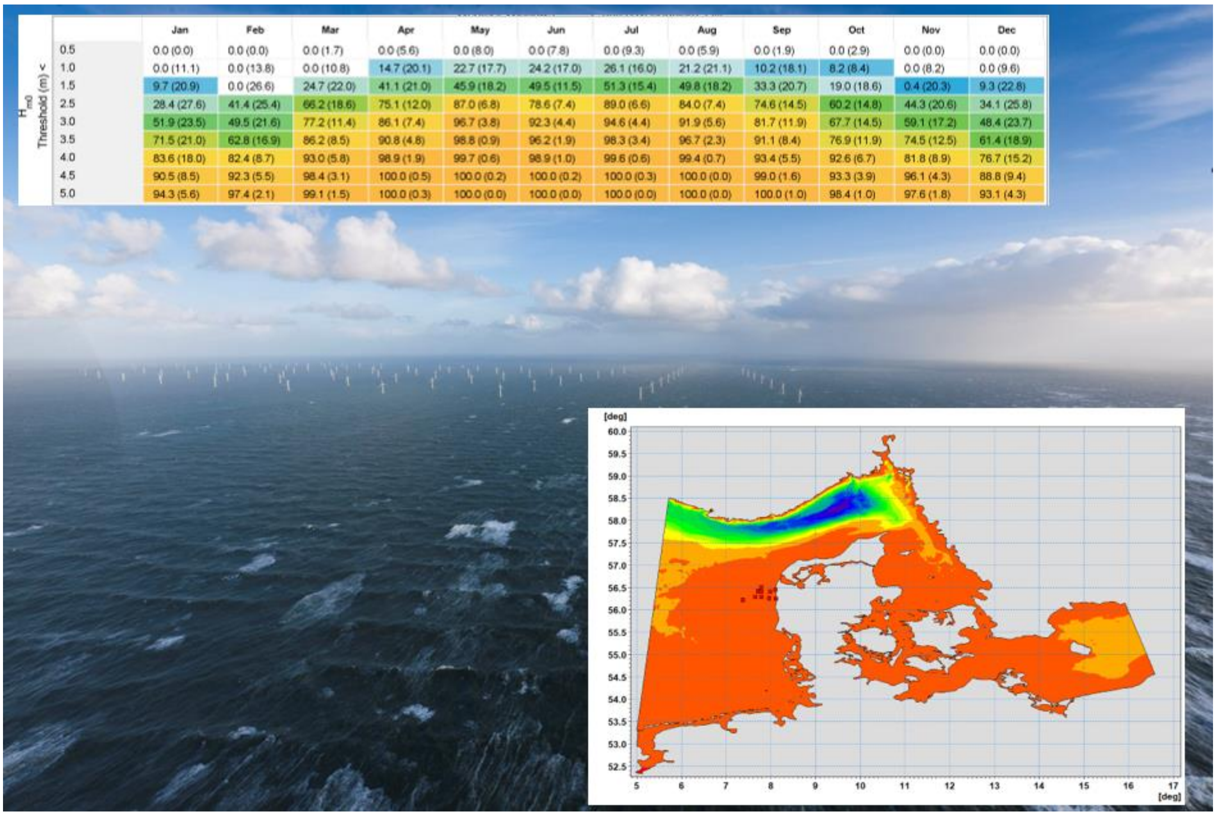
Metocean Data for Thor Offshore Wind Farm

Weather Windows



H_{m0} Threshold (m) <	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.5	0.0 (0.0)	0.0 (0.0)	0.0 (1.7)	0.0 (5.6)	0.0 (8.0)	0.0 (7.8)	0.0 (9.3)	0.0 (5.9)	0.0 (1.9)	0.0 (2.9)	0.0 (0.0)	0.0 (0.0)
1.0	0.0 (11.1)	0.0 (13.8)	0.0 (10.8)	14.7 (20.1)	22.7 (17.7)	24.2 (17.0)	26.1 (16.0)	21.2 (21.1)	10.2 (18.1)	8.2 (8.4)	0.0 (8.2)	0.0 (9.6)
1.5	9.7 (20.9)	0.0 (26.6)	24.7 (22.0)	41.1 (21.0)	45.9 (18.2)	49.5 (11.5)	51.3 (15.4)	49.8 (18.2)	33.3 (20.7)	19.0 (18.6)	0.4 (20.3)	9.3 (22.8)
2.5	28.4 (27.6)	41.4 (25.4)	66.2 (18.6)	75.1 (12.0)	87.0 (6.8)	78.6 (7.4)	89.0 (6.6)	84.0 (7.4)	74.6 (14.5)	60.2 (14.8)	44.3 (20.6)	34.1 (25.8)
3.0	51.9 (23.5)	49.5 (21.6)	77.2 (11.4)	86.1 (7.4)	96.7 (3.8)	92.3 (4.4)	94.6 (4.4)	91.9 (5.6)	81.7 (11.9)	67.7 (14.5)	59.1 (17.2)	48.4 (23.7)
3.5	71.5 (21.0)	62.8 (16.9)	86.2 (8.5)	90.8 (4.8)	98.8 (0.9)	96.2 (1.9)	98.3 (3.4)	96.7 (2.3)	91.1 (8.4)	76.9 (11.9)	74.5 (12.5)	61.4 (18.9)
4.0	83.6 (18.0)	82.4 (8.7)	93.0 (5.8)	98.9 (1.9)	99.7 (0.6)	98.9 (1.0)	99.6 (0.6)	99.4 (0.7)	93.4 (5.5)	92.6 (6.7)	81.8 (8.9)	76.7 (15.2)
4.5	90.5 (8.5)	92.3 (5.5)	98.4 (3.1)	100.0 (0.5)	100.0 (0.2)	100.0 (0.2)	100.0 (0.3)	100.0 (0.0)	99.0 (1.6)	93.3 (3.9)	96.1 (4.3)	88.8 (9.4)
5.0	94.3 (5.6)	97.4 (2.1)	99.1 (1.5)	100.0 (0.3)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (1.0)	98.4 (1.0)	97.6 (1.8)	93.1 (4.3)

Energinet Eltransmission A/S

Report

May 2019

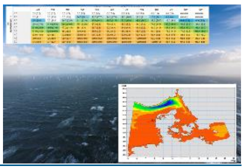
The expert in **WATER ENVIRONMENTS**

This report has been prepared under the DHI Business Management System
certified by Bureau Veritas to comply with ISO 9001 (Quality Management)

ISO 9001
Management System Certification
BUREAU VERITAS
Certification Denmark A/S

Metocean Data for Thor Offshore Wind Farm

Weather Windows



Prepared for Energinet Eltransmission A/S

Represented by Mr. Jens Colberg-Larsen

Project manager	Jesper Ulrik Fuchs
Author	Rodolfo Bolaños Sanchez
Quality supervisor	Jesper Ulrik Fuchs

Project number	11823770
Approval date	09/05/2019
Revision	Final 1.0
Classification	Restricted

DHI A/S • Agern Allé 5 • DK-2970 Hørsholm • Denmark
Telephone: +45 4516 9200 • Telefax: +45 4516 9292 • dhi@dhigroup.com • www.dhigroup.com
Company Reg. No.: 36466871

This page is intentionally blank

CONTENTS

FIGURES

TABLES

APPENDICES

NOMENCLATURE

Abbreviations	
CREA6	COSMO-REA6
CC	Correlation Coefficient
AME	Absolute Mean Error
HD	Hydrodynamic
MSL	Mean Sea Level
RMSE	Root Mean Square Error
SI	Scatter Index
SW	Spectral Wave

Subscripts	
NE	North Europe Model
DK	Danish Coastal Waters (local model)
m0	Zero spectral moment

Variables	
H_{m0}	Significant wave height (m)
U_{10}	Wind speed at 10 m (m/s)
WL	Water level (m)
CS	Current speed (m/s)

Definitions	
Time	Times are relative to UTC
Level	Levels are relative to MSL
Coordinate system	Long/Lat (if not specified otherwise)

1 Executive summary

This report describes the work done by DHI A/S (DHI) in response to the request from Energinet Eltransmission A/S (Energinet in the following) for the provision of weather windows at the Thor Offshore Wind Farm (OWF) area in the Danish sector of the North Sea (see Figure 2.1) and cable corridors between the farm area and the Danish coast.

Weather windows were produced on i) wave heights, ii) water levels, iii) current speeds, and iv) wind speeds. The weather windows (persistence) tables provide Q10, Q20, P30 …… through Q90 estimates of weather windows in 6 hrs increments (up to 72 hrs) for the agreed threshold levels.

The weather windows at ten points at the OWF and along the two cable corridors were required. The locations of the ten points were selected to provide a good coverage of conditions at the site, covering different water depths. Locations were agreed with Energinet prior to the production of weather windows. Data from the DHI Danish Waters models (23 years, from 1995 to 2017) was used to analyse the metocean conditions at the ten points to provide the weather windows.

Wind (U_{10}), hydrodynamics (CS and WL) and wave (H_{m0}) weather windows were delivered to Energinet in figure format and in Excel files.

This page is intentionally blank

2 Introduction

For tendering purposes, Energinet required weather windows covering the Thor OWF area and the associated cable corridors. The OWF area has a triangular shape defined by positions 56° 13,804' N7° 48,335' E, 56° 13,510' N 7° 22,516' E and 56° 31,189' N 7° 47,493' E (see Figure 2.1) with water depth ranging between 27 and 33 mDVR90.

The weather window tables produced for Energinet include nine quantiles (Q10, Q20 … through Q90) estimate of weather windows in 6 hr increments (up to 72 hr) for the following criteria:

- Wave height, H_{m0}: <0.5 m, <1.0 m, <1.5 m, <2.0 m, <2.5 m, <3.0 m, <3.5 m, <4.0 m, <4.5 m, <5.0 m
- Water level, WL: <-2 m, <-1.8 m, <-1.6 m, <-1.4 m, <-1.2 m, <-1 m, <-0.8 m, <-0.6 m, <-0.4 m, <-0.2 m, <-0.0 m

  <2 m, <1.8 m, <1.6 m, <1.4 m, <1.2 m, <1 m, <0.8 m, <0.6 m, <0.4 m, <0.2 m, <0.0 m
- Current speed, CS: <0.2 m/s, <0.4 m/s, <0.6 m/s, <0.8 m/s
- Wind speed, U_{10} (at 10 m MSL): <5 m/s, <10 m/s, <15 m/s, <20 m/s, <25 m/s

Description of weather window definition is provided in Appendix A.

Time series data from the DHI Danish Waters numerical wave and hydrodynamic hindcast models (see Section 3) was used as the basis for generating the weather windows.

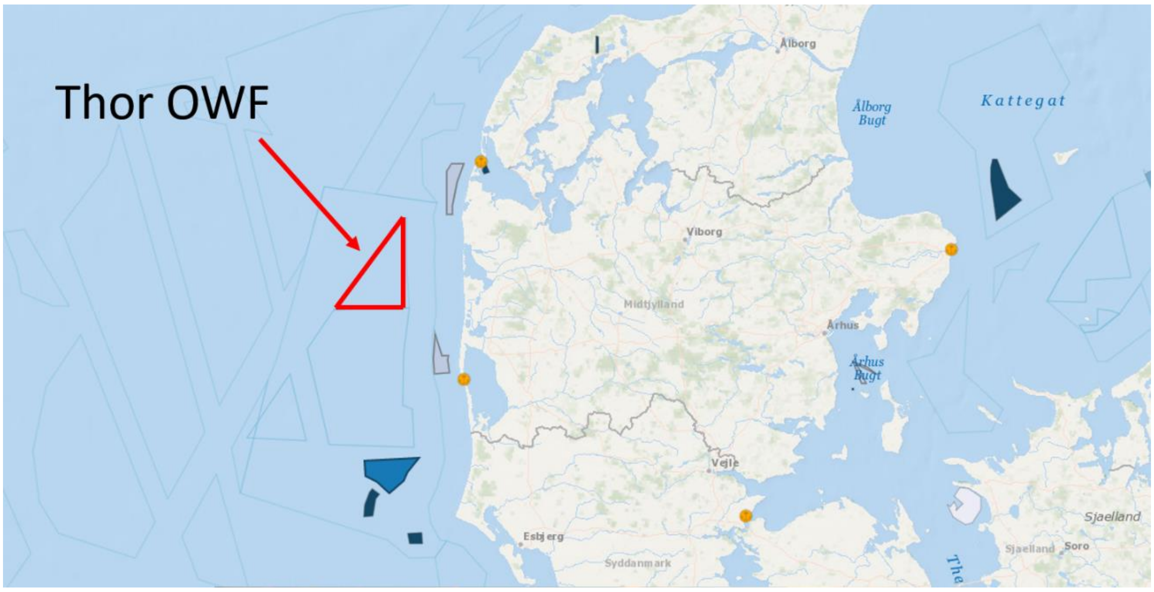


Figure 2.1 Location of Thor OWF (red triangle) at the west coast of Denmark.

This page is intentionally blank

3 Model Descriptions

Water levels, currents and wave data have been obtained from DHI Danish Waters numerical wave and hydrodynamic hindcast models [1], while the wind data was obtained from COSMO CREA6 hindcast dataset as described below. Data covers 23 years, from 1995 to 2017.

3.1 COSMO-REA6 (CREA6) wind fields

The regional atmospheric reanalysis COSMO-REA6 was developed by the DWD's Hans-Ertel Centre for Weather Research at the University of Bonn, [2]. The model grid covers the EURO-CORDEX (European Coordinated Regional Climate Downscaling Experiment) domain and the model is forced by the global reanalysis ERA-Interim from ECMWF (European Centre for Medium-Range Weather Forecasts). The characteristics of CREA6 are presented in Table 3.1. The reanalysis provides wind and pressure data on a 0.055° grid (~6.2 km) every hour from 1995 to 2017. Open access to the data is granted[1]. More information, e.g. relevant references, are available through \\dkcph1-nas07\POT\METEOROLOGY\COSMO_REA6\Documentation.

Table 3.1 Characteristics of CREA6 wind and pressure data

Dataset	Availability	Temporal resolution	Spatial resolution of wind data	Spatial resolution of air pressure data
CREA6	1995-2017	1h	0.055°	0.055°

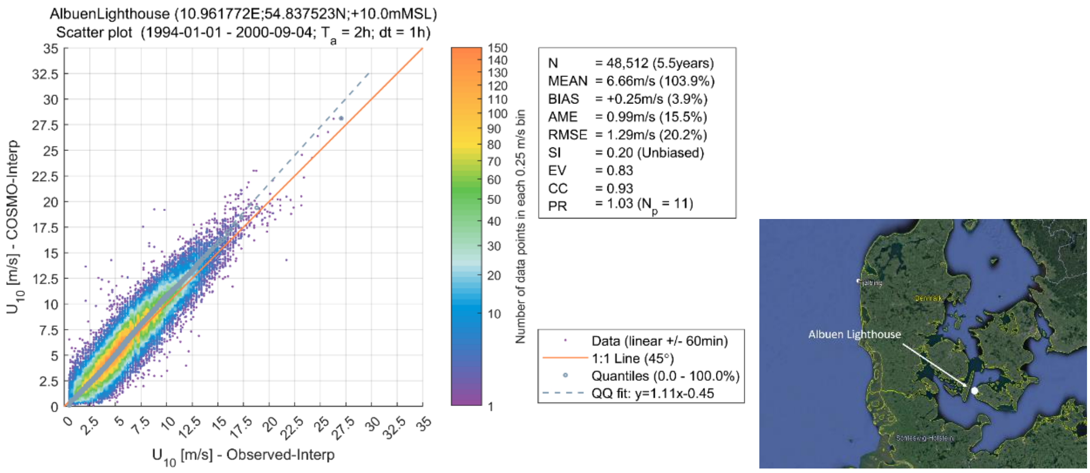


Figure 3.1 Wind speed validation of CREA6 at Albuen Lighthouse station. The model shows very good performance with low bias and errors.

The CREA6 wind fields have been used to force both hydrodynamic model (HD_{DK}, see Section 3.2) and wave model (SW_{DK}, see Section 3.3) and also to generate the wind speed weather windows.

[1] ftp://ftp-cdc.dwd.de/pub/REA/

3.2 Hydrodynamic model (HD_{DK})

The DHI hydrodynamic (HD) model, MIKE 21 HD FM, was used for obtaining water levels and depth-integrated current speed in the HD_{DK} model.

The MIKE 21 Flow Model is a modelling system for 2D free-surface depth-integrated flows that is developed and maintained by DHI and offered as part of MIKE Powered by DHI, [3].

The HD model (HD_{DK}) was forced by boundary conditions extracted from DHI's regional Northern Europe hydrodynamic model (HD_{NE}), and wind and pressure from CREA6 described in Section 3.1. The model includes both astronomical tide and meteorological effects including surge.

The established local hydrodynamic model extent is presented in Figure 3.2. The local model uses unstructured mesh with progressive increasing spatial resolution towards the Danish coastlines. The resolution varies from 3-4 km in the offshore areas and near non-Danish coastlines to around 2 km in the Danish waters. Near the Danish coastlines, the resolution varies from around 1 km to around 500 m at the coasts.

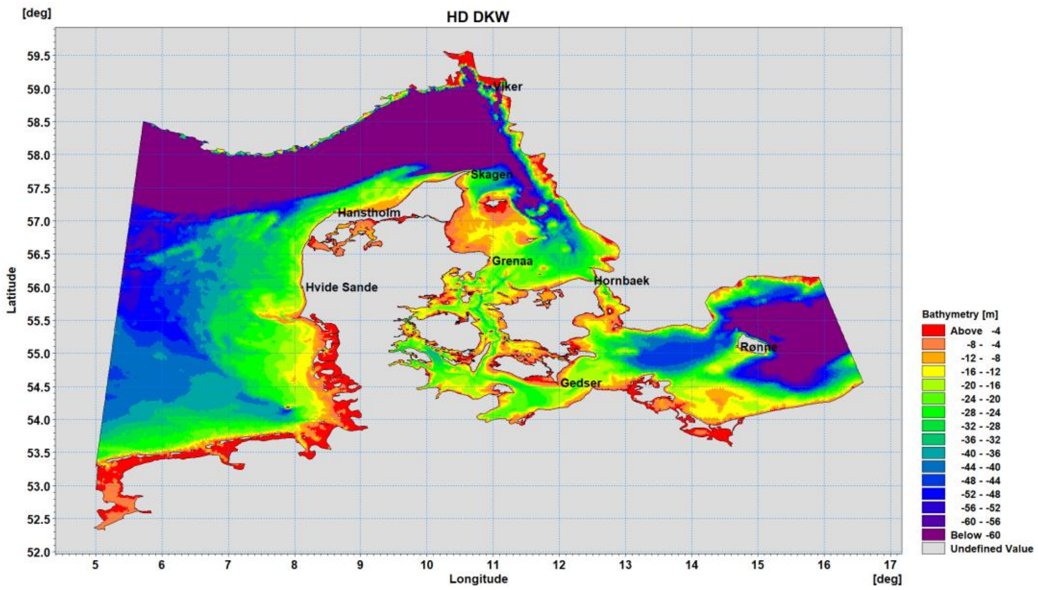


Figure 3.2 Extent of the hydrodynamic model HD_{DK} (bathymetry is shown in shaded colours) and location of stations used for calibration

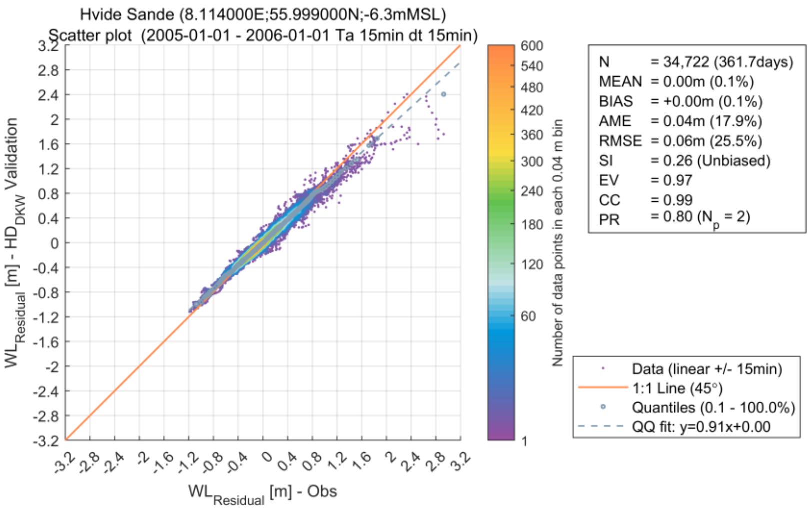


Figure 3.3 Comparison of water level measured and modelled with HD$_{DK}$ at Hvide Sande during 2005. The comparison shows a very good performance of the model in terms of water level simulation.

3.3 Wave model (SW$_{DK}$)

The MIKE 21 Spectral Wave (SW) Flexible Mesh (FM) model developed, supported and maintained by DHI was used for the Danish Waters wave hindcast model, SW$_{DK}$. Like the other modules included in the FM series of MIKE Powered by DHI, the spectral wave model is based on an unstructured, cell-centred finite volume method and uses an unstructured mesh in geographical space.

The wave model is forced by boundary conditions from DHI's regional Northern Europe spectral wave model (SW$_{NE}$), by wind from CREA6 wind data described in Section 3.1, and by the water level and current from the HD$_{DK}$ hydrodynamic model described in Section 3.2.

The SW$_{DK}$ model domain is the same as in Figure 3.2, however, the mesh resolution increases from 4 km close to the open boundaries to 1 km close to the Danish coastlines, with a 2-2.5 km intermediate layer (Figure 3.4). The objective of such a modelling strategy is to ensure the smooth propagation of waves into the domain and enable high-resolution outputs. Contrary to the hydrodynamic mesh, the deep-water channels were not considered in the mesh construction as they are irrelevant for a spectral wave model.

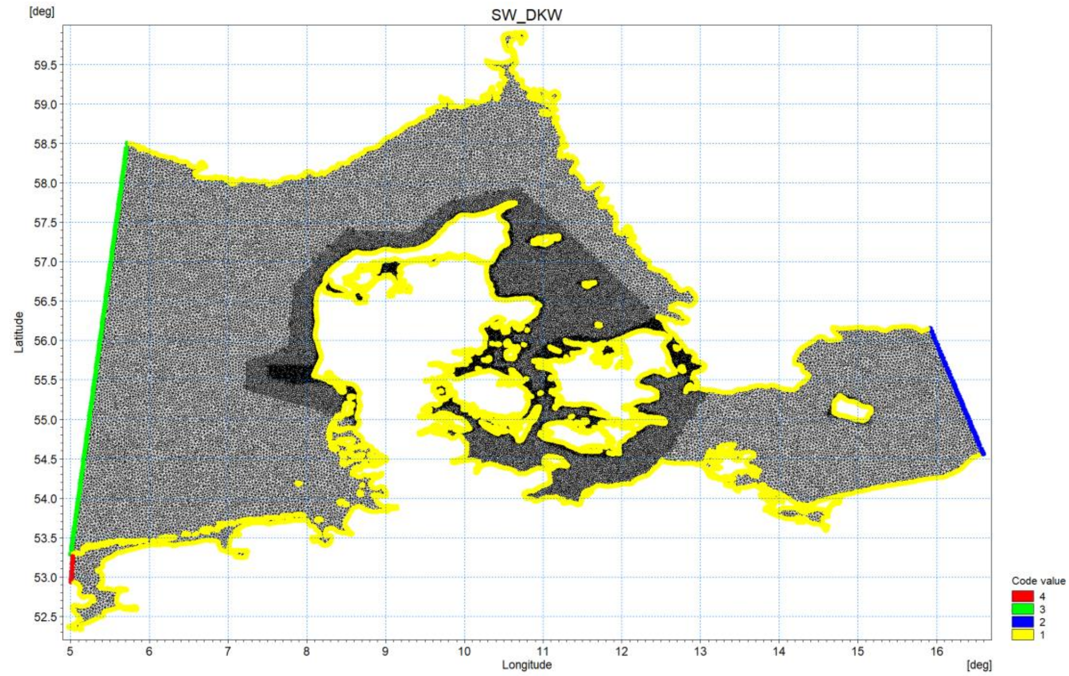


Figure 3.4 Mesh and open boundaries (blue, red and green lines) of the SW_{DK} model.

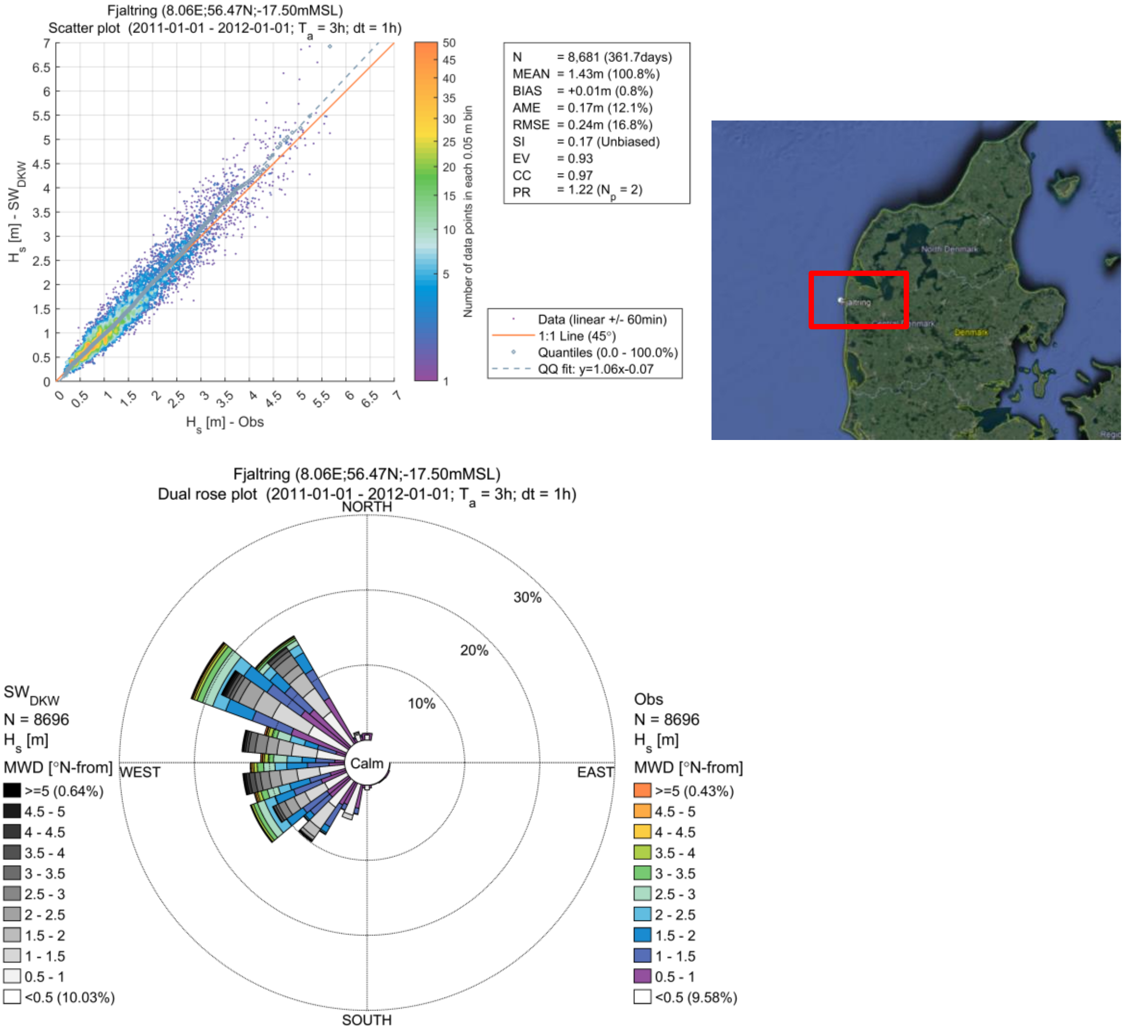


Figure 3.5 Scatter plots of the SW_{DK} significant wave height (top left) and against observations and wave rose plots (bottom) at Fjaltring (see location inside red square, top right map) during 2011.

Overall wind, hydrodynamic and wave models perform well in terms of wind speed, significant wave height and water levels. This gives confidence in the data used to estimate weather windows at Thor OWF area and cable corridor for Energinet.

This page is intentionally blank

4 Deliverables

Weather windows for 10 points in the Thor WWF area and the associated cable corridors (see Figure 4.1 and Table 4.1) have been generated. An example of a weather window of significant wave height (H_{m0}) is shown in Figure 4.2. Tables in figure format (PNG) and corresponding data in Excel files have been provided to Energinet.

A description of weather window and the underlying analysis methodology is presented in Appendix A.

For each variable and point, an .xls file has been provided containing the weather window for all the percentiles and window durations used. Note that the uncertainty for the 10th percentile might be large due to the duration of the time series.

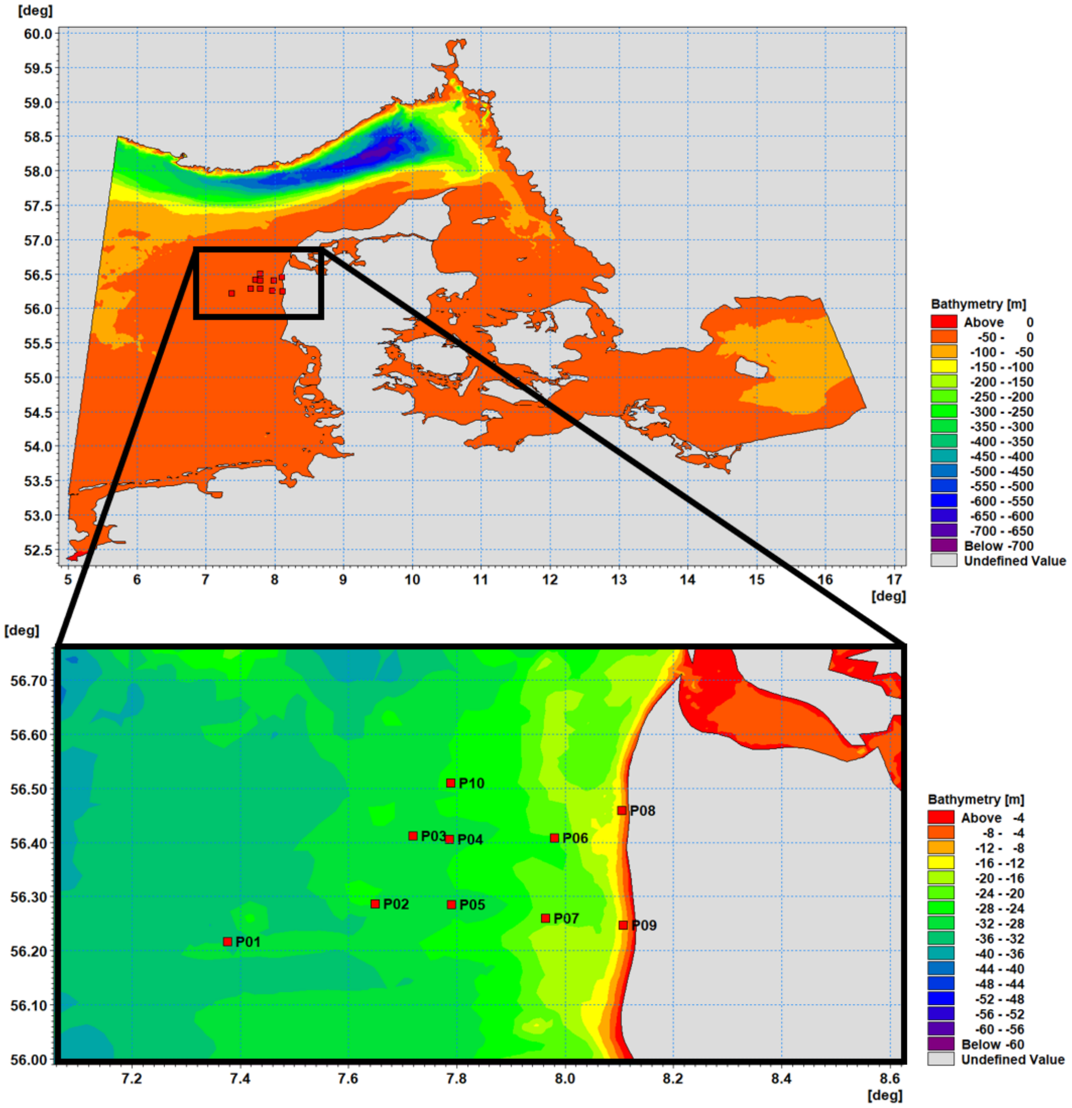


Figure 4.1 Location of the 10 point for obtaining the weather windows in the Thor OWF area and along cable corridors

Table 4.1 Description of points used to generate weather windows

Point	Longitude (ºE)	Latitude (ºN)	Water depth (m)
1	7.376966	56.2169	32
2	7.648981	56.28595	28
3	7.718938	56.41263	29
4	7.785457	56.40618	29
5	7.789918	56.2854	28
6	7.980308	56.40805	24
7	7.963665	56.25932	21
8	8.104741	56.45895	11
9	8.106704	56.2477	11
10	7.788982	56.50958	27

Point 5 (7.789918E;56.285400N)
Persistence (1994-12-31 - 2018-01-01) SW Δt = 1.0h, N = 201626 (23.00 years)
Weather Windows > 72h (Overlapping) [%]

H_{m0} Threshold (m) <	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.5	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (4.5)	0.0 (8.0)	0.0 (5.4)	0.0 (9.8)	0.0 (5.5)	0.0 (0.0)	0.0 (2.4)	0.0 (0.0)	0.0 (0.0)
1.0	0.0 (9.9)	0.0 (13.2)	0.0 (10.5)	14.2 (21.1)	22.7 (16.5)	14.3 (18.0)	24.9 (17.2)	19.1 (20.9)	8.5 (17.2)	0.4 (8.5)	0.0 (7.8)	0.0 (8.4)
1.5	2.1 (21.0)	0.0 (26.3)	24.7 (21.0)	40.6 (21.5)	45.9 (18.3)	47.8 (15.0)	49.0 (17.3)	47.3 (19.4)	33.3 (22.7)	16.7 (18.0)	0.0 (20.3)	9.3 (21.2)
2.0	13.1 (25.2)	25.9 (26.1)	48.5 (23.0)	57.3 (18.1)	64.8 (17.2)	66.4 (10.6)	77.2 (11.9)	68.2 (14.4)	55.3 (20.1)	40.2 (18.6)	22.0 (24.1)	18.7 (24.8)
2.5	25.6 (28.4)	36.5 (25.7)	66.2 (19.1)	72.0 (13.5)	87.0 (7.8)	77.7 (6.9)	87.3 (8.4)	82.2 (9.5)	73.7 (14.3)	58.2 (15.1)	41.6 (23.0)	31.8 (26.1)
3.0	44.0 (24.3)	47.4 (24.1)	74.8 (11.7)	85.3 (7.6)	96.7 (5.5)	91.7 (4.6)	94.6 (4.4)	91.9 (5.6)	81.7 (13.0)	67.6 (14.3)	58.5 (17.2)	41.6 (24.4)
3.5	64.8 (22.3)	62.8 (18.5)	84.2 (8.6)	90.8 (5.6)	98.8 (0.9)	96.2 (1.9)	98.3 (3.4)	96.7 (2.3)	89.4 (9.4)	76.9 (12.5)	73.0 (14.5)	52.6 (21.1)
4.0	79.9 (18.1)	82.4 (10.2)	93.0 (7.1)	98.9 (3.1)	99.7 (0.6)	98.9 (1.0)	99.6 (0.6)	99.4 (0.7)	93.4 (7.0)	92.6 (8.2)	81.5 (9.5)	67.6 (17.4)
4.5	90.5 (9.4)	88.9 (7.0)	97.0 (3.1)	100.0 (0.5)	100.0 (0.2)	100.0 (0.2)	100.0 (0.3)	100.0 (0.0)	99.0 (1.6)	93.3 (5.2)	90.2 (5.2)	88.8 (10.2)
5.0	94.3 (5.6)	97.4 (3.3)	99.1 (1.5)	100.0 (0.3)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	100.0 (1.0)	98.4 (1.0)	97.6 (1.8)	93.0 (4.6)

Figure 4.2 Example of a significant wave height (H_{m0}) weather window using a 80 percentile (Q80) for Point 5 for a duration of 72 hr. Values in the table are percent and values in brackets indicate the standard deviation.

5 References

[1] DHI, “Wave and water level hindcast of Danish waters. Spectral wave and hydrodynamic modelling,” Hørsholm, 2019.

[2] C. Bollmeyer, J. D. Keller, C. Ohlwein, S. Wahl, S. Crewell, P. Friederichs, A. Hense, J. Keune, S. Kneifel, I. Pscheidt, R. Redl and S. Steinke, “Towards a high-resolution regional reanalysis for the European CORDEX domain,” *Quaterly Journal of the Royal Meteorology Society,* vol. DOI: 10.1002/qj.2486, no. 141, pp. 1-15, 2015.

[3] DHI, “MIKE 21 FLOW MODEL FM, Hydrodynamic Module User Guide,” 2018.

This page is intentionally blank

APPENDICES

APPENDIX A – Persistence Analysis Methodology

This page is intentionally blank

A Persistence Analysis Methodology

A weather window is defined as a continued occurrence during which the given conditions (duration and threshold) are fulfilled, while downtime is defined as the remainder periods (i.e. all periods that are not weather windows). The sum of weather windows and downtime for any given condition thus equals 100% of the time.

The durations may be defined as either ‘Overlapping’ or ‘Non-overlapping’. Overlapping duration refers to persistence that includes the fraction of duration at the end of each weather window, while non-overlapping duration includes whole number of windows only. Overlapping duration thus results in higher occurrence of weather windows (and lower occurrence of downtime) and vice versa. The thresholds may be defined as being either above or below a given value depending on what is critical for the parameter in question.

An illustration of persistence during one month (31 days) is shown in Figure A.1. As an example, the persistence for an overlapping duration ≥ 1 day (24 hours) and a threshold H_{m0} < 4.0 m yields weather windows 93.2% of the time (28.9 days) and corresponding downtime of 6.8% (2.1 days) during that particular month.

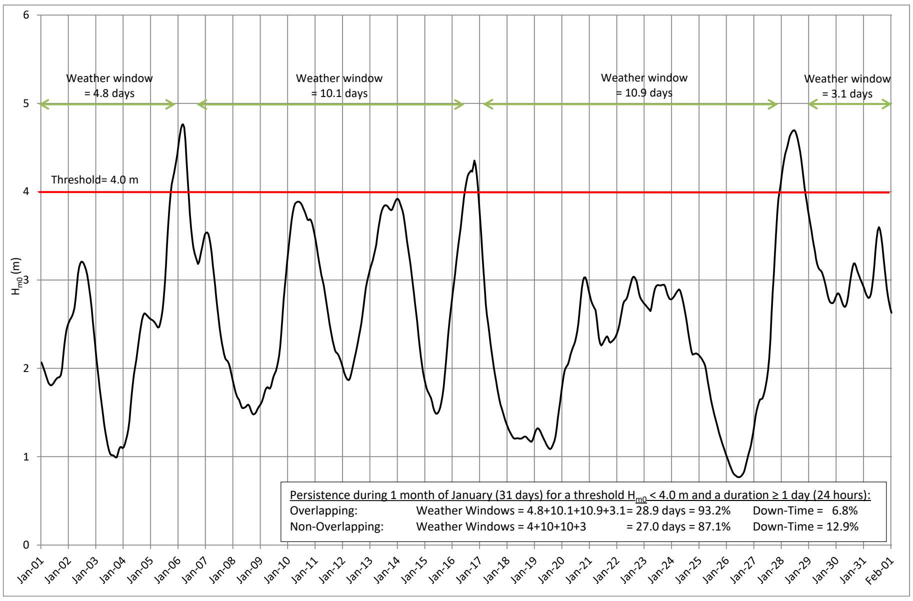


Figure A.1 Illustration of persistence during one month (example only)

Preferably, a long-term time series (several years) is applied for the calculation of persistence statistics in order to reduce the uncertainty related to yearly variations. The uncertainty may be estimated by calculating the persistence statistics for each available year and subsequently derive the mean, standard deviation and/or any given certainty percentile. A percentile (P) above 50% in this case refers to a more conservative estimate (i.e. less weather windows and more downtime) and vice versa.

The persistence statistics are presented in graphical and tabular format as a percentage of time during each considered interval (e.g. month). Windows stretching through more than one interval contribute with a corresponding fraction of the window to each of the intervals.

This page is intentionally blank