section was extracted from [26].

The two floating lidar systems were Seawatch Wind LiDAR Buoys (SWLB) deployed onsite by Fugro Norway AS. Each FLS is designated a number of sensors, including a ZephIR 300S lidar, which provided the main input for the wind measured data. The FLS were deployed at the measurement location on 08 April 2017 and 09 April 2017 from HKNA and HKNB, respectively. The measurement campaigns were officially started on 10 April 2017. The measurement campaign was finalized in April 2019.

The data has been post-processed and checked for quality by Fugro, while Deltares has performed secondary data quality checks on both the HKNA and HKNB datasets. The data was sourced by GHPC from the RVO portal in a post-processed format and quality-checked format. No further screening or data corrections were applied by GHPC.

Some key details of the measurement campaign are summarized in the table below. It can be observed that HKNA was subjected to a number of buoy changes during the measurement campaign. Further details on this can be found in [26].

Table 2-19. HKN measurement campaign parameters

Parameter	Description	
	HKNA	HKNB
Buoy	WS149/WS155/WS156/ WS158/WS140	WS170/WS140/WS158
Measurement type	ZephIR 300S lidar	ZephIR 300S lidar
Location [UTM ETRS89, Zone 31]*	583963 E, 5838212 N	583958 E, 5837731 N
Measurement period available for analysis	10.04.2017 - 09.04.2019	10.04.2017 - 09.04.2019
Measurement averaging interval	200 m, 180 m, 160 m, 140 m, 120 m, 100 m, 80 m, 60 m, 40 m, 30 m	200 m, 180 m, 160 m, 140 m, 120 m, 100 m, 80 m, 60 m, 40 m, 30 m
Distance from mainland coast [km]	Approximately 26 km	Approximately 26 km
Distance from TNWWFZ centre [km]	Approximately 180 km	

For the measurement period indicated in Table 2-19, the post-processed mean wind speed and data coverage for the measurement height of 140 m is presented in Table 2-20.

Table 2-20. HKN mean wind speed and data coverage at 140 m

Parameter	HKNA	HKNB
Height above LAT	140 m	140 m
Wind speed [m/s]	9.70 m/s	9.83 m/s
Data coverage (10.04.2017 - 09.04.2019)	84%	88%

2.8.1 Remarks on Data Usability of HKN

- The data quality of HKN lidars was found to be very good, with data coverage being very good, above 80% at the measurement height of 140 m, for the measurement period being considered.
- The measurement locations of HKN are more than 150 km off-site, therefore, the dataset has very restricted application in its representation of the wind conditions directly at the TNWWFZ. Nonetheless, the HKN measured datasets were considered suitable to assist in the verification the final wind spatial gradient model.

2.9 Uncertainty of Measured Wind Speed

GHPC has reviewed the uncertainty associated with the wind speed measured data in terms of instrument accuracy, mounting, the homogeneity of the surrounding wind flow as well as data quality and processing.

The second edition of IEC 61400-12-1 specifies the use of lidar, with a detailed procedure (Annex L) that ensures the traceability of the measurements and evaluates associated uncertainty components, which can be applied in wind resource assessments [27].

The uncertainties associated with accuracy of wind measurements of TNWA, TNWA-2 and TWNB have been analysed during pre-deployment verification and validation campaigns. GHPC conducted for each FLS unit a separate uncertainty assessment as shown in Table 2-21, and subsequently weighted these uncertainties based on measurement duration and availabilities to inform the uncertainty in measured wind speed at TNWA, TNWA-2 and TNWB locations.

GHPC assumed a slightly elevated variation in flow, data acquisition and post-processing uncertainty for the WS156 and WS170, as only onshore performance verification tests of the lidar units were available to inform the calibration uncertainty of the FLS system.

The uncertainty related to the inhomogeneity in the wind flow was assumed to be 0% for all FLS units . The mounting uncertainty is an assumed value of 0.5% due to the error in the orientation of the lidar, in relation to the installed FLS system.

Table 2-21. Uncertainty in measured wind speed (wind statistics) for the FLS units used at TNWWFZ

ID	FLS uncertainty description	WS190	WS170	WS191	WS199	WS156	WS187	WS181
F1	Calibration of lidar (from performance verification test)	2.1%	1.3%	2.2%	1.7%	1.2%	2.3%	1.8%
F2	FLS classification	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%	2.6%
F3	Non-homogenous flow uncertainty	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
F4	Mounting uncertainty	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
F5	Uncertainty in variation in flow, data acquisition and post processing	0.0%	1.5%	0.0%	0.0%	1.5%	0.0%	0.0%
F0	**Uncertainty in measurements (instrument)**	**3.4%**	**3.4%**	**3.5%**	**3.2%**	**3.4%**	**3.6%**	**3.3%**

Finally, the given values were analysed by GHPC and informed the weighted uncertainties for the TNWA, TNWA-2 and TNWB locations associated with the calibration of the FLS, as shown in Table 2-21. It is noted that the subtotal of the uncertainties in measured wind speed are derived from binwise calculations considering the specific wind climate at the project site.

Table 2-22. Uncertainty in measured wind speed (wind statistics) for TNWA, TNWA-2 and TWNB

ID	FLS uncertainty description	Corresponding generic uncertainty per Table 2-23	TNWA	TNWA-2	TNWB
F1	Calibration of lidar (from performance verification test)	G1, G3	2.1%	2.0%	1.9%
F2	FLS classification	G1, G3, G4	2.6%	2.6%	2.6%
F3	Non-homogenous flow uncertainty	G1, G4	0.0%	0.0%	0.0%
F4	Mounting uncertainty	G2	0.5%	0.5%	0.5%
F5	Uncertainty in variation in flow, data acquisition and post processing	G1, G3, G4	0.1%	0.0%	0.5%
F0	**Uncertainty in measurements (instrument)**	**G0**	**3.4%**	**3.3%**	**3.4%**

As the TNWA, TNWA-2 and TWNB might be subjected to wakes and induction effects from nearby Gemini wind farm, the data quality and processing of the TNWA, TNWA-2 and TWNB measurements are discussed in the subsequent sections and therefore are not included in the below Table 2-23 where an overview of uncertainties in measured wind speed from the remaining datasets are presented.

GHPC notes that no classification trial results have yet been published for the Fugro Seawatch FLS at the time of the TNW analysis, and the current type is considered stage 2 as per Carbon Trust roadmap. GHPC has assumed a class number of 4.5 for the Fugro Seawatch FLS based on the track record to date and verifications undertaken for the Project.

The uncertainty in measurement accuracy has been assessed for each of the following datasets in terms of instrument accuracy and mounting, as well as data quality and processing as shown in Table 2-23.

Table 2-23. Uncertainty in measured wind speed (wind statistics)

ID	Generic (mast) uncertainty description	FINO 1	MM OWEZ	MMIJ	HKN
G1	Instrument accuracy	2.1%	2.0%	2.0%	3.8%
G2	Instrument mounting	0.5%	2.5%	1.5%	
G3	Data quality	0.5%	0.5%	0.5%	
G4	Data processing	1.7%	1.0%	1.0%	
G0	**Uncertainty in measured wind speed (wind statistics)**	**2.8%**	**3.4%**	**2.7%**	**3.8%**

The overall descriptions of uncertainties in wind speed are provided in Appendix D. Each uncertainty in measurement wind speed is assumed to be independent and represented as a Gaussian distribution, so the subtotal uncertainty is calculated as the root-sum-square of all uncertainties.

3.0 Long-Term Wind Climate Calculation

In order to assess the long-term wind conditions across the TNWWFZ, a Measure-Correlate-Predict (MCP) method was applied to two measured datasets: at TNWWFZ and at FINO 1. The following calculations outline the necessary calculations that led to the quantification of the long-term climate across TNWWFZ.

1. Selection of the measurement height representative for the hub height (Section 3.1)
2. Study of wake impact on selected measured datasets and application of corrections where necessary (Section 3.2.1)
3. Study of induction impact on selected measured datasets and application of corrections where necessary (Section 3.2.2)
4. Data selection for the long-term correction, including the aggregation of TNWA and TNWB measured data (Section 3.3.1)
5. Long-term correction and extension of the short-term measured dataset (TNW and FINO 1) to a selected long-term period (Section 3.4)

The following sections describe the methodology employed in each of these steps.

3.1 Selection of the Representative Measurement Height

The height of 140 m above LAT was assumed to be the hub height of interest for this assessment. The historic development of offshore wind turbines shows an increase of hub heights for new turbines, while the average installed turbine hub height is growing with a time delay of several years [28], [29]. The target of RVO for the TNWFS-1 site is to install modern, state of the art turbines with 13/15 MW rated power. For the selected class of turbines, a hub height of 140 m corresponding to one of the measurement heights, is an appropriate choice.

The mean wind speed at this height at the TNWA and TNWB measurement locations, based on the remote sensing data gathered, are presented below.

Table 3-1. Mean wind speed at 140 m above LAT

Parameter	Value		
Location	TNWA	TNWA-2	TNWB
Selected measurement period	19.06.2019 to 31.12.2020	01.01.2021 to 20.06.2021	19.06.2019 to 20.06.2021
Measurement height above LAT [m]		140	
Data availability [%]*	84%	86%	71%
Mean wind speed [m/s]	10.4	10.1	9.8
Estimated uncertainty in vertical extrapolation [%]	-		-

* of the selected measurement period

A vertical wind speed profile was derived for the site to represent the variation of the wind speed over the rotor, and hub heights other than the target height (140 m) of this report. The vertical wind profiles of the short-term measured wind speed at TNWA and the long-term modelled data is shown in Section 5.2 in Figure 5-1.

The vertical profile was determined from:

- The long-term data for different heights
- Measurements of the vertical wind speed profile

A wind speed profile was fitted to the data above. The deviations of the data from the model can be used as an indicator of the vertical extrapolation uncertainty.

3.2 Study of Wake Impact on Selected Measured Dataset

The TNWA, TNWA-2 and TNWB FLS lie within 18 km distance of operational wind farms, as can be seen in Figure 2-3. Coordinates of the neighbouring Gemini wind turbines are presented in Appendix E.

To assess the wake impact of the operational wind farms on the data, a wake calculation was conducted. This was obtained by carrying out a series of simulations in WakeBlaster [30]. WakeBlaster provides a fast specialised CFD solver that has been independently tested in blind tests and shown to perform well in comparable situations [31], [32].

It is noted that the measurement period considered at FINO 1 is exclusive of any wake impact and the dataset is freestream, as described in section 2.5.4. Therefore, no wake corrections were applied to the FINO 1 dataset.

3.2.1 Wake Correction

Based on the rotor diameter of Gemini wind farm turbines, the selected datasets at TNWA and TNWB are approximately 137 rotor diameters apart from operational neighbouring turbines at Gemini wind farm and therefore the gathered data had inherent wake effects for wind from easterly directions. To mitigate this impact as much as possible and make use of data from the waked sector, a more detailed assessment of the wake effects at this measurement location was conducted. The wake speed factor is a relative measure of the wake effects on wind speed. The worst-case scenario of a strong wake at the measurement point is shown in Figure 3-1 below, here for the 80 m measurement height, the closest height to the Gemini wind farm hub height.

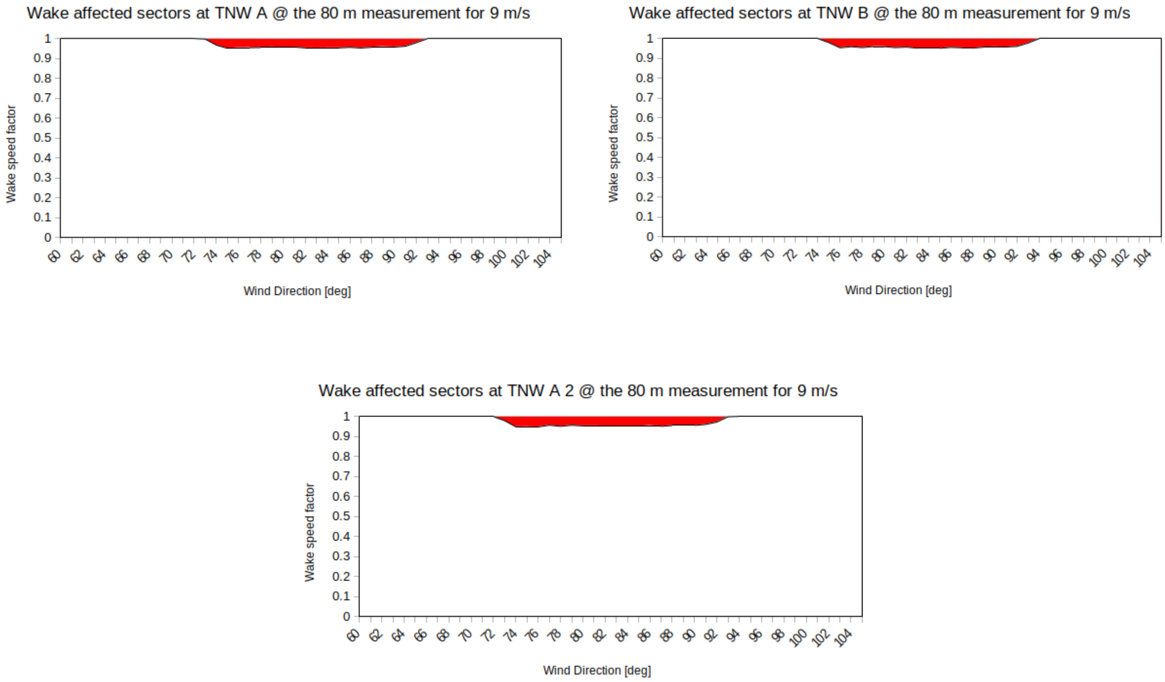

Figure 3-1. Maximum wake effect on the measurement at TNWA (left) and TNWB (right) per direction sector. The red area indicates directions with wake corrections.

For each relevant ambient undisturbed wind speed, wind direction and turbulence, the effect of the wake on a met mast was simulated using WakeBlaster, creating a look-up table. The effect of the wake was then removed from the actual measured short-term data, applying the look-up table in reverse. On the designated hub height of 140 m, this leads to an upward adjustment of 0.1% of the timeseries mean wind speed, with a maximum adjustment of 4.2% from 76 degrees for individual time steps, with wind directions as pictured in Figure 3-2. The wake correction introduced a small wind speed uncertainty which was considered in the uncertainty calculation.

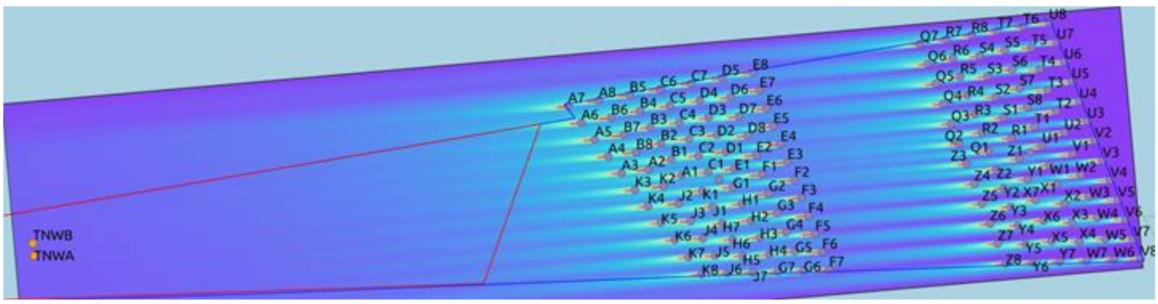

Figure 3-2. The development of the relative wind speed deficit between the wind farms, (example simulation with flow from 85 degrees and a speed of 9 m/s)

3.2.2 Upstream Impact (Induction and Blockage) from Gemini Wind Farms

The wind speed upstream of an existing wind turbine or wind farm is reduced during its operation. Such upstream effects, also known as ‘ induction’ or ‘ global blockage’. At TNWWFZ such effects are caused by the existing Gemini wind farm under westerly winds. This section considers any such impact onto the measurements at TNWA, TNWA-2 and TNWB[5].

The wind speed in this induction zone is a function of the axial thrust coefficient and varies depending on the prevailing meteorological conditions. The distances of each of the measurement locations TNWA, TNWA-2 and TNWB to the nearest wind turbine are above 130 RD (rotor diameters). The actual induction has been checked and found to be less than 0.02% of the wind speed in the worst-case scenario of wind speed, and wind direction with the highest ct value at the investigated locations. Hence it is concluded that the impact on the measurement at TNWA, TNWA-2 and TNWB is negligible. The negligible induction effect was expected due to the significant distance between the TNW measurement locations and the neighbouring Gemini wind farm.

3.2.3 Overall Wake and Induction Correction

The wake correction was derived for and applied to each individual timestep before further processing. The short-term wind-rose and sector-wise comparison of the measured and wake-free wind speeds are shown in Figure 3-3 to Figure 3-5.

Based on the above analysis, the overall wake and induction correction factor was found to be 0.1% for both TNWA and TNWB datasets throughout the analysed measurement campaign period.

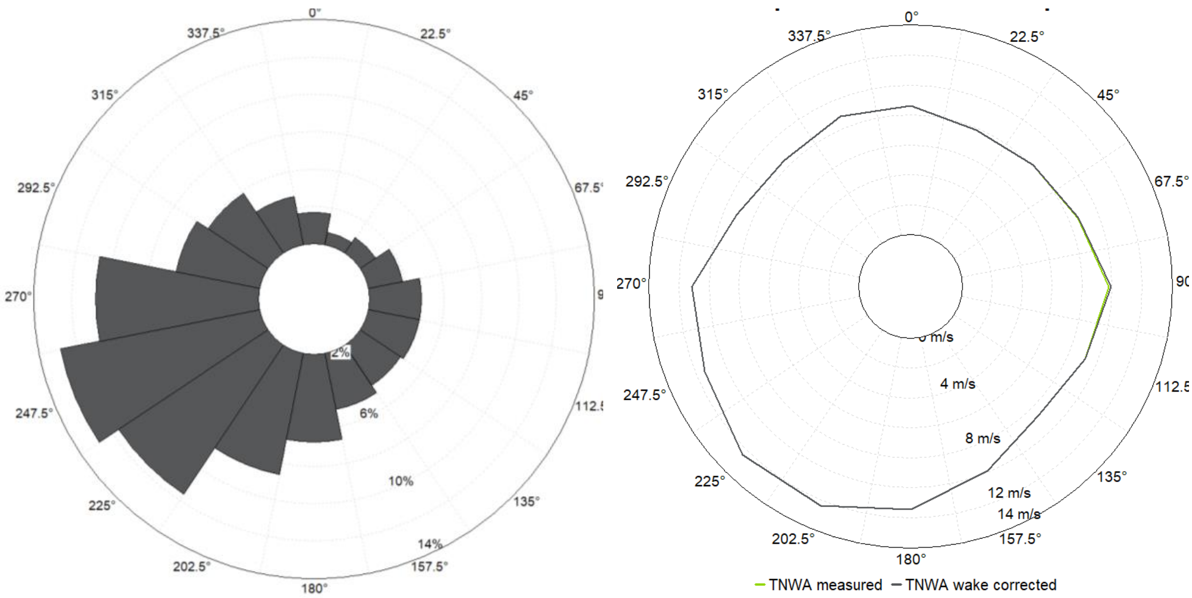

Figure 3-3. Wind rose (left) and comparison of measured and wake-free wind speeds (right) at TNWA

[5] Not covered in the scope of this report are meteorological effects that may be observed in extreme or rare weather situations without significant impact on the AEP of a wind farm.

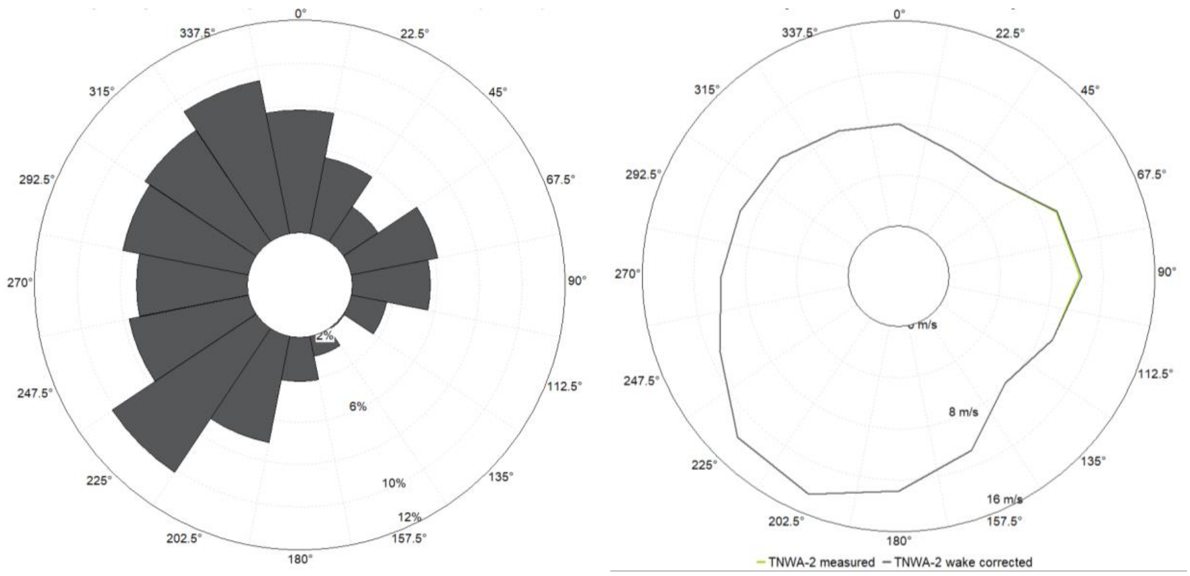

Figure 3-4. Wind rose (left) and comparison of measured and wake-free wind speeds (right) at TNWA-2

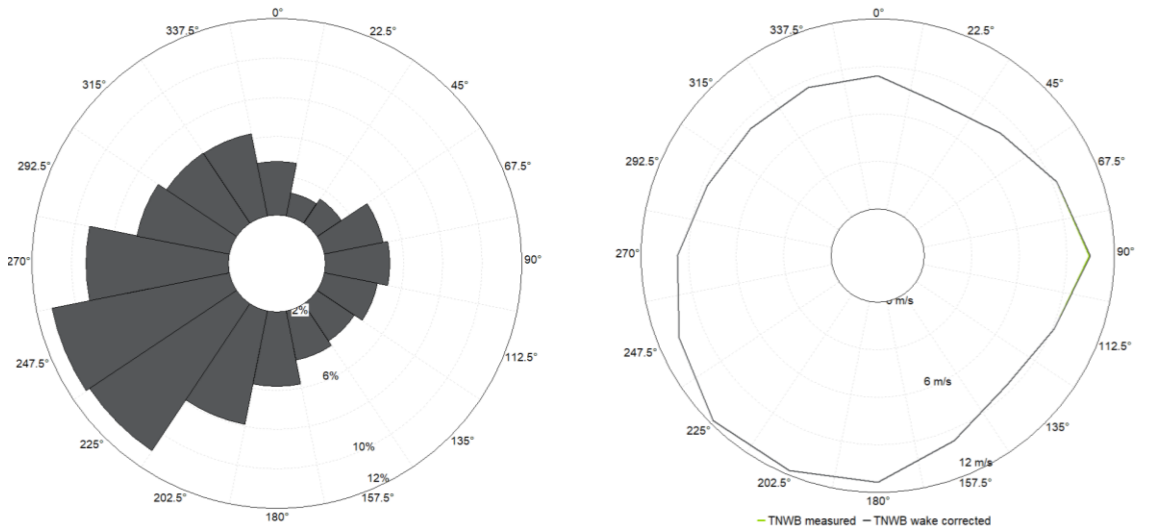

Figure 3-5. Wind rose (left) and comparison of measured and wake-free wind speeds (right) at TNWB

3.3 Data Selection for Long-Term Correction

The datasets selected for the long-term correction were chosen based on the distance from the TNWWFZ, the quality and duration of the data, the hub height of interest at 140 m and their contribution potential to deriving the final mesoscale model. The datasets selected were:

- Wake-corrected TNWA, TNWA-2 and TNWB wind speed and wind datasets at 140 m measurement height, covering the measurement period from 19.06.2010 to 20.06.2021.

- FINO 1 dataset at the 102.5 m and 92 m wind speed and wind direction measurement heights, respectively, covering a duration of five (5) years from 01.01.2004 to 31.12.2018.

These measurement heights were selected based on 140 m hub height of interest and the data quality and data coverage available.

It is noted that although the measured datasets at TNWA, TNWA-2 and TNWB were found to be of good quality, they have a 140 m wind speed data coverage of 84%, 86% and 71%, respectively. This is not considered to be fully adequate for a long-term correction, particularly for the TNWB dataset. Therefore, to mitigate the reduced data coverage, the measured datasets at TNWA, TNWA-2 and TWNB were combined to maximise the data coverage as much as possible.

The methodology employed is described in the following sections. The combined dataset is here forth described as the TNW dataset.

3.3.1 TNW Dataset: Combining TNWA, TNWA-2 and TNWB Datasets

The wake-corrected TNWA , TNWA-2 and TNWB datasets were aggregated to form a singular wake-free dataset representative of the onsite measurements and with maximised data coverage.

The final combined dataset was created by selecting TNWA and TNWA-2 as the primary datasets and TNWB as the backup dataset, filling up any gaps in TNWA and TNWA-2. This aggregated dataset will be referred to as TNW.

The following checks were conducted before the aggregation method was selected:

- Correlation checks between datasets TNWA and TNWB, TNWA-2 and TNWB
- Data coverage and data quality of each of the datasets
- Mean bias error in mean wind speed values for concurrent data
- Measurement uncertainty associated with each dataset

3.3.1.1 Wind speed and wind direction correlations

Two sets of data were correlated against each other for the same heights. The correlation was done for concurrent datasets between TNWA and TNWB and TNWA-2 and TNWB. As the height of interest is 140 m, the following descriptions focus on this measurement height.

The correlation coefficient R^2 was found to be 0.99 between the TNWA 140 m and TNW B 140 m and between TNWA-2 140 m and TNWB 140m, with wake-corrected data. This indicates a strong similar behavioural pattern between the datasets, as expected. A scatter plot of the datasets is shown in Figure and Figure for the wind speed and wind direction data gathered at the 140 m measurement height. Appendix F presents sectorwise scatter plots of TNWA versus TNWB 140 m wind speed data.

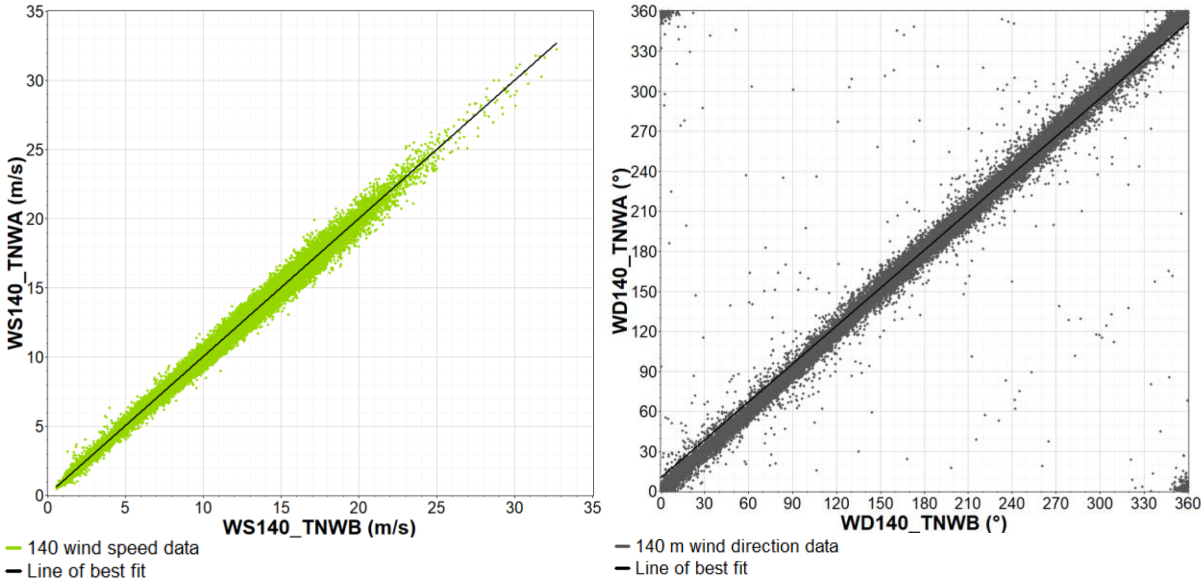

Figure 3-6. Scatter plot of TNWA and TNWB 140 m wind speed data

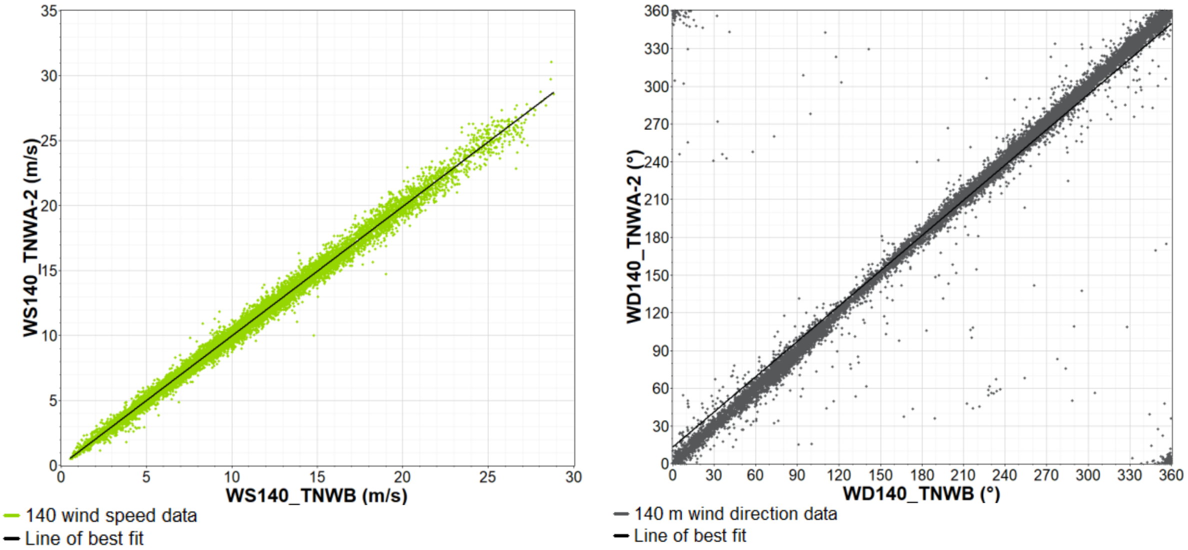

Figure 3-7. Scatter plot of TNWA-2 and TNWB 140 m wind speed data

The sectorwise correlation coefficient between the data were also observed on a 12-sector basis. Table 3-2 shows the results obtained. As can be observed in Table 3-2, the datasets show a strong relationship on sectorwise basis, showing that the two measurement locations underwent very similar wind exposure on a sectorwise basis.

Table 3-2. Coefficient of determination (R^2)

Sector	TNWA vs TNWB R^2 value	TNWA-2 vs TNWB R^2 value
345° - 15°	0.99	0.99

Sector	TNWA vs TNWB R^2 value	TNWA-2 vs TNWB R^2 value
15° - 45°	0.99	0.99
45° - 75°	0.99	0.99
75° - 105°	0.99	0.99
105° - 135°	0.99	0.99
135° - 165°	0.99	0.99
165° - 195°	0.99	0.99
195° - 225°	0.99	0.99
225° - 255°	0.99	0.99
255° - 285°	0.99	0.99
285° - 315°	0.99	0.99
315° - 345°	0.99	0.99
All	**0.99**	**0.99**

3.3.1.2 Mean wind speed values

The TNWA and TNWA-2 datasets have a higher data coverage than TNWB. Therefore, for a precise like-with-like comparison, the exact concurrent period between the two datasets was used to assess mean wind speed values. As can be observed in Table 3-3, the TNWB dataset was found to be measuring slightly lower wind speeds than TNWA, while in Table 3-5, TNWB is found to be measuring a marginally higher wind speed than TNWA-2. To assess the impact of the difference in wind speeds, the mean bias error (MBE) between the two datasets was calculated. The MBE is the mean of the TNWB values minus the TNWA/TNWA-2 values on a timestep basis and indicates how well the two datasets match.

Table 3-3 presents the results of this assessment. It can be observed that the MBE is well within the expected uncertainty margin of the measured datasets.

Table 3-3. TNWA and TNWB mean wind speed and mean bias error

Parameter	TNWA	TNWB
Mean wind speed – concurrent data [m/s]	9.92	9.88
Mean bias error [m/s]	-0.04	
Mean bias error [%]	-0.4%	

Table 3-4. TNWA-2 and TNWB mean wind speed and mean bias error

Parameter	TNWA-2	TNWB
Mean wind speed – concurrent data [m/s]	10.02	10.03
Mean bias error [m/s]	0.01	
Mean bias error [%]	0.10%	

3.3.1.3 TNW Dataset Aggregation

The data aggregation conducted to derive a single dataset TNW, is based on the following observations. It is noted that the points presented below are based on the wake-corrected data.

- The correlation coefficient of TNWA vs TNWB and TNWA-2 vs TNWB wind speed at 140 m measurement height is very strong, even on a sectorwise basis. This indicates a similar pattern between the two sets of data.
- For concurrent periods, TNWA dataset has a higher data coverage than TNWB dataset, at 84% and 71%, respectively.
- For concurrent periods, TNWA-2 has a higher data coverage than TNWB dataset, at 86% and 71%, respectively
- The combined measurement uncertainty associated with TNWA and TNWA-2 is in excellent agreement with TNWB, as presented in section 2.9.
- For concurrent TNWA and TNWB wind speed datasets at 140 m height, the mean bias error between the two datasets is well within the uncertainty associated with the measurements.
- For concurrent TNWA-2 and TNWAB wind speed datasets at 140 m height, the mean bias error between the two datasets is well within the uncertainty associated with the measurements.

Based on the above comments, TNWA and TNWA-2 were considered to be have higher associated confidence than TNWB. Therefore, the method of primary-backup was selected to aggregate the data, whereby TNWA and TNWA-2 were the primary consecutive datasets and TNWB was the backup dataset and used to fill any gaps in the TNWA and TNWA-2 datasets.

The final TNW dataset has a data coverage of 90% for the period 19 June 2019 to 20 June 2021 and a mean wind speed of 10.22 m/s and a prevailing wind direction of 238° at a height of 140 m. It is assumed that the reference location for the TNW dataset is midway between the TNWA and TNWB locations.

3.3.1.4 TNW Dataset Reference Location and Overview

The TNW dataset reference location was selected to be geographically midway between the TNWA and TNWB measurement locations. Given that the TNWA and TNWB measurement locations were approximately 500 m apart, the wind climate at the TNW reference location was considered to be negligibly different to those at TNWA and TNWB. It is noted that although TNWA-2 lies further east from TNWA, the TNW location previously reported in version 4.0 of this report was maintained. As can be seen in sections 3.3.1.1 and 3.3.1.2, TNWA-2 exhibits excellent correlation with TNWB and therefore the variation of climate from the TNWA and TNWB locations to TNWA-2 is considered to be negligible.

Table 3-5 below presents the coordinates for the selected TNW reference location and an overview of the associated values.

Table 3-5. Overview of TNW dataset

Parameter	TNW 140 m dataset
Location [UTM ETRS89, Zone 31]	667056 N, 5988751 E
Measurement period available for analysis	19.06.2019 to 20.06.2021
Measurement averaging interval	10 minutes

Parameter	TNW 140 m dataset
Mean wind speed at 140 m	10.22 m/s
Data coverage of 140 m wind speed	90%
Mean wind direction at 140 m	238°
Data coverage of 140 m wind direction	90%

3.3.2 Uncertainty in TNW Wind Speed Measurements

The uncertainty in measurement accuracy for the aggregated TNW dataset is presented in Table 3-6.

Table 3-6. Uncertainty in measured wind speed (wind statistics) for TNW

Uncertainty Description	TNW
Instrument accuracy	3.4%
Instrument mounting	
Data quality	
Data processing	
Data aggregation	0.2%
Wake and induction corrections	0.1%
Uncertainty in measured wind speed (wind statistics)	**3.4%**

The uncertainty in the data aggregation was estimated to be 0.2%, which is half the mean bias error presented in Table 3-3. The uncertainty inherent in the wake and induction corrections described in Section 2.9 is a nominal assumption to account for uncertainty in the methodology as the calculated uncertainty as a percentage of the total corrections conducted was negligible.

Finally, the uncertainty in measured wind speed for all datasets are shown in Table 3-7.

Table 3-7. Uncertainty in measured wind speed (wind statistics), including TNW

Uncertainty Description	TNW	FINO 1	MM OWEZ	MMIJ	HKN
Uncertainty in measured wind speed (wind statistics)	3.4%	2.8%	3.4%	2.7%	3.8%

3.4 Long-Term Climate Calculation

The ERA5 dataset was used to correct the TNW and FINO 1 datasets to the long-term with a Measure-Correlate-Predict (MCP) method. The MCP method analyses the relationship between the short-term measured dataset and the concurrent data from the reference dataset. The statistical relationship between the two datasets is used to predict and synthesise the onsite data to the long-term. The synthesis method extends the measured time series but does not replace the measured data.

The short-term datasets were as seasonally corrected in the MCP methodology. The data period used for the MCP procedure was from 01 November 2005 to 31 October 2020 to correct FINO 1 and 01 July 2005 to 31 June 2021 to correct TNW. The reference datasets were averaged to hourly timesteps for the following analyses.

3.4.1 Long-Term Reference Dataset Selection

A number of long-term data sources were considered as reference data. The suitability of each of these sources was assessed based on a thorough validation procedure as described in the following sections.

The following sources were considered, with further details described in Appendix G:

- EMD-WRF Europe+ mesoscale data (initiated with ERA5): High resolution mesoscale data modelled by EMD (http://www.emd.dk). The mesoscale model is run by EMD at a spatial resolution of 3x3 km with hourly temporal resolution. ERA5 data from ECMWF (http://www.ecmwf.int) has been used as the global boundary data set. The data set covers most parts of Europe. This data was sourced by GHPC.

- DOWA mesoscale data (initiated with ERA5): High resolution mesoscale modelled data by the DOWA project (consortium of project partner). It is run with a resolution of 2.5 km by 2.5 km with an hourly temporal resolution. The ERA5 data from ECMWF has been used as a global boundary dataset. This data is the successor of KNW and was sourced by GHPC.

- KNW mesoscale data (initiated with ERA-Interim): High resolution mesoscale modelled data by KNMI North Sea Wind. It is run with a spatial resolution of 2.5 km by 2.5 km with an hourly temporal resolution. The ERA-Interim reanalysis dataset was used as a global boundary dataset. This mesoscale data is the predecessor of DOWA. This data was sourced by GHPC.

- New European Wind Atlas (NEWA) mesoscale data (initiated with ERA5): NEWA by the NEWA Consortium is a mesoscale model with a nested grid and a maximum spatial resolution of 3 km. Data is available for Europe for the period 2009 to 2018. This data was sourced by GHPC.

- ERA5 data is a reanalysis data set, which is calculated and provided by the European Centre for Medium-Range Weather Forecasts, short ECMWF. A broad range of meteorological parameters is available for the time from 1950 to near real time (approximately 5 days). ERA5 data is calculated with a spatial resolution of 31 km and a temporal resolution of one hour (These values are valid for the atmospheric parameters under consideration here. For other parameters, different resolutions were used). This data was sourced by GHPC.

- MERRA-2 reanalysis data is the second version of the Modern-Era Retrospective analysis for Research and Application, provided by the NASA. MERRA-2 data is available for the period since 1980 at a temporal resolution of one hour and an unchanged spatial resolution compared to the older MERRA dataset, which is approximately 50 km in the latitudinal direction. This data was sourced by GHPC.

All the reference datasets were sourced for the most recent 10, and if available 20 years, concurrently covering the measurement period of the selected TNW and FINO 1 datasets. The selection of the reference dataset was based on a validation procedure as follows:

- Coefficient of determination with measured wind speed data (R^2)

- Height of reference dataset

- Distance of data node from the measurement locations.

- Data availability

- Acceptance within the industry.

Table 3-8 below shows the comparison of the above parameters for each source. It is noted that the selection of reference data was conducted after 12 months of measured data were available at TNWA and TNWB. Therefore, all R^2 values presented in Table 3-8 were estimated based on this period of measured data.

Table 3-8. MCP reference datasets comparison and validation at TNW

Source:	**EMD-WRF Europe+**	**DOWA**	**KNW***	**NEWA**	**ERA5**	**MERRA-2**	**CFSR**
Latitude	**54.03°N**	**-**	**54.01°N**	**-**	**54.09°N**	**54.00°N**	**53.66°N**
Longitude	**5.56°E**		**5.56°E**		**5.40°E**	**5.62°E**	**5.52°E**
Number of concurrent hourly timesteps	5206	0	1605	0	5208	5207	5208
R^2 with wind speed	0.88	*No concurrency*	0.81	*No concurrency*	0.90	0.89	0.82
Height [m]	100	-		-	100	50	10
Distance from TNW [km]	<1	-	<1	-	13	5	40
Data availability [%]	100	-	100	-	100	100	100
Grid resolution [km]	3	-	2.5	-	31	50	38

*concurrency is for approximately 2 months

Table 3-9. MCP reference datasets comparison and validation at FINO 1

Source:	**EMD-WRF Europe+**	**DOWA**	**KNW**	**NEWA**	**ERA5**	**MERRA-2**	**CFSR**
Latitude	**54.02°N**	**53.86°N**	**54.00°N**	**-**	**54.10°N**	**54.00°N**	**-**
Longitude	**6.59°E**	**6.80°E**	**6.59°E**		**6.75°E**	**6.88°E**	
Number of concurrent hourly timesteps	40148	7884	40148	0	40148	40148	0
R^2 with wind speed	0.90	0.89	0.90	*No concurrency*	0.92	0.89	*No concurrency*
Height [m]	100	100	100	-	100	50	-
Distance from FINO 1 [km]	<1	23	1	-	14	19	-
Data availability [%]	100	100	100	-	100	100	-
Grid resolution [km]	3	2.5	2.5	-	31	50	-

The NEWA, DOWA and CFSR datasets are considered to be an advanced and reliable datasets. Unfortunately, there is no overlap of data between both measured datasets and the NEWA and DOWA datasets. Therefore, they were excluded from the analysis. Moreover, the KNW and TNW datasets have approximately two (2) months of concurrency as the KNW data ends in August 2019. This concurrency period is not considered to be adequate for establishing a reliable relationship between the datasets for an MCP with high confidence; therefore KNW was also not considered suitable as a reference dataset.

Out of the remaining datasets, the ERA5 data shows the best correlation to the onsite data. As the reliability of the ERA5 dataset is well known in the industry, it was chosen as reference dataset.

The long-term data was checked for any trends. Different long-term periods ranging from 10 to 20 years were analysed. A period was selected that minimises the effect of a possible trend while a remaining representative for the long-term today. The selected long-term period was from 01 November 2005 to 31 October 2020, covering a period of 15 years. This long-term period was applied in the long-term correction at FINO 1.

The long-term period was reassessed due to the additional onsite measured data at TNW. A long-term period of 01 July 2005 to 30 June 2021 was selected for the long-term correction of TNW. The trend analysis of the selected periods is shown in Appendix H.

Causes of the long-term variation could be cyclic, statistical, or a long-term regional climatic trend. Wind speed maps that are based on older data will consequently and correctly show a substantially different picture from those based on most recent data. It was outside the scope of this report to discuss underlying mechanisms.

3.4.2 MCP Method

The MCP method using a least-square fit following time synchronization was applied to the different direction sectors independently. Different numbers of sectors were used in order to find the best possible MCP.

The quality of the correlation was estimated using the same method as for the uncertainty in the long-term correction (Section 3.4.4), Table 3-10. Based on this performance test, the total least squares (TLS) method with 12 directional sectors was selected as it covers the directional aspects of the data sets in a sufficient level of detail and the additional gains by increasing the number of sectors is minimal.

It is noted that TNW data shows significant gaps in the winter months of the year 2020, specifically in January 2020, with a 26% data coverage. Therefore, a sensitivity analysis was conducted to gain additional confidence in the results. This was done by conducting an omnidirectional correlation with the TLS method, split into 12 months on an hourly basis. The resulting long-term wind speed of 10.22 m/s and correlations (shown in Figure 3-8, with an overall weighted R^2 of 0.86) from this sensitivity analysis is in excellent agreement with the results of the final, 12-sectoral correlation shown in Figure 3-8. A recent analysis conducted in the Dutch North Sea concluded that the impact of gaps in short-term measurements significantly reduces following a long-term correction [33]. Accordingly, GHPC considers the MCP results robust and recommends an update of the analysis once a longer dataset with high availability will be available.

Table 3-10. Performance test results for MCP methods

MCP method	Correlation uncertainty [%]	
Input dataset (short-term)	TNW	FINO 1
MCP unidirectional	1.26	1.52
MCP with 12 sectors	1.24	1.49
MCP with 36 sectors	1.24	1.48

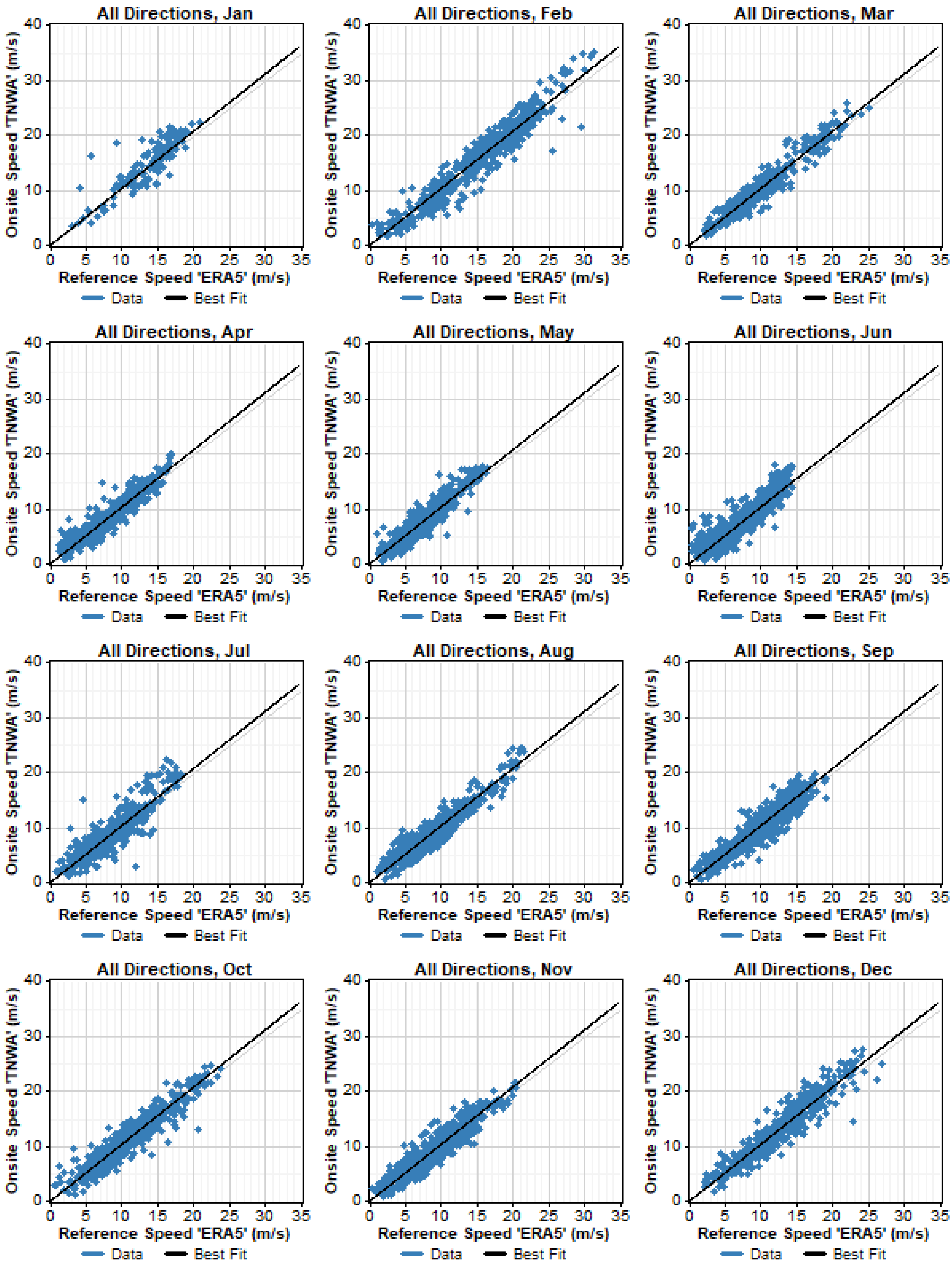

Figure 3-8. Sensitivity correlation analysis based on monthly correlations - TNW scatter plot of ST dataset vs LT dataset wind speeds

3.4.3 Long-Term Correction

The long-term adjustment of the short-term data is based on ERA5 data. It is noted that due to the geographical distance between TNW and FINO 1, the ERA5 reference nodes closest to each of the measurement locations were used to obtain the optimal correlations and resulting long-term corrections.

The analysis of the concurrent period with normalised wind speeds exhibit excellent alignment between the measured datasets and reference ERA5 nodes for the concurrent period, as shown in Figure 3-9. It is noted that the TNW dataset was seasonally balanced (50% winter, 50% summer) prior to conducting the MCP, to avoid any seasonal bias in the long-term correction.

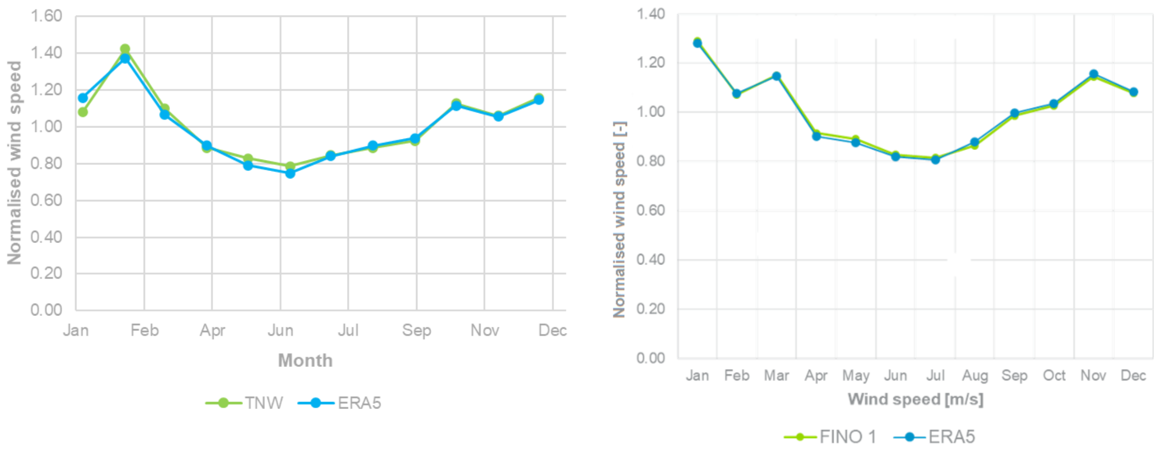

Figure 3-9. Normalised monthly wind speeds of the short-term and the respective reference datasets for the concurrent period, TNW (left) and FINO (right)

Similarly graphs of the concurrent period showing the wind mean speed versus wind direction, as presented in Figure 3-10, illustrate excellent alignment of ERA5 with the measured datasets, highlighting that the selected ERA5 reference datasets are representative for the measured datasets.

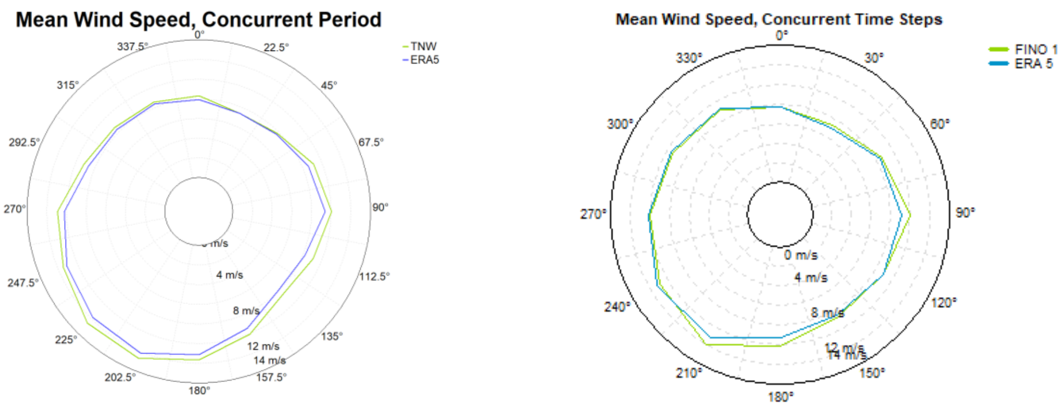

Figure 3-10. Directional wind mean speed graphs of the short-term and the respective reference datasets for the concurrent period, TNW (left) and FINO (right)

Correlation scatter graphs showing the sectorwise wind speed and wind direction are presented in Figure 3-11, Figure 3-13 for TNW, and in Figure , Figure 3-14 for FINO 1 respectively.

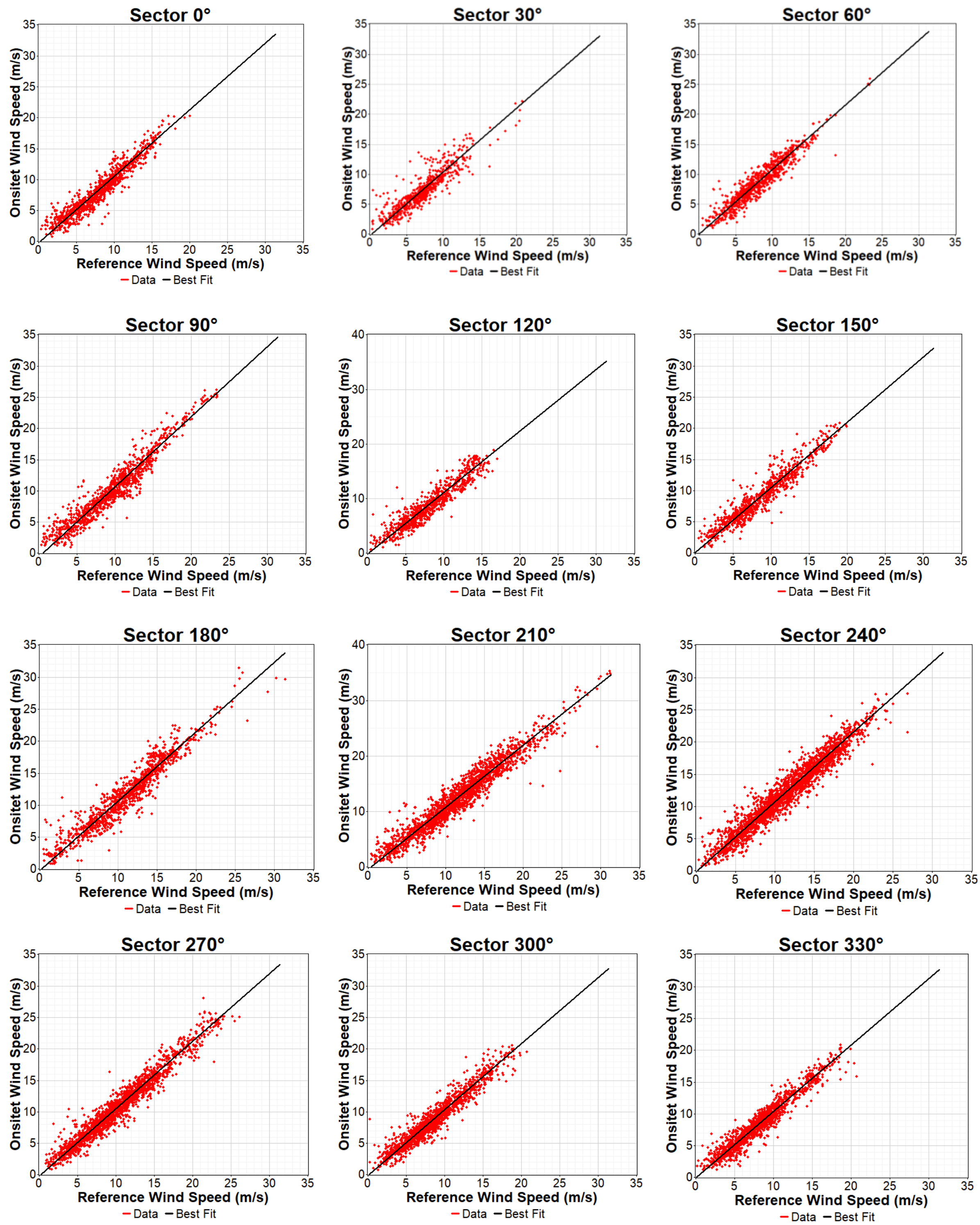

Figure 3-11. TNW scatter plot of ST dataset vs LT dataset wind speeds

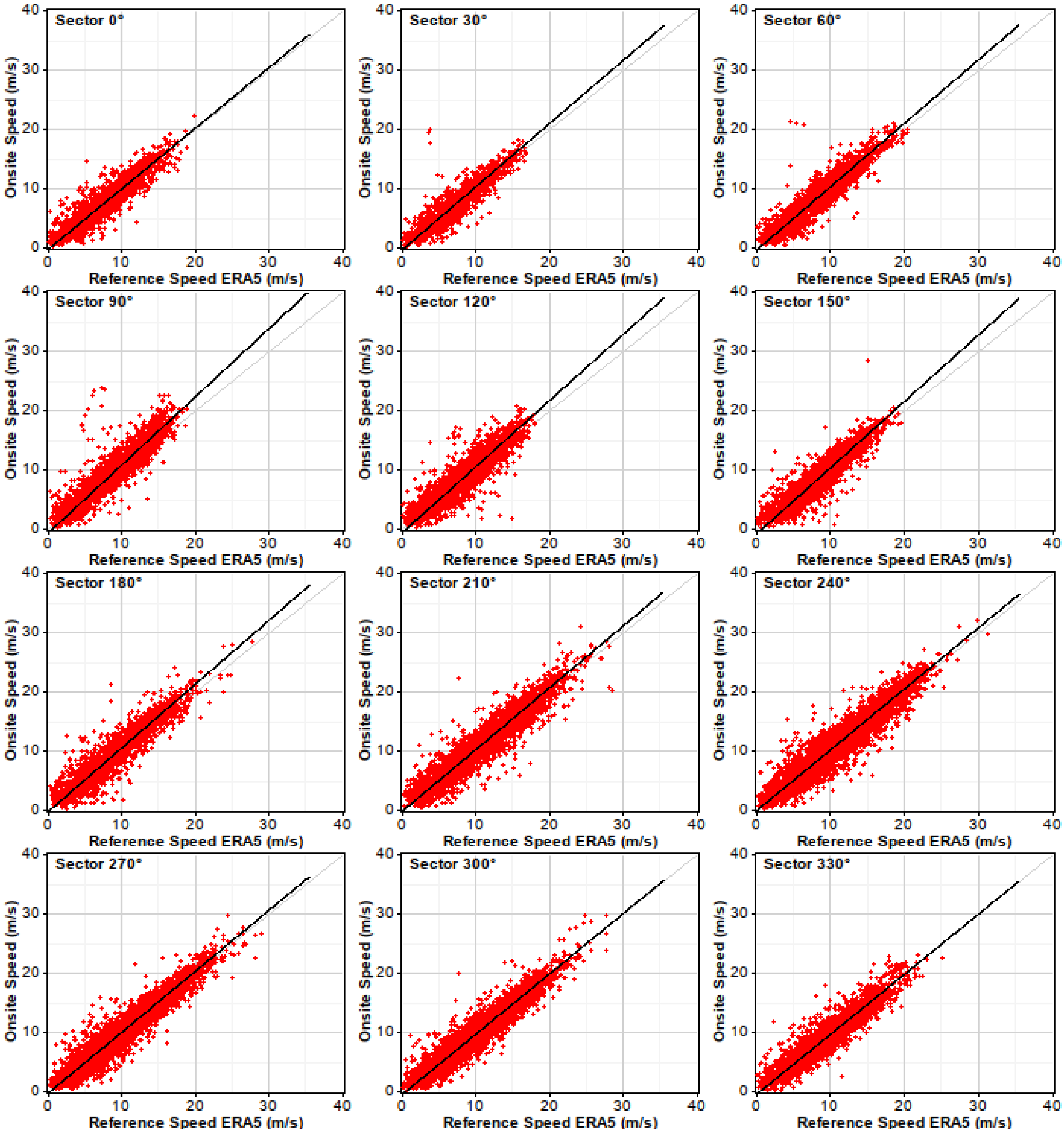

Figure 3-12. FINO 1 scatter plot of ST dataset vs LT dataset wind speeds

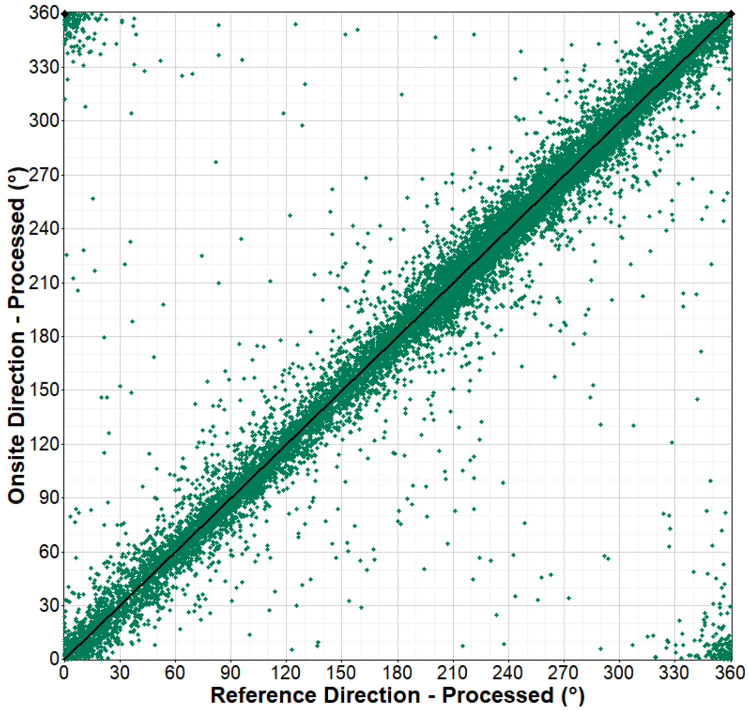

Figure 3-13. TNW scatter plot of ST dataset vs LT dataset wind directions

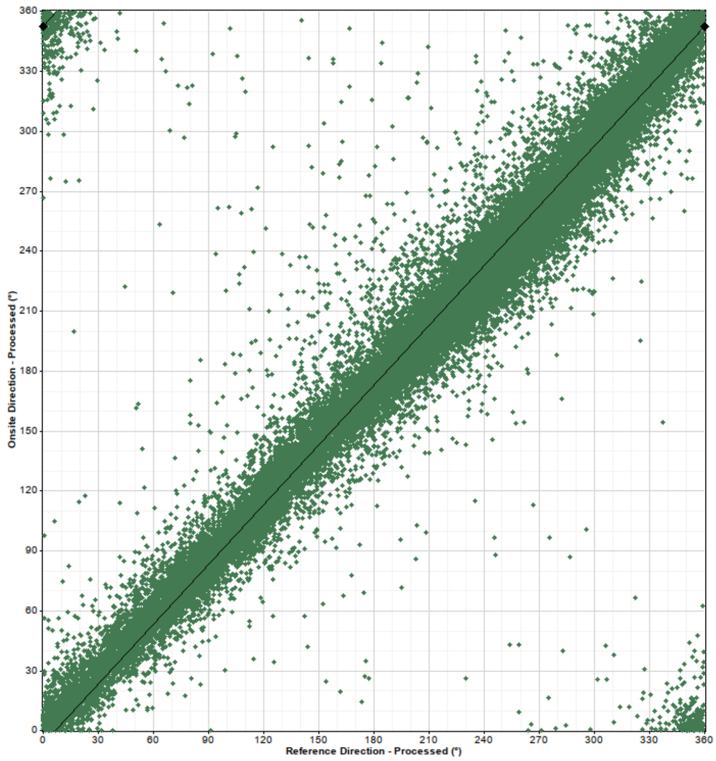

Figure 3-14. FINO 1 scatter plot of ST dataset vs LT dataset wind directions

The resulting long-term wind speed at the TNW reference location at a height of 140 m above LAT is 10.30 m/s while the long-term wind speed at FINO 1 at a height of 102.5 m above LAT is 9.94 m/s. The details of the MCP are presented in Table 3-11.

Table 3-11. MCP details

Dataset characteristic	Value	
Input dataset (short-term)	TNW	FINO 1
Measurement height above LAT [m]	140.0	102.5
Measurement period	19.06.2019 to 20.06.2021	01.01.2004 to 31.12.2008
Measured hourly mean wind speed [m/s]	10.25	9.93
ERA5 dataset (long-term reference)	54.09°N, 5.40°E	54.10°N, 6.75°E
Reference height	100 m	
Reference period	01.07.2005 to 30.06.2021	01.11.2005 to 31.10.2020
Mean wind speed concurrent period [m/s]	9.75	9.70
Mean wind speed total period [m/s]	9.80	9.70
Output (long-term) extended dataset		
Height above LAT [m]	140.0	102.5
Long-term period	01.07.2005 to 30.06.2021	01.11.2005 to 31.10.2020
Long-term mean wind speed [m/s]	10.30	9.94
Increase short-term to long-term [%]	+0.5%	+0.1%

A comparison of the short-term and long-term wind frequency roses are provided in Figure and Figure 3-16 for TNW and FINO 1 respectively.

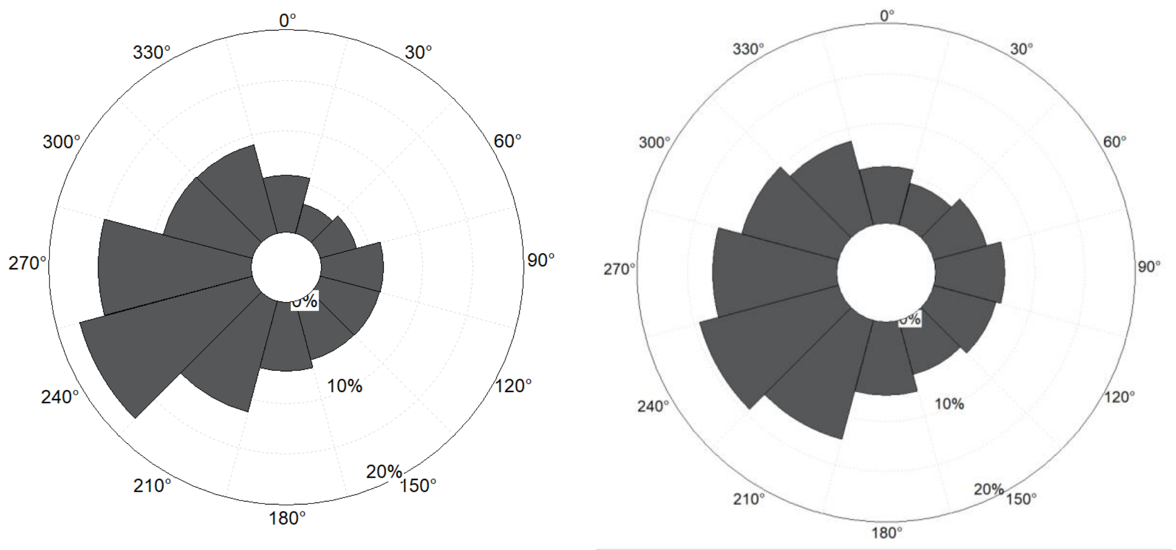

Figure 3-15. TNW wind frequency roses of ST dataset (left) and LT dataset (right)

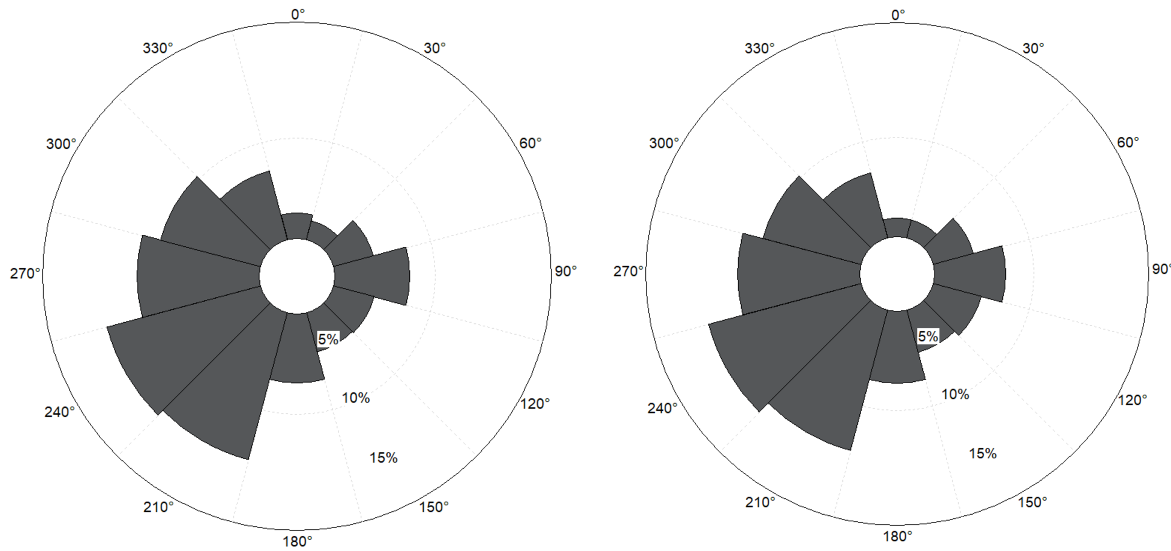

Figure 3-16. FINO 1 wind frequency roses of ST dataset (left) and LT dataset (right)

3.4.4 Uncertainty in Long-Term Correction

The uncertainty intrinsic to the MCP method was calculated by considering the quality of the reference dataset, the correlation between the reference dataset and the measurements, and the representativeness of the reference long-term data on the local wind conditions. On this basis the estimated uncertainty in the MCP method uncertainty (long-term correction) is 2.1% and 2.5% in terms of wind speed for TNW and FINO 1 respectively.

3.5 Total Uncertainty in Wind Speed at TNW and FINO 1

The combined uncertainty in the long-term wind speed at TNW reference location at 140 m height above LAT is shown in Table 3-12. Brief descriptions are also provided below and in Appendix J.

Table 3-12. Total uncertainty in long-term wind speed

Uncertainty description	TNW	FINO 1
Total uncertainty in measured wind speed (wind statistics)	3.4%	2.8%
Long-term representation	1.4%	1.4%
MCP method uncertainty (long-term correction)	2.1%	2.5%
Total uncertainty in long-term wind speed	**4.3%**	**4.0%**

The uncertainty in measured wind speed is the value of the respective uncertainty associated with the TNW wind speed, presented in Section 3.3.2.

The uncertainty intrinsic to the MCP method was calculated by considering the quality of the reference dataset, the correlation between the reference dataset and the measurements, and the representativeness of the reference long-term data for the local wind conditions. It is noted that the MCP method uncertainty of FINO 1 is marginally higher than TNW due to slight increase in the uncertainties related to correlation and representativeness (wind speed distribution).

The uncertainty related to the long-term representation (variability) is based on the length of the long-term extended measurements of 15 and 16 years, at FINO 1 and TNW, respectively.

4.0 Spatial Analysis for TNWWFZ

GHPC has developed a tailor-made mesoscale modelled dataset using the WRF model, driven with initial and boundary conditions from the ERA5 reanalysis, to assess the wind potential across TNWWFZ. The model was calibrated with the TNW and FINO 1 met mast datasets to bring it in alignment with the short-term on-site measurements, followed by a long-term adjustment to align with the long-term corrected wind speed at the TNW reference location and FINO 1.

An overview of the steps conducted to arrive at this final mesoscale model are presented below, and represent the chronological order in which the analysis was conducted.

1. GHPC developed a tailor-made mesoscale model using the Weather Research and Forecasting Model (WRF) model initiated with ERA5 reanalysis data and is hereafter referred to as the GHPC Tailored WRF. This model was developed by GHPC prior to the selection of the most appropriate mesoscale model and it's development was based on knowledge already attained from all the measured datasets described in section 2.0. The GHPC Tailored WRF model aimed to provide a comprehensive project-specific mesoscale model with a higher associated confidence than the alternative sources available. A description of its development and initial validations conducted is presented in section 4.1.

2. The most appropriate reference modelled dataset was selected by a detailed spatial analysis of the different datasets available to the GHPC team. This included the modelled datasets from: EMD-WRF ERA5, DOWA, KNW, NEWA and the aforementioned GHPC Tailored WRF model. This analysis is presented in section 4.2, along with a high-level description and comparison of each data source.

3. Following the selection process, the selected mesoscale model (the GHPC Tailored-WRF) underwent a further two-step optimisation process: firstly a calibration to adjust the mesoscale model to the measured onsite wind characteristics at the TNW and FINO 1 reference locations and secondly, a long-term adjustment to produce model outputs that are representative of the long-term. Further validations were then conducted to assess the final model performance. These validations also assisted in the quantification of the modelling uncertainties. These analyses are presented in section 4.3.

4. The final mesoscale model was then extrapolated across the TNWWFZ. The process associated with this is presented in section 4.4.

5. The final section 4.5 presents the uncertainties associated with the final model outputs, a comparison of the model outputs with the metocean study, alignment with previous studies conducted in the Dutch North Sea and a high-level comparison with other mesoscale models.

4.1 GHPC Tailored WRF Model Development and Validation

GHPC has developed a tailor-made mesoscale model using the WRF model, initiated using the ERA5 reanalysis dataset. The development process applied to produce this model is described in detail below. It is noted that the GHPC tailor-made mesoscale model was developed once 12 months of measured data gathered at TNWA and TNWB was available. No further changes were applied following 24 months of gathered data.

GHPC's customized mesoscale model simulation was developed in several stages. The first stage of development was to test for the best configuration of the WRF for the TNWWFZ offshore domain. There are many aspects of the model that could be configured to potentially affect its accuracy for a particular application, but the main motivator was the desire for near-surface wind speed accuracy and hence the testing of planetary boundary layer (PBL) representations. The PBL is the model physics option that is most likely to have an impact on the near-surface wind flow patterns.

GHPC tested three (3) commonly used PBL schemes: the Yonsei University Scheme (YSU), the Mellor-Yamada-Nakanishi-Niino (MYNN) scheme and the Total energy-mass flux (TEMF) scheme.

Using these schemes, GHPC performed configuration tests to evaluate which of the three candidate PBL scheme performs best. The configuration tests were run as follows:

- Four (4) unique years were selected such that they overlap with periods of unwaked observations from one or more of the five sites. It is noted that the measurement period of FINO 1 and OWEZ overlap, therefore the same year was used to validate against these two datasets. The following years were selected for each respective dataset:
    - June 2019 – June 2020 for TNW
    - July 2005 – June 2006 for FINO 1 and OWEZ
    - April 2017 – March 2018 for HKN
    - January – December 2015 for MMIJ
- For each of the years listed above, 30 random days spread evenly over all seasons within each respective year were simulated. Therefore, the simulations were run for a total of 120 days, spread across the indicated years.

Based on the 30 simulated days of overlap at each respective measurement site, the following metrics were used to select the final mesoscale modelled dataset:

- Hourly correlation coefficient R^2 values for wind speed and wind direction;
- Mean absolute error of wind speed
- Kolmogorov-Smirnov (K-S) test for equality of the wind speed distribution

In addition, GHPC evaluated the spatial pattern of mean wind speed, by calculating the root mean square error (RMSE) across these measurement locations. However, RMSE is sensitive to both overall bias and variability across the five (5) measurement locations. Therefore, the bias-corrected RMSE (bc-RMSE) was calculated. This gives the best indication of which model source is capturing the spatial variability across the different modelled measurement locations.

The results of this assessment is presented in Table 4-1. It is noted that the best performing scheme result is marked in **bold**.

Table 4-1. Statistical test results for the different PBL schemes

Location	Parameter	YSU PBL	MYNN PBL	TEMF PBL
TNW	Wind speed R^2	**0.96**	0.94	0.91
FINO1		**0.91**	**0.91**	0.83
HKN		**0.88**	0.87	0.85
OWEZ		**0.92**	**0.92**	0.82

Location	Parameter	YSU PBL	MYNN PBL	TEMF PBL
MMIJ		**0.93**	**0.93**	0.91
TNW	MAE	0.86	**1.04**	1.20
FINO1		**1.03**	0.94	1.31
HKN		**1.04**	1.18	1.26
OWEZ		**0.99**	0.97	1.37
MMIJ		**0.98**	1.09	1.14
TNW	K-S test	**0.03**	0.07	0.04
FINO1		**0.03**	0.04	0.05
HKN		**0.07**	0.10	0.06
OWEZ		**0.05**	0.06	0.08
MMIJ		**0.05**	0.08	0.05
TNW	Wind direction R^2	**0.98**	**0.98**	0.97
FINO1		**0.96**	**0.96**	0.86
HKN		**0.97**	**0.97**	0.96
OWEZ		**0.91**	**0.91**	0.84
MMIJ		**0.97**	**0.97**	0.96
Spatial RMSE of long-term mean wind speed [m/s]		**0.16**	0.29	0.18
Spatial bc-RMSE of long-term mean wind speed [m/s]		**0.11**	**0.11**	0.17

As can be observed in Table 4-1, the final result after evaluating all the metrics at all five measurement sites was that the YSU scheme performed somewhat better than the MYNN scheme, and much better than the TEMF scheme. Therefore, the YSU scheme was chosen for production runs.

The final model parameters are shown in Table 4-2.

Table 4-2. Final model parameters for the selected mesoscale model

Parameter	Setting
WRF model version	3.9.1.1
Land-use data	USGS 30-arcsecond Global Land Use
Atmospheric boundary conditions	ERA5
Sea surface conditions	ERA5
Grid nudging to reanalysis	Yes
Horizontal resolution	1.0 km (outer nests of 3.0 and 9.0 km)
Vertical resolution	37 levels from surface to 100 hPa
Model output interval	10 minutes
Planetary boundary layer scheme	YSU
Surface layer scheme	Monin-Obukhov similarity scheme
Grid-resolved clouds and precipitation	Thompson scheme

Atmospheric radiation	RRTM-G scheme

The second stage involved the creation of the production simulation: a continuous simulation for one (1) year, overlapping the TNW period of measurements from June 2019 to June 2020.

Following the GHPC Tailored WRF model, he production simulation were compared to other industry-standard mesoscale datasets, the results of which are described in the following sections.

4.2 Modelled Dataset Selection for Spatial Analysis

Several modelled data sources were considered to assist in the temporal and spatial analysis across the project site as shown in the below Table 4-3. It is noted that GHPC Tailored WRF was configured by the GHPC team specifically for application to the TNWWFZ. It is noted that the DOWA data is a successor of the KNW data, as an improved version that is forced with the more recently issued ERA5 reanalysis data.

Table 4-3. Modelled datasets for spatial analysis

Parameter	EMD-WRF E+	DOWA	KNW	NEWA	GHPC Tailored WRF
Scale	Mesoscale	Mesoscale	Mesoscale	Mesoscale	Mesoscale
Forcing	ERA5	ERA5	ERA-Interim	ERA5	ERA5
Centre / Provider	EMD	DOWA Project/ Royal Netherlands Meteorological Institute	Royal Netherlands Meteorological Institute	EU ERANET+ Project	GHPC
Model	WRF	HARMONIE	HARMONIE	WRF	WRF
Vertical levels	13	17	8	61	37
Output frequency	1 hourly	1 hourly	1 hourly	0.5 hourly	10 min
Spatial resolution	3 km	2.5 km	2.5 km	3 km	1 km
Period available	From 1980	2008 – 2018*	1979 – 2019**	2009-2018*	June 2019 – June 2020

* up to and including 2018
** up to August 2019

A detailed description of each modelled data source considered is presented in Appendix D. A comparison between the different models was conducted and supported by a validation of each model using measured data. The results of this exercise are presented in the subsequent section and details can be found in Appendix G.

It is noted that the assessment presented in the following sections were conducted with 12 months of measured data at TNW. No further assessments were conducted following the gathering of 24 months of measured data at TNW.

4.2.1 Overview of the measured and modelled datasets

Hourly time series were acquired for each modelled data source for the meteorologically nearest grid point to the measurement location at TNWWFZ as defined in Table 4-4. The majority of the datasets sourced had concurrent data with all the measured dataset at TNWWFZ, . The details of the selected modelled dataset heights and locations are presented in Table 4-4. The exact nodal locations of the modelled datasets considered are presented in Appendix I.

Table 4-4. Modelled and measured dataset validation heights

Dataset	Type [measured/modelled]	Height [m]
TNW	measured	140
EMD-WRF ERA5	mesoscale modelled	150
DOWA	mesoscale modelled	140
KNW	mesoscale modelled	150
NEWA	mesoscale modelled	150
GHPC Tailored WRF	mesoscale modelled	140

The TNW dataset used in this analysis is the combined measured dataset of TNWA and TNWB, as described in section 3.3.1. It is noted that the FINO1 dataset was not included in this validation study as it is significantly distant from the site and has an unwaked measurement period that is more than 12 years in the past. Moreover, GHPC attributes high confidence in the measurements at TNWWFZ and considers the gathered data to be of excellent quality. Therefore, the addition of FINO1 to the validation procedure would not have had any notable added benefit. However, it should be noted that the t FINO 1 dataset, as well as other measurements at OWEZ, MMIJ and HKN, were used to help choose the best physics configuration for the GHPC Tailored WRF (see section 4.1); and FINO1 will be used for the final wind resource grid output to present the final combined wind resource assessment of FINO 1 and TNW across the TNWWFZ.

4.2.2 Validation of Modelled Datasets for Spatial Analysis

The validation and selection of the final modelled dataset was based on an elimination process in a three-step procedure:

- Step 1: At this stage the modelled datasets were analysed to ensure that they fully overlap with the measured datasets to allow for full concurrency. Datasets that do not fully overlap with the measured datasets were eliminated at this stage.
- Step 2: The modelled datasets that had the best correlations with the measured wind speed and wind direction were selected and analysed in the next step.
- Step 3: The mean wind speed bias was calculated and distribution tests conducted between the modelled and measured datasets.

The steps described above were conducted with each pair of measured and respective modelled datasets (total of 5 pairs of datasets). These validation results were then weighted to obtain one final results table representative of the validation for TNWWFZ. Two other parameters related to each modelled dataset were also observed: the spatial resolution of each modelled dataset (in km) and the method of model optimisation to be conducted to determine the wind distribution grid at TNWWFZ.

Each parameter was then classified according to the following traffic light criteria shown in Table 4-5 below, where green, amber and red indicate very good, reasonable and poor performance, respectively. The best performing modelled dataset was selected.

Table 4-5. Classification criteria for modelled datasets

Evaluation Criteria	Green	Amber	Red
Colour			
Months of concurrency	>=12 months	12 to 6 months	<6 months
Resolution	<1 km	1 – 6 km	>6 km
Hourly wind speed correlations (R^2)	>0.80	0.80 - 0.60	<0.60
Hourly wind direction correlations (R^2)	>0.80	0.80 - 0.60	<0.60
Mean absolute difference in wind speed	<1%	1 - 2%	>2%
Kolmogorov-Smirnov test for wind speed distribution	<=2%	2 - 6%	>6%
Method of calibration to site	Multi-parameter bias correction	Simple one-parameter bias correction	-

4.2.2.1 Step 1 Concurrency of Datasets

Table 4-6 presented below indicates the concurrency of each of the modelled dataset with the measured TNW dataset. This is also depicted graphically in Figure 4-1. It can be observed that only two modelled data sources fully overlap with the TNW dataset: the EMD-WRF ERA5 and the GHPC Tailored WRF[6]. Therefore, only these two sources were considered in the next validation steps. Note that the measured TNW dataset has a data coverage of 83% out of the measurement period (19.06.2019- 24.06.2020). This translates to approximately 10 months of data, therefore full concurrency with the modelled datasets is a must.

It is noted that the mesoscale models DOWA, KNW and NEWA which are eliminated at this stage in the selection process were subsequently considered in the in-depth validation of the final selected mesoscale model for a more comprehensive comparison.

Table 4-6. Modelled and measured dataset concurrency

Parameter	TNW
Start date of measured dataset	19.06.2019
End date of measured dataset	24.06.2020
EMD-WRF ERA5	Full overlap
DOWA	No overlap
KNW	Partial overlap
NEWA	No overlap
GHPC Tailored WRF	Full overlap

[6] The GHPC Tailored WRF model was run for the period concurrent with the TNW measurements for the purpose of this study. Therefore, the modelled GHPC Tailored WRF dataset period shown in Figure 4-1 is not a limitation within the mesoscale model but a representation of the actual modelled data generated.

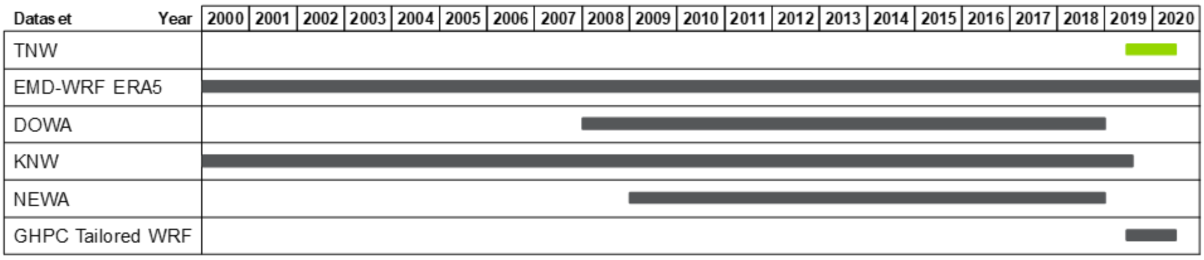

Figure 4-1. Gantt chart of modelled and measured datasets

4.2.2.2 Step 2 Correlation Values

In the next step of the analysis, correlation values between all the pairs of measured and modelled datasets were evaluated. The correlation coefficient R (Pearson) is a measure of the linear dependence between the measured and modelled wind speed. A correlation coefficient of +1 indicates that two values can be perfectly described by a linear equation. A high correlation in wind speeds indicates that two time series are largely in sync. This was done for both wind speed and wind direction.

Table 4-7 below presents the squared correlation values (coefficient of determination, R^2) of the measured TNW dataset with the modelled datasets EMD-ERF ERA5 and the GHPC Tailored WRF. It can be observed that the GHPC Tailored WRF modelled data correlates better with the measured TNW dataset than the EMD-WRF ERA5 data. Both modelled datasets were considered in the next validation steps.

Table 4-7. Wind speed and wind direction coefficient of determination values [R^2]

Dataset	TNW Wind speed R^2	TNW Wind direction R^2
EMD-WRF ERA5	0.88	0.95
DOWA	-	-
KNW	-	-
NEWA	-	-
GHPC Tailored WRF	0.94	0.97

4.2.2.3 Step 3 Mean Wind Speed Bias and Distribution Test

In the final step of the validation, two tests were performed to evaluate any bias in the modelled data, and the magnitude of the difference:

- Mean absolute difference in wind speed: The mean absolute difference shows the variation of the modelled wind speed to the measured wind speed in an absolute percentage (%). This statistical test can be used to estimate the confidence in correcting for bias.

- Kolmogorov-Smirnov test statistic: A two-sample Kolmogorov-Smirnov test compares the cumulative distribution of two datasets. The Kolmogorov-Smirnov test statistic quantifies the largest distance between the empirical distribution functions of both samples. The test is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples, and thus can indicate a goodness of fit curve. Two datasets with identical cumulative distributions will yield a test statistic of zero.

These tests were conducted at a height of 140 m for a like-with-like comparison. For this purpose, the EMD-WRF ERA5 data was vertically interpolated to this height of interest using modelled shear from its respective modelled data at the output heights of 100 m and 150 m.

For the GHPC Tailored WRF model, winds at 140 m were interpolated directly from native model pressure levels using modelled shear.

As can be seen in Figure 4-2, the GHPC Tailored WRF data exhibits a lower mean absolute difference in wind speed between measured and modelled data than the EMD-WRF ERA5, at 0.8% and 1.7%, respectively. A similar distribution of performance can be seen from the Kolmogorov-Smirnov Test in Figure 4-3, whereby the GHPC Tailored WRF data is the better performing modelled dataset with a Kolmogorov-Smirnov value of 1.1% as opposed to 1.8% by the EMD-WRF ERA5 data.

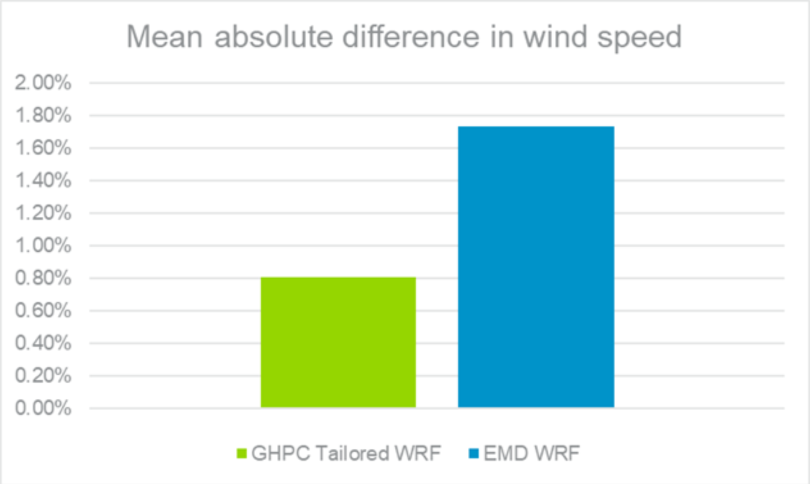

Figure 4-2. Mean absolute difference in wind speed

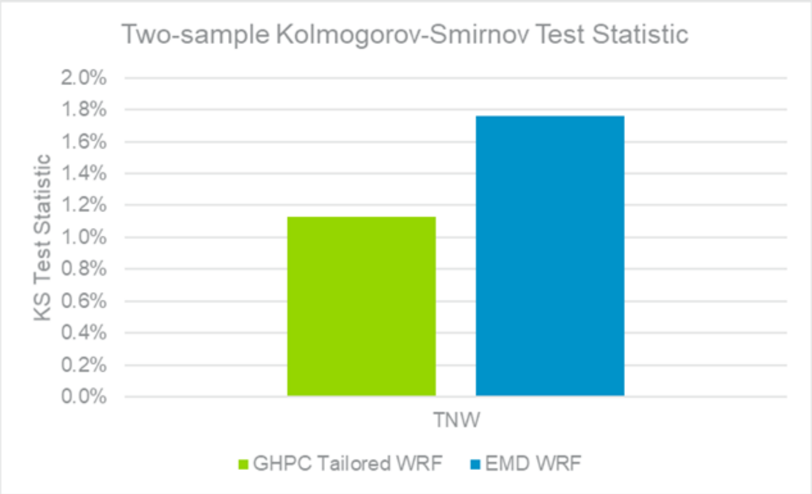

Figure 4-3. Two-sample Kolmogorov-Smirnov test

4.2.2.4 Method of Calibration to Site

The modelled datasets need to be adjusted based on measured data to represent an accurate estimation across TNWWFZ.

The two major options considered in this assignment is a simple scaling of the data or a sectorwise bias correction. Simple scaling refers to straightforward method of scaling of the modelled dataset at the measurement locations using the long-term wind speed measurement value at the specified height. Meanwhile, the sectorwise bias correction refers to the recalculation of the modelled dataset where correction factors are applied in the time and spatial domain. In the case of the GHPC Tailored WRF model this also means that the spatial resolution can also be changed to a finer grid, giving higher confidence in the results.

4.2.2.5 Selection of the Final Modelled Dataset

The results of the validation and capabilities of the considered modelled dataset are presented in Table 4-8 below. The colour classification is in accordance with the criteria defined in Table 4-5. Based on the results presented, the GHPC Tailored WRF model was chosen as the best performing mesoscale model for further evaluation.

Table 4-8. Evaluation of modelled datasets

Parameter	EMD-WRF E+	DOWA	KNW	NEWA	GHPC Tailored WRF
Resolution	3 km	2.5 km	2.5 km	3 km	1 km
Months of concurrent data	10	0	2	0	10
Hourly wind speed correlations (R^2)	0.88				0.94
Hourly wind direction correlations (R^2)	0.95				0.97
Mean absolute difference in wind speed	1.7%				0.8%
Kolmogorov-Smirnov test for wind speed distribution	1.8%				1.1%
Method of calibration to site	Simple one parameter scaling				Sectorwise bias correction with 100 m resolution

The wind flow model will be defined both horizontally and vertically across TNWWFZ using the mesoscale modelled dataset of GHPC Tailored WRF as described in Appendix D. This model was sectorwise bias corrected with a 100 m spatial resolution, calibrated with the measured datasets at TNW and FINO 1 and long-term adjusted to match the long-term wind speed derived at TNW and FINO 1.

4.3 Model Optimisation and In-Depth Validation

4.3.1 Model Calibration and Long-Term Adjustment

The main purpose of the model optimisation is to provide an accurate estimation of the long-term wind resource across TNWWFZ using the measured wind observations. This process allows the wind gradient model to have a more realistic representation of the wind distribution across the Project site with a higher associated confidence.

The below Figure shows the model optimisation process.

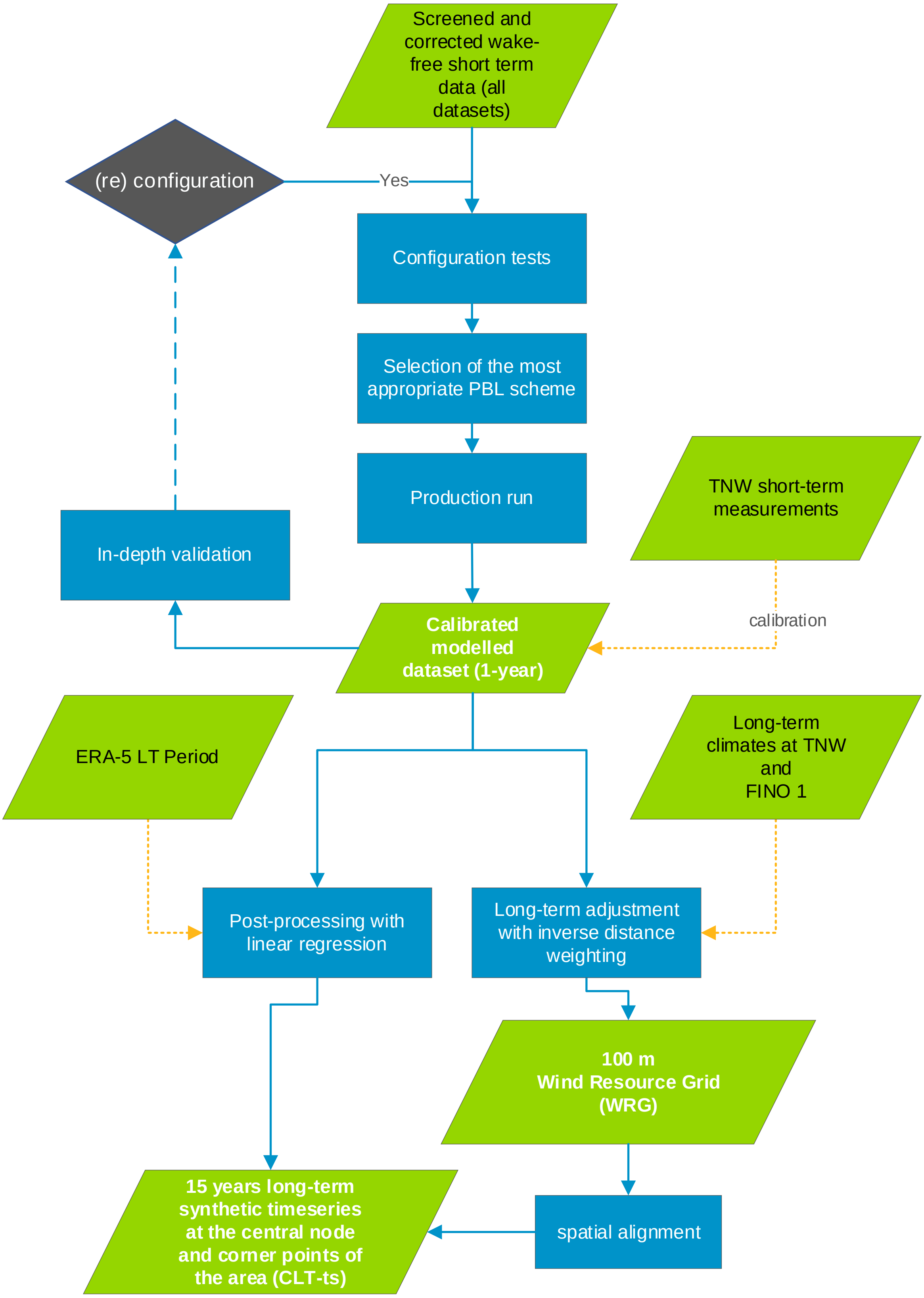

Figure 4-4. Mesoscale model development and optimisation

The modelled datasets need to be "calibrated" and "long-term adjusted" based on measured data to represent an accurate estimation across TNWWFZ, as depicted by the two separate short-dashed orange arrows in Figure 4-4. By "calibration" we mean changes to the raw model output that bring it into alignment with the short-term on-site measurements. By "long-term adjustment” we mean changes to the calibrated model output that force it to match the long-term mean wind speed and long-term climate characteristics. These two steps were performed somewhat differently for the two key deliverables: the Wind Resource Grid (WRG) file covering all of TNWWFZ, and the set of time series at 5 selected locations across the TNWWFZ. It is noted that the calibration was conducted with 24 months of data at TNW as well as the long-term adjustment which was based on the results presented in section 3.4, derived from 24 months of measured data at TNW.

For the WRG, which provides sectorized Weibull parameters, a calibration to the measured sectorized Weibull parameters from both TNW and FINO1 was performed. The measured shear at TNW location between 100 m and 140 m was used to derive an omnidirectional wind shear coefficient to vertically extrapolate the 102.5 FINO 1 frequency distribution to the 140 m height. Joint wind speed and direction frequency distribution files, including long-term adjustment, were prepared for TNW and FINO 1. The required corrections to the modelled sectorized Weibull parameters were determined by comparing the measured and modelled wind speed distributions at the two measurement sites. These correction factors were then applied across the WRG domain using an inverse distance squared weighting from the TNW and FINO 1 locations. This single step, therefore, achieved both the short-term calibration and long-term adjustment, because the long-term adjustment had already been included in the joint wind speed and direction frequency distributions. Therefore, the final WRG combines the long-term climates at both TNW and FINO 1 and is representative of the long-term both in climatic parameters and the wind gradient across the site.

Meanwhile, the time series derive their value from correctly depicting the temporal behaviour of the wind at various time scales. Therefore, to calibrate the time series, season/diurnal (12x24) look-up tables of correction factors were developed at all desired measurement heights at TNW. GHPC populated the 12 x 24 table from all valid time points of the TNW dataset. It is noted that there were cells in the table that had no data to generate a correction factor; primarily, the missing cells were in January, when there was low data recovery at TNW A and B. To fill in the missing cells, GHPC used an "inpainting" algorithm used in image processing techniques. Thus, January was interpolated between December and February, including a smoothing process by means of matrix colourisation. FINO1 could not be used for this purpose because it did not overlap in time. Table 4-9 shows a summary of the short-term measured wind speed at TNW at 140 m. The 12x24 lookup table was then applied to all five (5) time series nodes.

Once the short-term calibrated time series were derived, each dataset was post-processed to obtain the long-term synthetic timeseries at each nodal location. This was conducted using a sectorwise linear regression relationship with the same ERA5 data (54.09°N, 5.40°E) applied in the long-term correction described in section 3.4.1. Where necessary, corrections were applied to account for the long-term wind gradient observed in the WRG across the site, which incorporates the long-term climate from both TNW and FINO 1. This post-processing was also applied to the short-term calibrated time series at the FINO 1 location with the respective ERA5 dataset (54.10°N, 6.75°E). .

Table 4-9. Short-term measurements for model calibration

Measurement location	Height [m]	Period in years	Temporal resolution	Mean wind speed [m/s]
TNW	140	1 year	10 minutes	10.22

4.3.2 In-Depth Validation of the Selected Modelled Dataset

The validations presented in this section are additional validations to support the ones presented in section 4.1. As this was a tailor-made mesoscale model, it was necessary that the validations conducted in the development stage already provide high confidence in the results and in fact these validations also included the measurement locations that are also far afield (MMIJ, OWEZ, HKN). Therefore, the validations presented in this section provide further support to those conducted in the development stage and focus on the two datasets that are close to TNWWFZ, meaning: TNW and FINO 1.

It is noted that the extent of the calibrated modelled dataset also covers the FINO 1 location for validation purposes. The newly derived calibrated and long-term synthesised timeseries (CLT-ts) extends across a long-term period and is representative of the long-term. Therefore, long-term wind speeds from the calibrated model can be compared to the long-term wind speeds derived by the MCP procedure defined in section 3.3. The in-depth validation was conducted with the MCP long-term corrected wind speeds at TNW and FINO 1.

The in-depth validation exercise helps quantify the uncertainty in horizontal extrapolation. The validation was based on the long-term wind speeds derived from the calibrated and long-term synthesised timeseries, hereafter referred to as CLT-ts and the aforementioned TNW and FINO 1 MCP long-term corrected wind speeds.

4.3.2.1 Mean Wind Speed Bias of the Calibrated Model

Wind speeds were extracted at the nearest nodes and heights of the CLT-ts to the corresponding measurement height of the TNW and FINO 1 locations. The MCP long-term corrected wind speed values are compared to the long-term wind speed of the CLT-ts.

The comparisons show differences of -0.65% and -0.01% between the CLT-ts and FINO 1 and TNW long-term wind speeds, respectively, as shown in Table 4-10. It is noted the CLT-ts was corrected to match the long-term wind gradient observed in the WRG which incorporates the long-term climate of both TNW and FINO 1, which is evident in the validation presented in the table below. The results presented in Table 4-10 show very good performance by the mesoscale model with the difference in wind speeds being well within the expected wind speed uncertainty.

The next section investigates the horizontal gradient across these two locations and the associated uncertainties.

Table 4-10. Mean wind speed bias between CLT-ts and primary measurements

Parameter	FINO 1	TNW
Height of long-term corrected wind speed [m]	102.5	140
MCP long-term corrected wind speed [m/s]	9.94	10.30
Height of CLT-ts [m]	100	140
CLT-ts wind speed [m/s]	9.88	10.30
Difference between MCP LT wind speed and CLT-ts [%]	-0.65%	-0.02%

4.3.2.2 Validation of the Horizontal Gradient and Uncertainties

The wind speeds used in the previous section and presented in Table 4-10 were used in this analysis. The horizontal gradient investigation was based on a cross prediction exercise.
The ratio between the CLT-ts wind speeds at FINO 1 and TNW were calculated, to derive the modelled speed up effect between the two locations. This can also be considered to be a quantification of the modelled wind gradient. The modelled speed up values were then multiplied with the MCP long-term corrected wind speeds to cross-predict the wind speed at each of FINO 1 and TNW locations, respectively. The difference in the wind speeds between

the two values at the corresponding locations were calculated, as shown in Table 4-11 and Table 4-12.

Table 4-11. Derivation of modelled speed up values

Parameter	FINO 1	TNW
Height of CLT WS [m]	100	140
CLT WS [m/s]	9.88	10.30
Modelled speed up FINO 1/TNW (TNW predictor)	0.96	
Modelled speed up TNW/FINO 1 (FINO 1 predictor)	1.04	
MCP long-term corrected wind speed [m/s]	9.94	10.30

Table 4-12. Cross-predicted wind speeds and errors

Location	TNW predictor	FINO 1 predictor
FINO 1 predicted wind speed [m/s]	9.88	n/a
TNW predicted wind speed [m/s]	n/a	10.37
Location	**Error of MCP vs predicted wind speeds [%]**	
FINO 1	-0.63%	n/a
TNW	n/a	+0.64%

As can be seen in Table 4-12, maximum cross prediction error is estimated to be ±0.69% which is within the expected total uncertainty range of long-term wind speed. This is also in line with the mean wind speed bias observed in Table 4-10. Based on the configuration tests and cross-prediction exercise, the weighted horizontal extrapolation uncertainty across the modelled site is estimated at ±0.2% from the TNW reference location across all the TNWWFZ.

4.4 Extrapolation across TNWWFZ

The wind gradient model developed and described in the previous sections exhibits the wind gradient across the Project site, calibrated in accordance to the measured data as detailed in Section 4.3.1. The model results were also post-processed to derive the long-term climate. The calibration boundaries and the extrapolation process is visualized in the below Figure 4-5.

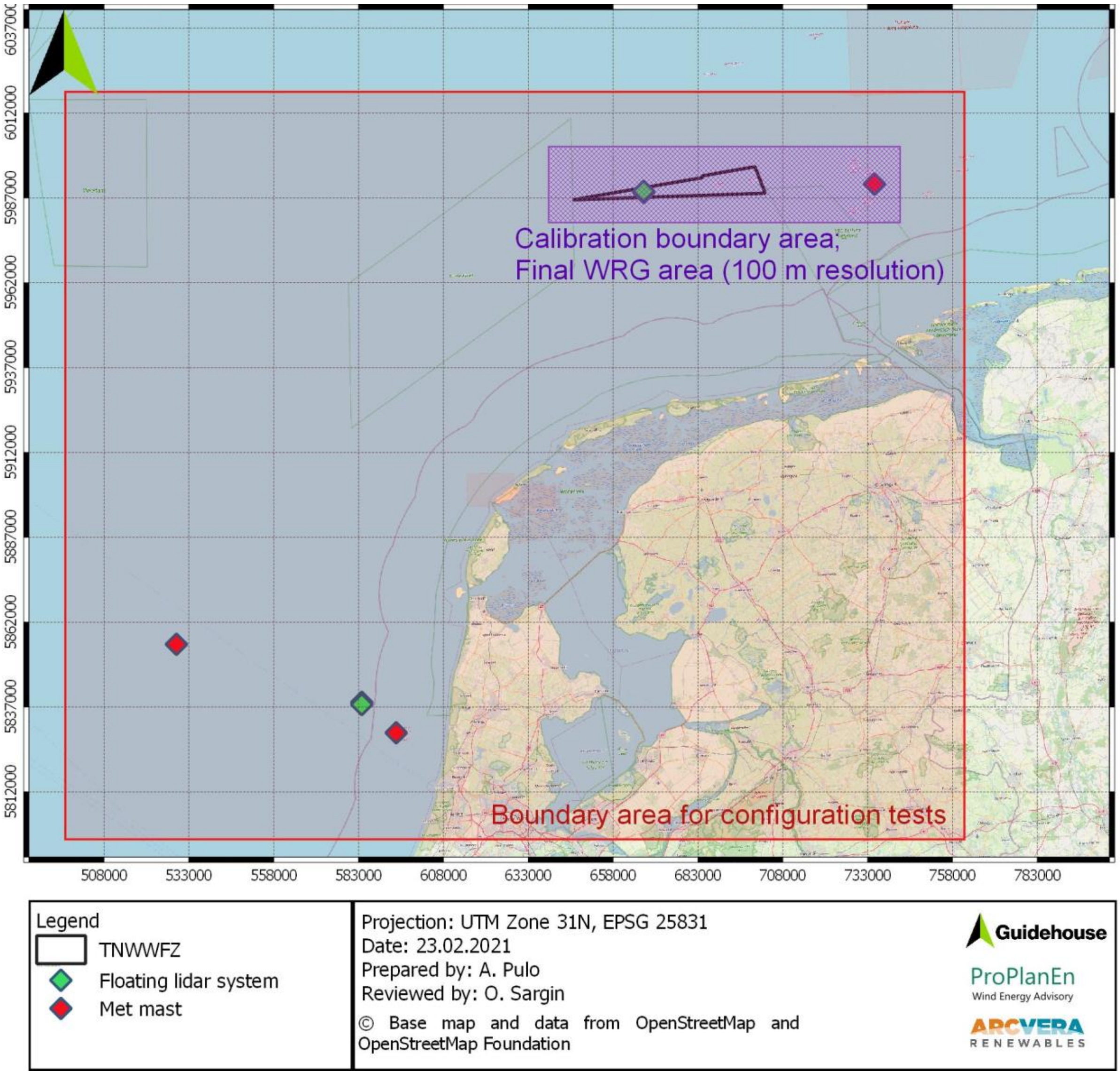

Figure 4-5. Calibration boundaries of the CLT-MM modelled dataset for TNWWFZ

Based on the descriptions provided in the preceding sections, the final wind gradient model is a mesoscale model based on ERA5 reanalysis data, calibrated with measured data and adjusted to the long-term. The final modelled output is representative of the long-term, both in terms of wind distribution and magnitude of resource with a spatial resolution of 100 m at multiple vertical heights. The associated horizontal extrapolation uncertainty was estimated to be 0.005% per km. The parameters of the final calibrated and long-term adjusted mesoscale model (CLT-MM) are presented in Table 4-13 for a holistic overview.

Table 4-13. Parameters of CLT-MM

Parameter	Value
Center / Provider	GHPC Tailored WRF
Model	WRF
Forcing	ERA5 reanalysis data
Scale	Mesoscale
Vertical levels	37
Temporal resolution	1 hour

Parameter	Value
Spatial resolution of final model	100 m

4.5 Final TNWWFZ Wind Climate

The final long-term wind gradient at TNWWFZ can be observed in Figure 4-6 for the height of 140 m. It can be seen that the wind gradient across the site is small, with wind speeds ranging from 10.25 m/s to 10.30 m/s across the site with the lower wind speed observed towards the south east of the site. In order to assess the long-term wind speed across the whole site, along with other parameters, 5 node locations were selected. Details of these node locations are presented in Table 4-14 and presented graphically in Figure 4-6.

Table 4-14. Coordinates of central and corner nodes of TNWWFZ

Designation	UTM Zone 31N EPSG 25831	
	X	Y
Node 1 – N1 West	646118	5986433
Node 2 – N2 North east	699836	5996180
Node 3 – N3 South east	702846	5988383
Node 4 – N4 TNW	667056	5988751
Node 5 – N5 Centre	682434	5990085

It is noted at the N4 TNW node is at the same location at the selected TNW reference location, located midway between TNWA and TNWB.

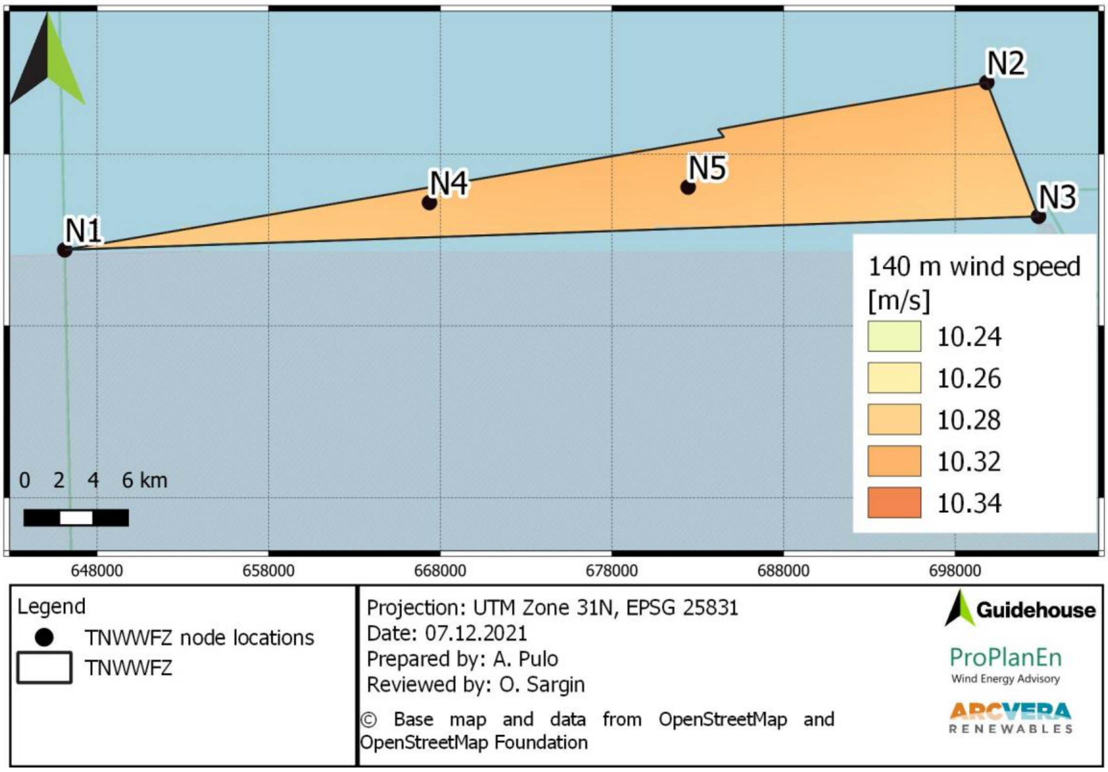

Figure 4-6. Horizontal modelled wind speed gradient at 140 m

The wind gradient across the whole modelled area and in relation to the coastline is presented in Appendix J.

4.5.1 Final Uncertainties in Wind Speed at Central and Boundary Nodes

The uncertainty associated with the long-term wind speed at each of the nodes is the total uncertainty of the wind speed measurement uncertainty (Section 2.9), the correction to the long-term with MCP (Section 3.4.4) and the uncertainty associated with the vertical and horizontal extrapolation within the wind gradient model (Section 4.3.2.2). It is noted that since measurements were taken at the height of 140 m and this is also the hub height of interest, the vertical extrapolation is 0% at TNW.

In order to derive the lowest possible uncertainty at the project regarding the wind climate, the two independent long-term climate assessments at TNW and FINO 1 are combined using the reciprocal weighting of the variance of the independent sources of the corresponding uncertainty. The combined approach's overall uncertainty is minimized by taking into account the independent elements of each calculation.

Table 4-15. Weighting of independent estimate of long-term climate

Designation	TNW	FINO 1
Wind speed uncertainty considering independent elements	4.3%	4.0%
Variance of independent elements of wind speed uncertainty	0.20	0.16
Inverse variance weighting	0.44	0.56

In line with the methodology applied to derive the wind speeds for the final calibrated mesoscale model across the TWNWFZ, GHPC combined the independent and dependent uncertainties in wind speed with an inverse distance weighting for vertical (for FINO 1) and horizontal extrapolation in the model, where the weights were obtained with the following formula;

$$w_i = \frac{R^2}{\left(R^2 + d_i^2\right)}$$

where R is a constant, and d is the distance from the measurement site to the point of interest. GHPC applied R = 0.5 km. Each weight is then normalised by the sum of the weights for all the measurements sites being considered, so that the sum of all weights is equal to one.

The calculated weights for each node are presented in the below Table 4-13.

Table 4-16. Distance weights for modelling used in uncertainty assessment

Designation	TNW	FINO 1
Node 1 – N1 West	0.95	0.05
Node 2 – N2 North east	0.53	0.47
Node 3 – N3 South east	0.45	0.55
Node 4 – N4 TNW	1.00	0.00
Node 5 – N5 Centre	0.92	0.08

The total uncertainty associated with the long-term wind speed at the representative TNW node at the height of 140 m is presented in Table 4-17 to Table 4-21.

Table 4-17. Total uncertainty in long-term wind speed at node 1 location at 140 m

Uncertainty category	Uncertainty Description	Independence	Weight	TNW	FINO 1
Site measurement	Total uncertainty in measured wind speed (wind statistics)	Independent	Inverse variance	3.4%	2.8%
Historic wind resource	Long-term representation	Independent	Inverse variance	1.4%	1.4%
	MCP method uncertainty	Independent	Inverse variance	2.1%	2.5%
Vertical extrapolation	Modelled vertical extrapolation	Independent	Distance	0.0%	0.4%
Future wind variability	Inter-annual variability (10 year uncertainty)	Dependent	Inverse variance	1.7%	1.7%
Spatial variation	Modelled horizontal extrapolation to node	Dependent	Distance	0.1%	0.4%
			Combined total uncertainty in long-term wind speed at TNWWFZ	**3.4%**	

Table 4-18. Total uncertainty in long-term wind speed at node 2 location at 140 m

Uncertainty category	Uncertainty Description	Independence	Weight	TNW	FINO 1
Site measurement	Total uncertainty in measured wind speed (wind statistics)	Independent	Inverse variance	3.4%	2.8%
Historic wind resource	Long-term representation	Independent	Inverse variance	1.4%	1.4%
	MCP method uncertainty	Independent	Inverse variance	2.1%	2.5%
Vertical extrapolation	Modelled vertical extrapolation	Independent	Distance	0.0%	0.4%
Future wind variability	Inter-annual variability (10 year uncertainty)	Dependent	Inverse variance	1.7%	1.7%
Spatial variation	Modelled horizontal extrapolation to node	Dependent	Distance	0.2%	0.2%
			Combined total uncertainty in long-term wind speed at TNWWFZ	**3.4%**	

Table 4-19. Total uncertainty in long-term wind speed at node 3 location at 140 m

Uncertainty category	Uncertainty Description	Independence	Weight	TNW	FINO 1
Site measurement	Total uncertainty in measured wind speed (wind statistics)	Independent	Inverse variance	3.4%	2.8%
Historic wind resource	Long-term representation	Independent	Inverse variance	1.4%	1.4%
	MCP method uncertainty	Independent	Inverse variance	2.1%	2.5%
Vertical extrapolation	Modelled vertical extrapolation	Independent	Distance	0.0%	0.4%
Future wind variability	Inter-annual variability (10 year uncertainty)	Dependent	Inverse variance	1.7%	1.7%
Spatial variation	Modelled horizontal extrapolation to node	Dependent	Distance	0.2%	0.2%
	Combined total uncertainty in long-term wind speed at TNWWFZ			**3.4%**	

Table 4-20. Total uncertainty in long-term wind speed at TNW node 4 location at 140 m

Uncertainty category	Uncertainty Description	Independence	Weight	TNW	FINO 1
Site measurement	Total uncertainty in measured wind speed (wind statistics)	Independent	Inverse variance	3.4%	2.8%
Historic wind resource	Long-term representation	Independent	Inverse variance	1.4%	1.4%
	MCP method uncertainty	Independent	Inverse variance	2.1%	2.5%
Vertical extrapolation	Modelled vertical extrapolation	Independent	Distance	0.0%	0.4%
Future wind variability	Inter-annual variability (10 year uncertainty)	Dependent	Inverse variance	1.7%	1.7%
Spatial variation	Modelled horizontal extrapolation to node	Dependent	Distance	0.1%	0.3%
	Combined total uncertainty in long-term wind speed at TNWWFZ			**3.4%**	

Table 4-21. Total uncertainty in long-term wind speed at node 5 location at 140 m

Uncertainty category	Uncertainty Description	Independence	Weight	TNW	FINO 1
Site measurement	Total uncertainty in measured wind speed (wind statistics)	Independent	Inverse variance	3.4%	2.8%
Historic wind resource	Long-term representation	Independent	Inverse variance	1.4%	1.4%
	MCP method uncertainty	Independent	Inverse variance	2.1%	2.5%
Vertical extrapolation	Modelled vertical extrapolation	Independent	Distance	0.0%	0.4%
Future wind variability	Inter-annual variability (10 year uncertainty)	Dependent	Inverse variance	1.7%	1.7%
Spatial variation	Modelled horizontal extrapolation to node	Dependent	Distance	0.1%	0.3%
		Combined total uncertainty in long-term wind speed at TNWWFZ		**3.4%**	

4.5.2 Comparison with Metocean Study

A metocean desk study (MDS) has been undertaken by DHI covering the TNWWFZ. The results of this study are accessible at the Metocean data portal, which can be accessed through https://www.metocean-on-demand.com/. The MDS presents information on the feasibility level on both the meteorological (wind) and the oceanographic (wave/current) climate at the TNWWFZ for the wind farm (structural) design process.

NOAA's CFSR wind dataset was corrected and modified by DHI for the Dutch Offshore Wind Farm areas for the MDS study. The original data has a spatial resolution of 0.3° from 1979 to 2010 and 0.2° from 2011 and onwards.

The MDS covering TNW has been adjusted to the design level and therefore a comparable height of 140 m was evaluated. The period of MDS is the same period as that of the CLT-MM, covering from 01.07.2005 to 30.06.2021. Therefore GHPC uses this period to compare the CLT-ts and MDS normal climate model at the common height of 140 m. The comparison was conducted at three nodes: N1, N4 and N5.

As shown in the Table 4-22, the comparison shows excellent agreement with absolute deviations between -0.04 m/s and -0.06 m/s, within a threshold of 0.1 m/s. This indicates that there is minimal variation of wind speed at the height of 140 m between the two studies, attributing higher confidence in the results presented in this report.

Table 4-22. Comparison of CLT-ts with the MDS wind speed values at nodes at 100 m

Mesoscale model	Period	Para-meter	N1	N4	N5
GHPC tailored WRF (CLT-MM) *final, calibrated*	01.07.2005 to 30.06.2021	Wind speed [m/s]	10.30	10.30	10.30
MDS	01.07.2005 to 30.06.2021 (14 years)*	Wind speed [m/s]	10.24	10.25	10.26
		Wind speed variation from GHPC [m/s]	-0.06	-0.05	-0.04

The MDS figures are intended to be used for the design basis and site suitability calculations. However, it is noted that the GHPC results are marginally more conservative.

Further details are shown in Appendix K, where the metocean and wind resource assessment alignment document issued by DHI is presented.

4.5.3 Alignment with Previous Studies

The long-term modelled wind speeds derived from the mesoscale model were compared to those from previous wind resource studies commissioned by RVO. The following offshore wind farms and associated studies were considered in the comparison. All values were extracted from the reports cited below.

- Hollandse Kust (zuid) wind farm zone (HKZWFZ), study conducted in 2017 [24]
- Hollandse Kust (noord) wind farm zone (HKNWFZ), study conducted in 2019 [26]
- Hollandse Kust (west) wind farm zone (HKWWFZ), study conducted in 2020 [20]

Table 4-23 presents a comparison of wind speeds at the centre of each site at a height of 100 m. It can be observed in Table 4-23 that the wind speed increases with distance from the coastline, which is also noted in [20]. As TNWWFZ is the furthest away from the coast, the TNWWFZ N5 central node exhibits the highest wind speed which is reasonably aligned with the wind speeds observed in the previous studies.

Table 4-23. Comparison of wind speed at different wind farm zones

Location	Wind speed at 100 m	Distance from coast
TNWWFZ N5 centre	9.99 ± 0.35 m/s	Approximately 80 km
HKZWFZ centre	9.44 ± 0.38 m/s	Approximately 25 km
HKNWFZ centre	9.53 ± 0.38 m/s	Approximately 25 km
HKWWFZ centre	9.72 ± 0.31 m/s	Approximately 62 km

It is noted that the Hollandse Kust wind farm zones and TNWWFZ are more than 150 km apart and therefore some variations in the wind climate is expected.

4.5.4 Comparison with Other Mesoscale Models

The long-term wind speeds derived from the final long-term synthesised timeseries at the node location were compared to long-term wind speeds from the mesoscale models DOWA, NEWA, KNW and Global wind atlas (GWA). The data from each of these mesoscale models were sourced from the meteorologically closest grid point to the nodal locations. Further information on the mesoscale models (DOWA, NEWA, KNW and GWA) are provided in Appendix G. It is noted that the GWA was added to this comparison to present an additional independent mesoscale source widely used in the offshore wind industry as the other mesoscale sources exhibited a slightly different wind gradient to that of GHPC Tailored WRF.

The comparison was conducted at each of the five (5) nodal locations selected and with each mesoscale model. Table 4-24 presents the data sources and grid nodes and associated long-term wind speeds. The variation in the long-term wind speeds between the GHPC Tailored WRF results and each of the DOWA, KNW, NEWA and GWA mesoscale models are presented in Table 4-24 and graphically in Figure 4-7. The speed up between each node wind speed and the corresponding N4 wind speed is also presented numerically in Table 4-24 and graphically in Figure 4-9 to observe the wind gradient across the site from various mesoscale sources. It is noted that KNW and NEWA mesoscale models do not provide data at the height of 140 m, therefore the comparison with these sources was conducted just at the height of 100 m.

It can be observed in Table 4-24, Figure 4-7 and Figure 4-8 that the wind speed variation of DOWA, KNW and GWA from the GHPC Tailored WRF mesoscale model (CLT-ts) results is well within the expected uncertainty. The DOWA mesoscale model showing excellent agreement with the GHPC Tailored WRF modelled results, with the lowest variation being at N1 at -0.1% at a height of 100 m. Meanwhile NEWA shows a greater discrepancy to the CLT-ts results with the variation being higher than 3%, across all the node locations. Meanwhile the GHPC Tailored WRF speed ups observed across the site are in reasonable agreement with the other mesoscale sources, indicating a decrease in wind speed from west to east, as can be seen in Figure 4-9. It can be observed that the GWA shows a different wind gradient to that of the other sources, with an increase in wind speed from west to east.

Table 4-24. Comparison of mesoscale model wind speed values at nodes

Mesoscale model	Parameter	N1	N2	N3	N4	N5
GHPC Tailored WRF *final, calibrated (CLT-MM)*	Data height #1 [m]	100	100	100	100	100
	Wind speed #1[m/s]	9.98	9.96	9.93	9.98	9.98
	Speed up vs. N4	1.000	0.998	0.995	1.000	0.999
	Data height #2 [m]	140	140	140	140	140
	Wind speed #2[m/s]	10.30	10.28	10.25	10.30	10.30
	Speed up vs. N4	1.000	0.998	0.995	1.000	1.000
DOWA	Grid node coordinates	53.88°N, 5.42°E	53.93°N, 6.28°E	54.86°N, 6.30°E	53.89°N, 5.77°E	53.88°N, 6.00°E
	Data height #1 [m]	100	100	100	100	100
	Wind speed #1 [m/s]	9.97	9.91	9.85	9.94	9.90
	Speed up vs N4	1.003	0.997	0.991	1.000	0.996
	Wind speed #1 variation from GHPC [%]	-0.1%	-0.5%	-0.8%	-0.4%	-0.8%
	Data height #2 [m]	140	140	140	140	140
	Wind speed #2 [m/s]	10.24	10.18	10.12	10.21	10.17
	Speed up vs N4	1.003	0.997	0.991	1.000	0.996
	Wind speed #2 variation from GHPC [%]	-0.6%	-1.0%	-1.3%	-0.9%	-1.2%
KNW	Grid node coordinates	54.00°N, 5.21°E	54.07°N, 6.06°E	54.00°N, 6.10°E	54.02°N, 5.56°E	54.03°N, 5.79°E
	Data height [m]	100	100	100	100	100
	Wind speed [m/s]	10.05	10.03	9.99	10.04	10.04

Mesoscale model	Parameter	N1	N2	N3	N4	N5
	Speed up vs N4	1.001	0.999	0.995	1.000	0.999
	Wind speed variation from GHPC [%]	0.70%	0.73%	0.63%	0.61%	0.60%
NEWA	Grid node coordinates	54.01°N, 5.24°E	54.07°N, 6.04°E	54.01°N, 6.09°E	54.03°N, 5.57°E	54.02°N, 5.81°E
	Data height [m]	100	100	100	100	100
	Wind speed [m/s]	9.59	9.57	9.55	9.58	9.57
	Speed up vs N4	1.001	0.999	0.996	1.000	0.998
	Wind speed variation from GHPC [%]	-3.9%	-3.9%	-3.9%	-4.0%	-4.1%
GWA	Grid node coordinates	54.01°N, 5.23°E	54.08°N, 6.05°E	54.00°N, 6.10°E	54.02°N, 5.55°E	54.03°N, 5.79°E
	Data height [m]	100	100	100	100	100
	Wind speed [m/s]	9.82	9.87	9.86	9.84	9.86
	Speed up vs N4	0.998	1.003	1.002	1.000	1.002
	Wind speed variation from GHPC [%]	-1.6%	-0.9%	-0.7%	-1.4%	-1.2%

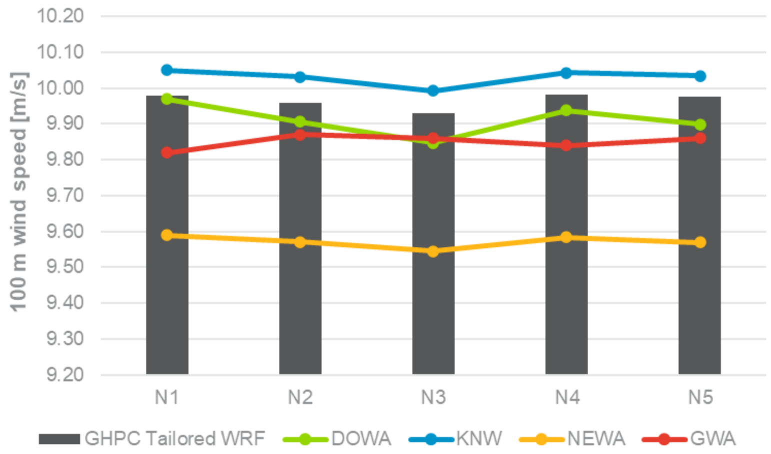

Figure 4-7. 100 m long-term wind speed variation between GHPC Tailored WRF and other mesoscale models

Figure 4-8. 140 m long-term wind speed variation between GHPC Tailored WRF and other mesoscale models

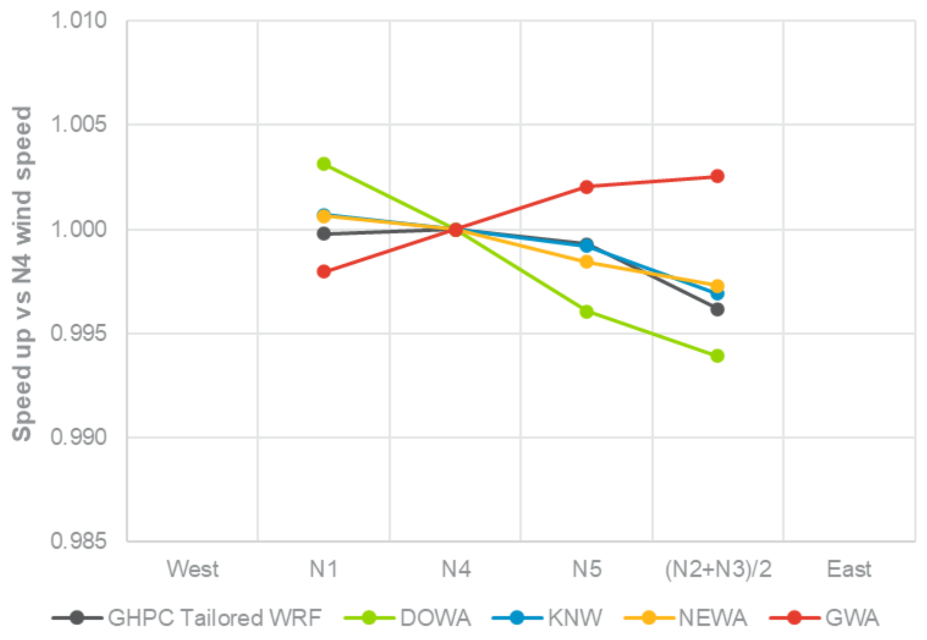

Figure 4-9. Graphical representation of nodal speed up versus N4 wind speed

5.0 TNWWFZ Long-Term Climate

The results from the final GHPC Tailored WRF mesoscale model (CLT-MM) are presented in this section, based on the wind distribution presented in Figure 4-6. The results are presented for the selected node locations within TNWWFZ, depicted in Figure 4-6, and presented in Table 4-14.

In addition to the wind gradient output, a synthetic time series representative of the long-term was extracted at each of the nodal locations at multiple heights.

5.1 Mean Wind Speed

The long-term mean wind speed at each nodal location was extracted at selected multiple heights, as shown in Table 5-1. It can be observed that similar wind speed distributions are exhibited across the different nodal points and heights. Meanwhile Table 5-2 displays the long-term sectorwise frequency distribution of the 140 m wind speed at the N4 node in TNWWFZ.

Table 5-1. Long-term mean wind speeds within TNWWFZ at various heights

Height above LAT [m]	Mean Wind Speed [m/s]				
	Node 1	Node 2	Node 3	Node 4	Node 5
10	8.06	8.04	8.02	8.06	8.06
60	9.54	9.52	9.49	9.54	9.54
100	9.98	9.96	9.93	9.98	9.98
120	10.15	10.13	10.10	10.15	10.15
140	10.30	10.28	10.25	10.30	10.30
200	10.64	10.63	10.61	10.64	10.64
250	10.85	10.84	10.83	10.86	10.85
300	10.97	10.96	10.95	10.98	10.98

Table 5-2. Sectorwise annual frequency distribution of wind speed at N4 at 140 m [%]

Wind speed 140 m (m/s)	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°	All
0-1	0.04	0.04	0.03	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.48
1-2	0.14	0.12	0.12	0.11	0.11	0.13	0.14	0.14	0.15	0.12	0.12	0.13	1.51
2-3	0.22	0.18	0.21	0.21	0.20	0.21	0.23	0.24	0.24	0.22	0.28	0.23	2.68
3-4	0.39	0.32	0.29	0.27	0.27	0.28	0.26	0.33	0.33	0.32	0.36	0.38	3.80
4-5	0.49	0.43	0.36	0.38	0.32	0.34	0.38	0.44	0.42	0.47	0.52	0.53	5.08
5-6	0.51	0.47	0.49	0.44	0.39	0.36	0.43	0.49	0.52	0.58	0.60	0.66	5.93
6-7	0.55	0.46	0.58	0.51	0.43	0.47	0.52	0.63	0.74	0.70	0.71	0.77	7.06
7-8	0.59	0.47	0.54	0.55	0.53	0.46	0.52	0.69	0.87	0.81	0.91	0.81	7.75
8-9	0.62	0.44	0.54	0.61	0.57	0.44	0.54	0.77	0.89	0.97	0.97	0.84	8.19
9-10	0.48	0.34	0.49	0.57	0.56	0.49	0.53	0.82	1.06	1.03	0.96	0.82	8.13
10-11	0.44	0.31	0.45	0.59	0.63	0.53	0.55	0.89	1.13	1.10	0.88	0.69	8.19
11-12	0.36	0.24	0.43	0.57	0.53	0.45	0.48	0.92	1.15	0.99	0.74	0.63	7.46
12-13	0.29	0.17	0.32	0.41	0.41	0.34	0.46	0.86	1.13	0.92	0.67	0.52	6.51
13-14	0.25	0.12	0.18	0.39	0.40	0.31	0.44	0.88	1.01	0.82	0.59	0.44	5.83
14-15	0.20	0.08	0.15	0.39	0.42	0.24	0.41	0.72	0.90	0.69	0.49	0.36	5.06
15-16	0.14	0.05	0.10	0.29	0.26	0.15	0.33	0.65	0.80	0.56	0.39	0.30	4.02
16-17	0.07	0.04	0.05	0.21	0.21	0.14	0.23	0.51	0.72	0.52	0.28	0.18	3.16
17-18	0.04	0.02	0.04	0.12	0.13	0.11	0.19	0.48	0.58	0.43	0.20	0.14	2.47
18-19	0.02	0.01	0.03	0.08	0.08	0.06	0.14	0.40	0.48	0.31	0.18	0.12	1.89
19-20	0.01	0.01	0.01	0.07	0.05	0.03	0.11	0.36	0.36	0.24	0.14	0.08	1.46
20-21	0.01	0.00	0.01	0.06	0.03	0.01	0.07	0.24	0.34	0.22	0.09	0.04	1.12
21-22	0.01	0.00	0.00	0.04	0.01	0.01	0.03	0.17	0.21	0.17	0.06	0.03	0.72
22-23	0.00	0.00	0.00	0.02	0.00	0.01	0.02	0.13	0.18	0.12	0.04	0.02	0.54
23-24	0.00	0.00	0.00	0.01	0.00	0.00	0.03	0.09	0.12	0.08	0.03	0.01	0.37
24-25	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.06	0.09	0.06	0.02	0.01	0.26
25-26	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.05	0.05	0.01	0.01	0.16
26-27	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.03	0.02	0.01	0.00	0.09
27-28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.03
28 - 29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.03
29 - 30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02
30 - 31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
31 - 32	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32 - 33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
33 - 34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34 - 35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total [%]	**5.87**	**4.32**	**5.40**	**6.93**	**6.56**	**5.61**	**7.09**	**12.06**	**14.52**	**12.55**	**10.29**	**8.78**	**100.00**

5.1.1 Mean Wind Speed at Different Probability Levels

The long-term mean wind speed at the height of 140 m at each nodal location is presented for different probability levels in Table 5-3.

Table 5-3. Different probability levels for long-term mean wind speed at 140

Probability level	Mean Wind Speed at 140 m [m/s]				
	Node 1	Node 2	Node 3	Node 4	Node 5
P10	10.75	10.73	10.70	10.75	10.75
P25	10.54	10.52	10.49	10.54	10.54
P50	10.30	10.28	10.25	10.30	10.30
P75	10.06	10.04	10.01	10.06	10.06
P90	9.85	9.83	9.80	9.85	9.85

5.2 Wind Shear

The vertical long-term wind speed profile at each of the modelled node locations is shown in Figure 5-1, along with the seasonally balanced short-term measured wind speeds at TNWA, covering a period of 18 months. It can be observed that the difference in wind shear across the different node locations is negligible. The short-term TNWA measured data exhibits higher wind speeds across all heights, but still exhibiting a similar wind shear profile as the long-term data at the different nodes.

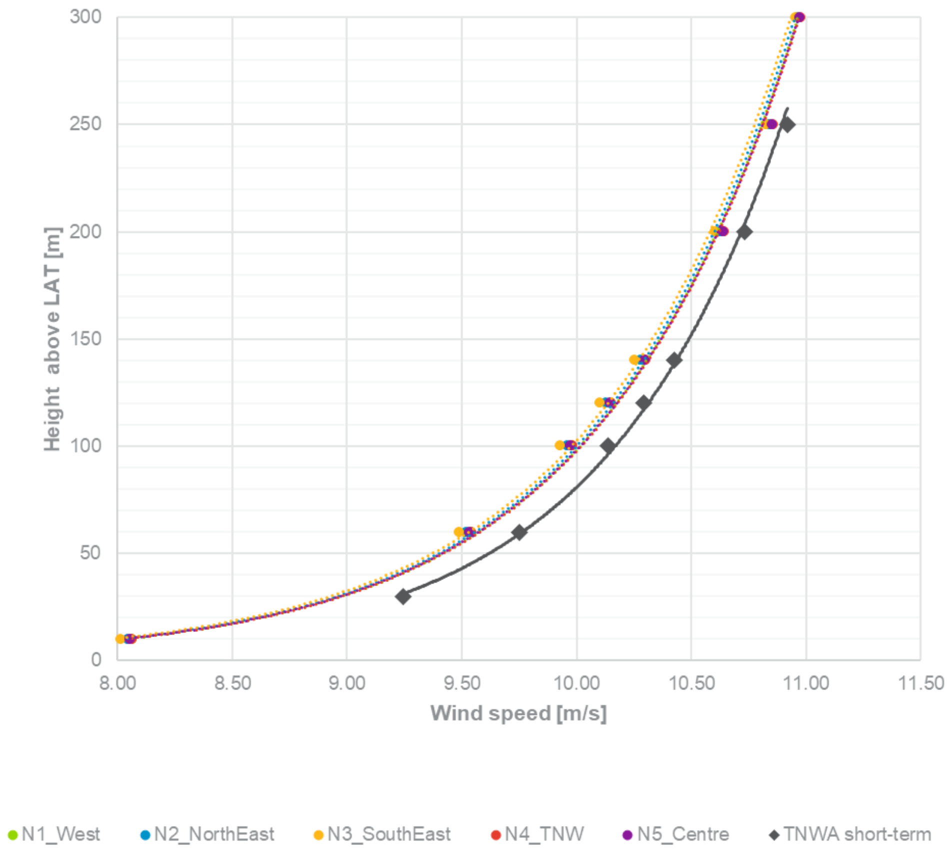

Figure 5-1. Mean wind speed profile at TNWWFZ

The wind shear show in Figure 5-1 can be characterized by the power law exponent (α) in the power law equation:

$$U_2 = U_1 \times \left(\frac{z_2}{z_1}\right)^{\alpha}$$

U is horizontal wind speed in m/s, z is measurement height in m and α is the power law exponent.

The power law exponent is calculated to represent the best-fit of the vertical wind speed profile of the power law profile by means of linear least squares regression. Accordingly, the measured seasonally balanced short-term at TNWA and modelled long-term wind shear coefficient values at the N4 node within TNWWFZ were derived. These are presented on a sectorwise basis in Table 5-4 and Figure 5-2. Additionally, the overall modelled long-term wind shear coefficients with different height combinations are shown in Table 5-5. It can be observed that there is very good agreement in the wind shear coefficients between the measured and long-term modelled results.

Table 5-4. Sectorwise wind shear at TNWA and N4

Sector	Wind shear coefficient	
	TNWA short-term measured (200 m, 140 m, 100 m)	N4 long-term modelled (200 m, 140 m, 100 m)
0°	0.04	0.04
30°	0.06	0.07
60°	0.05	0.09
90°	0.14	0.15
120°	0.01	0.06
150°	0.04	0.09
180°	0.10	0.13
210°	0.13	0.12
240°	0.10	0.12
270°	0.08	0.08
300°	0.06	0.06
330°	0.05	0.04
All sectors	**0.08**	**0.09**

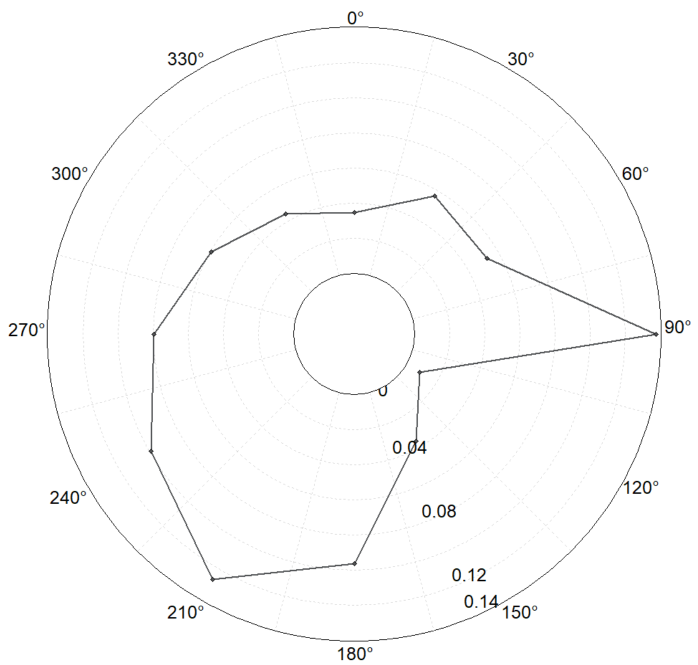

Figure 5-2. Measured seasonally balanced short-term wind shear rose at TNWA (200 m, 140 m, 100 m wind speed)

Figure 5-3. Modelled long-term wind shear rose at N4 (200 m, 140 m, 100 m wind speed)

As shown in Table 5-5, the variation of the long-term modelled wind shear varies minimally across the different heights in the vertical plane.

Table 5-5. Long-term modelled wind shear with different heights at N4

Heights for shear calculation	Modelled wind shear coefficient at N4
10 m and 300 m	0.09
60 m and 300 m	0.09
60 m and 250 m	0.09
100 m and 250 m	0.09
100 m and 200 m	0.09
140 m and 250 m	0.09

5.3 Temporal Variation in Wind Speed

The figures below represent the diurnal and monthly variation in the synthesised long-term wind conditions at the selected node location N1 to N5 compared to the TNW short-term measured data and the TNW long-term corrected data from the MCP (section 3.4).

Figure below shows the synthetic long-term and the TNW seasonally balanced short-term measured and long-term corrected diurnal wind speed variation, along with the data coverage of the TNW short-term dataset. It can be seen that very similar patterns are exhibited across each of the node locations with a dip in wind speed from 06:00 to 14:00, after which there is a gradual increase in wind speed, leading to peak wind speeds during the evening and night-time hours. This diurnal variation is in good agreement with the TNW long-term corrected data.

GHPC notes that the slight dips at 11:00 and 23:00 in Figure 5-4 are likely to be caused by the known discontinuity problem of the ERA5 diurnal cycle for winds due to a mismatch in the analysed near-surface wind speed between the end of one assimilation cycle and the beginning of the next [34]. Although this problem mainly occurs in low latitude oceanic regions, GHPC notes it has observed this phenomenon in the Dutch North Sea and throughout onshore Netherlands. Given that FINO 1 short-term dataset shows a slight dip in wind speeds towards the end of the day and the relatively low value of the discontinuity, GHPC considers the diurnal profile reasonably representative of the diurnal cycle at TNW.

Meanwhile, Figure 5-5 shows the synthetic long-term monthly distribution at the node locations during a full calendar year and the corresponding values for the TNW short-term measured and long-term corrected data. It can be observed that there is a seasonal variation in wind speeds, with the winter months and summer months exhibiting higher and lower wind speeds, respectively. Moreover, there is excellent agreement between the synthetic long-term and long-term corrected TNW monthly pattern.

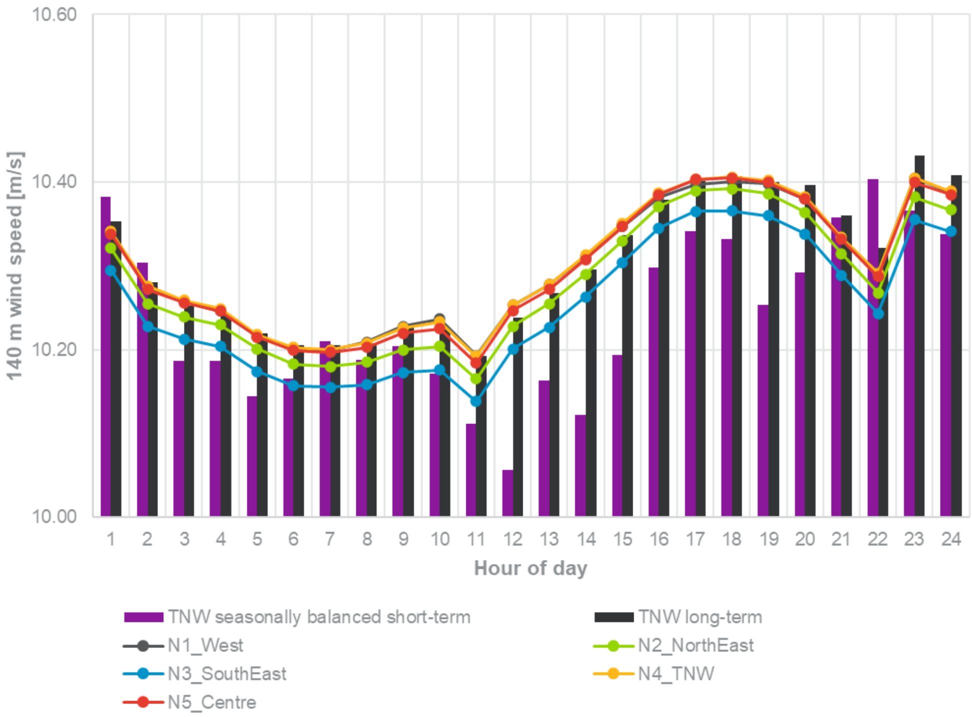

Figure 5-4. Long-term diurnal wind speed variation (UTC+1)

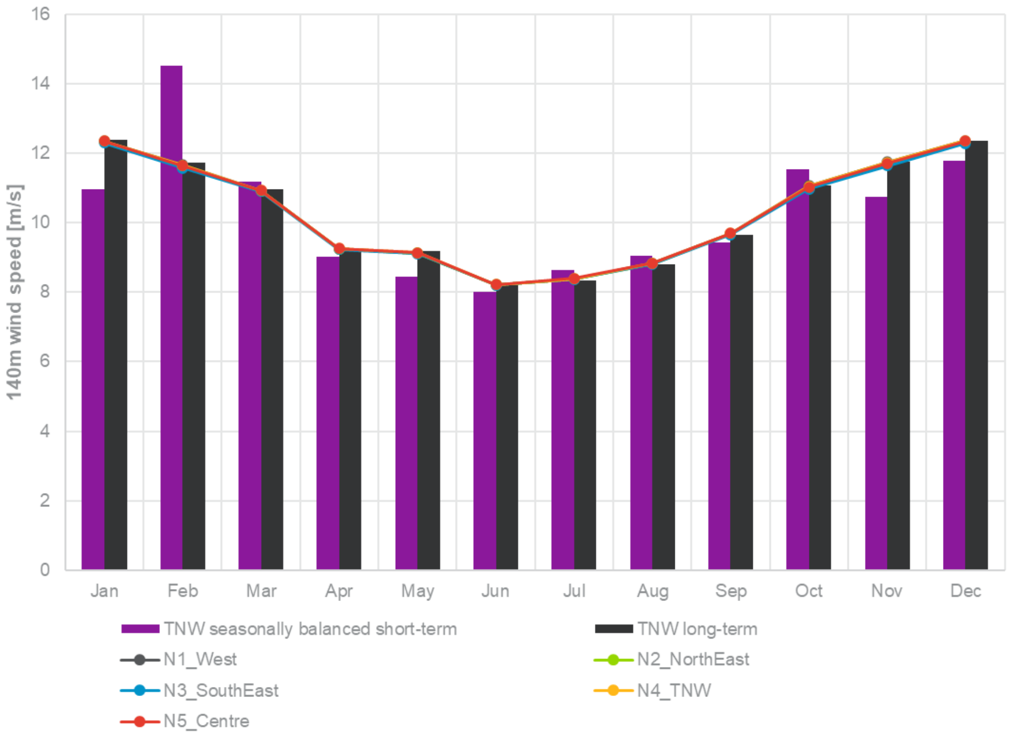

Figure 5-5. Long-term monthly wind speed variation

5.3.1 Inter-annual Variation

Figure 5-6 below compares annual mean wind speeds between the measured FINO 1 data, the synthetic long-term data at N4 at the 140 m height and the selected ERA5 datasets used in the MCP (ERA5 at 54.10°N, 6.75°E near FINO 1, ERA5 at 54.09°N, 5.40°E near TNW). It can be observed that the trends in mean annual wind speed are similar at different measurement heights at FINO 1. These are also in reasonable agreement with the synthetic long-term data at N4 and the reference dataset ERA5 as seen in Figure 5-6.

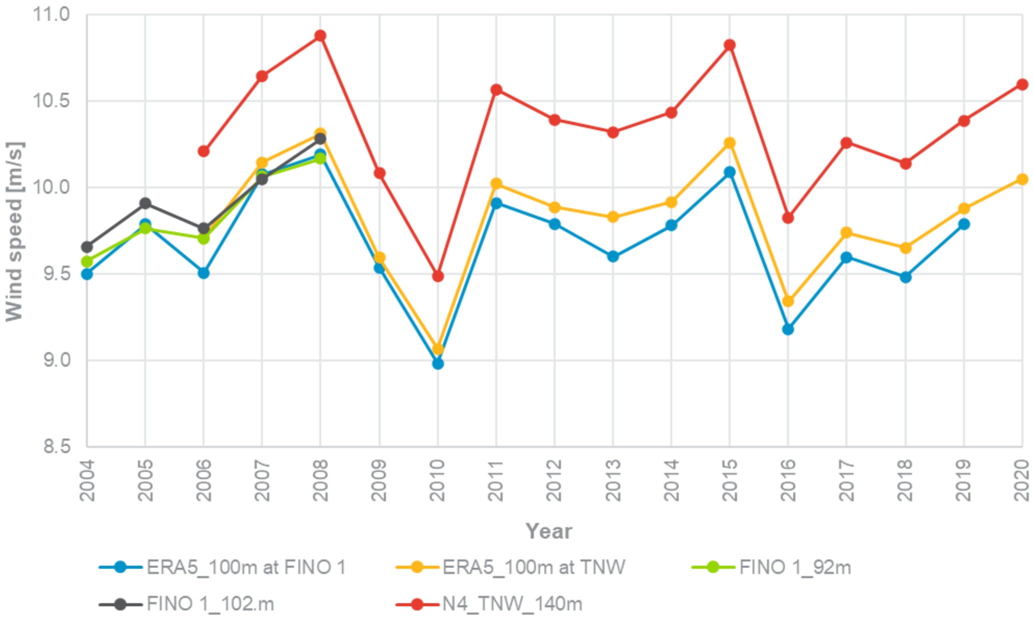

Figure 5-6. Annual mean wind speeds from different sources

5.4 Frequency Distribution

The long-term wind speed frequency distribution with a Weibull fitting at the N4 node within TNWWFZ for the height of 140 m can be seen in Figure 5-7. It can be observed that the wind speed distribution has a good fit to a Weibull distribution with the highest percentage of events occurring around the 10 m/s bin.

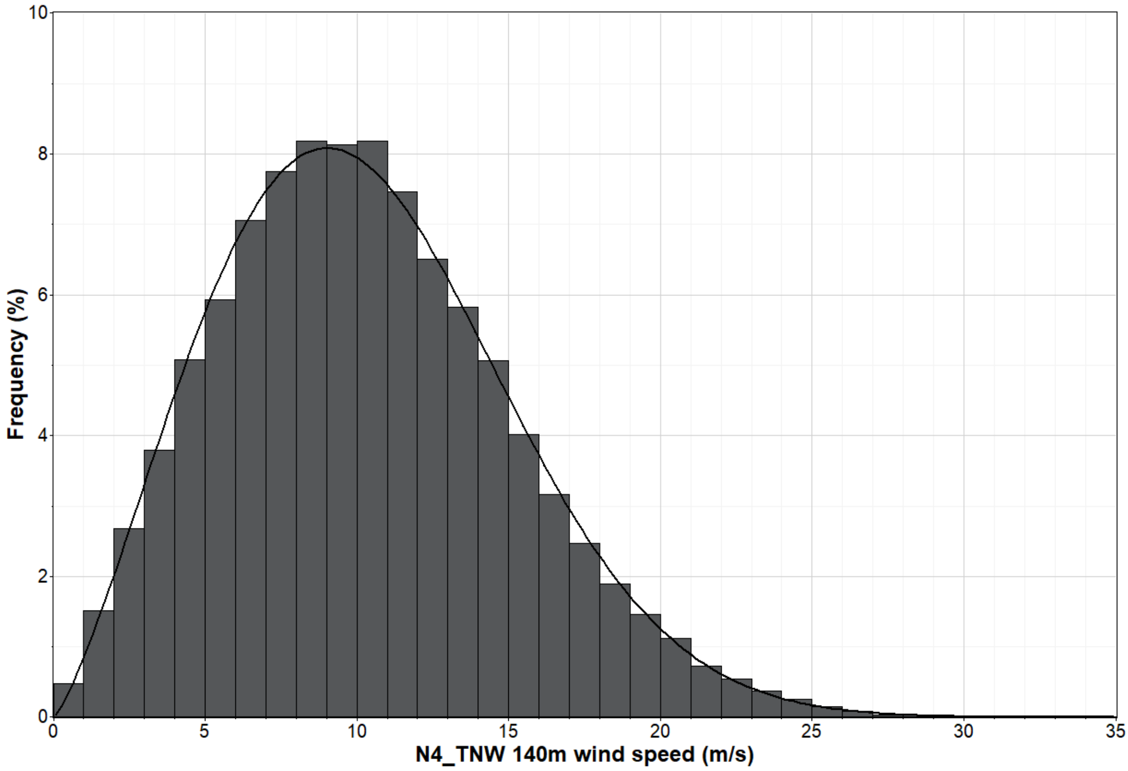

Figure 5-7. N4 long-term wind speed frequency distributions at 140 m with Weibull fit

5.5 Weibull Parameters

The long-term Weibull parameters, A and k, that are representative of the TNWWFZ at the five nodal locations are presented in Table 5-6 and Table 5-7 at multiple selected heights. The corresponding sectorwise values for the Weibull parameters for each nodal location and each height selected are presented in Appendix J.

Table 5-6. Weibull A within TNWWFZ at various heights

Height above LAT [m]	Weibull A [m/s]				
	Node 1	Node 2	Node 3	Node 4	Node 5
10	9.10	9.08	9.05	9.10	9.09
60	10.77	10.75	10.71	10.77	10.76
100	11.27	11.24	11.21	11.27	11.26
120	11.46	11.43	11.40	11.46	11.45
140	11.63	11.60	11.57	11.63	11.62
200	12.01	12.00	11.97	12.02	12.01
250	12.25	12.24	12.22	12.26	12.25
300	12.38	12.38	12.37	12.39	12.39

Table 5-7. Weibull k within TNWWFZ at various heights

Height above LAT [m]	Weibull k [-]				
	Node 1	Node 2	Node 3	Node 4	Node 5
10	2.304	2.290	2.294	2.300	2.297
60	2.291	2.286	2.289	2.290	2.290
100	2.286	2.287	2.290	2.287	2.288
120	2.282	2.284	2.287	2.283	2.284
140	2.278	2.281	2.284	2.279	2.281
200	2.260	2.267	2.270	2.263	2.266
250	2.244	2.250	2.253	2.248	2.250
300	2.225	2.233	2.235	2.229	2.231

5.6 Wind Rose

The seasonally balanced short-term wind rose and MCP long-term wind rose at TNW reference location can be seen in Figure 5-8 and Figure 5-9, respectively. This is followed by the synthetic long-term wind rose at each of the nodal locations selected for the selected height of interest 140 m in Figure 5-10 to Figure 5-14.

It can be observed that the prevailing wind directions are the south south west (240°) and west directions (270°) in both the long-term and short-term wind roses.

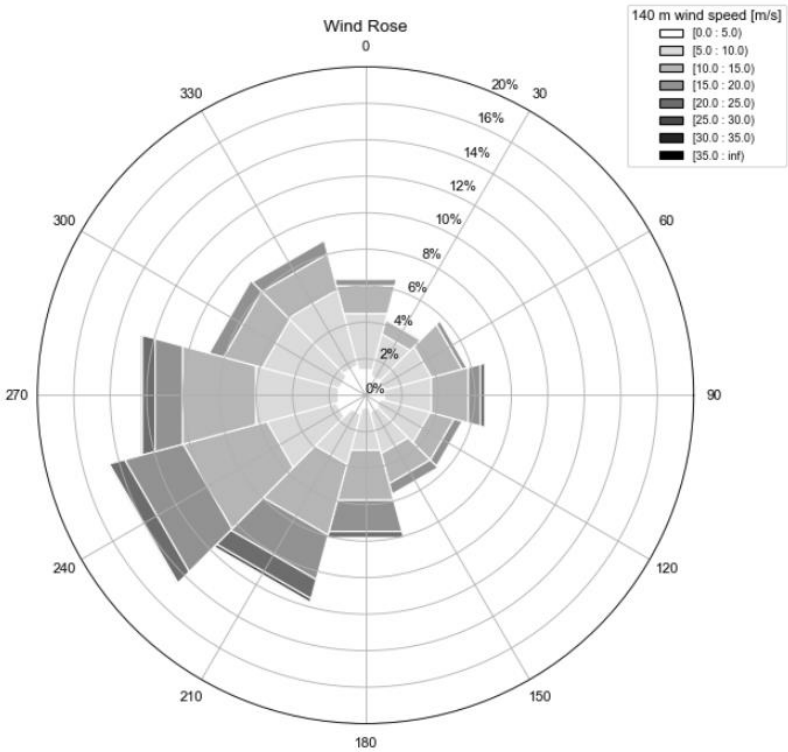

Figure 5-8. Short-term TNW frequency wind rose at 140 m

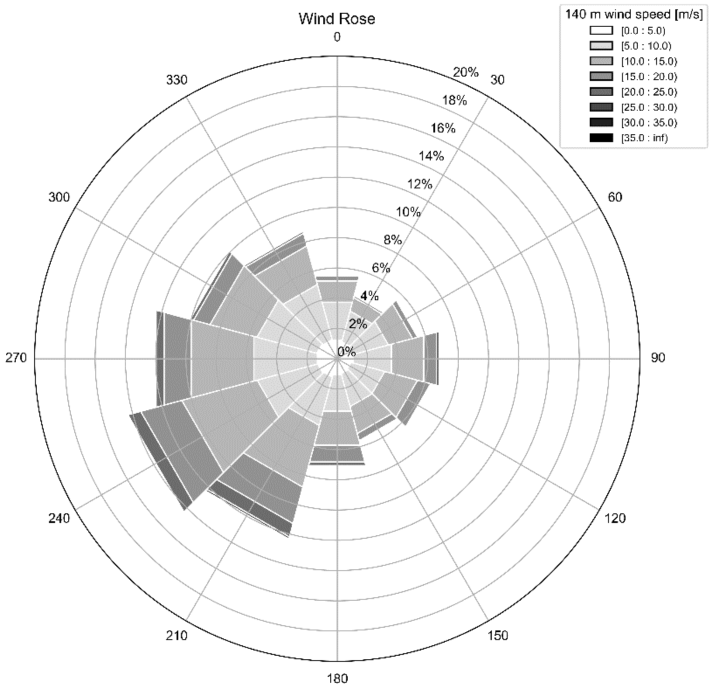

Figure 5-9. MCP long-term TNW frequency wind rose at 140 m

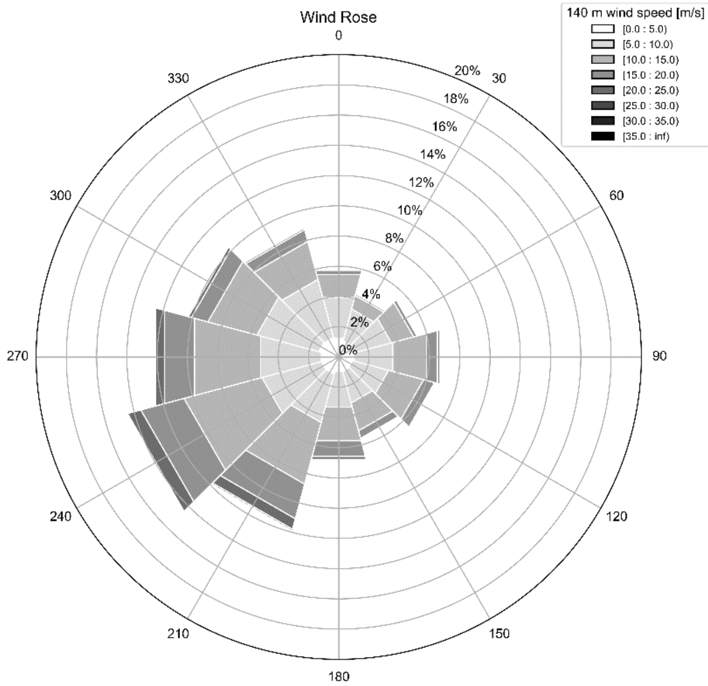

Figure 5-10. Synthetic long-term N1 frequency wind rose at 140 m

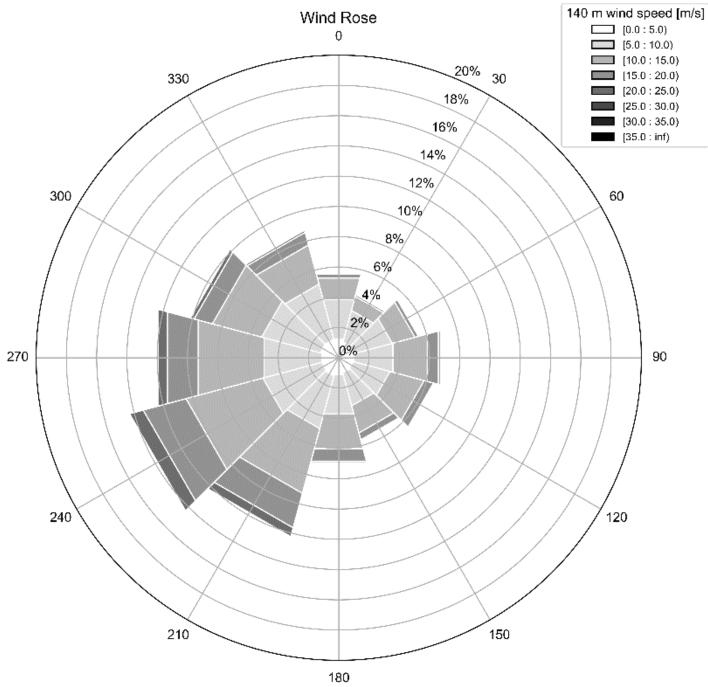

Figure 5-11. Synthetic long-term N2 frequency wind rose at 140 m

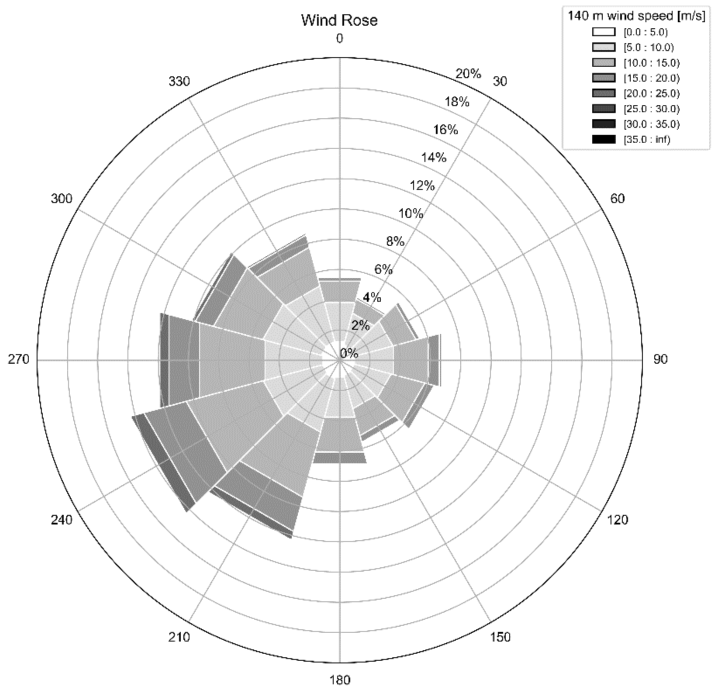

Figure 5-12. Synthetic long-term N3 frequency wind rose at 140 m

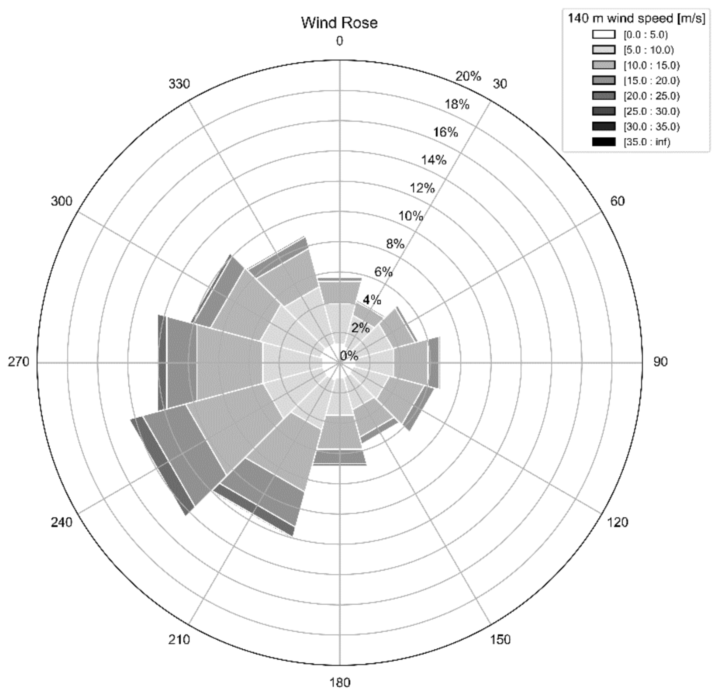

Figure 5-13. Synthetic long-term N4 frequency wind rose at 140 m

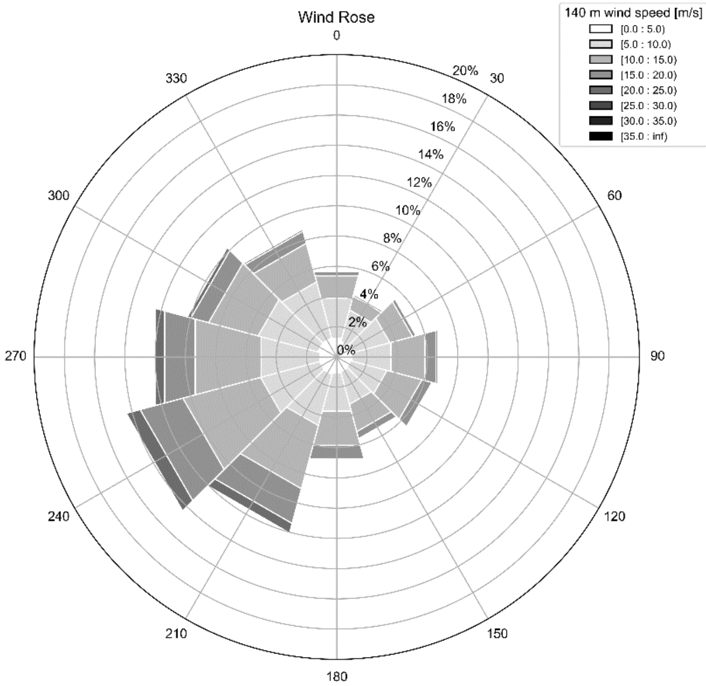

Figure 5-14. Synthetic long-term N5 frequency wind rose at 140 m

5.7 Other Climatological Parameters

The following sections present the thermodynamic meteorological parameters form the TNWA and TNWA-2 combined and FINO 1 measured data, and at the ERA5 data from the selected node near TNW (54.09°N, 5.40°E). The TNWA and TNWA-2 measured data is based on the period 19.06.2019 to 20.06.2021 and the FINO 1 measured data is based on the period 01.01.2004 to 31.12.2008. It is noted that although TNWA and TNWA-2 lie some distance apart, the difference in climatic parameters between these two locations is considered to be negligible. Therefore the TNWA and TNWA-2 data was combined as one dataset for presenting climatic parameters.

5.7.1 Air Temperature

Table 5-8 below presents the measured and modelled air temperatures at various locations and heights.

Table 5-8. Mean, minimum and maximum air temperature

Dataset	Height above LAT [m]	Air temperature [°C]		
		Mean	Minimum	Maximum
TNWA, TNWA-2 measured data (2 years)	4	11.53	-3.29	23.73
FINO 1 measured data (5 years)	101	10.9	-3.6	28.7
N4_TNW (modelled short-term)	10	11.2	2.2	31.9
N4_TNW (modelled short-term)	140	10.4	0.7	32.0
N5_Centre (modelled short-term)	140	10.3	0.7	32.1

Dataset	Height above LAT [m]	Air temperature [°C]		
		Mean	Minimum	Maximum
ERA5 (54.09°N, 5.40°E) (long-term period)	100	10.7	-3.9	24.0

5.7.2 Air Pressure

Table 5-9 below presents the measured and modelled air pressure at various locations and heights.

Table 5-9. Mean, minimum and maximum air pressure

Dataset	Height above LAT [m]	Air pressure [hPa]		
		Mean	Minimum	Maximum
TNWA, TNWA-2 measured data (2 years)	0.5	1013	972	1046
FINO 1 measured data (5 years)*	21	1012	969	1046
N4_TNW (modelled short-term)	10	1012	973	1044
N4_TNW (modelled short-term)	140	996	957	1028
N5_Centre (modelled short-term)	140	996	958	1028
ERA5 (54.09°N, 5.40°E) (long-term period)	100	1014	967	1048

*a barometer was also installed at 93 m height above LAT, however most of the recorded data was erroneous in the measurement period considered

5.7.3 Relative Humidity

Table 5-10 below presents the measured and ERA5 modelled air pressure at various locations and heights.

Table 5-10. Mean, minimum and maximum relative humidity

Dataset	Height above LAT [m]	Relative humidity [%]		
		Mean	Minimum	Maximum
TNWA, TNWA-2 measured data (2 years)	4	81	44	99
FINO 1 measured data (5 years)	101	83	25	100
ERA5 (54.09°N, 5.40°E) (long-term period)	100	81	39	100

5.7.4 Air Density

Table 5-11 below presents the measured and modelled air density. It is noted that the measured air density is calculated from the values of air temperature, air pressure and relative humidity.

Table 5-11. Mean, minimum and maximum air density

Dataset	Height above LAT [m]	Air density [kg/m³]		
		Mean	Minimum	Maximum
TNWA, TNWA-2 measured data (2 years)	4	1.223	1.167	1.335
FINO 1 measured data (5 years)	101	1.222	1.148	1.292
N4_TNW (modelled short-term)	10	1.235	1.175	1.303
N4_TNW (modelled short-term)	140	1.219	1.130	1.290
N5_Centre (modelled short-term)	140	1.219	1.130	1.291
ERA5 (54.09°N, 5.40°E) (long-term period)	100	1.240	1.171	1.346

6.0 Wake Effects and Blockage

In TNWWFZ, one (1) wind farm site (WFS) has been designated as Ten noorden van de Waddeneilanden wind farm site I (TNWWFS I), with a total area of 70.6 km^2. The layout given below excludes (for example, and among many other parameters) the cost impact of water depth, financing, electrical losses, and grid connection. Such detailed analysis is always specific to the developer preferences and choices for a specific project; it is therefore outside the scope of this report. The layouts described here serve only to illustrate what could be realised.

It is noted that the results presented below were based on the long-term climate derived from the first 12 months of measured data gathered at TNWA and TNWB. No further changes were applied following 24 months of gathered onsite data.

6.1 Project Setup

A key input for the layout design is the wind resource, as described in previous chapters. Additional inputs to the design process are the wind farm site boundaries, external turbines to be considered, and characteristics of the generic turbine types used, as well as any other parameters that help describe the project as a whole.

6.1.1 Wind Farm Site

The wind farm site TNWWFS I[7] encompasses an area of 70.6 km^2 and is provided as a site boundary in the data package. The following condition applies to the wind farm site boundaries: The boundaries of the wind farm site may not be crossed by any part of the turbine. The maximum distance between the tower centre and rotor tip is given by the Pythagorean sum of the rotor radius and distance between the hub-centre and tower-centre.

6.1.2 Wind Turbine Data

Considering the recent development in commercially available wind turbines, two layouts are designed for wind turbines with 13 MW and 15 MW rated capacity, each with a hub height of 140m. The table below shows the key parameters of the turbines used. Power and thrust curves are reproduced Appendix M.

Table 6-1. Key parameters of the two wind turbine types

Parameter	NREL 15 MW	HKW 13 MW
Rated power [MW]	15	13
Diameter [m]	240	220
Power density [W/m^2]	332	342
Rated wind speed [m/s]	-	13
Cut-out wind speed	25	28
Reference	IEA report [35]	HKW WRA report [20]

6.1.3 Wind Resource Data

At the reference location (TWA), the wind resource data described in previous chapters provide: the frequency distribution of wind speed, wind direction, and turbulence intensity.

[7] The boundaries of the wind farm site (TNWWFS I) are preliminary and may be subject to change after preparation of this report.

When designing the layout, we are assuming standard atmospheric conditions with an air density of 1.225 kg/m³ at sea level and neutral atmospheric conditions.

6.1.4 External Wind Farms

Two wind farms, named Gemini, are already constructed within the TNWWFZ. These wind farms are considered as external wind farms. A layout for Gemini has been received from public sources, and the turbine type used is described on the project's web page. No information was available on the existence of any project-specific modifications, curtailments, details of availability, or operation. For this report, it has been assumed that all Gemini wind farm turbines are operating, and that no power enhancing modifications have been installed.

Further external turbines exist to the east and north-east of the wind farm site. These are more than 20 km away and are not in a principal wind direction; they are thus considered of negligible influence on AEP. The possible impact of wind farms not yet constructed has not been considered in the design of example layouts, or in the assessment of wake losses. It is recommended that a search for future projects is carried out when the detailed design phase begins.

6.2 Design of Layout

A wind farm layout is designed by identifying the turbine locations that best meet the objective (target) function. The problem is described by the number of turbines on a continuous space, multiple parameter dimensions, and interdisciplinary objective functions – in industry practice wind farm design is a complex iterative process subject to frequently changing boundary conditions and parameters. For this report, we use to derive two example layouts the energy yield as objective function.

6.2.1 Target Capacity Density

If the capacity density is defined as the installed wind farm capacity per wind farm site area, then the energy density for the average offshore wind farm in the North Sea is 6.0 MW/km^2, based on [36], [37] and [38]. The capacity density is substantially constant, across different turbine sizes and technologies. This is because, due to wake effects, inter-turbine spacing scales proportionate to rotor diameter, while the turbine rated capacity scales proportionate to the rotor area. Larger turbines yield more energy per unit, but not per water area available.

Variations between wind farms are down to a few project-specific factors, like the availability of suitable turbines, usage of the surrounding offshore area, the cost of infrastructure components, etc. Previous Dutch wind farms featured an above average capacity density and in this instance RVO requested a total capacity of 700 MW, corresponding to 9.9 MW/km^2.for the area of the wind farm site. This increases the expected wake losses.

For the site TNWWFS 1 with an area of 70.6 km^2 two configurations are proposed:

- Layout 1: 705 MW capacity from 47 wind turbines with 15 MW each
- Layout 2: 702 MW capacity from 54 wind turbines with 13 MW each

The shape of the available area for TNWWFS 1 is broadly aligned with the principal wind direction.

6.2.2 Design Tools

All wind farm design tools allow for manual positioning of turbines. As manual placement can be tedious, automatic layout generators have been implemented. WindPRO can also offer support with manually manipulation of an existing wind farm design object.

Table 6-2. Comparison of wind farm design tools

Method	WindFarmer	windPRO	Openwind	Comment
Automatic	Metropolis Hastings	Random	Metropolis-Hastings	Best onshore
Parameter adjustment	Symmetrical layouts	Regular pattern	Manual	Best offshore

Other methods commonly used for wind farm layout optimisation include simulated annealing, particle swarm, genetic algorithms, evolutionary strategies [39], [40] and [41]. The algorithms need to cope with complex boundary conditions, such as disjunct areas, or exclusion zones that limit the cumulative environmental (noise, visual, shadow) impact of turbines.

To obtain a clean layout, each of the automated placement options requires manual post processing, which considers the specific boundary conditions for the site. Automatically generated layouts have potential weaknesses: They can lead to high directional sensitivity in wind farm power production, amplifying errors or shifts in wind direction distribution. Automatically generated layouts may also optimise the layout with respect to specific wake model and parameterisation possibly resulting in a maximum yield that is not reproduced in nature.

6.2.3 Design Strategies

The industry tools mentioned above are used in a semi-automatic iterative way, to obtain a high performing, compact, and regularly structured layout. Some of the concepts used are:

Onshore, resource variation due to terrain is a dominant factor, whereas offshore, layouts with regular patterns are often desired/required. Due to the high cost of the electrical infrastructure, some energy may be sacrificed for a compact layout.

String of pearls: Automatic optimisation often leads to a concentration of turbines around the wind farm boundary. In manual layout design, this is sometimes enhanced by placing wind turbines like a string of pearls around the wind farm site. This is a valid strategy if there are no neighbouring wind farms. A variation on the theme is to modify turbine density throughout the wind farm, with lower turbine density in inner areas.

Staggered layout: A staggered layout is one where every second row is shifted against the first row of a wind farm. This can be useful to increase downstream spacing, and space out individual rows, thereby reducing induction effects, and it may also reduce the need for columnar shutdown.

Curved layout: A curved layout has the potential advantage of lowering the sensitivity of the wind farm power curve to wind direction changes. Due to a shift in wind turbine symmetry the wakes of a row of upstream turbines will not impact all the downstream turbines at the same time.

The interaction of geometrically arranged turbines may also serve to channel or deflect the wind for some directions and meteorological conditions. The impact of such patterns requires further research and is not represented in the current industry models.

6.3 Wake Effects and Blockage

Wind turbines slow the wind flow down from ambient levels, while extracting energy from it. This reduction in wind speed starts well before the rotor in the induction zone, and the wind speed continues to decrease up to several rotor diameters downstream in the near wake zone. Further downstream the wind speed recovers, until it again reaches the ambient wind speed.

The recovery of the wake is driven by turbulent mixing from the side, bottom and top of the wind flow.

6.3.1 Wake Models

The recovery of wakes is impacted by the presence of other turbines, the proximity of the ground and the structure of the atmospheric boundary layer.

Table 6-3. Key features of the main wake models available in the industry standard software packages

Model Elements	WindFarmer EV+LWF	WindPRO EMD Park-2	Openwind EV+DAWM	WindPRO Park	WakeBlaster[8]
Initial profile	Gaussian	Rectangular	Rectangular	Rectangular	Blunt Lissaman
Single wake model	Symmetric	Symmetric	Symmetric	Symmetric	Numerical
Wake-wake interaction	Dominant	Linear	Dominant	Square	Numerical
Wake-ground interaction	LWF correction	Mirror turbines	DAWM	(Mirror turbines)	Numerical
Ambient turbulence	Initial profile Ainslie	Empirical k(TI)	Initial profile Ainslie	Empirical k(TI)	Initial profile, propagation
Wind farm turbulence	Empirical Quarton	n/a	Empirical Quarton	n/a	Shear generated
Near wake	Fixed	n/a	Fixed	n/a	Variable
Atmospheric stability	Neutral, variable TI	Neutral, TI per sector	Neutral, variable TI	Neutral, TI per sector	Variable, variable TI

Most wake models used in the industry describe an axis-symmetrical wake, using empirical corrections to account for the interaction between wakes, and between the wake and boundary layer.

6.3.2 Blockage Models

Blockage is sometimes used as a catch-all term to include a multitude of effects and mechanisms not described by other models. In a previous report for HKW, blockage was described as a wind farm boundary layer interaction. This report differentiates between:

- Wind turbine induction (flow expansion and acceleration around a wind turbine)
- Ground interaction (interaction of the wake with the atmospheric boundary layer)
- Wake interaction (superposition of neighbouring wakes)
- Flow blockage (channelled flow in a valley or wind tunnel)
- Flow displacement (gravity waves or flow over an escarpment)
- Wind farm induction (reduced wind speed before a group of turbines)

[8] Service operated via WindPRO or Openwind software packages or operated stand-alone via Python.

The first three mechanisms are commonly seen as integral to describing wakes and are addressed (to a greater or lesser extent) by the different wake models. Flow blockage can impact flow either under very stable conditions or in a physically constrained flow. Flow displacement and acceleration over or around the wind farm is always happening (mass conservation) and is an integral element of any model of a wind turbine immersed in the boundary layer. Further research is needed to determine its impact on the wake recovery further downstream. A detailed discussion of these mechanisms can be found in [42].

Wind farm induction is the type of blockage that is of interest here. Wind farm induction is a slowdown in wind speed upstream of a wind farm, which extends substantially further upstream than the induction of a single turbine. The slowdown can be modelled using numerical or semiempirical models. Two established and accessible models of wind farm induction are that by Madsen and Frandsen [43], [44], and Branlard's vortex model [45]. The overall impact of wind farm induction on wind farm AEP is the subject of ongoing research It should be considered when calculating the AEP but is outside the scope of this report.

For the two example layouts proposed in this report we considered the impact wind farm induction can have on the placement of turbines. In absence of an industry consensus approach, open questions, and ongoing research, two simplifying assumptions are made for designing the example layouts:

- Wind farm induction from turbines in the planned layout impacts in first approximation all planned turbines evenly.[9] Any potential impact on layout design decisions is unknown, but in any case, is considered of much smaller importance than that of wakes and is thus neglected.
- The additional upstream wind farm induction from Gemini wind farms will make the turbine positions in the east of the site slightly less attractive for winds from the principal wind direction.

To minimise and assess the impact of the Gemini wind farm induction while still in the design phase, a correction is baked into the wind resource grid before it is used to design the layouts for TNWWFS 1.

6.4 Example Layouts

This section presents the optimised layouts. It also compares the wake losses predicted by using different models for the optimised layouts. Layouts have been generated using the tools available in three industry software packages and the two examples with the highest performance are presented.

6.4.1 Layout 1 (15 MW)

Figure 6-1 shows an example layout with the ellipsis indicating a spacing of 7 D in the long axis and 4.5 D in the short axis. The direction of the axis is 60 degrees. Ratio of axis and direction of long axis are suggested by the WindFarmer software based on the wind speed and direction distribution for the site. Table 6-4 below shows the losses due internal wakes in the wind farm and external wakes due to the turbines in Gemini. The model comparison shows broad agreement and some model-specific outliers. In the ensemble the WakeBlaster model, as the highest fidelity model of the models used, was given a higher weight.

[9] This assumption is an approximation based on the reasoning that an impact on AEP can, as a matter of principle, not be detected or verified using relative wake losses, making it very hard to detect wind farm induction using SCADA data alone. Secondary effects may be present, also wake models may implicit contain induction to a varying degree -which is neglected here.

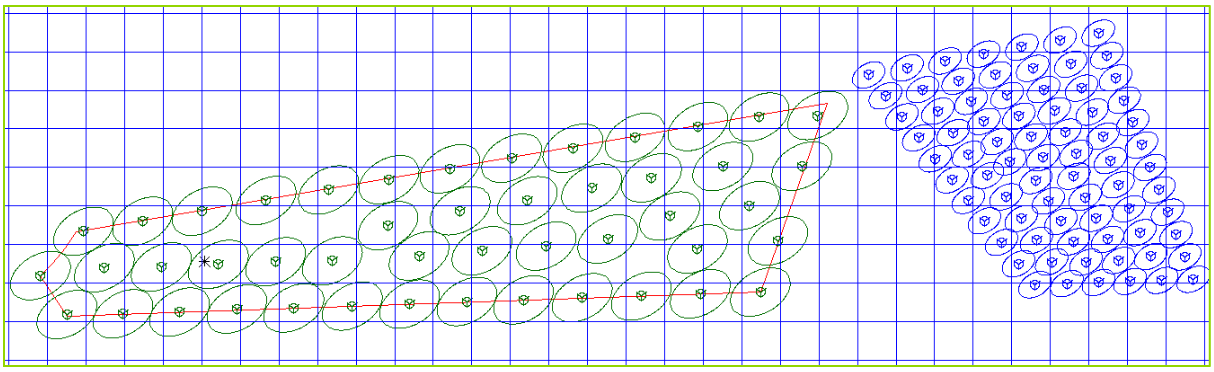

Figure 6-1. Example layout for 47 x 15 MW wind turbines (green), also shown are the existing turbines of the western half of the Gemini wind turbines (blue)

The coordinates of the example layout are presented in Appendix N.

Table 6-4. Results of wake modelling for layout 1 for 47x15 MW wind turbines

Layout 1	Internal wake losses [%]	External wake losses [%]	Total wake losses [%]	Weight [%]
WindFarmer 3.5 EV+LWFC	8.83	0.41	9.24	20
Openwind 3.6 EV+ DAWM	7.75	2.70	10.45	20
WindPRO 3.4 Park-2	10.25	1.21	11.46	20
WakeBlaster 2.4 (Python)	8.99	1.30	10.29	40
Ensemble Total	**8.96**	**1.38**	**10.34**	

Internal blockage effects should be considered among other loss factors when calculating the AEP. They are not expected to substantially impact on the design of the example layout and thus not considered further in this report.

The Gemini wind farms will, in addition to external wake effects also cause losses due to wind farm induction on the target layout. None of the wind turbines is placed directly in the north-eastern corner. Using a conservative simulation based on the model of Branlard the impact on the energy yield is estimated to be below 0.1%.

The uncertainty of the wake loss model is estimated to be 2% (at 20% of the total wake loss).

6.4.2 Layout 2 (13 MW)

Figure 6-2 shows an example layout with the ellipsis indicating a spacing of 7 D in the long axis and 4.5 D in the short axis. The direction of the axis is 60 degrees. Ratio of axis and direction of long axis are suggested by the WindFarmer software based on the wind speed and direction distribution for the site. Table 6-5 below shows the losses due internal wakes in the wind farm and external wakes due to the turbines in Gemini. The model comparison shows broad agreement and some model-specific outliers. In the ensemble the WakeBlaster model, as the highest fidelity model of the models used, was given a higher weight.

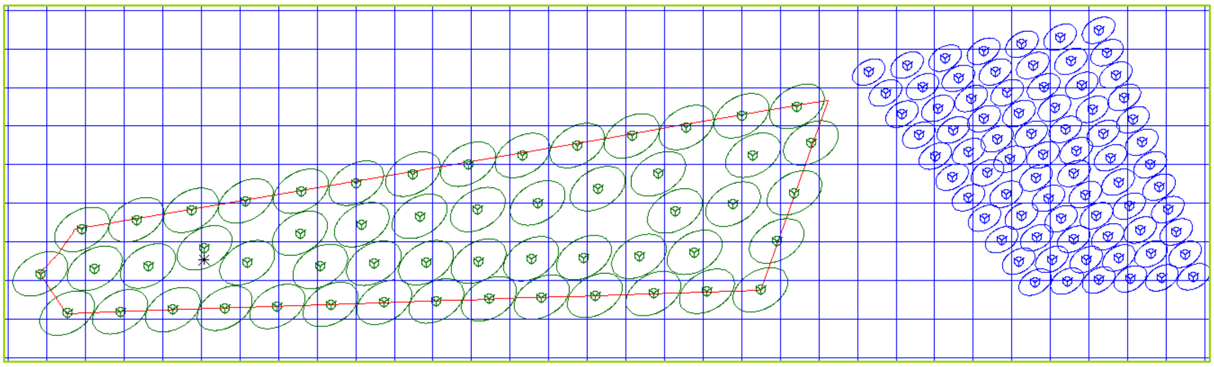

Figure 6-2. Example layout for 54 x 13 MW wind turbines (green), also shown are the existing turbines of the western half of the Gemini wind turbines (blue).

The coordinates of the example layout 2 are presented in Appendix N.

Table 6-5. Results of wake modelling for layout 2 for 54 x13 MW wind turbines

Layout 2	Internal wake losses [%]	External wake losses [%]	Total wake losses [%]	Weight [%]
WindFarmer 3.5 EV+LWFC	9.86	0.40	10.26	20
Openwind 3.6 EV+ DAWM	10.93	2.36	13.29	20
WindPRO 3.4 Park-2	11.38	1.18	12.56	20
WakeBlaster 2.4 (Python)	8.49	1.24	9.73	40
Ensemble Total	**9.83**	**1.28**	**11.11**	

Internal blockage effects should be considered among other loss factors when calculating the AEP. They are not expected to substantially impact on the design of the example layout and thus not considered further in this report.

The Gemini wind farms will, in addition to external wake effects also cause losses due to wind farm induction on the target layout. None of the wind turbines is placed directly in the north-eastern corner. Using a conservative simulation based on the model of Branlard the impact on energy yield is estimated to be below 0.1%.

The uncertainty of the wake loss model is estimated to be 2.2% (at 20% of the total wake loss).

6.4.3 Summary for example layouts

The structure of the two example layouts for TNWWFS 1 are dominated by basic design decisions:

- Wind turbine rated power (13/15 MW)
- Wind turbine rotor diameter (220/240 m)
- Wind farm capacity (700 MW)
- Capacity density (9.9 MW/km^2)

Making use of these decisions and at the same time maximising the energy yield for the meteorological conditions found at the site, results in an inter-turbine downstream/crosswind spacing of approx. 7 RD /4.5 RD.

Two compact example wind farm layouts have been created, one for each of the wind turbines. The wake losses predicted by different wake models have been compared and tabulated above, with predicted losses of 10.3±2% for layout 1 (47x15 MW), and 11.1±2.2% for layout 2 (54x13 MW).

7.0 Conclusions

The Guidehouse Project Consortium (GHPC, the Consortium) has performed an assessment of the wind resource across Ten noorden van de Waddeneilanden Wind Farm Zone (TNWWFZ, Project site), located approximately 80 km from the northern coast of the Netherlands mainland. The Consortium is a collaboration between Guidehouse WTTS B.V, ProPlanEn GmbH, OWC GmbH, and Arcvera.

TNWWFZ has been identified by of Rijksdienst voor Ondernemend Nederland (RVO, "Client") as an area of potential wind energy development. The site is located in the Dutch Exclusive Economic Zone in the Dutch shelf in the North Sea.

The aim of the study was to assess the wind resource across the TNWWFZ to inform possible future investment in offshore wind development. The long-term ambient wind conditions for the development area were analysed on behalf RVO.

This study is based on a combination of onsite and off-site wind measured data. Measurements were gathered onsite by two floating vertical scanning lidars, labelled as TNWA and TNWB, which are located approximately 500 m apart. TNWA gathered data for approximately 18 months, after which it was relocated further east for a further six months. This second location was denoted as TNWA-2. TNWB gathered data for 24 months. These datasets were supported by measurements from the FINO 1 offshore met mast, Offshore Windpark Egmond aan Zee (OWEZ) offshore met mast (OWEZ MM), IJmuiden offshore met mast (MMIJ) and the vertical scanning lidar measurements taken at the Hollandse Kust Noord (HKN) offshore site by two floating lidar systems (HKNA and HKNB).

The data from TNWA, TNWA-2 and TNWB were gathered, screened and post-processed by Fugro for both measurement locations. GHPC has analysed the screened and post-processed datasets and found the data to be of good quality for TNWA, TNWA-2 and TNWB. The uncertainty associated with the measured wind speed gathered by the floating lidars units was assessed based on the wind speed measured data in terms of instrument accuracy, mounting, the homogeneity of the surrounding wind flow as well as data quality and processing. The uncertainty in measured wind speed was estimated to be 3.4% at TNWA, 3.3% at TNWA-2 and 3.4% at TNWB.

The data gathered by the TNW lidars was found to be marginally impacted by wakes from the neighbouring Gemini wind farms. Corrections were applied to remove these effects. Following wake corrections at the onsite locations. The onsite datasets were aggregated to compile a wake-free single dataset, consisting of TNWA, TNWA-2 data as the primary datasets and TNWB as the backup dataset, filling in any gaps in TNWA and TNWA-2. The resulting dataset is representative of the short-term measurements within TNWWFZ and called TNW.

The TNW dataset and FINO 1 data were considered to be the most suitable for long-term correction to derive the final wind speed gradient across TNWWFZ. The TNW and FINO 1 datasets were corrected to the long-term by means of an MCP procedure. The data was corrected with the ERA5 modelled reference dataset using the period from 01 November 2005 to 31 October 2020 for FINO 1 and 01 July 2005 to 31 June 2021 for TNW. The long-term wind speed at TNW at a height of 140 m was found to be 10.30 m/s with a total associated uncertainty of 4.3%, Meanwhile the long-term wind speed at FINO 1 was found to be 9.94 m/s with a total associated uncertainty of 4.0%.This incorporates uncertainties related to the measured wind data, the quality of the reference dataset, the correlation between the reference dataset and the measurements, and the representativeness of the reference long-term data on the local wind conditions.

Following the long-term correction, an optimised mesoscale model was developed to assess the historic wind potential across TNWWFZ. The first step was to select the most appropriate modelled dataset for the spatial analysis to evaluate the wind distribution across the site. A number of different sources were assessed: EMD-WRF ERA5 mesoscale data, KNW mesoscale data, DOWA mesoscale data, NEWA mesoscale data and the GHPC Tailored WRF mesoscale data. These sources were validated based on their data availability, concurrency and strength of correlation with measured data (TNW, FINO 1, MM OWEZ, MMIJ, HKNA), calculated mean wind speed distribution and bias tests, spatial resolution and calibration method. The final selected source was the GHPC Tailored WRF mesoscale dataset.

The selected GHPC Tailored WRF mesoscale dataset was used to derive a wind resource grid that combines the long-term climate at both TNW and FINO 1. This was done by applying corrections that account for variations between measured and modelled wind speed distributions and the long-term frequency distribution files at TNW and FINO 1. The corrections were applied across the domain using an inverse distance squared weighting. This achieved a long-term wind resource grid and long-term wind gradient across the site.

Following the derivation of the WRG, the short-term modelled timeseries datasets were calibrated using seasonal/diurnal adjustments. These timeseries were then post-processed to obtain long-term synthetic timeseries. Corrections were applied to account for the long-term wind gradient observed in the WRG which incorporates the long-term climates from both TNW and FINO 1.

The resulting synthetic long-term timeseries were further validated by calculating the mean wind speed bias between the long-term synthetic wind speed and long-term calculated wind speed at TNW and FINO 1. A cross-prediction exercise was also conducted, and the horizontal extrapolation uncertainty associated with the model was found to be 0.2%. It is noted that no vertical extrapolation uncertainty was applied since the measured data at TNW was at a height of 140 m, which is also the hub height of interest.

The final wind gradient model is a downscaled mesoscale model based on ERA5 reanalysis data. The final modelled WRG output is representative of the long-term, both in terms of wind distribution and magnitude of resource with a spatial resolution of 100 m. The short-term calibrated mesoscale model timeseries outputs were post-processed to obtain long-term synthetic timeseries with an hourly temporal resolution.

The long-term synthetic timeseries were compared to the metocean study conducted at TNWWFZ, to the DOWA, KNW, NEWA and Global wind atlas mesoscale datasets and to previous wind resource assessment studies commissioned by RVO. The wind speeds were found to align within the expected margin uncertainty with all the different sources, with the exception of the NEWA mesoscale dataset. Meanwhile the wind gradient across the site was found to be in reasonable alignment with KNW and DOWA.

Based on the long-term synthetic timeseries the long-term wind speed, wind direction and other climatic conditions at five (5) selected nodes were observed. The long-term wind speed at the central node within TNWWFZ was found to be 10.30 m/s at a height of 140 m with a total associated wind speed uncertainty of 3.4%.

In addition to the long-term wind resource assessment, optimised layouts were designed for an identified site within the TNWWFZ. RVO has identified one (1) possible wind farm site (WFS) within TNWWFZ, and designated as Ten noorden van de Waddeneilanden wind farm site I (TNWWFS I), with 70.6 km^2 out of a total area of 120 km^2. Preliminary layouts for the TNWWFS I was designed based on 15 MW (layout 1) and 13 MW (layout 2) turbine models and a capacity target of 700 MW. The wake impact of these designed wind farms was modelled, and the resulting wake losses were found to be 10.3 ± 2% for layout 1 and 11.1 ± 2.5% for layout 2.

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9.0 References

[1] Deltares, “Ten Noorden van de Waddeneilanden Field Measurement Campaign Validation Report - June 19 2019 to July 31 2019,” 2019.
[2] E. Commission, “English Style Guide English Style Guide A handbook for authors and translators in the European Commission,” 2020. Accessed: Jul. 27, 2020. [Online]. Available: https://ec.europa.eu/info/sites/info/files/styleguide_english_dgt_en.pdf.
[3] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: 19 June - 31 July 2019,” 2019.
[4] DNV GL, “Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 190 Pre-Deployment Validation at Frøya, Norway,” 2019.
[5] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: December 2019,” 2020.
[6] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: January 2020,” 2020.
[7] DNV, “Independent performance verification of Seawatch Wind Lidar Buoy at the LEG offshore platform; WS170,” 2021.
[8] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: February 2020,” 2020.
[9] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: March 2020,” 2020.
[10] Fugro Norway AS, “Supply of Meteorological and Oceanographic data at Ten Noorden van de Waddeneilanden Monthly Data Report: April 2020,” 2020.
[11] DNV GL, “Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 191 Pre-Deployment Validation at Frøya, Norway,” 2019.
[12] DNV GL, “Independent performance verification of Seawatch Wind Lidar Buoy at Frøya, Norway; WS199,” 2021.
[13] DNV GL, “Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 156 Pre- Deployment Validation on Frøya, Norway,” 2016.
[14] DNV GL, “Independent analysis and reporting of ZX Lidars performance verification executed by ZX Lidars at the UK Remote Sensing Test Site; ZP501,” 2019.
[15] DNV GL, “Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 187 Pre-Deployment Validation at Frøya, Norway,” 2019.
[16] DNV GL, “Independent performance verification of Seawatch Wind Lidar Buoy at Frøya, Norway; WS181,” 2021.
[17] Offshore Wind Accelerator, “Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology.,” 2018.
[18] Natural Power, “Floating lidar validation analysis, seawatch wind lidar buoy. Tech. Rep. ref. no. 1124607/D,” 2015.
[19] DNV GL, “Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 170 Pre-Deployment Validation at Frøya, Norway,” 2017.
[20] Tractabel Engineering S.A., “Site Studies Hollandse Kust: Wind Resource Assessment Wind Farm Zone Hollandse Kust (west),” 2020. [Online]. Available: https://offshorewind.rvo.nl/file/view/55040748/01.
[21] T. Leiding *et al.*, “Abschlussbericht - Standardisierung und vergleichende Analyse der meteorologischen FINO-Messdaten (FINO123),” 2016.
[22] H. Kouwenhoven, “User manual data files meteorological mast NoordzeeWind,” 2007.
[23] P. J. Eecen, L. A. . Machielse, and A. P. W. . Curvers, “Meteorological Measurements OWEZ Half year report 01-07-2005 - 31-12-2005,” 2007.
[24] Ecofys, “Hollandse Kust (zuid) Offshore Wind Farm Zone Combined Wind Resource Assessment,” 2017.
[25] ECN, “Offshore meteorological mast IJmuiden abstract of instrumentation report, ECN-Wind-Memo-12-010,” 2012.
[26] Oldbaum, “Wind Resource Assessment for Hollandse Kust (noord) Wind Farm Zone; Document No.: HKN_20190930_OBL_WRA-HKN_V6_0F,” 2019.

[27] IEC, *International Standard IEC 61400-12-1 Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*, 2nd ed. IEC, 2017.

[28] K. Rohrig, *Windenergie Report Deutschland 2018*. 2019.

[29] W. (NREL) Musial, P. (NREL) Beiter, P. (DOE) Spitsen, J. (NREL) Nunemaker, and V. (NREL) Gevorgian, "2018 Offshore Wind Technologies Market Report," 2018. Accessed: Aug. 28, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2019/09/f66/2018 Offshore Wind Technologies Market Report.pdf.

[30] P. Bradstock and W. Schlez, "Theory and verification of a new 3D RANS wake model," *Wind Energy Sci.*, vol. 5, no. 4, pp. 1425–1434, Oct. 2020, doi: 10.5194/wes-5-1425-2020.

[31] J. S. Rodrigo, "'OWA Wake Modelling Challenge' The Wind Vane Tube," *Task31 online meeting 17-06-2020, (1:04:49-1:28:50)*, 2020. .

[32] J. S. Rodrigo *et al.*, "Validation of Meso-Wake Models for Array Efficiency Prediction Using Operational Data from Five Offshore Wind Farms," *J. Phys. Conf. Ser.*, vol. 1618, p. 062044, Sep. 2020, doi: 10.1088/1742-6596/1618/6/062044.

[33] M. Dörenkämper, "Understanding and mitigating the impact of data gaps on offshore wind resource estimates," *Wind Energy Sci.*, vol. 6, pp. 505–520, 2021, doi: 10.5194/wes-6-505-2021.

[34] H. Hersbach *et al.*, "The ERA5 global reanalysis," *Q. J. R. Meteorol. Soc.*, 2020, doi: 10.1002/qj.3803.

[35] E. Gaertner *et al.*, "Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report," 2020. Accessed: Feb. 24, 2021. [Online]. Available: www.nrel.gov/publications.

[36] W. Musial, Z. Parker, J. Fields, G. Scott, D. Elliott, and C. Draxl, "Assessment of Offshore Wind Energy Leasing Areas for the BOEM Massachusetts Wind Energy Area," 2012. Accessed: Feb. 24, 2021. [Online]. Available: www.nrel.gov/publications.

[37] R. Borrmann, D. K. Rehfeldt, A.-K. Wallasch, and S. Lüers, "CAPACITY DENSITIES OF EUROPEAN OFFSHORE WIND FARMS Report conducted by Deutsche WindGuard GmbH," 2018.

[38] A. Neubert, A. Shah, and W. Schlez, "Maximum Yield From Symmetrical Wind Farm Layouts," 2010.

[39] S. Voutsinas, "Prediction of the Energy Efficiency and Optimal Design of Wind Parks," 1998.

[40] H. . et al. Beyer, "Optimising the Geometrical Arrangement of Wind Farms," 1994.

[41] P. Lewis and A. Garrad, "Wind Farm Layout Optimisation," 1994.

[42] W. Schlez, "Unlocking Blockage - white paper on wind farm induction," Nov. 2020, doi: 10.5281/ZENODO.4288324.

[43] H. . Madsen, "A CFD Analysis of the Actuator Disc Flow compared with Momentum Theory Results," 1996.

[44] S. Frandsen *et al.*, "Redefinition power curve for more accurate performance assessment of wind farms," *Wind Energy*, vol. 3, no. 2, pp. 81–111, Apr. 2000, doi: 10.1002/1099-1824(200004/06)3:2<81::AID-WE31>3.0.CO;2-4.

[45] E. Branlard, E. Quon, A. R. Meyer Forsting, J. King, and P. Moriarty, "Wind farm blockage effects: Comparison of different engineering models," in *Journal of Physics: Conference Series*, Sep. 2020, vol. 1618, no. 6, p. 062036, doi: 10.1088/1742-6596/1618/6/062036.

[46] "EMD-WRF Europe+ (ERA5) - Wiki-WindPRO." http://help.emd.dk/mediawiki/index.php?title=EMD-WRF_Europe%2B_(ERA5) (accessed Jul. 27, 2020).

[47] M. Lybech Thøgersen, "Technical Note: Validation of EMD-WRF EUROPE+ (ERA5) mesoscale dataset."

[48] I. L. Wijnant *et al.*, "The Dutch Offshore Wind Atlas (DOWA): description of the dataset," 2019.

[49] I. L. Wijnant, A. Stepek, M. Savenije, and H. W. van den Brink, “User manual of the (KNMI North Sea Wind) KNW-atlas,” 2016.
[50] B. Witha *et al.*, “WRF model sensitivity studies and specifications for the NEWA mesoscale wind atlas production runs,” May 2019, doi: 10.5281/ZENODO.2682604.
[51] “MERRA-2.” https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/ (accessed Jul. 27, 2020).
[52] R. Gelaro *et al.*, “The modern-era retrospective analysis for research and applications, version 2 (MERRA-2),” *J. Clim.*, vol. 30, no. 14, pp. 5419–5454, Jul. 2017, doi: 10.1175/JCLI-D-16-0758.1.
[53] DTU, “Global wind atlas.” https://globalwindatlas.info/about/introduction (accessed Mar. 30, 2021).
[54] IEC, “IEC 61400-12-1:2017 Edition 2.0 Wind energy generation systems – Power performance measurements of electricity producing wind turbines,” *Int. Stand.*, 2017, Accessed: Feb. 26, 2021. [Online]. Available: https://webstore.iec.ch/publication/26603.

Appendix A. Guidehouse Project Consortium

The Consortium is a collaboration between Guidehouse Energy Germany GmbH and ProPlanEn GmbH. The following sections give a brief introduction to the Consortium participants.

A.1 Guidehouse

With over 600 consultants, Guidehouse's global energy segment is the largest energy and sustainability consulting team in the industry. We have done substantial work for the European Commission, national governments, TSOs and investors regarding development of offshore energy in the North Sea and in the Baltic Sea.

We collaborate with utilities and energy companies, government and NGOs, large corporations, product manufacturers, and investors to help them thrive in a rapidly changing energy environment. Our clients include the world's 50 largest electric, water, and gas utilities; the 20 largest independent power generators; and the 20 largest gas distribution and pipeline companies. Guidehouse's seasoned professionals and highly skilled specialists form exceptional teams to help clients transform their businesses, manage complexity and accelerate operational performance, meet compliance requirements, and transform organisations and systems to address upcoming changes as the energy transition accelerates. Supporting customers interested in offshore energy development is one of our key strengths and we have substantially contributed to the work on offshore energy developments, in particular in the North Sea.

Our international core team has a combined experience of over 40 years working the wind energy sector globally. Our team has practical technical and commercial experience in developing, financing, constructing and operating offshore wind farms in Europe. Our staff supported the development, financing, construction, and operation of over 20 realized offshore wind farms with over 9 GW. We have detailed knowledge and an excellent understanding of offshore wind resource assessments (including floating lidar technology) and energy yield estimation from our involvement in wind resource assessment and energy yield estimations for over >5 GW of on and offshore wind farms globally. Our team is familiar with the offshore wind climate in key offshore wind markets and we understand how fundamental robust energy yield assumptions are for building a business case.

We help clients build, manage, and protect their future by:

- Supporting new market developments and strategy developments
- Exploring new technology solutions for a low-carbon future
- Building capabilities and innovative solutions that advance and transform their businesses.
- Managing complexity and removing barriers to accelerate operational performance.
- Protecting their business from adversity by meeting compliance requirements, keeping assets secure, and vigilantly managing risks.

We focus on achieving sustainable value for our clients and offer a broad set of transformation offerings that evolve to align with shifting energy industry demands.

This study was conducted by the specialized wind turbine testing and services (WTTS) team of Guidehouse, certified according to ISO 9001 for wind analysis and measurements.

A.2 ProPlanEn

ProPlanEn was founded as an independent wind energy consultancy in 2015 by Dr Wolfgang Schlez., and the ProPlanEn team has since delivered a wide range of independent advice and specialist tools to the wind energy industry.

ProPlanEn is well connected in the industry. It is member of the industry associations WindEurope and the German Wind Energy Association (BWE), and it actively contributes to national and international expert working groups including Wind Resource Group (UK), Wind Resource Assessment Group (EU), Vindkraftnet (DK), IEA-Task 31 Wakebench, and BWE Windgutachterbeirat.

ProPlanEn has carried out confidential industrial research (strategic studies, literature research summarizing the state of the art for specific topics, and product and methodology development) for major clients in the industry, including for major global developers, utilities, and manufacturers.

ProPlanEn has delivered commercial assessments of wind farm wake losses, and effective turbulences for many offshore wind farms in German, French, English and Taiwanese waters. It has also assessed the operational performance of over 20 operational wind farms, based on SCADA data.

ProPlanEn holds commercial licences for the wind farm design software tools, WindPRO, WindFarmer, WAsP, and OpenWind and it employs consultants who are experienced in operating these tools. ProPlanEn operates at a high level of quality, and environmental, social and corporate responsibility.

In 2016/7 ProPlanEn attracted co-funding from Innovate UK to develop WakeBlaster - a new 3D RANS wake model, suited to accurately modelling the yield of very large wind farms with up to, and exceeding, 10,000 wind turbines.

The model has been validated against production data from onshore and offshore wind farms, it recently achieved very good results in the OWA wake model blind test for 5 offshore wind farms. After intensive testing, WakeBlaster was recently integrated into WindPRO and Openwind, two of the worldwide leading software packages for designing wind farms.

WakeBlaster is not an adaptation of a general purpose CFD toolbox. Instead, it was developed as a flexible tool and from scratch. As its developer, ProPlanEn has full access to all details regarding WakeBlaster, as well as the in-depth know-how and capability to implement any modifications that prove necessary.

A.3 Arcvera

ArcVera Renewables provides expert insights, targeted analysis and reporting for renewable energy prospecting, development, sponsor financing, portfolio transactions, post-construction operational analysis, and repowering. ArcVera's wind energy resource assessment service is anchored in principles of atmospheric science and wind engineering, and uses mesoscale numerical weather prediction as the foundation of its wind resource assessment methods. The company's experienced team of atmospheric scientists, data analysts, and engineers are known for their expertise, precision, responsiveness, and reliability. Services in measurement and analysis comprise: resource measurement, measurement campaign strategy, instrument specification, design, IEC standards and placement of meteorological station(s) and remote sensors.

A.4 OWC

OWC, an AqualisBraemar LOC company, is a specialised independent consultancy offering project development services, owner's engineering and technical due diligence to the offshore wind industry, developing and realising projects across the globe.

OWC's core team possesses strong industry expertise which dates to the first offshore wind farm development in the UK. Since then, OWC has been involved in the majority of the major offshore wind projects in Europe, Asia and the US.

OWC wind & site team supports clients with early conceptual design, site screening and pre-feasibility assessments, ensemble wake modelling, layout and turbine optimization, mesoscale modelling, wind resource assessments, post-construction operational yield assessments, and third-party energy yield reviews.

OWC offices are located in Boston, Edinburgh, Hamburg, London, New York, Seoul, Taipei, Tokyo and Warsaw.

OWC is active in the markets: fixed and floating offshore wind, ocean energy, subsea cables and energy storage.

Appendix B. Measurement Campaign Documentation

B.1 TNWA, TNWA-2 and TNWB

The following measurement campaign documentation is an excerpt from [3] and is applicable to the buoys installed both at TNWA, TNWA-2 and TNWB. It is noted that [3] is the first monthly report issued by Fugro. The information presented below can be found in any of the monthly reports issued by Fugro.

The two SWLB systems installed for the TNWWFZ measurement campaign present a redundant arrangement of instrumentation, particularly to safeguard against data loss. The data gathered at each buoy is formed into a digital package that is both store on the buoy and transmitted via satellite. This allowed almost real-time operation checks, maintenance scheduling and monthly reporting. It is noted that for the purpose of this study the data stored on the buoy and later downloaded was used as there are no gaps due to lack of transmission.

Each SWLB buoy is equipped with the sensors:

- Wavesense 3 3-directional wave sensor
- ZephIR ZX300 CW lidar
- Gill Windsonic M acoustic wind sensor
- Nortek Aquadopp 600kHz current profiler
- Vaisala PTB330A air pressure sensor
- Vaisala HMP155 air temperature and humidity sensor
- DualGPS Septentrio position tracking
- Acoustic receiver for Thelma TBR700 water pressure sensor.

An illustration of the buoy and the lidar measurement configuration is shown in Figure B-1.

The ZephIR lidar is a continuous wave lidar system whereby a continuous beam is emitted from the window at the top of the lidar. The beam is emitted at a slanted angle from the vertical plane and rotates with a period of 1 second around the central axis to form a continuous scan in the shape of a cone. The return signal is focused on one elevation using an optical focus stage and samples individual line of sight points around the circle within that elevation. The Doppler shift of the backscattered individual line of sight sample is used for the reconstruction of the 1 second wind field.

These measurements are averaged to give a 10-minute averaged time series of horizontal and vertical wind speeds. The wind direction is then calculated using the measurement of the buoy heading from the Septentrio DGPS. Wind directions are also checked in real-time against the data from the Gill wind sensor to resolve the 180° ambiguity in the results due to the ambiguity in the magnitude of the Doppler shift, which is typical of a ZephIR lidar. The Gill sensor is factory calibrated, but is not validated in the pre-deployment validation of the buoys.

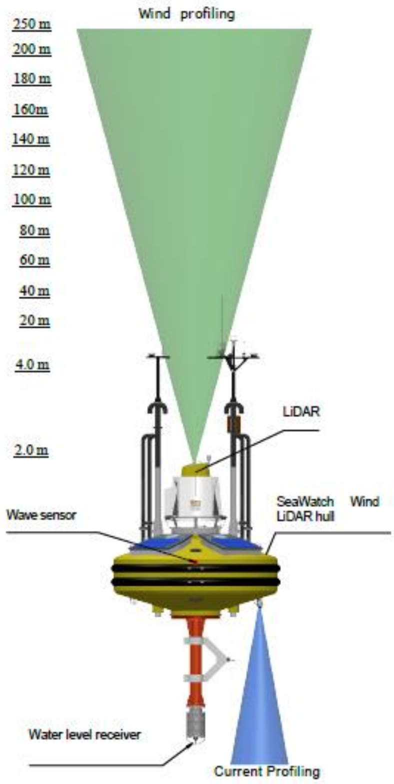


Figure B-1. Wind measured profile by the lidar unit on the buoy [3]

B.2 FINO 1 Met Mast

The following measurement campaign documentation is a translated excerpt from [21].

B.2.1 FINO Project (Research in the North and Baltic Seas), Environmental and Pollution Measurements

FINO1, wind measurements Project duration: since 2003 – ongoing

Wind measurements on FINO1

- Conception and installation of the wind measurement system,
- Maintenance, calibration and operation of the wind measurement system,
- Preparation, plausibility check and transfer of the data.

B.2.2 FINO Project, Environmental and Pollution Measurements FINO1, Wind Measurements

The measurements of the cup anemometer and wind vane are recorded with two data loggers (1-minute averages, maximum, minimum, standard deviation for wind speed measurement, 1-minute averages, standard deviation for wind direction measurement). After reading the data logger regularly, the measurements are made monthly calibrated and in a format with 10-minute averages and the corresponding statistics merged. The measurements of the Sonic anemometer are recorded by another measuring system (temporal resolution 10 Hz, speed components u, v, w). Monthly, the 10-minute averages and standard deviation of the horizontal wind speed and wind direction are calculated from the wind speed components in the above named format.

B.2.3 Methodology of Data Processing and Quality Control of the Data

Quality control is a combination of automated and manual detection of invalid measured values (Figure B-2). Valid ranges of values for the individual measured variables are defined in advance. In a first run, values that lie outside a valid value range are automatically deleted. Plots of various types (scatterplots, availabilities, statistical values, correlation, spikes, repeated values, etc.) are then also output automatically, which assist in the search for further incorrect measurements. As a result of this analysis, invalid measured values can be specified, which are also deleted.

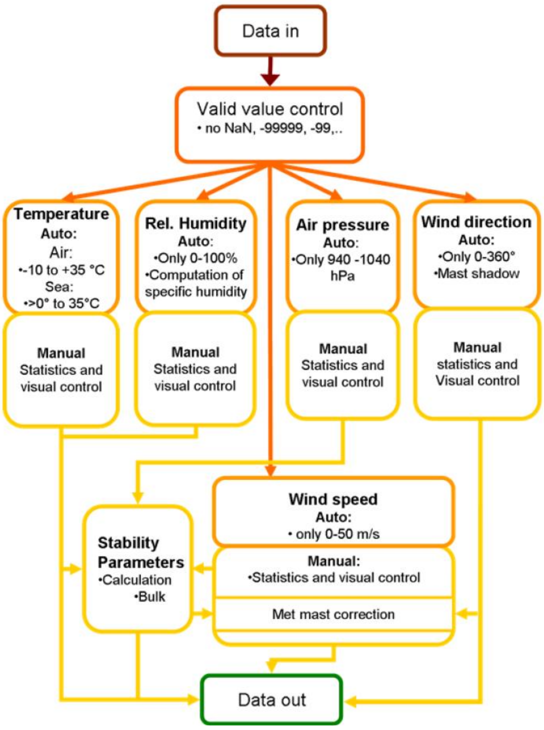


Figure B-2. Data flow of validation and correction

B.2.4 Definition of Valid Sectors

The wind speed measurements and, to a lesser extent, the wind direction measurements are influenced by the flow effects of the measuring mast or neighboring measuring instruments as well as neighboring large obstacles (wind farms, turbines). For this reason, measurements from certain wind direction sectors are only taken into account with corrections or not at all. A correction of the flow effects is carried out - if possible. The effects in the direct mast shadow but also from neighboring wind farms cannot be reliably corrected; wind measurements from these sectors are not considered. These sectors must be identified based on information from the operator, technical drawings and maps, but also based on an analysis of the measurement data; a start time for the construction work must also be found, especially for wind farms. Experience has shown that these two influences (mast shadow, wind farm) are the greatest factors with reduced availability. The method of the IEC 2005 guideline (wind turbine performance) is used to determine the disturbed area by neighboring wind turbines. The distance between the mast and the wind turbines Ln and the rotor diameter of the wind turbines Dn are required here. The division of Ln by Dn gives the relative distance with which the disturbed wind direction sector α is determined. Here, α is calculated using the following formula:

$\alpha = 1.3 \arctan(2.5Dn/Ln + 0.15) + 10$

Appendix C. Measurement Campaigns' Monthly Values

Table C-1. Monthly mean wind speed and data coverage values at TNWA

Month	Wind Speed [m/s]				Wind Speed Data Coverage [%]			
	100 m	120 m	140 m	160 m	100 m	120 m	140 m	160 m
Jun.19*	8.11	8.20	8.25	8.28	90	90	89	89
Jul.19	8.66	8.84	8.96	9.07	93	91	91	91
Aug.19	9.02	9.12	9.20	9.27	100	100	99	99
Sep.19	9.75	9.81	9.91	9.98	98	97	97	97
Oct.19	10.83	10.97	11.09	11.21	98	97	97	97
Nov.19	9.60	9.65	9.72	9.75	96	94	93	93
Dec.19	12.44	12.64	12.84	13.04	75	75	74	73
Jan.20	12.96	13.24	13.51	13.74	25	25	25	25
Feb.20	14.94	15.28	15.60	15.87	84	84	84	84
Mar.20	11.01	11.23	11.43	11.64	61	61	61	61
Apr.20	8.74	8.94	9.10	9.25	66	66	66	66
May.20	7.92	8.06	8.18	8.27	94	94	93	93
Jun.20	8.08	8.28	8.43	8.54	95	95	95	94
Jul-20	9.25	9.39	9.51	9.61	71	71	71	71
Aug-20	9.17	9.32	9.45	9.55	98	98	98	98
Sep-20	8.75	8.84	8.92	8.99	100	100	100	99
Oct-20	11.74	11.88	12.00	12.13	99	98	99	98
Nov-20	11.68	11.85	11.99	12.14	88	88	88	88
Dec-20	10.67	10.84	10.97	11.11	80	80	80	80
All data	**10.06**	**10.22**	**10.35**	**10.47**	**84**	**84**	**84**	**84**

*partial month

Table C-2. Monthly mean wind speed and data coverage values at TNWA-2

Month	Wind Speed [m/s]				Wind Speed Data Coverage [%]			
	100 m	120 m	140 m	160 m	100 m	120 m	140 m	160 m
Jan-21*	10.69	10.82	10.95	11.06	97	97	97	97
Feb-21	12.94	13.25	13.51	13.70	94	94	93	93
Mar-21	10.47	10.76	11.02	11.24	93	92	92	92
Apr-21	8.78	8.87	8.95	9.04	100	100	99	99
May-21	8.43	8.60	8.75	8.89	98	98	97	97
Jun-21*	6.92	7.03	7.09	7.12	90	89	88	88
All data	**9.75**	**9.94**	**10.10**	**10.24**	**95**	**95**	**95**	**94**

*partial month

Table C-3. Monthly mean wind speed and data coverage values at TNWB

Month	Wind Speed [m/s]				Wind Speed Data Coverage [%]			
	100 m	120 m	140 m	160 m	100 m	120 m	140 m	160 m

Jun.19*	8.32	8.40	8.46	8.51	92	91	91	90
Jul.19	8.66	8.84	8.98	9.09	91	91	90	90
Aug.19	8.95	9.06	9.13	9.20	98	98	97	97
Sep.19	9.59	9.67	9.76	9.85	93	93	92	92
Oct.19	10.63	10.77	10.90	11.00	86	86	85	85
Nov.19	9.95	10.00	10.08	10.12	70	69	69	68
Dec.19	13.62	13.83	14.05	14.31	51	50	50	50
Jan.20	-	-	-	-	0	0	0	0
Feb.20	-	-	-	-	0	0	0	0
Mar.20	-	-	-	-	0	0	0	0
Apr.20	8.69	8.88	9.04	9.18	66	66	66	66
May.20	7.87	8.01	8.14	8.23	94	93	93	93
Jun.20	8.57	8.71	8.85	8.95	73	73	73	73
Jul-20	8.09	8.22	8.31	8.40	100	100	100	100
Aug-20	9.11	9.27	9.39	9.49	100	100	100	100
Sep-20	8.80	8.89	8.96	9.03	99	99	99	99
Oct-20	11.36	11.47	11.58	11.68	79	79	79	79
Nov-20	11.73	11.91	12.07	12.23	68	68	68	67
Dec-20	10.55	10.69	10.81	10.91	99	99	99	99
Jan-21	10.12	10.23	10.35	10.42	98	98	98	98
Feb-21	12.49	12.57	12.63	12.71	52	52	52	52
Mar-21	10.58	10.87	11.12	11.34	91	91	90	90
Apr-21	11.11	11.24	11.35	11.43	13	13	13	13
May-21	8.46	8.64	8.80	8.95	90	90	90	89
Jun-21*	6.93	7.03	7.09	7.13	84	83	83	82
All data	**9.58**	**9.72**	**9.84**	**9.95**	**71**	**71**	**71**	**70**

*partial month

Table C-4. Monthly mean wind speed and data coverage values at FINO 1

Month	102.5 m wind speed [m/s]	102.5 m wind speed data coverage [%]
Jan-04	10.80	100
Feb-04	10.55	100
Mar-04	10.63	100
Apr-04	8.87	100
May-04	7.80	100
Jun-04	9.12	100
Jul-04	7.29	100
Aug-04	9.12	99
Sep-04	10.98	99
Oct-04	10.96	75
Nov-04	9.91	100
Dec-04	10.30	99

Month	102.5 m wind speed [m/s]	102.5 m wind speed data coverage [%]
Jan-05	14.46	83
Feb-05	11.11	100
Mar-05	11.27	70
Apr-05	9.62	93
May-05	8.73	100
Jun-05	7.84	100
Jul-05	7.58	100
Aug-05	8.51	99
Sep-05	8.60	100
Oct-05	10.42	100
Nov-05	10.61	97
Dec-05	11.36	100
Jan-06	9.83	100
Feb-06	9.26	100
Mar-06	10.74	100
Apr-06	9.09	95
May-06	10.84	100
Jun-06	7.56	100
Jul-06	6.77	100
Aug-06	7.36	100
Sep-06	9.14	99
Oct-06	10.84	100
Nov-06	13.42	100
Dec-06	12.24	100
Jan-07	15.58	97
Feb-07	10.73	99
Mar-07	11.68	91
Apr-07	9.10	98
May-07	8.24	100
Jun-07	7.70	100
Jul-07	9.43	100
Aug-07	8.55	100
Sep-07	11.04	96
Oct-07	7.81	99
Nov-07	11.06	68
Dec-07	10.35	82
Jan-08	14.75	51
Feb-08	11.47	100
Mar-08	12.79	100
Apr-08	8.79	99
May-08	8.67	100

Month	102.5 m wind speed [m/s]	102.5 m wind speed data coverage [%]
Jun-08	8.91	87
Jul-08	9.36	100
Aug-08	9.38	100
Sep-08	9.14	100
Oct-08	11.12	100
Nov-08	11.81	100
Dec-08	9.20	100
All data	**9.93**	**96**

Appendix D. Description of Uncertainties

D.1 Uncertainties – Wind speed

Wind statistics

Measurement errors can be affected by the quality of the instruments, the calibration process, the meteorological mast design, data coverage and data processing.

Traceability of the wind data is an important factor in assessing the quality of the wind statistics. Highly traceable data allows for a precise analysis of uncertainties, while more uncertainty must be attributed to poorly traceable data.

MCP method uncertainty

The intrinsic uncertainty on MCP method and setup to extrapolate the short-term wind measurement to the long-term is composed of four sub-categories:

- Correlation between the onsite wind measurements and the reference long-term dataset;
- Quality of the reference long-term dataset;
- Representativeness of the reference long-term dataset on the local wind climate;
- Intrinsic uncertainty on the MCP method used.

Long-term representation

The annual variability of wind speed leads to an uncertainty in the long-term representation of short-term measurements. The standard error for a single year of measurements has been statistically determined to be 5.5% (based on a large number of Dutch meteorological stations) and 6% (based on stations throughout Europe). Therefore, the standard error in measurements with a longer duration can be approximated as: $\sigma=(5.5\%)/\sqrt{\text{years}}$.

The long-term representation is based on the assumption that long-term measurements at a site are a good estimator of the future wind climate. Possible impacts of global warming on the wind climate are not considered.

Horizontal extrapolation

The accuracy in the horizontal extrapolation of wind speeds depends primarily on the distance between the measurement site and the wind turbines.

Vertical extrapolation

In order to minimise errors in vertical extrapolation, the measurement height should be close to the proposed hub height. Using a met mast with multiple instrument heights, it is possible to verify the vertical profile and estimate the uncertainties.

Larger uncertainties are inherent using measurements at the WMO standard height of 10 m (for instance, meteorological stations). The vertical profile is highly dependent on the site climatic conditions, as well as the accuracy of the measurement height.

Other

This uncertainty can cover any additional errors related to wind speed.

Appendix E. Neighbouring Wind Farms

The coordinates presented below are in the coordinate system of ETRS89 UTM 31N, EPSG 25831.

E.1 Gemini wind farm

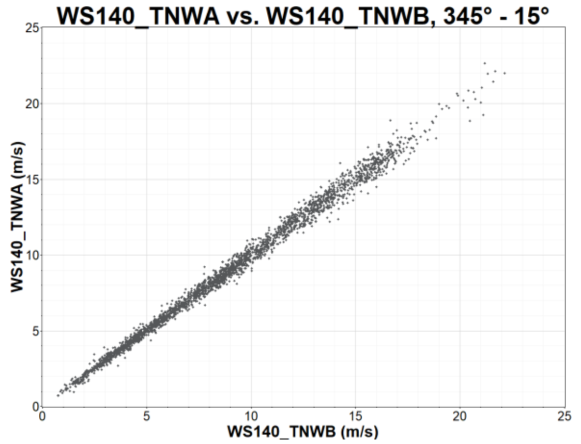
Turbine label	Easting	Northing
Z1	688604	5987959
Z2	688173	5988503
Z3	687742	5989047
Z4	687311	5989591
Z5	686879	5990135
Z6	686447	5990679
Z7	686016	5991223
Z8	685585	5991767
Z9	685154	5992311
Z10	684722	5992855
Z11	684291	5993398
Z12	689426	5987987
Z13	689032	5988550
Z14	688637	5989113
Z15	688243	5989675
Z16	687848	5990238
Z17	687368	5990792
Z18	686884	5991341
Z19	686483	5991900
Z20	686083	5992460
Z21	685682	5993019
Z22	685282	5993579
Z23	690248	5988016
Z24	689923	5988544
Z25	689597	5989073
Z26	689272	5989601
Z27	688947	5990130
Z28	688622	5990659
Z29	687953	5991145
Z30	687617	5991668
Z31	687281	5992190
Z32	686944	5992713
Z33	686608	5993236
Z34	686272	5993759
Z35	688804	5991254
Z36	688496	5991791
Z37	688187	5992328
Z38	687879	5992865
Z39	687571	5993402
Z40	687262	5993939
Z41	691065	5988044
Z42	690774	5988589
Z43	690483	5989135
Z44	690192	5989681
Z45	689901	5990226
Z46	689610	5990772
Z47	689661	5991364
Z48	689380	5991915
Z49	689100	5992467
Z50	688820	5993018
Z51	688540	5993569
Z52	688260	5994121
Z53	691887	5988072
Z54	691604	5988691
Z55	691320	5989310
Z56	691037	5989929
Z57	690753	5990548
Z58	690553	5991180
Z59	690360	5991812
Z60	690083	5992434
Z61	689805	5993057
Z62	689528	5993679
Z63	689251	5994301
Z64	692709	5988100
Z65	692484	5988680
Z66	692260	5989260
Z67	692036	5989840
Z68	691812	5990420
Z69	691588	5990999
Z70	691362	5991582
Z71	691138	5992162
Z72	690914	5992742
Z73	690690	5993322
Z74	690465	5993901
Z75	690241	5994481
B1	698397	5988296
B2	698146	5988942
B3	697895	5989588
B4	697643	5990234
B5	697392	5990880
B6	697141	5991526
B7	696889	5992175
B8	696638	5992821
B9	696387	5993467
B10	696136	5994113
B11	695885	5994759
B12	695634	5995405
B13	699266	5988325
B14	699033	5988927
B15	698800	5989528
B16	698566	5990130
B17	698333	5990731
B18	698099	5991333
B19	697865	5991937
B20	697632	5992538
B21	697398	5993139
B22	697165	5993741
B23	696932	5994342
B24	696698	5994944
B25	696465	5995545
B26	700136	5988355
B27	699878	5989021
B28	699620	5989688
B29	699362	5990354
B30	699104	5991020
B31	698846	5991686
B32	698586	5992355
B33	698328	5993021
B34	698070	5993687
B35	697812	5994353
B36	697554	5995019
B37	697295	5995685
B38	701012	5988385
B39	700772	5989005
B40	700532	5989625
B41	700292	5990245
B42	700053	5990865

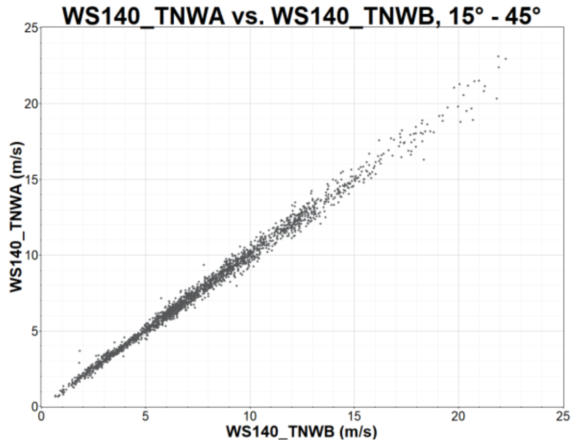
Turbine label	Easting	Northing
B43	699813	5991485
B44	699572	5992107
B45	699332	5992727
B46	699092	5993347
B47	698852	5993967
B48	698612	5994587
B49	698372	5995207
B50	698133	5995827
B51	701882	5988415
B52	701617	5989101
B53	701351	5989788

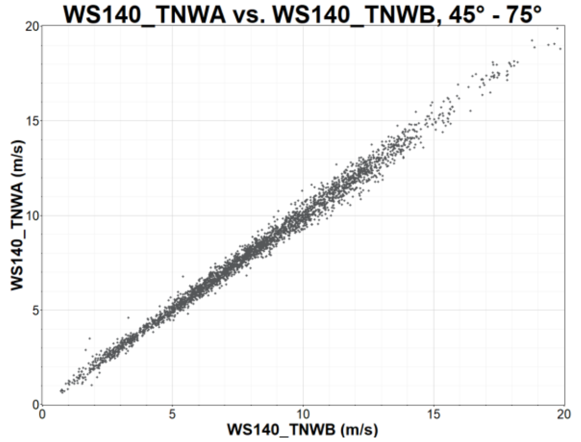
Turbine label	Easting	Northing
B54	701086	5990474
B55	700821	5991160
B56	700556	5991846
B57	700289	5992536
B58	700024	5993222
B59	699759	5993908
B60	699494	5994594
B61	699228	5995281
B62	698963	5995967
B63	702752	5988445
B64	702505	5989083

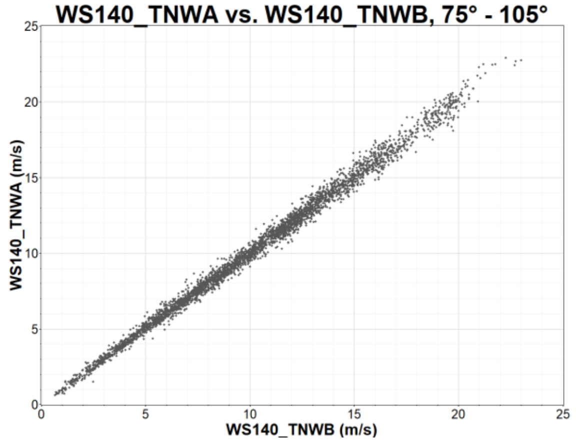
Turbine label	Easting	Northing
B65	702259	5989721
B66	702013	5990360
B67	701766	5990998
B68	701520	5991636
B69	701272	5992278
B70	701026	5992916
B71	700779	5993554
B72	700533	5994192
B73	700287	5994831
B74	700040	5995469
B75	699794	5996107

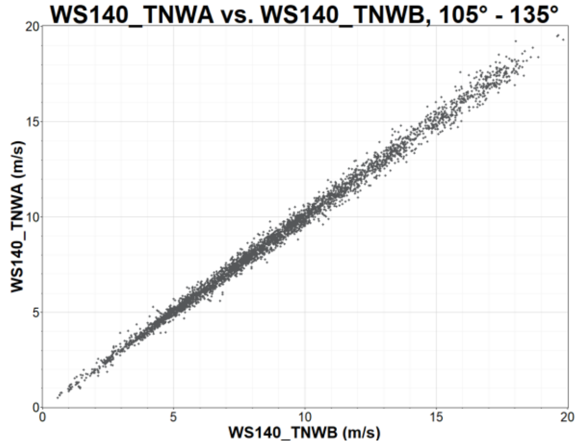
Appendix F. Scatter Plots of TNWA vs TNWB 140 m Wind Speed

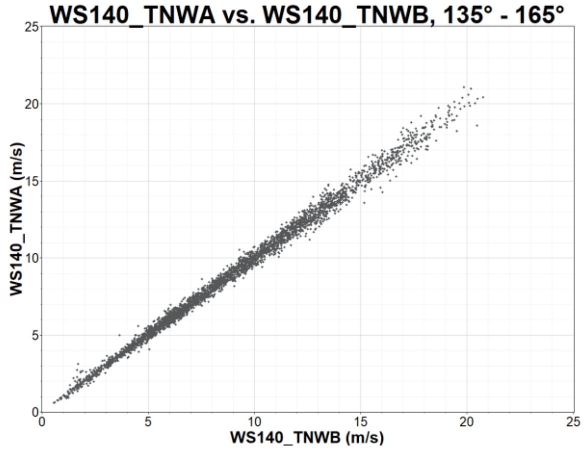


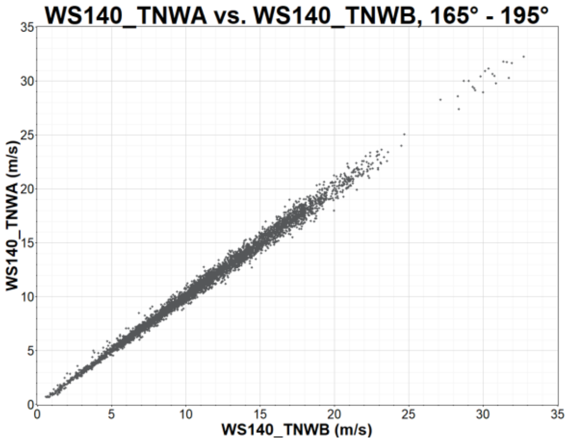


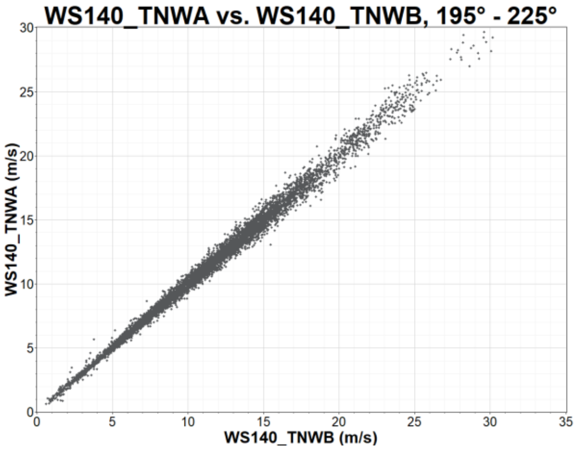


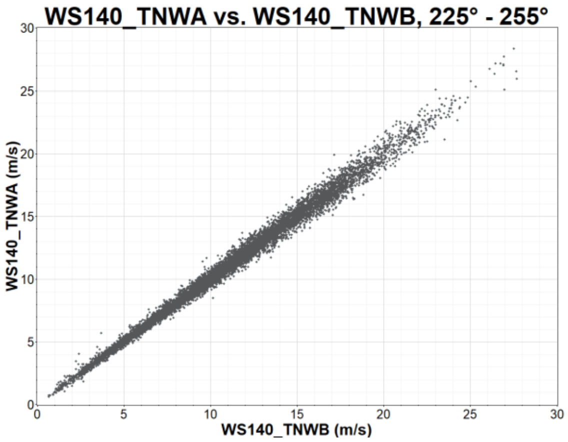


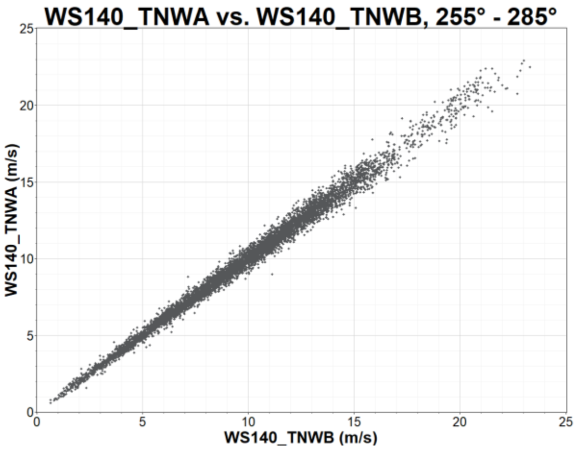


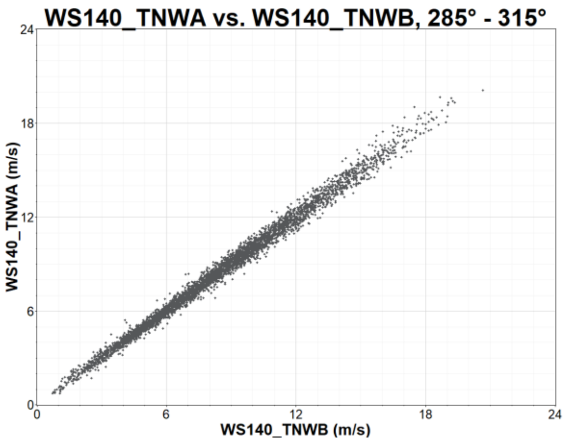


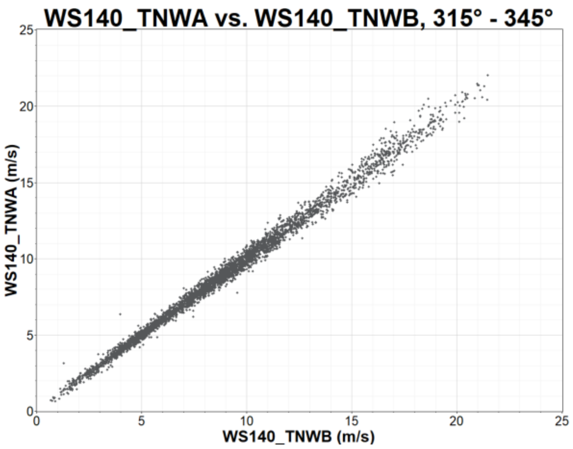

WS140_TNWA vs. WS140_TNWB, 165° - 195°
WS140_TNWA (m/s)
WS140_TNWB (m/s)


WS140_TNWA vs. WS140_TNWB, 195° - 225°
WS140_TNWA (m/s)
WS140_TNWB (m/s)


WS140_TNWA vs. WS140_TNWB, 225° - 255°
WS140_TNWA (m/s)
WS140_TNWB (m/s)


WS140_TNWA vs. WS140_TNWB, 255° - 285°
WS140_TNWA (m/s)
WS140_TNWB (m/s)


WS140_TNWA vs. WS140_TNWB, 285° - 315°
WS140_TNWA (m/s)
WS140_TNWB (m/s)


WS140_TNWA vs. WS140_TNWB, 315° - 345°
WS140_TNWA (m/s)
WS140_TNWB (m/s)

Appendix G. Overview of the Mesoscale/Global Datasets

G.1 EMD-WRF Europe+

The EMD-WRF Europe+ (ERA5) dataset (or short, 'EMD-EUR+') is the high-resolution mesoscale dataset covering Europe. The mesoscale dataset is based upon ECMWF (http:/www.ecmwf.int) reanalysis data from ERA5 as its boundary conditions. 'EMD-WRF Europe+ (ERA5)' is provided by EMD. The model domain of EMD-WRF Europe+ is shown in Figure G-1.

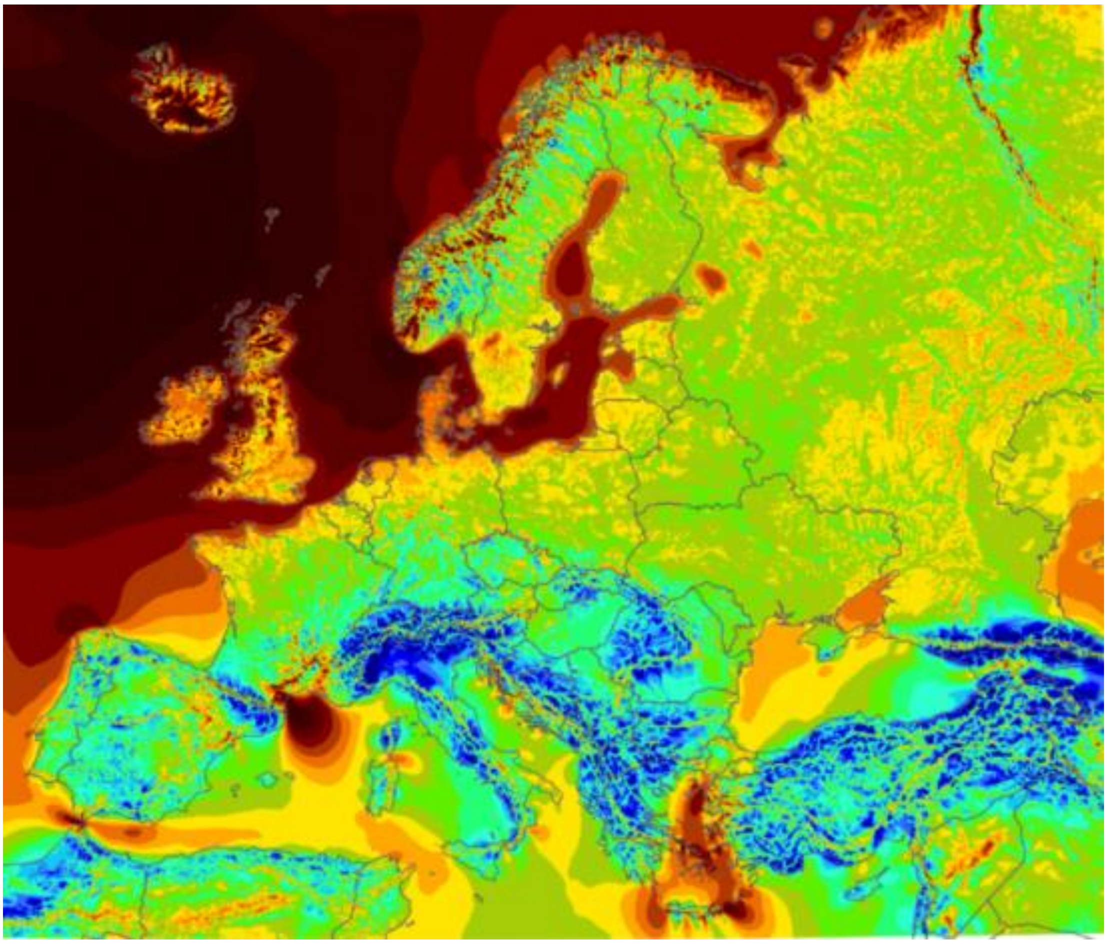


Figure G-1. EMD-WRF Europe+ Model Domain [46]

EMD-EUR+ is based on the global reanalysis model ERA5 and a WRF modelling system that is significantly improved and optimized compared to the one used for EMD ConWx. A detailed validated study conducted by EMD gives an overview of the EMD-EUR+ dataset (Section 1) and a comprehensive analysis of the EMD-EUR+ data as opposed to alternative data sets (Section 2) [47].

G.2 DOWA

The Dutch Offshore Wind Atlas (DOWA) is a wind atlas covering a period of 11 years, from 2008 until and including 2018. Regional numerical weather model HARMONIE and additional satellite and aircraft measurements were used to downscale the global re-analysis ERA5 to a dataset of hourly information on a 2.5 by 2.5 km grid spacing and up to 600 m height [48].

The DOWA is the successor of the KNMI North Sea Wind (KNW) atlas. Both the DOWA and the KNW-atlas are a “downscaled” global re-analysis, but they are made with improved versions of the models and in a fundamentally different way.

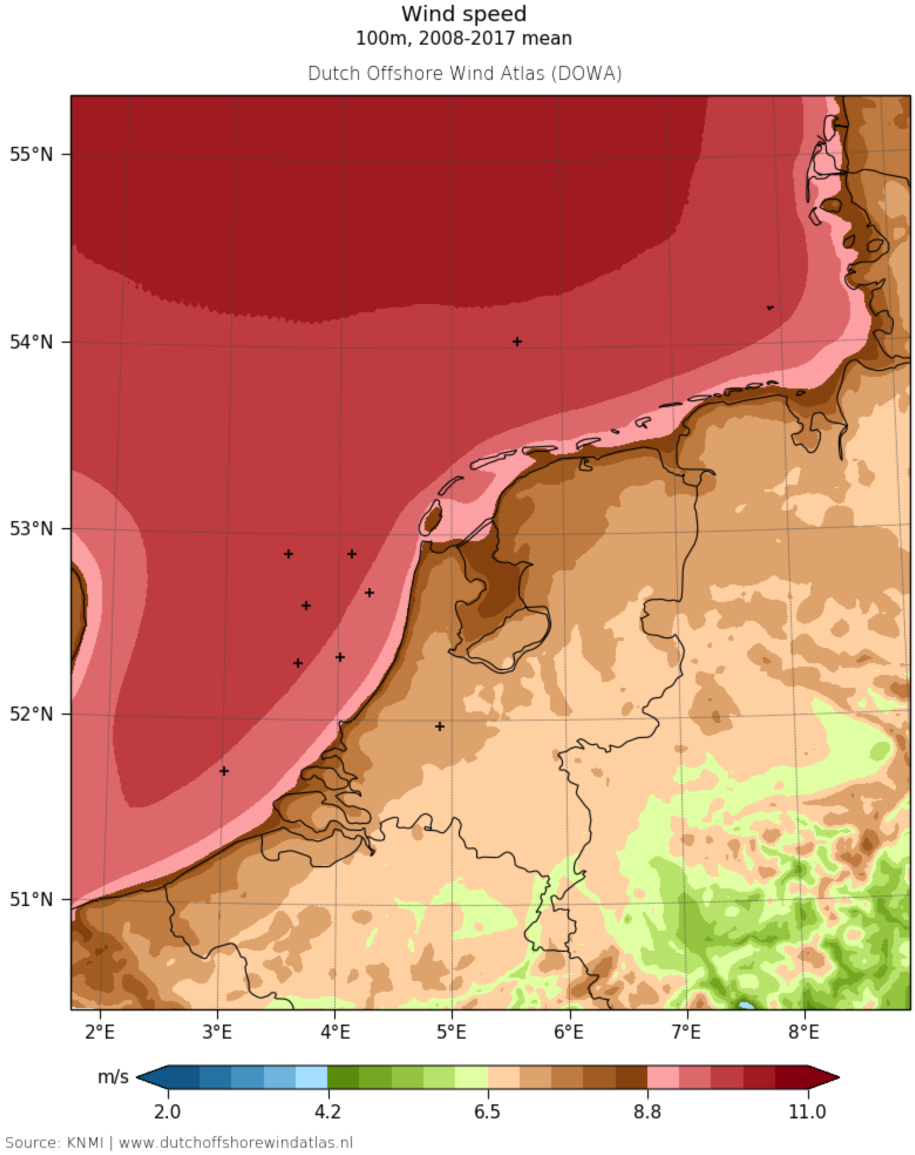


Figure G-2. 10 year (2008 – 2017) average wind speed at 100 m height [48]

Making the Dutch Offshore Wind Atlas (DOWA) was part of the DOWA-project. The DOWA project is executed by the project partners ECN part of TNO, Whiffle and KNMI and supported with Topsector Energy subsidy from the Ministry of Economic Affairs and Climate Policy (SDE+ Hernieuwbare Energie Call). Information on the project can be found on the DOWA website: (https://www.dutchoffshorewindatlas.nl/about-the-atlas)

G.3 KNW

The KNW-atlas is a 4D wind atlas based on the ERA-Interim reanalyses dataset which captures 35 years (1979-2013) of meteorological measurements and generates every 6 hours 3D fields on a horizontal grid of 80 km which are consistent with these measurements and the laws of physics. This dataset is “downscaled” using the state-of-the-art weather forecasting model HARMONIE which generates hourly data on a horizontal grid of 2.5 km. The wind speeds were then tuned to match the measurements made at KNMI’s 200 m tall meteorological mast at Cabauw by increasing the vertical shear of the horizontal wind speed by 15%. The same wind shear correction factor was applied uniformly throughout the whole KNW-atlas domain and period. The result is a high resolution dataset of 35 years: the KNW-atlas [49].

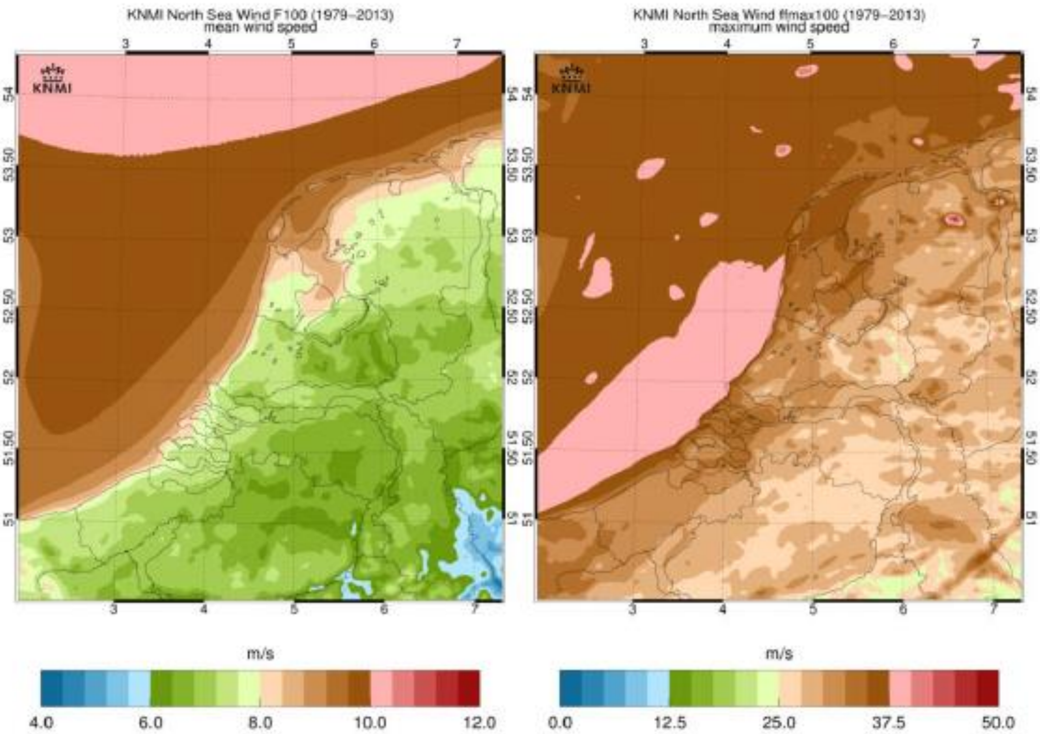


Figure G-3. Example of the average (left) and maximum (right) wind speed at 100 m for the whole KNW-domain and the whole 35 year period [49]

G.4 NEWA

The New European Wind Atlas (NEWA) simulation on the mesoscale includes the entire EU plus Turkey and 100 km offshore including the entire North and Baltic Seas. The WRF model has been used in a configuration developed by the NEWA consortium, with a grid spacing and simulation time of 3 km covering 30 years (1989-2018). The model domains of NEWA are shown in Figure G-4.

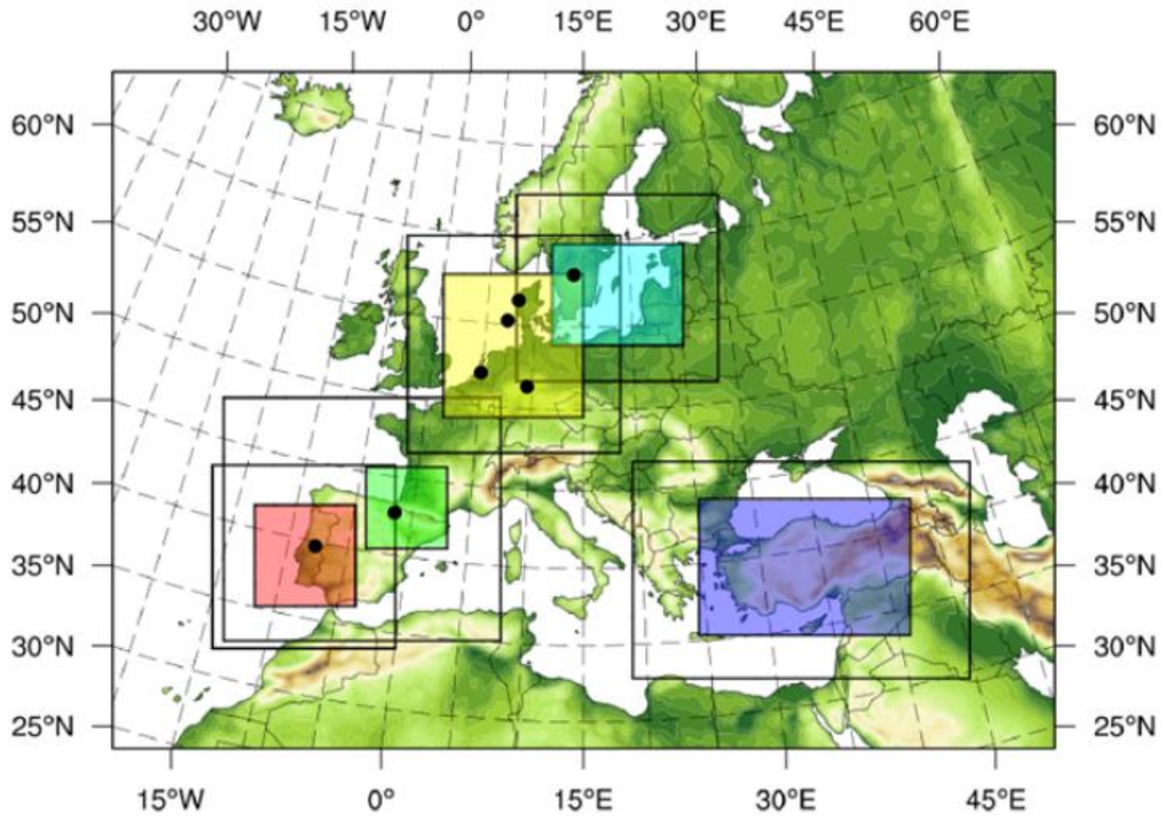


Figure G-4. The five WRF model domains used in the initial model sensitivity runs [50]

The NEWA includes information on site suitability conditions (turbulence intensity, wind shear, extreme wind speed), wind variability as well as predictability of wind power from day-ahead to decadal time scales, in addition to the wind resources information.

G.5 ERA5

ERA5 was generated using 4D-Var data assimilation in CY41R2 of ECMWF's Integrated Forecast System (IFS), with a vertical level of 137 hybrid sigma / pressure (model) and a top level of 0.01 hPa. At these levels, atmospheric data are available, and they are also interpolated to 37 pressure levels, 16 potential temperature levels, and 1 potential vorticity level. Both satellite and in-situ observations are used as input into ERA5. ERA5 benefits from a decade of developments related to ERA-Interim in model physics, core dynamics, and data assimilation. An assimilation diagram for ERA5 is shown in Figure G-5 [34].

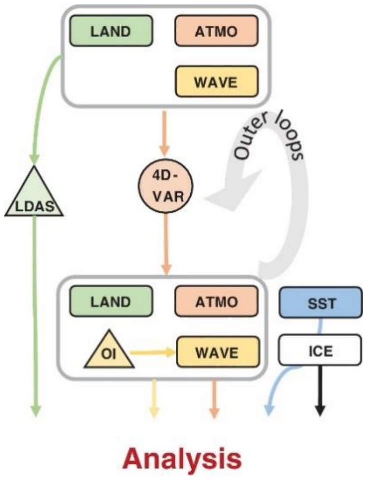


Figure G-5. Assimilation diagram for ERA5 [34]

ERA5 superseded ERA-I with better capacity to use several important types of observational data. An overview of the conventional observations for ERA5 is shown in Figure G-6. [34]

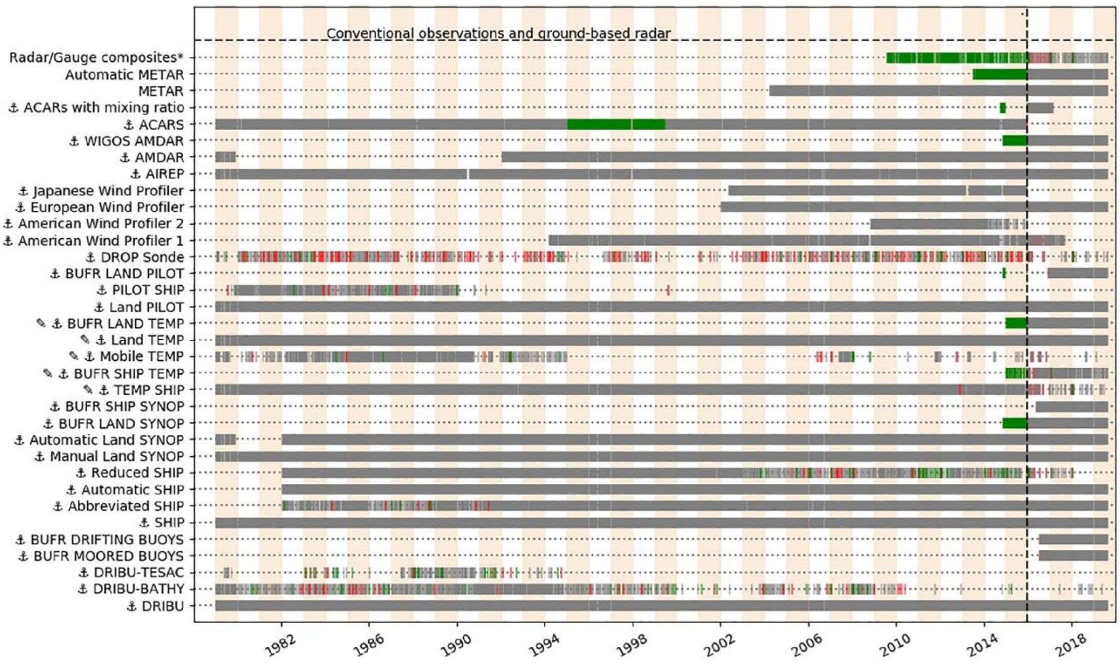


Figure G-6. Conventional observations in ERA5 (1979-2018) [34]

G.6 MERRA-2

The Research and Applications Modern-Era Retrospective Analysis, Version 2 (MERRA-2) provides data that began in 1980. MERRA-2 was introduced to supersede the original MERRA dataset due to the advances made in the assimilation system that allow the assimilation of modern hyperspectral radiance and microwave observations together with GPS-Radio Occultation data sets. [51].

MERRA-2 assimilates observation forms which are not applicable to its predecessor, MERRA, and provides improvements to the Goddard Earth Observing System (GEOS) model and analysis scheme to provide a viable ongoing climate study beyond the terminus of MERRA. An overview of the observations for MERRA-2 is shown in Figure G-7.

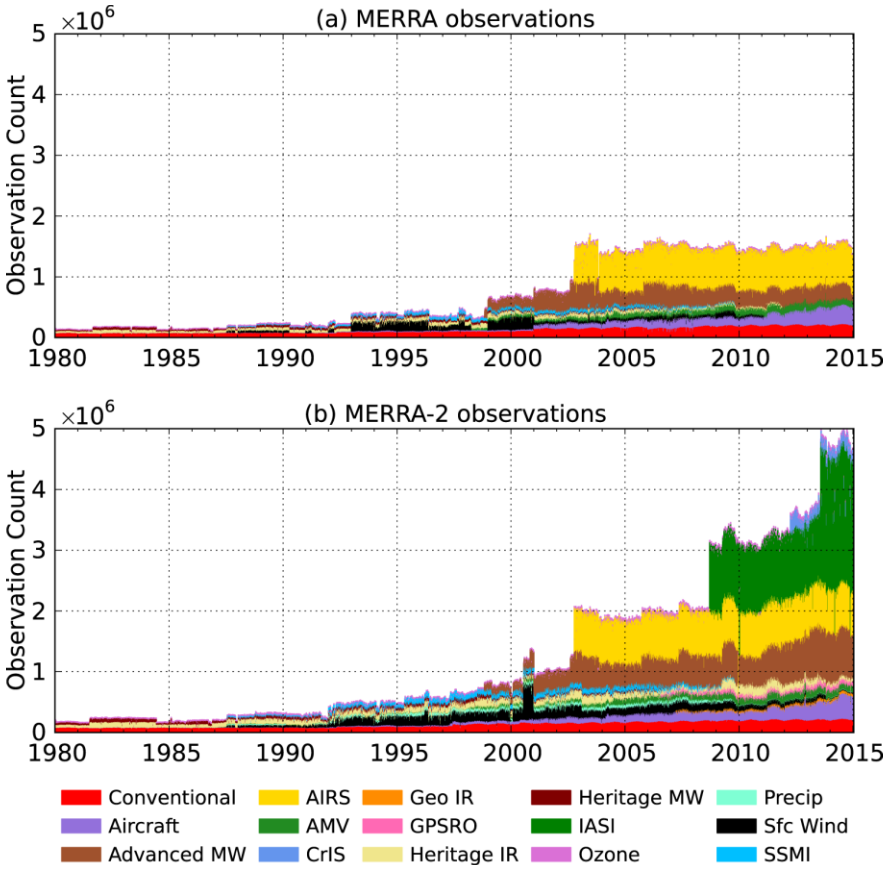


Figure G-7. MERRA-2 observations [52]

G.7 Global Wind Atlas

The Global wind atlas is a free, web-based application developed by the Department of Wind Energy at the Technical University of Denmark (DTU Wind Energy) and the World Bank Group.

GWA is a downscaled mesoscale model generated using a WRF mesoscale model initiated with ERA5 data with a 30 km grid. The ERA5 data is downscaled to a grid spacing of 3 km and simulates a period from 2008 to 2017. This generates a set of generalised wind climates which are then applied in DTU's microscale modelling system over the globe to produce local wind climates with a 250m spatial resolution at five heights.

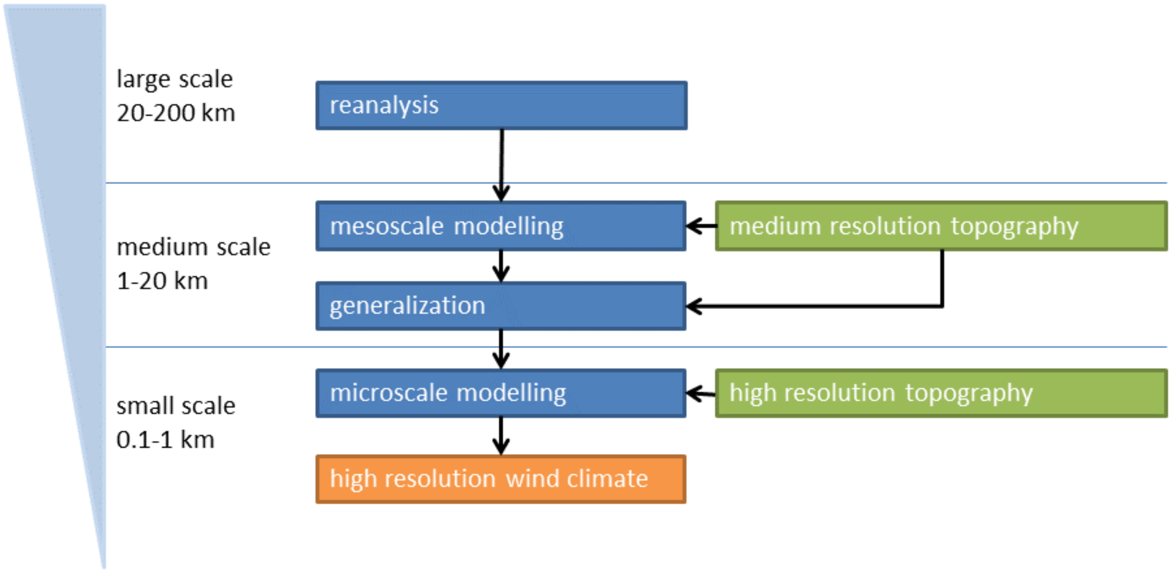


Figure G-8. Schematic showing the methodology of GWA downscaling [53]

Appendix H. Trend Analysis for Long-Term Period

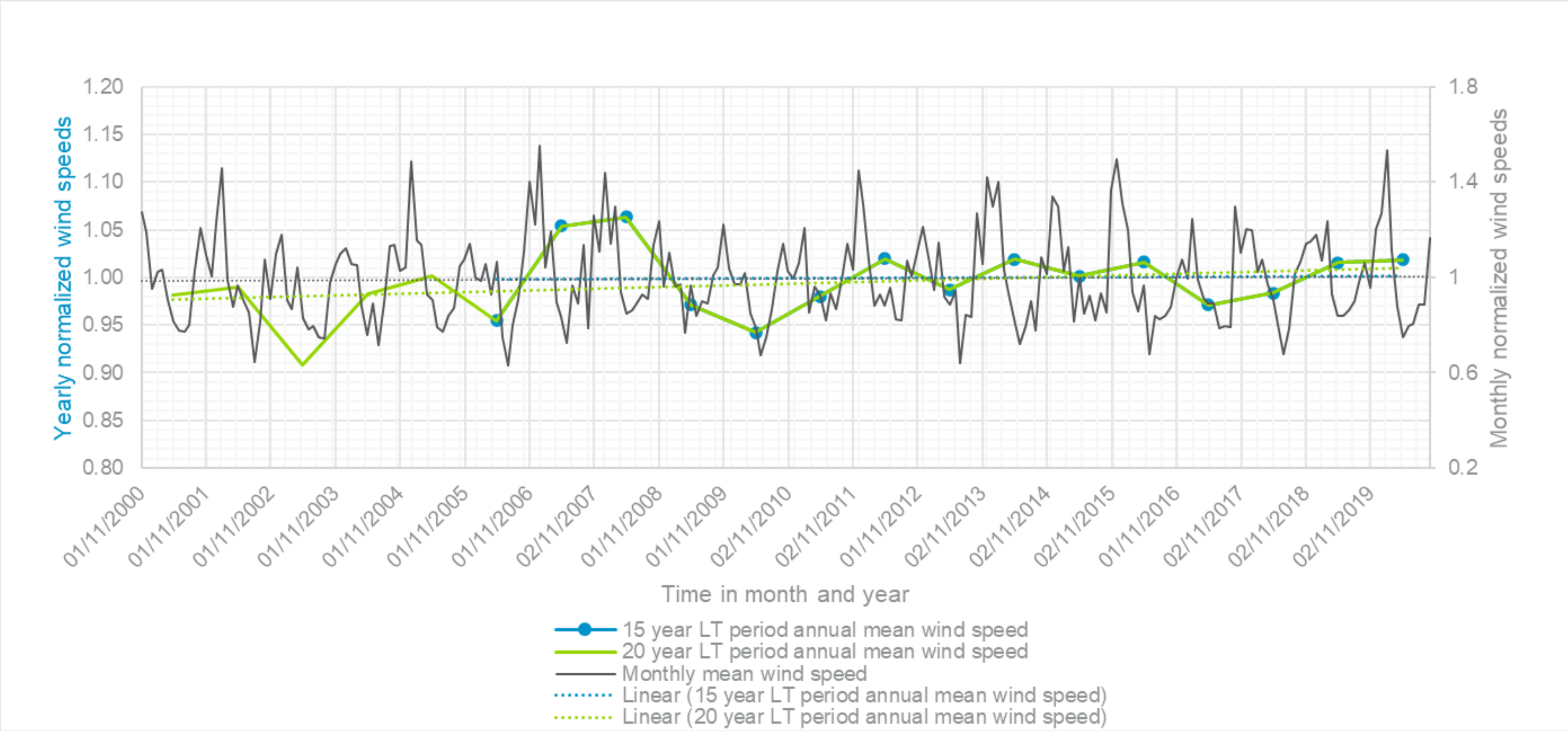


Figure H-1. Trend analysis for selected long-term period(01 November 2005 to 31 October 2020) vs 20 years

Appendix I. Nodal Locations of Modelled Datasets

Modelled Dataset	Node closest to TNW [Latitude, Longitude]
EMD-WRF ERA5	54.03°N, 5.56°E
DOWA	53.89°N, 5.77°E
KNW	54.02°N, 5.56°E
NEWA	54.00°N,5.57 °E
GHPC Tailored WRF (CLT-MM)	54.02°N, 5.55°E

Appendix J. Wind speed gradient map at 140 m

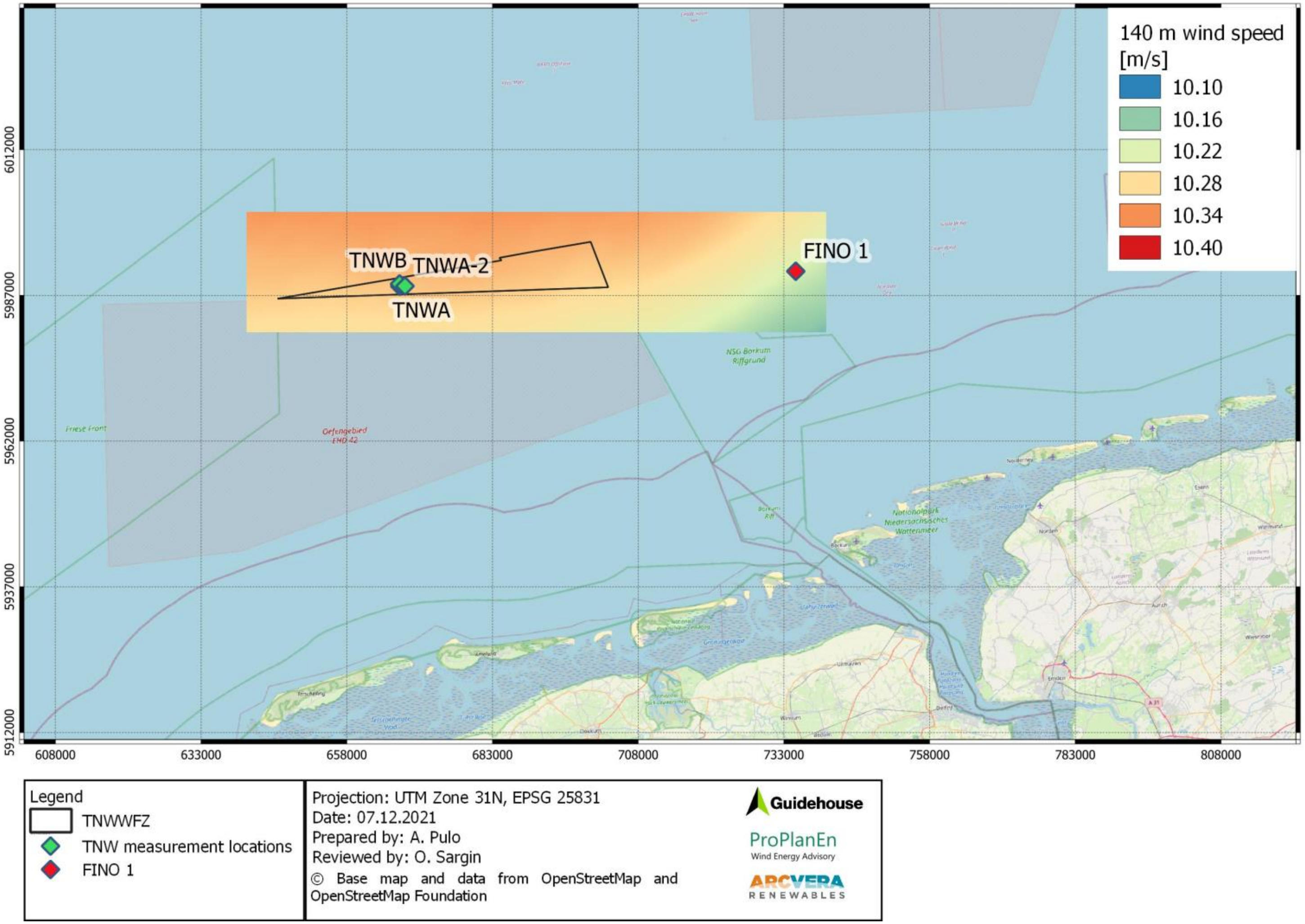


Figure J-1. Horizontal modelled wind speed gradient at 140 m in relation to the coastline

Appendix K. Comparison with Metocean Study Results

DHI

Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone

Wind Resource Assessment (WRA) Alignment

Technical Note
Project No 202007170 / WOZ2210266

Rijksdienst voor Ondernemend Nederland

4th March 2022 Prepared for Rijksdienst voor Ondernemend Nederland (RVO)

The expert in **WATER ENVIRONMENTS**

Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone

Wind Resource Assessment (WRA) Alignment

Technical Note
Project No 202007170 / WOZ2210266

Prepared for: Rijksdienst voor Ondernemend Nederland (RVO)
Represented by Mr. Behzad Aziz

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Project No.:	11822658-01
Approved by:	Maziar Golestani
Approval date:	4th March 2022
Revision:	Final 1.0
Classification:	**Confidential**
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Revision History

Version	Date	Status	Project Manager	Quality Check	Management Approval
Draft 0.1	2022-01-03	Draft issue for client review	HEWR	MGO	n/a
Draft 0.2	2022-01-17	Draft issue for client review	HEWR	n/a	n/a
Draft 0.3	2022-01-24	Draft issue for client review	HEWR	MGO	MGO
Final 1.0	2022-03-04	Final	HEWR	MGO	MGO

Version	Revision log
Draft 0.1	• First draft issue for review by RVO and review/input by Guidehouse WTTS
Draft 0.2	• Include data set summary by GHPC (Section 2) • Minor corrections and clarifictions (all sections)
Draft 0.3	• Minor correction to data set summary by GHPC (Section 2) • Add clarification on alpha used by DHI (Section 2)
Final 1.0	• Change 'RVO.nl' to 'RVO' (entire document) • Update specification of 'GHPC' (Nomenclature, Section 2)

Nomenclature

Abbreviations	
CFSR	Climate Forecast System Reanalysis
GHPC	Guidehouse project consortium (Guidehouse in cooperation with OWC, ProPlanEn and ArcVera)
RVO	Rijksdienst voor Ondernemend Nederland
TNW	Ten Noorden van de Waddeneilanden
WRA	Wind Resource Assessment

Definitions	
Time	Times are relative to UTC
UTM coordinate system	ETRS89 UTM 31N (EPSG:25831)
Direction	Wind: °N coming from and positive clockwise
	Waves: °N coming from and positive clockwise
	Currents: °N going to and positive clockwise

Symbols	
WS_x	Wind Speed @ x m
WD_x	Wind Direction @ x m

1 Introduction

In September 2021 Rijksdienst voor Ondernemend Nederland (RVO) has commissioned DHI to conduct a metocean desk study for the Ten Noorden van de Waddeneilanden (TNW) investigation area. As part of this study, an alignment with the Wind Resource Assessment (WRA) has been performed and is presented in this technical note.

For the WRA assessment, the Guidehouse project consortium (GHPC) (Guidehouse in cooperation with OWC, ProPlanEn and ArcVera) has produced a wind dataset, which is herein referred to as **GHPC WRA 24**. For the metocean study, DHI has used another source for the wind fields, herein referred to as **$CFSR_{DWF}$**.

To ensure that both studies are aligned (particularly at the hub height), the work has been performed by having inputs from both DHI and GHPC. It entails **comparison of wind speed and wind direction at 140m**. This has been confirmed by RVO as reference hub height for the purpose of this comparison.

The comparisons have been performed at three locations within the TNW investigation area, as shown in Figure 1.1 and Table 1.1. N4 is the location that is closest to the positions of the LiDAR buoys (compare for example [1]).

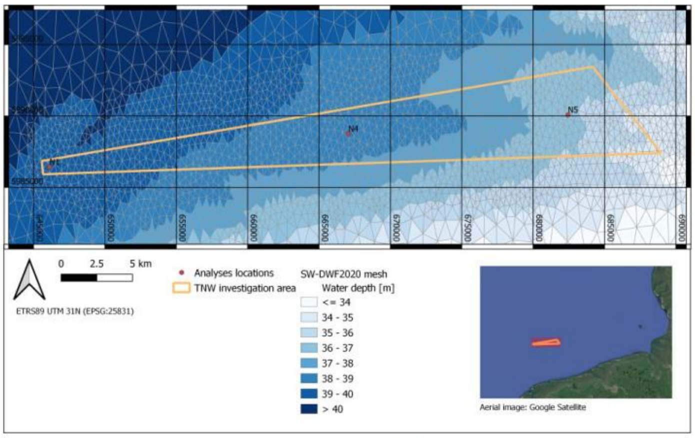


Figure 1.1 **Analyses locations for the WRA alignment.**
Three locations (red) at which WRA data is available within the TNW investigation area (orange) and computational mesh of the $SW_{DWF2020}$.

Table 1.1 **Coordinates of analyses locations for the WRA alignment.**
The UTM coordinates (Easting, Northing) are provided in ETRS89 UTM 31N (EPSG:25831).

Name	Easting [m]	Northing [m]	Longitude [°E]	Latitude [°N]
N1	646118	5986433	5.2296	54.0055
N4	667056	5988751	5.5500	54.0200
N5	682434	5990085	5.7853	54.0267

2 Datasets

This section provides a summary of the two datasets involved in the here presented comparison.

For the WRA assessment, GHPC has produced the wind dataset **GHPC WRA 24**. A detailed description is provided in [2]. The GHPC 24 WRA dataset is a long-term synthetic timeseries at 5 locations within the TNWWFZ, derived from the downscaled mesoscale model developed for the project. The mesoscale model was adjusted by means of the 24-month wind measurements at TNW to account for variations between the measured and modelled wind speed distributions and corrected for the long-term.

The same dataset of LiDAR measurements that were available to GHPC have been made available to DHI on November 22nd 2021. A detailed description of the LiDAR measurements is provided in [1].

For the metocean study, DHI has generated the wind dataset **$CFSR_{DWF}$**, which is described in detail in [1]. The $CFSR_{DWF}$ is based on the CFSR reanalysis data and has been interpolated to the computational mesh of the $SW_{DWF2020}$ model. The native wind parameters of CFSR are WS_{10} and WD_{10}, which have been used to force DHI's hydrodynamic and spectral wave models.

In the metocean study by DHI, WS10 has been extrapolated to 60, 100, 120, 140, 160, 200, 250 and 300mMSL for time series delivery and normal conditions analyses (not extreme values). The power law has been assumed for the extrapolation. The wind direction has not been scaled and WD_{10} is adopted for all levels. For the extrapolation, the shear factor (alpha) has been based on a profile assessment of the LiDAR measurements at TNW, referred to above. Following detailed analyses, it has been concluded by DHI to apply a constant **alpha** of **0.0701** (for all locations, directions, speed ranges and heights). Details on the profile assessment are provided in [1].

It should be noted that this shear factor has been derived by DHI to scale CFSR from 10m to all levels from 60 – 300m, applicable to normal metocean conditions at the TNW investigation area. DHI has adopted another shear factor to scale the extreme wind speeds. Due to the different height range, background dataset or models and purpose, the values of alpha in [1] cannot directly be compared with the values provided by GHPC in [2]. It is therefore that WS_{140} and WD_{140} are compared in the WRA alignment and not shear factors.

3 Analyses

This section provides the results of the comparison of GHPC WRA 24 and $CFSR_{DWF}$.

The comparison of WS_{140} has been performed at locations N1, N4 and N5, where the GHPC WRA 24 time series data was available within the TNW investigation area. The $CFSR_{DWF}$ at the three $SW_{DWF2020}$ mesh elements that contain N1, N4 and N5, respectively, has been used for the comparison, which is in line with data extraction via the MetOcean On Demand (MOOD) portal.

The comparison was carried out at 1hr timesteps (timestep of both datasets) for the period 2005-07-01 to 2021-06-30, which was covered by the GHPC WRA 24 dataset.

A summary of the comparison of WS_{140} at locations N1, N4 and N5 is provided in Table 3.1.

Scatter plot and dual rose plot comparisons of WS_{140} are provided in Figure 3.1. The dual rose plots contain 12 directional sectors. For GHPC WRA 24 WS_{140} was grouped by WD_{140}. For $CFSR_{DWF}$, WD10 is adopted for all levels and, hence, WS_{140} was grouped by WD10 in the rose plots.

Table 3.1 Summary of WS_{140} WRA alignment.
GHPC WRA 24 and $CFSR_{DWF}$ mean and bias of WS_{140} [m/s] at locations N1, N4 and N5.

Parameter	Units	Mean Wind Speed @ 140m		
		N1	N4	N5
GHPC WRA 24, Mean WS_{140}	m/s	10.30	10.30	10.30
$CFSR_{DWF}$, Mean WS_{140}		10.24	10.25	10.26
Bias WS_{140} ($CFSR_{DWF}$ – GHPC WRA 24)		-0.06	-0.05	-0.04

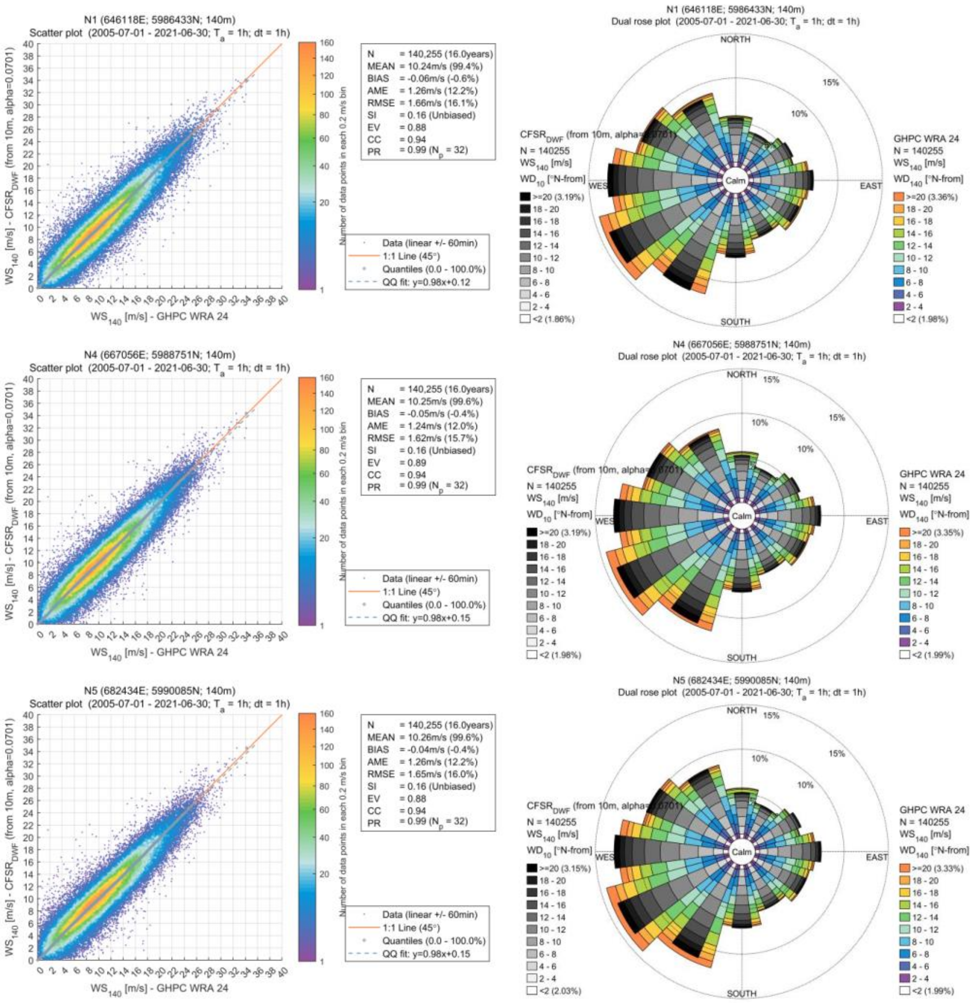


Figure 3.1 WS_{140} comparison of GHPC WRA 24 and $CFSR_{DWF}$.
Top to bottom row: Locations N1, N4 and N5.
Left column: Scatter comparison of WS_{140} of GHPC WRA 24 (x-axis) and CFSRDWF (y-axis).
Right column: Dual rose plot of WS_{140} for 12 directional sectors. GHPC WRA 24 (colour scale) grouped by WD_{140} and $CFSR_{DWF}$ (grey scale) grouped by WD_{10}.

4 Conclusion

It was concluded the datasets from GHPC's wind resource assessment and DHI's metocean desk study are in good agreement.

The **bias of WS_{140}** ranges from **-0.04 to -0.06m/s** ($CFSR_{DWF}$ < GHPC WRA 24). This is well within the defined range of +-0.1m/s allowable bias that has been agreed with RVO and previously discussed with DNV in HKW and HKN projects.

Both studies show small spatial variation in terms of mean wind speed across the TNW investigation area in terms of mean WS_{140}. For GHPC WRA 24 the mean WS_{140} is 10.30 m/s at all three locations (only varying at the further decimals) and for $CFSR_{DWF}$ it ranges from 10.24 m/s to 10.26m/s.

The reports of both studies provide additional wind climate information beyond the average wind conditions. Each study is determined by its scope which is clearly defined by RVO. The WRA by GHPC [2] on the one hand, describes the mean wind climate. This information is intended for wind farm modelling, yield assessment and business case calculation. The report by DHI [1] on the other hand, describes the normal and extreme wind conditions, which are intended for design.

5 References

[1] DHI, “Ten Noorden van de Waddeneilanden (TNW) Wind Farm Zone, Metocean Desk Study, not published,” RVO, 2022.

[2] P. a. A. Guidehouse project consortium (Guidehouse in cooperation with OWC, “Ten noorden van de Waddeneilanden Wind Farm Zone, Wind Resource Assessment, version 6.0 final,” RVO, 2022.

Appendix L. Long-Term Sectorwise Weibull Parameters

The results presented in this appendix are an extension of the results presented in section 5.5. For each of the nodal locations the sectorwise Weibull parameters, A and k, are presented for a number of selected heights.

L.1 Node 1 – Sectorwise Weibull Parameters

Table L-1. Sectorwise Weibull A within at N1 at various heights [m/s]

Height [m]	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	7.73	6.95	7.51	8.05	8.38	8.33	9.30	10.26	10.28	9.92	9.21	8.77
60	8.92	8.08	8.82	9.84	10.13	9.80	10.99	12.35	12.30	11.80	10.62	10.04
100	9.17	8.38	9.21	10.53	10.79	10.25	11.42	12.94	12.99	12.33	11.00	10.33
120	9.26	8.49	9.34	10.83	10.95	10.38	11.63	13.19	13.27	12.54	11.13	10.45
140	9.37	8.59	9.47	11.09	11.09	10.51	11.84	13.40	13.53	12.73	11.24	10.55
200	9.56	8.80	9.65	11.59	11.27	10.78	12.34	13.99	14.17	13.14	11.56	10.74
250	9.65	8.90	9.69	11.81	11.32	10.89	12.71	14.42	14.58	13.43	11.78	10.84
300	9.69	8.88	9.57	11.81	11.28	10.91	12.93	14.73	14.87	13.67	11.89	10.92

Table L-2. Sectorwise Weibull k within at N1 at various heights

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	2.298	2.297	2.438	2.403	2.514	2.329	2.263	2.459	2.550	2.423	2.343	2.326
60	2.296	2.294	2.430	2.395	2.518	2.341	2.268	2.448	2.548	2.429	2.349	2.322
100	2.302	2.283	2.441	2.375	2.535	2.353	2.265	2.432	2.548	2.444	2.354	2.318
120	2.303	2.278	2.452	2.370	2.532	2.363	2.261	2.424	2.553	2.445	2.354	2.322
140	2.309	2.275	2.450	2.361	2.538	2.360	2.271	2.416	2.552	2.447	2.353	2.320
200	2.315	2.277	2.429	2.370	2.532	2.374	2.276	2.403	2.553	2.445	2.364	2.317
250	2.312	2.279	2.424	2.366	2.532	2.385	2.286	2.398	2.546	2.450	2.363	2.319
300	2.316	2.278	2.411	2.372	2.520	2.399	2.295	2.389	2.542	2.451	2.369	2.322

L.2 Node 2 – Sectorwise Weibull Parameters

Table L-3. Sectorwise Weibull A within at N2 at various heights [m/s]

Height [m]	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	7.68	6.93	7.33	8.02	8.06	8.17	8.81	10.11	10.37	10.08	9.52	8.96
60	8.82	8.20	8.75	9.82	9.75	9.57	10.36	12.10	12.42	11.96	10.98	10.29
100	9.10	8.53	9.20	10.54	10.42	10.01	10.75	12.68	13.04	12.50	11.34	10.61
120	9.23	8.60	9.36	10.83	10.62	10.16	10.93	12.91	13.30	12.74	11.46	10.72
140	9.32	8.68	9.48	11.11	10.80	10.29	11.11	13.08	13.57	12.95	11.58	10.80
200	9.51	8.83	9.68	11.64	11.04	10.64	11.62	13.62	14.20	13.38	11.84	11.03
250	9.64	8.88	9.70	11.85	11.11	10.76	12.04	14.04	14.63	13.67	12.01	11.14
300	9.69	8.87	9.65	11.79	11.11	10.74	12.32	14.37	14.95	13.86	12.15	11.21

Table L-4. Sectorwise Weibull k within at N2 at various heights

Height [m]	0°	30°	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	2.293	2.305	2.425	2.421	2.499	2.335	2.269	2.465	2.549	2.409	2.338	2.335
60	2.299	2.308	2.427	2.410	2.511	2.328	2.273	2.455	2.554	2.413	2.342	2.330
100	2.294	2.295	2.433	2.400	2.517	2.337	2.267	2.454	2.548	2.424	2.349	2.324
120	2.296	2.291	2.429	2.395	2.518	2.342	2.267	2.448	2.548	2.431	2.348	2.323
140	2.303	2.287	2.437	2.386	2.524	2.353	2.268	2.439	2.546	2.439	2.349	2.318
200	2.305	2.282	2.451	2.367	2.535	2.362	2.266	2.421	2.551	2.445	2.355	2.319
250	2.318	2.273	2.441	2.364	2.539	2.365	2.273	2.410	2.554	2.447	2.354	2.317
300	2.317	2.279	2.427	2.369	2.532	2.379	2.280	2.400	2.553	2.445	2.362	2.316

L.3 Node 3 – Sectorwise Weibull Parameters

Table L-5. Sectorwise Weibull A within at N3 at various heights [m/s]

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	7.65	6.99	7.40	8.07	8.03	8.08	8.74	10.02	10.33	10.08	9.50	8.87
60	8.79	8.23	8.83	9.88	9.73	9.48	10.25	12.01	12.39	11.95	10.94	10.21
100	9.06	8.57	9.30	10.59	10.39	9.90	10.68	12.57	13.02	12.48	11.32	10.53
120	9.17	8.67	9.45	10.88	10.59	10.09	10.84	12.81	13.27	12.72	11.45	10.65
140	9.29	8.74	9.58	11.14	10.79	10.23	11.03	12.99	13.53	12.91	11.56	10.74
200	9.46	8.86	9.79	11.65	11.04	10.59	11.56	13.54	14.16	13.36	11.84	10.95
250	9.59	8.91	9.83	11.84	11.12	10.73	12.00	14.01	14.58	13.66	12.01	11.08
300	9.65	8.90	9.76	11.80	11.12	10.75	12.26	14.33	14.94	13.84	12.17	11.15

Table L-6. Sectorwise Weibull k within at N3 at various heights

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	2.291	2.303	2.425	2.425	2.492	2.339	2.266	2.472	2.543	2.408	2.342	2.330
60	2.298	2.309	2.427	2.414	2.507	2.327	2.270	2.460	2.552	2.411	2.341	2.331
100	2.297	2.296	2.437	2.402	2.515	2.331	2.263	2.457	2.549	2.425	2.344	2.325
120	2.296	2.291	2.431	2.395	2.521	2.344	2.269	2.447	2.548	2.429	2.347	2.323
140	2.302	2.287	2.433	2.394	2.517	2.352	2.265	2.444	2.546	2.433	2.353	2.317
200	2.303	2.279	2.451	2.371	2.532	2.362	2.265	2.423	2.550	2.446	2.356	2.320
250	2.315	2.276	2.443	2.362	2.541	2.363	2.272	2.412	2.552	2.448	2.355	2.318
300	2.315	2.278	2.428	2.371	2.530	2.375	2.277	2.402	2.552	2.445	2.365	2.316

L.4 Node 4 – Sectorwise Weibull Parameters

Table L-7. Sectorwise Weibull A within at N4 at various heights [m/s]

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	7.74	6.96	7.46	8.04	8.26	8.22	9.14	10.24	10.31	9.98	9.35	8.84
60	8.91	8.13	8.77	9.85	10.01	9.66	10.74	12.32	12.35	11.86	10.77	10.14
100	9.20	8.40	9.21	10.54	10.71	10.09	11.19	12.89	13.00	12.41	11.13	10.41
120	9.30	8.53	9.34	10.83	10.89	10.26	11.34	13.13	13.29	12.63	11.26	10.53
140	9.36	8.62	9.47	11.12	11.04	10.40	11.56	13.38	13.53	12.79	11.37	10.60
200	9.59	8.83	9.62	11.61	11.24	10.71	12.05	13.88	14.19	13.24	11.67	10.84
250	9.68	8.92	9.72	11.78	11.29	10.83	12.48	14.33	14.61	13.50	11.88	10.95
300	9.73	8.93	9.60	11.78	11.24	10.87	12.71	14.65	14.90	13.73	12.03	11.02

Table L-8. Sectorwise Weibull k within at N4 at various heights

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	2.297	2.306	2.431	2.407	2.515	2.328	2.270	2.458	2.551	2.414	2.346	2.329
60	2.297	2.294	2.431	2.402	2.517	2.337	2.266	2.456	2.548	2.424	2.347	2.325
100	2.303	2.287	2.437	2.386	2.524	2.353	2.268	2.439	2.546	2.439	2.349	2.318
120	2.302	2.283	2.441	2.374	2.535	2.353	2.265	2.432	2.548	2.444	2.354	2.318
140	2.302	2.283	2.439	2.375	2.534	2.354	2.264	2.432	2.548	2.443	2.354	2.318
200	2.316	2.275	2.435	2.366	2.535	2.370	2.272	2.407	2.555	2.447	2.355	2.320
250	2.315	2.278	2.430	2.368	2.533	2.376	2.277	2.402	2.552	2.446	2.364	2.317
300	2.309	2.282	2.420	2.366	2.529	2.388	2.291	2.393	2.545	2.449	2.368	2.322

L.5 Node 5 – Sectorwise Weibull Parameters

Table L-9. Sectorwise Weibull A within at N5 at various heights [m/s]

Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	7.72	6.97	7.42	8.04	8.19	8.19	8.97	10.17	10.34	10.04	9.41	8.88
60	8.88	8.17	8.81	9.86	9.91	9.59	10.56	12.22	12.38	11.91	10.86	10.18
100	9.17	8.47	9.24	10.56	10.61	10.04	10.97	12.82	13.00	12.47	11.21	10.48
120	9.28	8.57	9.38	10.84	10.80	10.20	11.16	13.02	13.30	12.69	11.35	10.59
140	9.37	8.67	9.51	11.11	10.97	10.36	11.30	13.24	13.56	12.88	11.48	10.68
200	9.56	8.85	9.69	11.62	11.19	10.67	11.85	13.79	14.18	13.32	11.74	10.90
250	9.67	8.92	9.75	11.80	11.24	10.82	12.25	14.22	14.62	13.58	11.94	11.02
300	9.70	8.93	9.65	11.80	11.20	10.81	12.51	14.56	14.92	13.78	12.10	11.08

Table L-10. Sectorwise Weibull k within at N5 at various heights

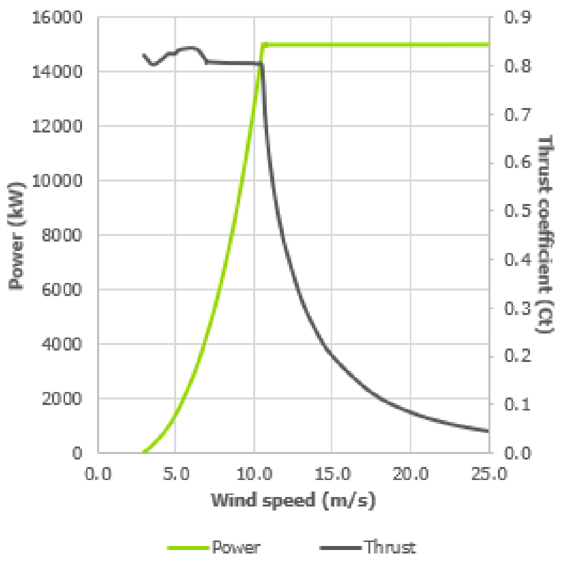
Height [m]	0°	30	60°	90°	120°	150°	180°	210°	240°	270°	300°	330°
10	2.299	2.307	2.429	2.414	2.507	2.328	2.272	2.457	2.554	2.411	2.341	2.331
60	2.294	2.297	2.434	2.405	2.514	2.332	2.267	2.457	2.551	2.420	2.344	2.328
100	2.296	2.291	2.429	2.395	2.518	2.342	2.267	2.448	2.548	2.431	2.348	2.323
120	2.300	2.288	2.440	2.382	2.527	2.353	2.267	2.438	2.548	2.439	2.349	2.320
140	2.302	2.283	2.441	2.374	2.535	2.353	2.265	2.431	2.548	2.444	2.354	2.318
200	2.313	2.275	2.445	2.363	2.537	2.365	2.271	2.413	2.553	2.447	2.353	2.319
250	2.318	2.278	2.427	2.372	2.531	2.375	2.270	2.406	2.555	2.444	2.363	2.314
300	2.312	2.279	2.425	2.366	2.532	2.385	2.282	2.401	2.546	2.450	2.363	2.319

Appendix M. Wind Turbine Power and Thrust Curves

For the example layouts, which were created as part of this project (Section 6.4), it was agreed to use generic, publicly available power and thrust curves. For the power class of 15 MW, the NREL 15 MW Reference Wind Turbine was selected. For 13 MW, in order to stay consistent with what has been done previously, the power curve from [19] was used.

M.1 15 MW Turbine Type

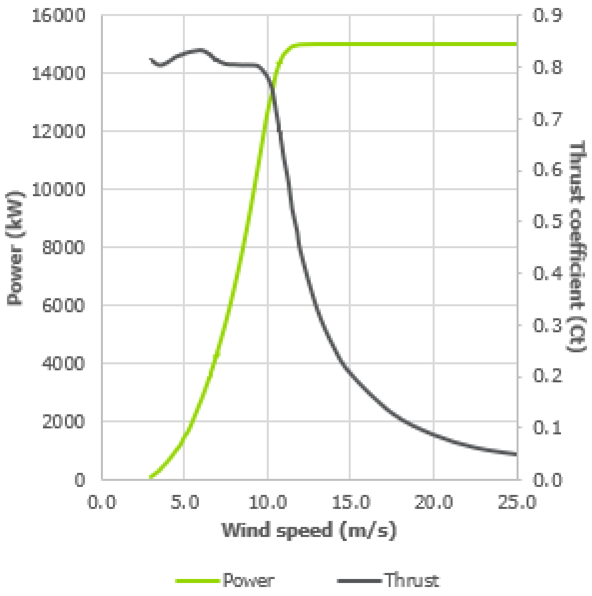
Item	Description
Wind turbine type:	NREL 15 MW Reference Wind Turbine
Mode:	n/a
Reference document(s):	IEA-15-240-RWT_tabular.xlsx
Source:	NREL
Rotor diameter:	240 m
Hub height considered:	140 m
Reference air density:	1.225 kg/m³



Hub height wind speed [m/s]	Power [kW]	Thrust coefficient (Ct)
3.0	70	0.820
3.5	302	0.801
4.0	595	0.808
4.5	965	0.822
4.8	1185	0.823
5.0	1429	0.823
5.2	1695	0.831
6.0	2656	0.835
6.2	2957	0.834
6.4	3276	0.832
6.5	3443	0.829
6.6	3529	0.827
6.6	3615	0.825
6.7	3791	0.820
6.8	3972	0.816
6.9	4156	0.811
6.9	4192	0.810
6.9	4211	0.809
6.9	4229	0.808
7.0	4247	0.808
7.0	4265	0.807
7.0	4284	0.807
7.0	4302	0.806
7.0	4320	0.807
7.0	4339	0.807
7.5	5339	0.805
8.0	6481	0.805
8.5	7775	0.804
9.0	9229	0.804
9.5	10855	0.804
10.0	12661	0.803
10.2	13638	0.802
10.5	14661	0.802
10.6	14995	0.769
10.7	14995	0.707
10.7	14995	0.699
10.7	14995	0.690
10.8	14995	0.682
10.8	14995	0.675
10.8	14995	0.673
10.8	14995	0.673
10.8	14995	0.672
10.8	14995	0.672
10.8	14995	0.672
10.8	14995	0.671
10.8	14995	0.668
10.9	14994	0.635
11.0	14994	0.607
11.2	14994	0.549
11.5	14994	0.501
11.8	14994	0.461
12.0	14994	0.426
13.0	14995	0.321
14.0	14995	0.251
15.0	14995	0.201
17.5	14995	0.126
20.0	14995	0.085
22.5	14996	0.061
25.0	14998	0.046

The power and thrust curves shown above are for a zero-turbulence case. In order to make the power curve useable for power and wake calculations, the method described in IEC 61400-12-1 Annex M was applied to the power and thrust curves [54]. The resulting curves for a turbulence intensity of 5.55% - which is more in line with the expectations on site – are shown in the table below.

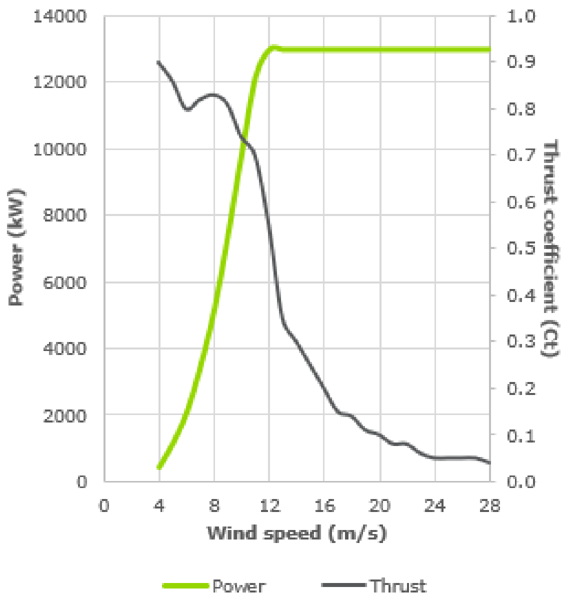
Item	Description
Wind turbine type:	NREL 15 MW Reference Wind Turbine
Mode:	n/a
Reference document(s):	IEA-15-240-RWT_tabular.xlsx
Source:	NREL (TI adjusted)
Rotor diameter:	240 m
Hub height considered:	140 m
Reference air density:	1.225 kg/m³



Hub height wind speed [m/s]	Power [kW]	Thrust coefficient (Ct)
3.0	98	0.814
3.5	307	0.804
4.0	603	0.809
4.5	977	0.820
4.8	1198	0.823
5.0	1444	0.826
5.3	1715	0.829
6.0	2685	0.833
6.2	2986	0.831
6.4	3306	0.828
6.5	3473	0.825
6.6	3558	0.824
6.6	3644	0.823
6.7	3820	0.820
6.8	4000	0.817
6.9	4184	0.815
6.9	4221	0.814
6.9	4240	0.814
6.9	4259	0.814
7.0	4278	0.814
7.0	4297	0.814
7.0	4316	0.813
7.0	4335	0.813
7.0	4354	0.813
7.0	4373	0.813
7.5	5388	0.806
8.0	6541	0.805
8.5	7846	0.804
9.0	9314	0.804
9.5	10939	0.801
10.0	12592	0.782
10.3	13318	0.757
10.5	13911	0.721
10.6	14105	0.703
10.7	14273	0.685
10.7	14304	0.681
10.7	14334	0.677
10.8	14363	0.673
10.8	14391	0.669
10.8	14396	0.668
10.8	14399	0.668
10.8	14400	0.668
10.8	14401	0.667
10.8	14403	0.667
10.8	14403	0.667
10.8	14417	0.665
10.9	14539	0.645
11.0	14639	0.624
11.3	14813	0.573
11.5	14908	0.525
11.8	14956	0.482
12.0	14978	0.443
13.0	14994	0.331
14.0	14995	0.257
15.0	14995	0.206
17.5	14995	0.129
20.0	14995	0.087
22.5	14996	0.062
25.0	14997	0.049

M.2 13 MW Turbine Type

Item	Description
Wind turbine type:	13 MW turbine type
Mode:	n/a
Reference document(s):	[22]
Source:	[22]
Rotor diameter:	220 m
Hub height considered:	140 m
Reference air density:	1.225 kg/m³



Hub height wind speed [m/s]	Power [kW]	Thrust coefficient (Ct)
4	450	0.900
5	1180	0.860
6	2100	0.800
7	3490	0.820
8	5200	0.830
9	7450	0.810
10	9900	0.740
11	12200	0.700
12	13000	0.550
13	13000	0.350
14	13000	0.300
15	13000	0.250
16	13000	0.200
17	13000	0.150
18	13000	0.140
19	13000	0.110
20	13000	0.100
21	13000	0.080
22	13000	0.080
23	13000	0.060
24	13000	0.050
25	13000	0.050
26	13000	0.050
27	13000	0.050
28	13000	0.040

Appendix N. Wind Turbine Coordinates TNWWFZ

N.1 Example Layout 1 (47 wind turbines with 15 MW)

The example layout has a total capacity of 705 MW and consists of 47 wind turbines, each with a rated power of 15 MW. The proposed coordinates are given in the table below. The coordinates presented below are in the coordinate system of ETRS89 UTM 31N, EPSG 25831.

Table N-1. Example Layout 1 coordinates

Turbine label	Easting	Northing	Turbine label	Easting	Northing	Turbine label	Easting	Northing
WT_1	662817	5988196	WT_17	670901	5987407	WT_33	677523	5989144
WT_2	663500	5987186	WT_18	671827	5989489	WT_34	678237	5991781
WT_3	663931	5989343	WT_19	671855	5990683	WT_35	678395	5987666
WT_4	664473	5988400	WT_20	672389	5987458	WT_36	678661	5990730
WT_5	664953	5987205	WT_21	672632	5988704	WT_37	679131	5989740
WT_6	665464	5989605	WT_22	673433	5990964	WT_38	679850	5988887
WT_7	665948	5988420	WT_23	673698	5989878	WT_39	679863	5992061
WT_8	666423	5987251	WT_24	673874	5987524	WT_40	679924	5987723
WT_9	667012	5989866	WT_25	674262	5988839	WT_41	680507	5991025
WT_10	667430	5988488	WT_26	675030	5991238	WT_42	681201	5990009
WT_11	667908	5987329	WT_27	675339	5987566	WT_43	681450	5992305
WT_12	668665	5990144	WT_28	675437	5990136	WT_44	681482	5987769
WT_13	668911	5988555	WT_29	675926	5988961	WT_45	681934	5989096
WT_14	669389	5987357	WT_30	676619	5991496	WT_46	682556	5991033
WT_15	670283	5990417	WT_31	676863	5987624	WT_47	682971	5992347
WT_16	670386	5988576	WT_32	677104	5990463			

N.2 *Example Layout 2 (54 wind turbines with 13 MW)*

The example layout has a total capacity of 702 MW and consists of 54 wind turbines, each with a rated power of 13 MW. The proposed coordinates are given in the table below. The coordinates presented below are in the coordinate system of ETRS89 UTM 31N, EPSG 25831.

Table N-2. Example Layout 2 coordinates

Turbine label	Easting	Northing	Turbine label	Easting	Northing	Turbine label	Easting	Northing
WT_1	662828	5988175	WT_19	671014	5990522	WT_37	677268	5990381
WT_2	663527	5987158	WT_20	671156	5989448	WT_38	677198	5987617
WT_3	663909	5989325	WT_21	671472	5988451	WT_39	678838	5990765
WT_4	664239	5988317	WT_22	671739	5987440	WT_40	678155	5991747
WT_5	664897	5987193	WT_23	672481	5990756	WT_41	678342	5988628
WT_6	665317	5989576	WT_24	672656	5989664	WT_42	678714	5987667
WT_7	665619	5988378	WT_25	672825	5988465	WT_43	679271	5989804
WT_8	666261	5987247	WT_26	673089	5987473	WT_44	679563	5991964
WT_9	666739	5989820	WT_27	673914	5991014	WT_45	679779	5988731
WT_10	667082	5988848	WT_28	674164	5989839	WT_46	680777	5989980
WT_11	667608	5987285	WT_29	674183	5988503	WT_47	680995	5992268
WT_12	668153	5990063	WT_30	674455	5987531	WT_48	681290	5991246
WT_13	668190	5988465	WT_31	675322	5991239	WT_49	681488	5987762
WT_14	668971	5987331	WT_32	675545	5988565	WT_50	681908	5989027
WT_15	669556	5989223	WT_33	675714	5990012	WT_51	682363	5990272
WT_16	669580	5990315	WT_34	675820	5987571	WT_52	682429	5992510
WT_17	670081	5988365	WT_35	676738	5991497	WT_53	682795	5991564
WT_18	670351	5987383	WT_36	676915	5988595	WT_54	680098	5987724

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The information in this document is valid at the time of publishing (see month/year). Updates will be published on the website https://offshorewind.rvo.nl/ at the relevant Wind Farm Site, General Information, submap Revision Log and Q & A.
In the Revision Log is indicated which versions are the latest and what the changes are in relation to previous versions. The documents can be found at the relevant sites, indicated in the List of all reports and deliverables.

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