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Reference Site Conditions for Floating Wind Arrays

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List of Acronyms

AnEn	Analog Ensemble
BOEM	Bureau of Ocean Energy Management
CDF	cumulative distribution function
CFSR	Climate Forecast System Reanalysis
CLV	cable-laying vessel
CPT	cone penetration test
CTV	crew transfer vessel
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis v5
FLOW	floating offshore wind
GDG	Gavin and Doherty Geosolutions
GEBCO	General Bathymetric Chart of the Oceans
GEV	generalized extreme value
GPD	generalized Pareto distribution
GWA	Global Wind Atlas
HFRNet	high-frequency radar current measurements
HLV	heavy-lift vessel
IDEA-IRL	Integrated Design of Floating Wind Arrays Ireland
IEA Wind	IEA Wind Technology Collaboration Programme
IEA	International Energy Agency
LOA	length overall
MERA	Maine Research Array
mMSL	meters above mean seal level
MSL	mean sea level
NDBC	National Data Buoy Center
NEWA	New European Wind Atlas
NOW-23	2023 National Offshore Wind dataset
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
pre-FEED	preliminary front-end engineering design
R&D	research and development
SOV	service operations vessel
WRF	Weather Research and Forecasting Model
WTG	wind turbine generator

Executive Summary

The commercial scale deployment of floating wind projects is expected to take place in a diverse range of sites, which may differ significantly from existing fixed-bottom projects. Floating wind arrays are particularly sensitive to the water depth and to meteorological ocean (metocean) and geotechnical conditions at the project site due to the wave-induced system motions and loads as well as the anchoring system constraints imposed by the seafloor conditions. Uncertainty around the site conditions will permeate through all aspects of project design, leading to suboptimal and overly conservative designs, increased costs, and adversely affected performance. As floating wind expands into a global industry, metocean and geotechnical conditions will increasingly vary for projects located in different geographic regions or in far-from-shore, deep-water sites. It is important to test new developments and design factors of floating arrays under various site conditions using computer simulations.

This report, prepared within Work Package 1 of International Energy Agency Wind Technology Collaboration Programme Task 49, presents reference site conditions for floating wind arrays to serve as a design basis for the techno-economic design of reference floating wind arrays. Data from the reference sites presented here are publicly available in an open database and thus support fast development and comparable design of floating wind arrays for various relevant conditions. The development of these reference sites drew on existing open access datasets and ongoing research projects of task participants.

Six classes were identified that describe relevant key conditions for the design and development of floating wind arrays: metocean conditions, seabed conditions, coastal infrastructure, environmental impact, socioeconomic impact, and regulations and permissions. The reference sites for the techno-economic design of floating wind arrays are based on a concept that uses building blocks to synthesize purpose-built site representations. In each of the identified classes with influencing design factors, building blocks are used to describe the characteristic properties and their spread. However, the latter three classes (i.e., environmental impact, socioeconomic impact, regulations and permissions) are not included in the reference site conditions due to limited knowledge and lack of reliable criteria to quantify their impact on the techno-economic design in numeric parameters. Building blocks with key parameters for the techno-economic design of floating wind arrays are provided for metocean conditions, seabed conditions, and coastal infrastructure.

For metocean conditions, multiple sites were selected for detailed analysis that represent a range of conditions across the pipeline of floating wind projects. Wind conditions and sea states are separated, and each location considers both the severity of wind and waves, e.g., one site may have a moderate wave condition but severe wind condition. From this pipeline, 11 representative sites were selected where site-specific analysis was available within the consortium and where they represent different parts of the global pipeline. The 11 sites are: Hannibal (Italy), Humboldt Bay (United States), Ulsan (South Korea), Moneypoint Offshore One (Ireland), Havbredey (United Kingdom), Fukushima (Japan), Utsira Nord (Norway), Gulf of Maine (United States), Sud de la Bretagne II (France), and Sørlige Nordsjø II (Norway). Each of these sites is summarized in the main report, and more details about the studies and analyses behind the datasets are provided in the appendix. The data for these sites is publicly available on Zenodo [1].

For seabed conditions, general information about the geotechnical parameters is provided and a baseline is established for the geotechnical parameters and stratigraphy that may be encountered on the sites. A set of six “synthetic cases” are defined as building blocks to provide the different parameters required for design under each case/soil condition.

For the coastal infrastructure, general information about the main requirements is provided that a port should comply with to provide a satisfactory service during the construction of floating offshore wind arrays. Minimum port infrastructural requirements are provided for three types of ports.

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1 Introduction

The International Energy Agency (IEA) predicts a significant increase of installed wind power capacity to meet the net-zero carbon dioxide emissions target by 2050 [2]. While fixed-bottom wind turbines currently dominate offshore wind technology, the IEA net-zero scenario estimates that floating offshore wind turbines will provide a major contribution from onward 2030 [3].

Research and development (R&D) have focused mainly on single floating wind turbines, particularly on the design of the floating platform and its mooring and anchoring systems. Such single floating wind structures were tested in pilot projects like Equinor's Hywind Demo in Norway. However, floating wind energy on a larger scale implies installing clusters of wind turbines connected to each other and to the seafloor using the same electrical infrastructure to export the power. The optimal design and operation of such floating wind arrays requires a system perspective starting from the early planning phase.

Previous and ongoing research projects defined reference sites to study the design, installation, and operation of floating wind turbines and arrays. Examples of European projects that defined reference sites in their deliverables include LEANWIND (2013–2017) [4], Lifes50+ (2015–2019) [5], ARCWIND (2017–2023) [6], FLOTANT (2019–2022) [7], COREWIND (2019–2023) [8], HIPERWIND (2020–2024) [9], and FLOATECH (2021–2023) [10]. This non-exhaustive list of projects that developed and used reference sites for floating wind illustrates the need for open reference site conditions.

The aim of the IEA Wind Technology Collaboration Programme (IEA Wind) Task 49 Reference Sites for Floating Wind Arrays is to provide a realistic and publicly available set of reference site conditions to the floating wind energy community as a baseline set of data for individual research projects. Such open reference sites for floating wind arrays will increase the comparability of R&D work on the design of floating wind arrays and thus accelerate the maturation of floating wind technology. This report develops and provides reference site conditions for floating wind arrays. The supporting datasets are published and publicly available [1].

The remaining report is organized as follows: Section 2 sketches key conditions of sites for floating wind arrays. Section 3 introduces the suggested building block concept to generate reference sites, and Sections 4–9 define the blocks for the six parameter categories: Section 4 elaborates on the metocean conditions and presents real floating array sites that build the mentioned blocks; Section 5 and Section 6 define building blocks for relevant seabed conditions and coastal infrastructure, respectively; Section 7 and Section 8 discuss the environmental and socioeconomic impacts, respectively, of floating array design; and Section 9 discusses the dimension of permissions and regulations in the design process. Finally, Section 10 summarizes and concludes the report.

2 Key Conditions of Sites for Floating Wind Arrays

One of the key parameters for the design of floating wind arrays is obviously the water depth. A large water depth of more than about 60 meters (m) makes technology for fixed-bottom wind turbines more challenging [11]. The water depth defines suitable floating wind technologies but is not the only relevant design factor.

In IEA Wind Task 49, the following classes of key factors were identified as relevant for the design of floating wind arrays:

- Metocean conditions
- Seabed conditions
- Coastal infrastructure
- Environmental impact
- Socioeconomic impact
- Regulations and permissions.

The metocean conditions are key to estimate the overall potential of wind energy deployment, as they are directly linked to the capacity for power production and the accumulation of structural fatigue. The evaluation of metocean conditions at specific sites considers wind, waves (wind and wave characteristics as well as joint wind/wave probability distributions), and currents. This includes values for both typical operation and extreme events for the determination of the fatigue limit states and ultimate limit states of the structures.

The seabed conditions define suitable technologies and costs for fixing and anchoring the wind turbines to the seafloor. This means foremost the soil type and strength, but the slope and roughness of the seabed also influence the design of the mooring system. On the extreme site, seismic hazards could dictate the floating array design. It should be noted that the seabed conditions are site-specific and can vary significantly across a site; hence, multiple types of anchoring technology may be used on the same site.

The coastal infrastructure is another important factor because it determines the availability of vessels for installation and maintenance. Port access channels and related infrastructure dictate the available vessel types and construction methods. The distance to shore and water depth are key parameters in the context of coastal infrastructure, as is the existing maritime workforce. As part of the coastal infrastructure, the power grid capacity decides if a wind energy project can be connected to the regional grid without further expansion.

The environmental impact, both short and long term, cannot be neglected when developing wind energy projects. Offshore wind energy deployment means invading natural maritime habitats with technical installations, foreign materials, noise, light, and traffic. The impacts to the local environment are highly dependent on the regional marine flora and fauna.

The socioeconomic impact is important for the sustainable development of wind energy and for the support and acceptance of wind energy by the local communities and society at large. Technical and social challenges should be solved using an interdisciplinary approach to successfully mitigate climate change [12]. Although local communities are less affected by visual and noise impacts from floating wind arrays because they are farther from shore than fixed-bottom arrays, community interests and concerns should be considered throughout the project lifetime. Ocean users have diverse interests, and wind energy deployment should strive for coexistence.

Regulations and permissions have a significant impact on wind energy projects. Permitting pathways and regulatory barriers depend on political support. In light of the green energy transition, wind energy currently receives high attention. The European Union and many of its member states, for example, seek to accelerate permissions to reach targets for zero greenhouse gas emissions by 2050. Floating wind is in the early stages of technological development, and regulations unifying the procedures are yet to be established.

3 Building-Block Concept

This report provides reference sites for the techno-economic design of floating wind arrays, utilizing a building-block concept to synthesize purpose-built site representations. Figure 1 summarizes the six identified classes of relevant factors for floating wind arrays. The first three classes contain key parameters for floating wind array design that will be addressed using the building-block concept. The remaining three classes are important for both design and site selection, but their degree of region-specific variability makes them impractical to include in the building-block concept. We instead discuss them qualitatively and leave deeper treatment for future work.

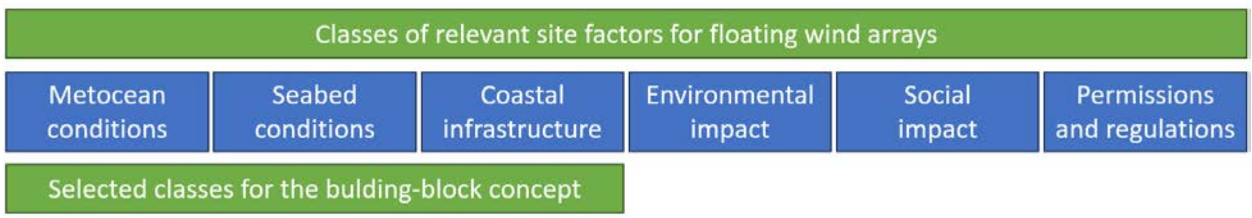


Figure 1. Categorization into classes with relevant factors for site selection and design of floating wind arrays

Each of the three selected classes of site factors for floating wind array design are represented by interchangeable building blocks that describe the characteristic properties and their degree of variation, as summarized in Figure 2. The motivations behind all six classes are briefly outlined below, including those excluded from the building-block approach. Sections 4–9 provide more in-depth explanations.

- **Metocean conditions**: We select multiple sites for detailed analysis that represent a range of conditions across the pipeline of floating wind farm projects. Wind conditions and sea states are separated, and each location considers both the severity of wind and waves—e.g., one site may have a moderate wave condition but severe wind condition.
- **Seabed conditions**: For one specific type of anchor, certain soil conditions might be favorable while others might be unfavorable. Therefore, we do not give recommendations on site-specific data required for detailed design but outline a set of “synthetic cases” that provide the different parameters required for design under each case/soil condition. In Task 49 Work Package 2, a specific case can be chosen based on the anchor type used.
- **Coastal infrastructure**: Minimum port infrastructural requirements are provided for three types of ports.
- **Environmental impact**: We assume that the environmental impact is considered in marine spatial planning. The site with the lowest expected or least detrimental environmental impact is selected for the floating wind array. Thus, the main design decisions are taken without specific consideration of the environmental impact, and the reference sites do not include building blocks for them.
- **Social impact**: We assume that the socioeconomic impact of floating wind arrays is considered in marine spatial planning. Stakeholders should be involved during and after the site selection. However, the anticipated influence of socioeconomic impacts on technical design choices is limited once a site has been selected. Thus, the reference sites do not include building blocks for socioeconomic impact.

- **Permissions and regulations**: Floating wind is an immature technology with only a few commissioned projects worldwide. Simultaneously with technological development, permissions and regulations are emerging in single countries and regions. Currently, no general regulatory landscapes defining the design of floating wind arrays can be determined. Permissions and regulations are thus not included in the building blocks.

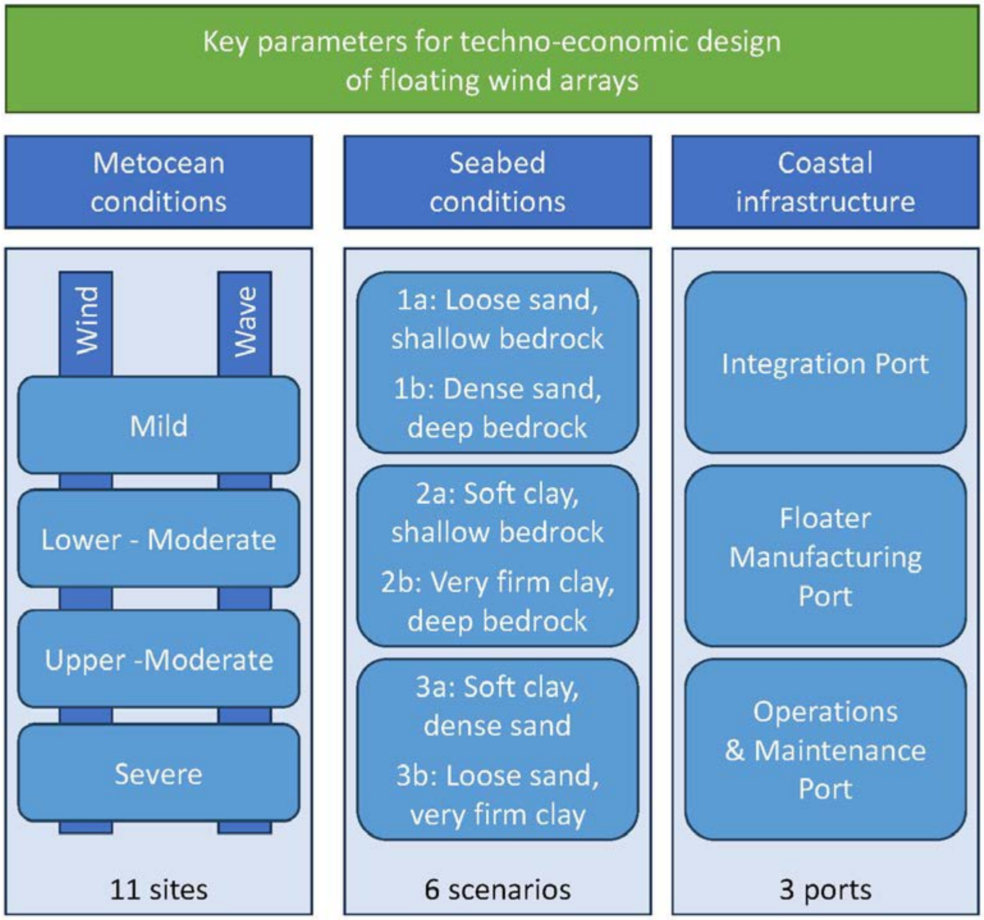


Figure 2. Building block concept for the synthesis of reference sites for techno-economic design of floating wind arrays

4 Metocean Conditions

4.1 Floating Array Pipeline

To deliver a set of fully defined reference sites characteristic of the international global floating wind deployment pipeline, a database of existing and proposed locations for floating arrays was first constructed. The 4C Offshore [13] map of floating offshore wind (FLOW) arrays provided a base for this database. This map identifies a total of 581 FLOW farms organized into the following development status:

- Concept/early planning
- Consent application submitted
- Consent authorized
- Development zone
- Fully commissioned
- Partial generation/under construction
- Preconstruction
- Under construction.

Using expert knowledge from our consortia members, one to three sites per country were selected to represent the general range of metocean conditions expected in each region. This resulted in a database of 69 representative sites. Details of these sites are presented in Section 4.2.

4.2 Classification of Metocean Conditions

For these 69 representative sites, the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) dataset [14] was leveraged to identify a number of "severity" categories that could be used to describe the metocean conditions characterizing the global pipeline. ERA5 is the fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at the ECMWF and is based on the 2016 version of the integrated forecasting system. It produces data from 1950 to the present. Its outputs include atmospheric, ocean wave, and land surface data. The reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. The horizontal resolution of the model is 0.25° x 0.25° (atmosphere variables) and 0.5° x 0.5° (ocean wave variables). Parameters of interest for this study are displayed in Table 1. Data from the closest grid point to each site were downloaded and analyzed. A detailed description of the model and each parameter can be found on the ECMWF website [14]. This time series dataset is available for all sites as supplementary material. The General Bathymetric Chart of the Oceans (GEBCO) gridded bathymetry dataset was used to extract water depth information for each representative site for further analysis. The GEBCO 2023 dataset is a global terrain model for ocean and land, providing elevation data in meters on a grid with 15 arc-second intervals [15].

Table 1. Wind and Wave Variables Obtained From the ERA5 Model

ERA5 Code	Parameter	Metocean Discipline	Units	Time Frame	Temporal Resolution (hours)
hmax	Maximum individual wave height	Wave	m	1979–2022	1
pp1d	Peak wave period	Wave	s	1979–2022	1
swh	Significant wave height of combined wind waves and swell	Wave	m	1979–2022	1
mwd	Mean wave direction	Wave	degrees	1979–2022	1
u10	10-m u-component of wind	Wind	m/s	1979–2022	1
v10	10-m v-component of wind	Wind	m/s	1979–2022	1
u100	100-m u-component of wind	Wind	m/s	1979–2022	1
v100	100-m v-component of wind	Wind	m/s	1979–2022	1

Extreme value analysis was carried out for significant wave height and wind speed to get an understanding of the range of conditions across the database. The raw ERA5 time series was used for this analysis; therefore, any phenomena that are not included in this climate reanalysis model are not represented, for example, tropical cyclone analysis and typhoons.

For this study, a generalized extreme value (GEV) model (DNV 100396_63-HOU-01) was chosen to calculate the extreme values for wave height and wind speed at each location. Due to the adequate length of the wind and wave datasets, the block maxima (annual maxima) approach was chosen to extract extreme events over the 43-year time period as input into the extreme value analysis.

The GEV model has been developed as a combination of Gumbel, Frechet, and Weibull models. The GEV distribution is a family of continuous probability distributions developed within extreme value theory. Extreme value theory provides the statistical framework to make inferences about the probability of very rare or extreme events. The GEV distribution unites the Gumbel, Fréchet, and Weibull distributions into a single family to allow a continuous range of possible shapes. These three distributions are also known as types I, II and III extreme value distributions. The GEV distribution is parameterized with a shape parameter, location parameter, and scale parameter. The GEV is equivalent to types I, II and III when a shape parameter is equal to 0, greater than 0, and lower than 0, respectively. Based on the extreme value theorem, the GEV distribution is the limit distribution of properly normalized maxima of a sequence of independent and identically distributed random variables. Thus, the GEV distribution is used as an approximation to model the maxima of long (finite) sequences of random variables.

The cumulative distribution function (CDF) of the GEV distribution is

$$F(x;\ \mu,\sigma,\xi) = exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \tag{1}$$

where the three parameters, ξ, μ, and σ represent a shape, location, and scale of the distribution function, respectively. Note that σ and 1 + ξ(x-μ)/σ must be greater than zero. The shape and location parameter can take on any real value.

The resulting probability distribution function for two categories of shape parameter (i.e., whether it is equal to zero or not) is

$$\frac{1}{\sigma} t(x)^{\xi+1} e^{-t(x)} \tag{2}$$

where:

$$t(x) = \begin{Bmatrix} \left(1 + \xi \frac{x-\mu}{\sigma}\right)^{-1/\xi} & if\ \xi \neq 0 \\ e^{-(x-\mu)/\sigma} & if\ \xi = 0 \end{Bmatrix} \tag{3}$$

In this case, the numerical method used to estimate the parameters of the extreme value distribution is maximum likelihood.

To calculate the 10-minute extreme wind speeds at hub height, in this case 150 m, the predicted 1-hour extreme wind speeds at 10 m above sea level were converted to 10-minute extreme wind speeds using the Frøya wind speed profile, which is documented in DNV-RP-C205: 2021 [16]:

$$U(T, z) = U_0.\left\{1 + C.\ln\frac{z}{H}\right\}.\left\{1 - 0.41.I_U(z).\ln\frac{T}{T_0}\right\} \tag{4}$$

where U_0 represents the 1-hr mean wind speed at height *H* above sea level (10 m) to the mean wind speed *U* with averaging period *T* at height *z* above sea level. T_0 is fixed at 3,600 s. The expression for *C* is given as:

$$C = 5.73x10^{-2}\sqrt{1 + 0.148U_0} \tag{5}$$

and

$$I_U = 0.06.(1 + 0.043U_0).\left(\frac{z}{H}\right)^{-0.22} \tag{6}$$

These 10-minute extreme wind speeds at 10 m above sea level were extrapolated to hub height (150 m) using the power with the shear exponent value 0.11 as recommended by IEC 61400-3-1: 2019 [17] for extreme conditions:

$$V_{power\ law} = V_{ref} * \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{7}$$

Where $V_{power\ law}$ and V_{ref} are the wind speeds at z and z_{ref}, respectively, and α is the shear exponent.

The resulting 50-year return values for significant wave height and 10-minute averaged wind speeds at hub height were calculated. The threshold water depth between fixed and floating wind is considered to be 60 m. Using this water depth as a threshold, the 69 sites were then reduced to 49 representative sites. The resulting extreme values are presented in Table 2.

Table 2. Resulting 49 Sites With Calculated 50-Year Return Significant Wave Height ($H_s 50$) (1-Hour Sea State) and 50-Year Return 10-min Wind Speeds at Hub Height (150 m) ($V_{hub} 50$)

The colors visualize the magnitudes from least (blue) to greatest (red) in each column.

Wind Farm ID	Wind Farm Name	Country Name	Lat	Long	$H_s 50$ (m)	$V_{hub} 50$ (m/s)	Water Depth (m)
DK2C	Bornholm Bassin Øst	Denmark	55.2186	15.9466	8.03	40.79	-89
ES0C	Nordes Phase 1	Spain	44.1285	-8.4464	11.53	40.75	-383
ES63	Spain	Spain	43.468	-2.882	8.85	32.34	-76
FR82	Méditerranée II	France	42.9013	3.9757	7.62	33.59	-128
FR87	Sud de la Bretagne II	France	47.3247	-3.6594	10.05	43.09	-94
GR65	MUSICA - phase 1	Greece	38.548	26.2623	5.05	30.28	-72
IE24	Atlantic Marine Energy Test Site	Ireland	54.2669	-10.2599	14.99	42.78	-98
IE30	Emerald (Commercial)	Ireland	51.3565	-8.0761	10.53	38.87	-90
IE34	Moneypoint Offshore One	Ireland	52.519	-10.276	13.75	41.23	-102
IS01	HIP Atlantic	Iceland	63.6325	-16.3756	12.57	35.32	-98
IT0T	APENESTE offshore wind farm	Italy	42.1522	16.593	4.98	29.07	-161
IT95	Hannibal	Italy	37.842	12.0722	7.13	35.41	-353
LV12	Marine Spatial Plan: Energy Research Area E4	Latvia	57.1238	20.9436	7.08	33.87	-71
LV14	Kurzéme offshore Wind Project	Latvia	56.5499	20.2663	8.81	36.19	-93
MT05	MUSICA - phase 3	Malta	36.0547	14.1581	7.20	32.13	-200
NO04	UNITECH Zefyros by Hywind Technology	Norway	59.1403	5.0297	9.87	34.51	-207
NO44	Utsira nord - phase 1	Norway	59.2761	4.5405	10.99	37.46	-273
NO66	Sørlige Nordsjø II - phase 2	Norway	56.783	4.918	10.82	45.61	-60
PT12	Leixões	Portugal	40.9678	-9.1979	9.15	36.25	-151
PT15	Sines (Norte e Sul)	Portugal	37.9104	-9.0344	8.67	29.63	-169
SA01	Plambeck Emirates (Floating)	Saudi Arabia	27.8881	34.9282	3.31	22.92	-395
SE82	Dyning	Sweden	58.2189	17.8602	5.86	34.08	-141
SE83	Mareld	Sweden	58.1617	10.5755	7.98	35.93	-233

Wind Farm ID	Wind Farm Name	Country Name	Lat	Long	H_s50 (m)	V_{hub}50 (m/s)	Water Depth (m)
UK6L	Havbredey	United Kingdom	58.862	-5.54	12.52	43.72	-91
UK6U	North Channel Wind 2	United Kingdom	54.7577	-5.3528	5.06	34.90	-133
UK76	Hywind Scotland Pilot Park	United Kingdom	57.4843	-1.3626	8.21	40.83	-104
UK7C	INTOG (WoSc)	United Kingdom	60.3772	-4.2344	13.40	42.79	-499
CNL5	CNOOC Wenchang deep-sea floating wind power	China	20.9126	113.439	11.33	41.49	-77
JP2Z	NEDO Green Innovation Fund Phase 2	Japan	36.5544	136.288	8.55	38.33	-114
JP92	Kuji City - Development Zones	Japan	40.2395	142.005	8.97	32.30	-108
KR0R	Ulsan Floating - RWE	South Korea	35.4486	129.949	9.39	48.77	-188
KR88	Geomundo	South Korea	34.0393	126.901	6.68	47.95	-70
PH39	Frontera II Wind Power Project	Philippines	14.4207	120.339	6.51	29.40	-101
PH41	Real Wind Power Project	Philippines	14.4214	121.899	5.66	38.95	-83
TW0B	Hsinchu Fengfan	Taiwan	25.0025	120.776	11.32	47.35	-73
TW0Y	Laizhong Offshore Wind Power Project	Taiwan	24.5607	119.989	9.53	47.84	-61
AU21	Hunter Coast	Australia	-33.32	152.016	8.62	34.07	-146
AU29	Gippsland Declared Area	Australia	-39.078	146.724	6.03	35.74	-76
AU33	Bass Strait 3 - Mistral	Australia	-39.446	146.911	7.72	34.83	-67
AU36	Velella Offshore Wind Farm	Australia	-32.014	115.299	8.72	31.28	-126
NZ03	Waikato	New Zealand	-36.427	173.472	8.52	34.39	-1100
NZ06	Waikato - BlueFloat/Energy Estate Phase 2	New Zealand	-37.594	174.328	8.06	33.39	-93
MU02	Expressions of Interest for the development of Offshore Wind Farms for the Republic of Mauritius	Mauritius	-19.771	57.9	9.87	39.15	-494
ZA1	Genesis Hexicon	South Africa	-30.045	31.645	8.20	38.51	-848
BB01	Large Scale Ocean Energy - Feasibility study	Barbados	12.99	-59.489	4.15	28.07	-151

Wind Farm ID	Wind Farm Name	Country Name	Lat	Long	$H_s 50$ (m)	$V_{hub} 50$ (m/s)	Water Depth (m)
US0M	Oahu South - Call Area	United States	20.9937	-157.863	5.43	29.40	-567
US0W	Humboldt SW	United States	40.928	-124.708	8.70	35.51	-707
US0Z	Morro Bay E	United States	35.5276	-121.693	6.92	32.28	-968
US7U	Galveston II	United States	28.613	-94.567	8.64	45.42	-99
USZ3	Gulf of Maine Draft Call Area	United States	43.25	-69.5	10.63	35.07	-148

The extreme value analysis results were analyzed alongside the extracted GEBCO water depth information to address two main aims:

- To identify the dependency of water depth on significant wave height
- To identify clusters of data or select a "spread" of sites that represent the global dataset.

Results presented in Figure 3 and Figure 4 show that a strong correlation is not evident between extreme significant wave height values and water depth. Although significant wave height is generally influenced by water depth [18], in the analyzed FLOW sites where the minimum water depth across all sites is 60 m, the geographical location tends to be more important. The relatively more exposed oceanic sites display more extreme significant wave height values in comparison to more sheltered locations regardless of water depth. An example of the range of metocean conditions alongside different water depths is highlighted in Table 3.

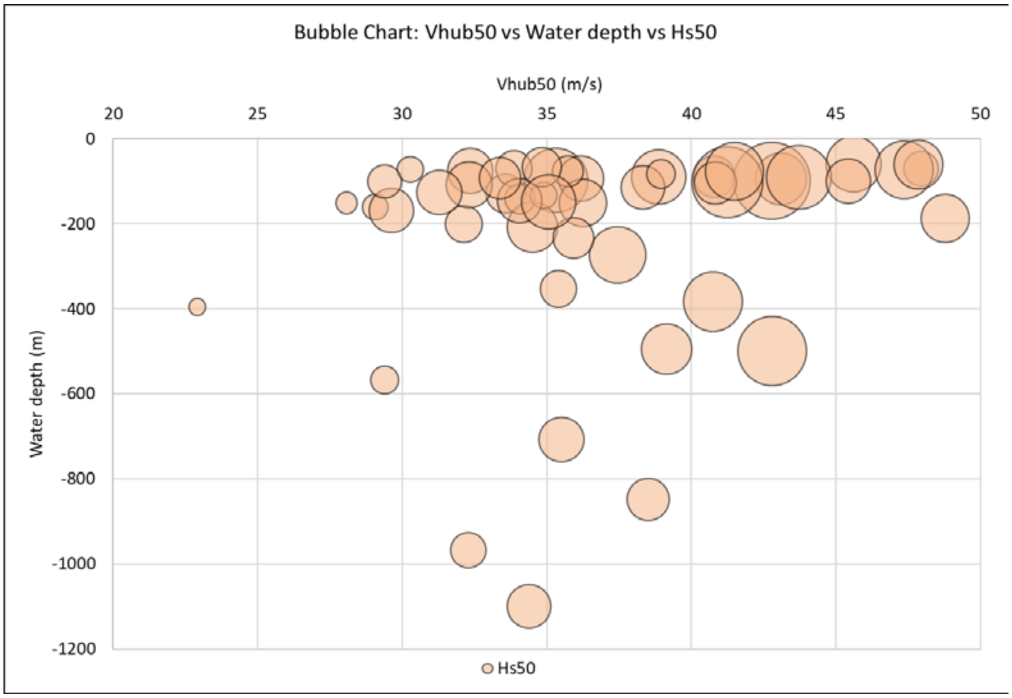


Figure 3. **Bubble chart of 50-year 10-min wind speed at hub height (V_{hub}50) vs. water depth vs. 50-year significant wave height (H_s50) (based on ERA5 data and GEBCO bathymetry)**

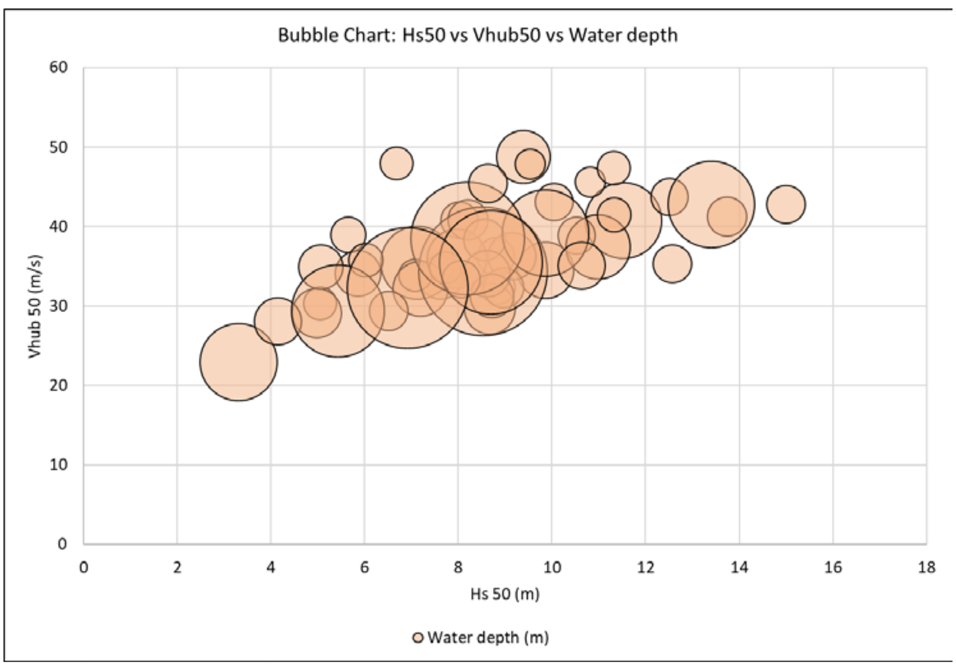


Figure 4. **Bubble chart of 50-year significant wave height (H_s50) vs. 50-year 10-min wind speed at hub height (V_{hub}50) vs. water depth (based on ERA5 data and GEBCO bathymetry)**

Table 3. Comparison of Moderate and Severe Sea State Conditions Against Water Depths at Selected Global Sites

Name	Location	$H_s 50$ (m)	$V_{hub} 50$ (m/s)	Water Depth (m)	Description
AU33 Bass Strait 3 – Mistral	Australia	7.72	34.83	-67	Moderate sea-state
IT95 Sicily- GreenIT and CIP	Mediterranean Sea (Sicily)	7.13	35.41	-353	Moderate sea-state
IE34 Moneypoint Offshore One	Atlantic Ocean (Ireland)	13.75	41.23	-102	Severe sea-state
ES0C Nordes Phase 1	Atlantic Ocean (Spain)	11.53	40.75	-383	Severe sea-state

Considering the pipeline of international FLOW projects, based on Figure 5 and Figure 6, a number of severity categories are defined in Table 4 that represent the pipeline. Eleven selected sites are based on the availability and accessibility of in situ data in the consortium but also consider their representation of different wind and wave conditions in the global pipeline of FLOW projects. The selected representative sites are outlined in Table 5.

A preliminary front-end engineering design (pre-FEED) metocean study has been carried out by consortia members for the selected sites, the results of which are presented in the following sections of the report. As site-specific datasets are used and presented later in the report, the importance of collected in situ observational datasets and the development/calibration of local numerical sea state models to produce parameters for detailed design becomes apparent. For example, the severity of these representative sites presented in Table 5 are first based on ERA5 data analysis. This analysis provides its purpose and presents a good overview and characterization of the global FLOW pipeline. However, the site characterization study for the Ulsan FLOW project that uses site-specific observational datasets demonstrates that the extreme 50-year return significant wave height is underestimated by ERA5 by 1.7 m. Ultimately, using the most accurate datasets available is required for design optimization and will significantly reduce risk for future FLOW projects.

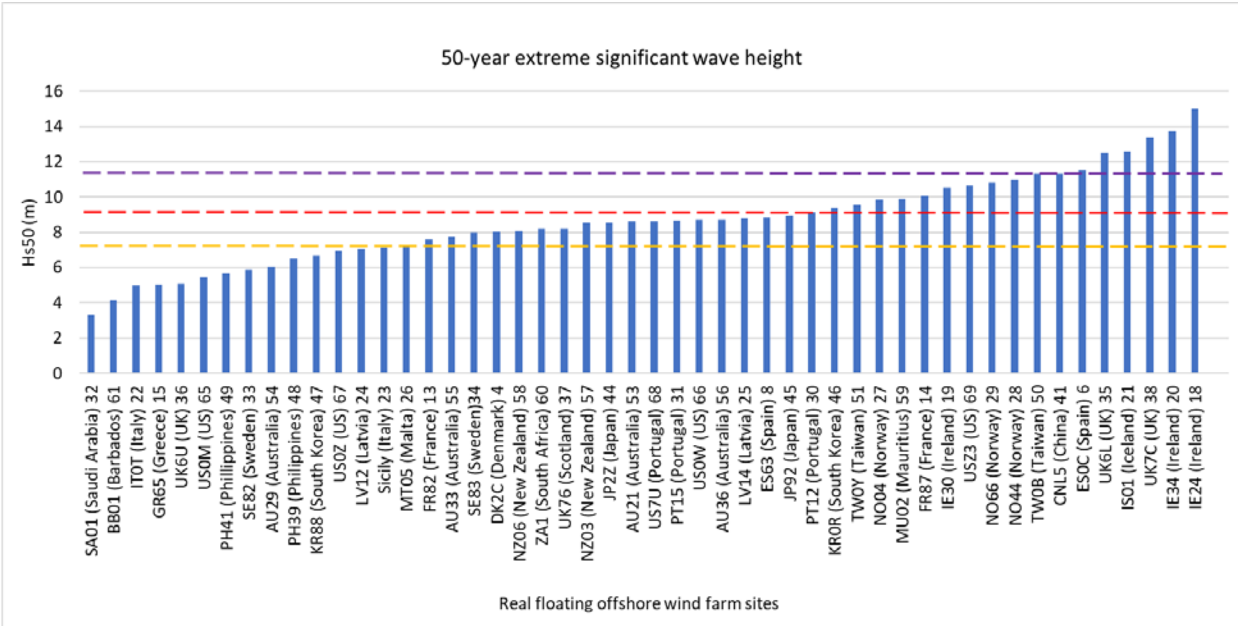


Figure 5. Bar chart of calculated 50-year return values of significant wave height for each of the 49 selected floating wind farm sites in the global pipeline.

FLOW site label refers to "[4C Offshore Map code] [(Country)] [data analysis key number]." Severity categories are indicated by dashed line: Below yellow = mild (<7.5 m); between yellow and red = lower-moderate (7.5–9 m); between red and purple = upper-moderate (9–11 m); above purple = severe (>11 m).

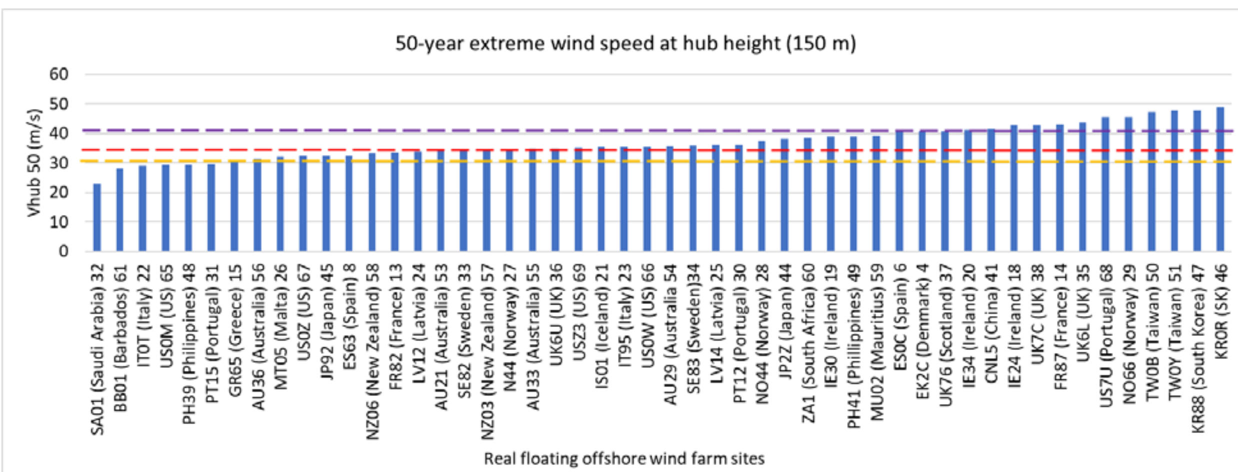


Figure 6. Bar chart of calculated 50-year return values of 10-min wind speeds at hub height (150 m above sea level) for each of the 49 selected floating wind farm sites in the global pipeline.

FLOW site label refers to "[4C Offshore Map code] [(Country)] [data analysis key number]." Severity categories are indicated by dashed line: Below yellow = mild (<33 m/s); between yellow and red = lower-moderate (33–36 m/s); between red and purple = upper-moderate (36–42 m/s); above purple = severe (>42 m/s).

Table 4. Severity Categories

Severity	Wind Threshold (m/s)	Wave Threshold (m)
Mild	<33	<7.5
Lower-Moderate	33–36	7.5–9
Upper-Moderate	36–42	9–11
Severity	>42	>11

Table 5. Selected Representative Sites Where Both Site-Specific Analysis Is Available Within the Consortium and Where They Represent Different Parts of the Global Pipeline

Synthetic Case No.	Wind Condition Severity (ERA5)	Wave Condition Severity (ERA5)	Severity Category Change Based on Site-Specific Study	Site
1	Lower-Moderate	Mild	N/A	Hannibal (Italy/Mediterranean)
2	Lower-Moderate	Lower - Moderate	N/A	Humboldt (U.S.)
3	Severe	Upper Moderate	Wave Condition Severity: Severe	Ulsan (South Korea)
4	Upper-Moderate	Severe	N/A	Moneypoint Offshore One (Ireland)
5	Severe	Severe	N/A	Havbredey (UK)
6	N/A	N/A	Wind and Wave: Severe	Fukushima (Japan)
7	Upper-Moderate	Upper-Moderate	N/A	Utsira Nord (Norway)
8	Lower-Moderate	Upper-Moderate	N/A	Gulf of Maine (U.S.)
9	Severe	Upper-Moderate	N/A	Geomundo (South Korea)
10	Severe	Upper-Moderate	N/A	Sud de la Bretagne II (France)
11	Severe	Upper-Moderate	N/A	Sørlige Nordsjø II (Norway)

4.3 Environmental Conditions Required for Floating Offshore Wind Farm Design

The main aim of Section 4 is to deliver a set of metocean conditions for each representative site that will be used to inform the design of the reference floating wind arrays in Task 49 Work Package 2. These data will be made open-source and available to the wider research community to facilitate future multidisciplinary FLOW research. Through Work Package 1 and cross-work-package discussions, the relevant standards and guidelines for floating offshore wind design and operation were compiled and are summarized in Table 6. Aligning with these documents, the minimum parameters/level of analysis required for the pre-FEED-level design basis were determined. These parameters are summarized in Table 7. Time series information for each representative site is provided as supplementary material. In the case where analysis has been carried out, results are presented in Section 4.4. For all analysis, the standards and guidance documents presented in Table 6 should be followed.

Table 6. Relevant Standards and Codes

Document Reference	Document Title
DNV-RP-C205	Environmental Conditions and Environmental Loads, September 2021
IEC 61400-3-1	Wind Energy Generation Systems - Part 3-1: Design Requirements for Fixed Offshore Wind Turbines, April 2019
DNV-ST-0437	Loads and Site Conditions for Wind Turbines. Edition 2016-11 - Amended 2021-11
DNV-ST-0119	Design of Floating Wind Turbine Structures http://rules.dnvgl.com/docs/pdf/dnv/codes/docs/2013-06/os-j103.pdf
DNV 10039663-HOU-01	Metocean Characterization Recommended Practices for U.S. Offshore Wind Energy https://www.boem.gov/sites/default/files/environmental-stewardship/Environmental-Studies/Renewable-Energy/Metocean-Recommended-Practices.pdf
CTC870	Carbon Trust Offshore Wind Accelerator Recommended Practice for Floating LiDAR Systems, October 2016 https://www.carbontrust.com/media/673560/owa-floatinglidarrecommendedpractice-25oct2016-final.pdf
API RP 2MET	API Recommended Practice 2MET – Derivation of Metocean Design and Operating Conditions (modified version of ISO 19901-1:2015); November 2014 https://www.techstreet.com/api/standards/api-rp-2met?product_id=1886618
MEASNET ESSWC	MEASNET Procedure: Evaluation of Site-Specific Wind Conditions. Version 2, April 2016
ISO 19901-1	Petroleum and Natural Gas Industries – Specific Requirements for Offshore Structures – Part 1: Metocean Design and Operating Considerations https://www.iso.org/standard/60183.html
DNV-ST-N001	Marine Operations and Marine Warranty https://rules.dnvgl.com/docs/pdf/dnvgl/st/2016-11/DNVGL-ST-N001.pdf
DNV-SE-0190	Project Certification of Wind Power Plants https://www.dnv.com/energy/standards-guidelines/dnv-se-0190-project-certification-of-wind-power-plants.html

Document Reference	Document Title
IEC 61400-12-1	Power Performance Measurements of Electricity Producing Wind Turbines https://webstore.iec.ch/publication/60076

Table 7. Environmental Conditions – Minimum Pre-FEED Design Basis Requirements

Variable	Parameter
Water Levels	MSL (mean sea level)
	HAT (highest astronomical tide)
	LAT (lowest astronomical tide)
	HSWL (highest still water level)
	LSWL (lowest still water level)
Wind – Normal Conditions	Wind rose plot (10 m and 150 m)
	Annual/monthly statistics (mean/min/max) (tabular format) (10 m and 150 m)
	Turbulence intensity
Wind – Extreme Conditions	1-year, 50-year and 100-year extreme 10-min wind speeds at hub height (150 m)
Normal Sea States	3-D scatter diagram of H_s, T_p, and V_{hub}
	Lumped scatter diagram derived from the 3-D scatter tables
	Wave rose
	Annual/monthly statistics (mean/min/max) (tabular format)
	Wind-wave persistence (weather window)
	Wind-wave misalignment information
Extreme Sea States	1-, 50- and 100-year return values of significant wave height H_s
	1-, 50- and 100-year return values of upper and lower limits of peak wave period T_p.
	1-, 50- and 100-year return values of individual maximum wave height H_{max}
	1-, 50- and 100-year return values of upper and lower limits of wave period associated with maximum wave height, T_{Hmax} or T_{assoc}
Severe Sea States	Provide a table with severe sea state values between cut-in and cut-out wind speeds
Currents – Normal Conditions	Current rose
	Annual/monthly statistics (mean/min/max) (tabular format)
Currents – Extreme Conditions	1- and 50-year return maximum total omni directional surface current speeds
Marine Growth	Thickness of marine growth over time with water depth
Other Considerations if Relevant	Tropical cyclone analysis, tsunami analysis, ice-related conditions

4.4 Floating Array Sites

With the objective of having realistic input parameters for design, 11 commercial/prototype floating sites were selected by the project partners for more detailed analyses focused on the metocean conditions. The selection criteria aimed to select sites that cover a wide range of countries, water depths, and metocean conditions. Figure 7 shows an overview of the location of all 11 selected reference sites previously outlined in Table 5.

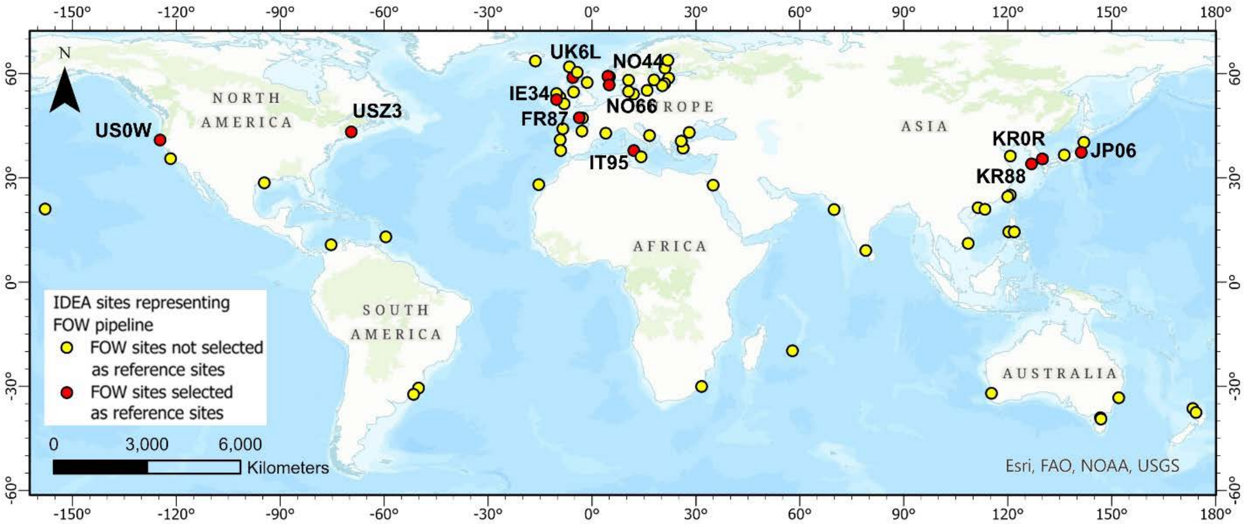


Figure 7. Overview of the 11 reference sites selected for metocean analyses

IDEA = Integrated Design of Floating Wind Arrays; FOW = floating offshore wind

Each reference site was analyzed using different input datasets and methods. The dataset of each reference site is open-source and shared within the framework of this project (see the appendices for more information on the data available for each site). Therefore, the results of this section, particularly on extreme conditions, should be treated as site-specific and solely for the purpose of preliminary design.

Table 8 presents details of each reference site with the ID and name from the 4C Offshore database [13] (accessed in February 2023), analysis points, water depth according to GEBCO (version 2019), and distance to shore. The selected reference sites cover eight countries and water depths from 70 m to more than 700 m.

Table 8. Details of the 11 Reference Sites

ID	Name	Latitude [deg] [13]	Longitude [deg] [13]	Water depth [m] (GEBCO) [15]	Distance from shore [km]
IT95	Hannibal	37.842	12.0722	-353	35
US0W	Humboldt	40.928	-124.708	-707	43.8
KR0R	Ulsan	35.449	129.949	-188	32
IE34	Moneypoint Offshore One	52.519	-10.276	-102	23.4
UK6L	Havbredey	58.862	-5.54	-91	41.6
JP06	Fukushima	37.311	141.251	-90	19.4
NO44	Utsira Nord	59.276	4.541	-273	42.4
USZ3	Gulf of Maine	43.25	-69.5	-148	138
KR88	Geomundo	34.039	126.901	-70	47
FR87	Sud de la Bretagne II	47.325	-3.659	-94	30.7
NO66	Sørlige Nordsjø II - phase 2	56.78	4.92	-60	180

The data presented in this report adhere to the following conventions, unless stated otherwise:

- Wind and waves: The direction of where the wind and waves are coming from is measured in degrees clockwise (0–360), with north as 0° and east as 90°.
- Ocean currents: The direction toward which ocean currents are flowing is measured in degrees clockwise, (0–360), with north as 360° and east as 90°. Zero means that no current could be measured.

4.4.1 Hannibal

A detailed analysis was performed for the Hannibal site. A summary of normal sea state conditions and two extreme analyses for wind and waves are presented in Table 9 to Table 11 and Figure 8, with full analysis presented in Appendix A.

Both wind speed datasets at 10-m and 150-m hub height are extrapolated from AEOLIAN (https://atlanteeolico.rse-web.it/), the new Italian wind atlas developed by RSE by means of a novel approach combining numerical weather modeling based on the Weather Research and Forecasting (WRF) Model with the Analog Ensemble (AnEn) statistical technique. Datasets cover a period of 30 years, from 1990 to 2019 [19]. An extreme value analysis has been conducted on datasets at 10-m hub height, using the "generalized extreme value" methodology with “block maxima” approach (1-year temporal window). Values for 150 m have been calculated with the Frøya equation.

Table 9. Return Values for Wind Speed

Return Period [year]	Wind Speed at 10 m [m/s]	Wind Speed at 150 m [m/s]
5	24.58	33.12
10	26.06	35.11
20	27.70	37.31
50	30.19	40.66
100	32.37	43.61
500	38.74	52.18

For wave characteristics the DICCA MetOcean Re-Analysis [20] has been used [21]. The wave dataset covers a period of 41 years, from 1979 to 2020.

Due to the availability of a long period of data, the block maxima approach and generalized extreme value have been conducted as analysis on extreme events.

Table 10. Return Values for Wave

Return Period [year]	Wave Height [m]	Minimum Peak Period [s]	Maximum Peak Period [s]
5	6.67	9.16	11.80
10	7.17	9.49	12.22
20	7.65	9.80	12.63
50	8.30	10.21	13.16
100	8.81	10.52	13.55
500	10.04	11.23	14.47

The relationship between waves and wind is shown in Table 11 and Figure 8.

Table 11. Lumped Scatter Diagram

Wind Speed [m/s]	Mean Wave Peak Period [s]	Mean Wave Height [m]	Occurrence [%]
2	5.31	0.58	13.54
4	5.36	0.68	25.87
6	5.67	0.94	23.81
8	6.21	1.35	15.97
10	6.70	1.78	10.23
12	7.30	2.30	5.82
14	7.91	2.86	2.73
16	8.55	3.49	1.02
18	9.13	4.12	0.33
20	9.18	4.51	0.09
22	9.57	5.18	0.02
24	9.30	4.89	0.01

Wind Speed [m/s]	Mean Wave Peak Period [s]	Mean Wave Height [m]	Occurrence [%]
26	9.20	4.27	0.00
28	7.80	2.47	0.00

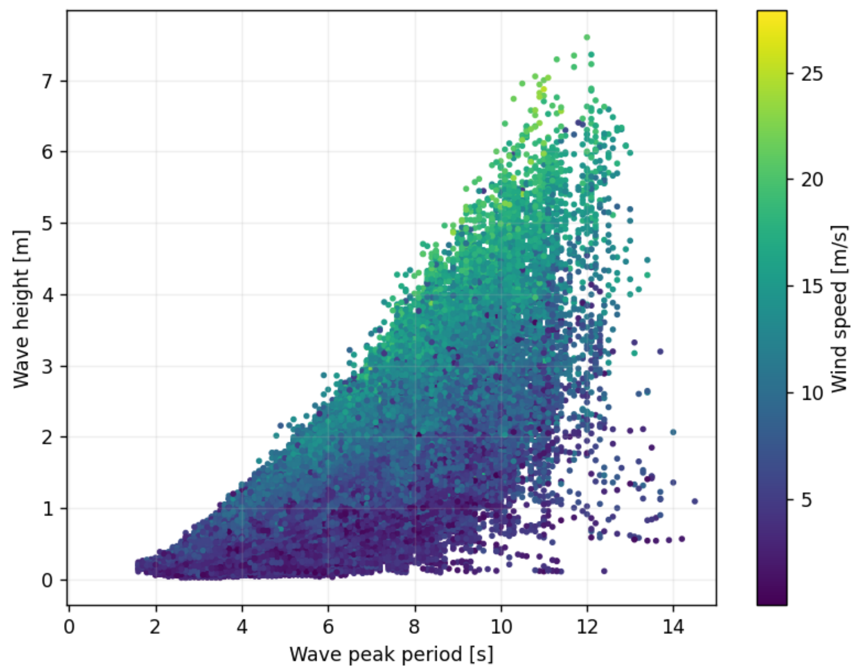


Figure 8. Scatter diagram with significant wave height (H_s), wave peak period (T_p) and wind speed at 10-m hub height

4.4.2 Humboldt

The Humboldt reference site is based on conditions representative of the Humboldt Bay lease areas awarded by the Bureau of Ocean Energy Management (BOEM) in 2023. The water depths of the leased areas range from 550 m to 1,300 m. The target location (40.928, -124.708) is the centroid of the western lease area because it is located further offshore (25 nautical miles [nm] to shore) and in deeper waters (800 m) than the adjacent lease area. This can lead to slightly higher loads and is therefore considered representative for both lease areas.

Data for the reference site conditions come from the 2023 National Offshore Wind dataset (NOW-23), measurement data from metocean buoys operated by the National Data Buoy Center (NDBC) and the National Oceanic and Atmospheric Administration, and high-frequency radar current measurements (HFRNet) from SCRIPPS Institution of Oceanography. The wind data (from the NOW-23 dataset) were interpolated directly at the lease area centroid. All other data sources were chosen based on their proximity to this location and the data coverage of respective stations. Figure 9 shows the Humboldt lease areas and locations of data sources used when developing the site conditions, and the details are listed in Table 12. More details are given in Appendix B. The content of this section is based on NREL's reference site conditions datasets for floating wind arrays in the United States [22].

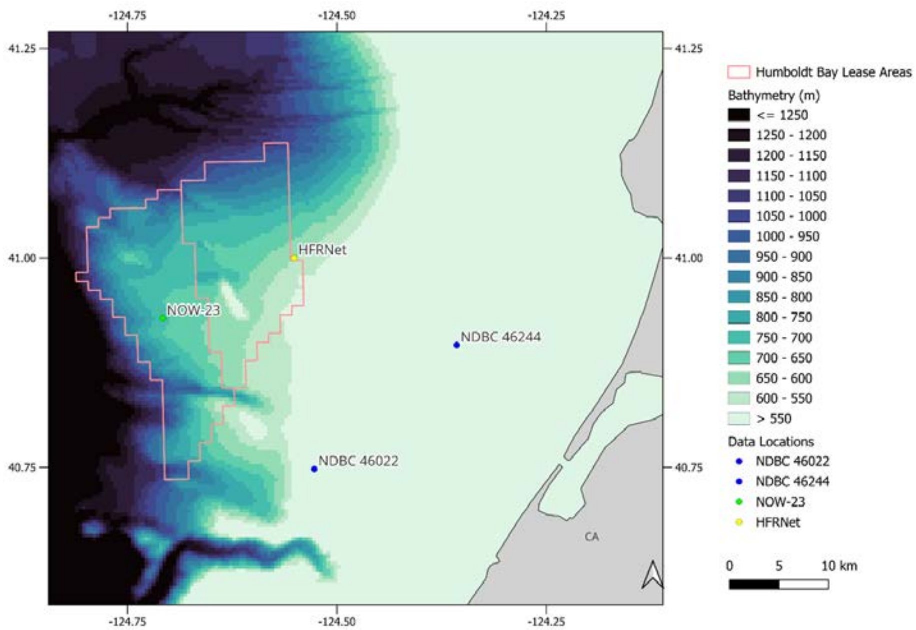


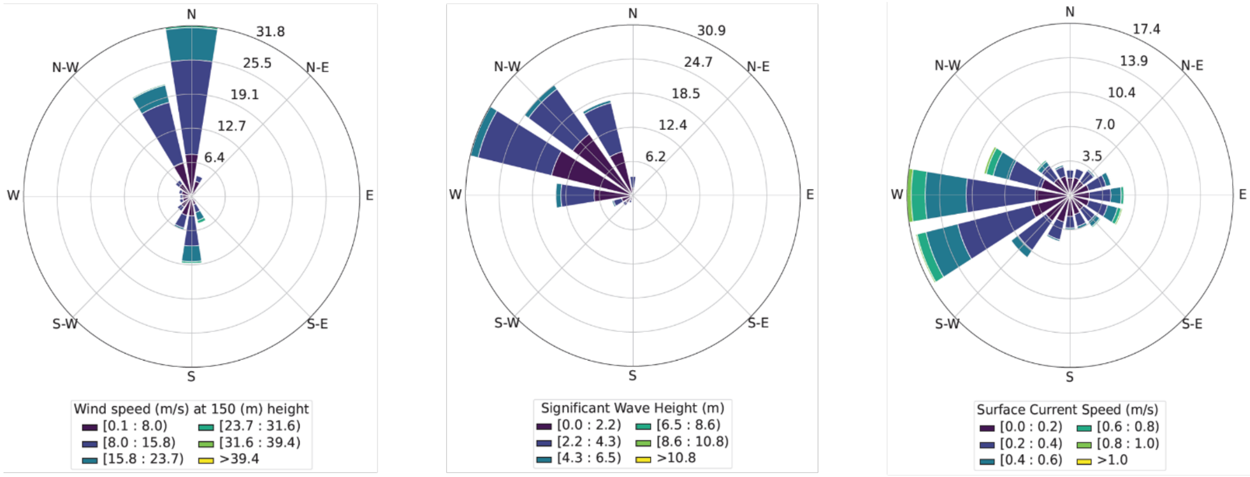
Figure 9. Humboldt Bay metocean data sources near Humbolt lease areas

Table 12. Humboldt Bay Locations of Data Sources and Covered Years per Data Type

Data Type	Data Sources	Latitude (deg)	Longitude (deg)	Water Depth (m)	Distance to Shore (nm)	Start Year	End Year
Wave/ metocean (primary)	NDBC station 46022	40.748	-124.527	419	17	1982	2022
Wave/ metocean (secondary)	NDBC station 46244	40.896	-124.357	110	8	2010	2022
Wind	NOW-23	40.928	-124.708	800	25	2000	2022
Current	HFRNet	41	-124.551	600	20	2012	2023

The metocean analysis uses data from 2000 to 2020 to have a consistent time span

The speed and directional distributions of wind, waves, and current data are shown in a wind rose format in Figure 10. For waves, significant wave height is plotted in place of wind or current speed.



(a) (b) (c)

Figure 10. Humboldt Bay (a) wind, (b) wave, and (c) current roses

Extreme wind, wave, and current parameters for return periods ranging from 1 year to 500 years are shown in Table 13. The mean directions of the peaks used for the extrapolation are 339° for wind, 302° for waves, and 264° for currents.

Table 13. Extreme Metocean Parameters for Humboldt Bay

Return Period (years)	Wind Speed (m/s)	Significant Wave Height (m)	Peak Wave Period (s)	Current Speed (m/s)
1	31.0	8.5	16.8	0.92
5	34.9	9.8	18.1	1.09
10	36.4	10.4	18.6	1.15
50	39.4	11.8	19.8	1.28
100	40.6	12.4	20.3	1.33
500	43.0	13.7	21.4	1.44

Conditional values of wave height, wave period, and current speed, for wind speed bins of every 2 m/s, are given in Appendix B. To represent the joint distribution of metocean conditions for fatigue analysis, a maximum dissimilarity algorithm was used to generate 100 clusters of the hourly metocean data points, representing 100 fatigue bins that can be used for fatigue loads analysis. The parameters of these bins are also provided in Appendix B.

4.4.3 Ulsan

Currently in South Korea, floating offshore wind farms with a total capacity of 9.5~11 gigawatts (GW) are planned in Ulsan. The five-member international consortium listed in Table 14 is leading the development plan.

Table 14. Overview of Development Plan for Floating Offshore Wind Farms in Ulsan, South Korea

Floating Offshore Wind Farm Business Plan (5 International Consortia)	Date	Total 9.5 GW (Total 11.5 GW)	Source
Equinor	Dec 7, 2022	4 GW (6 GW)	https://www.equinor.co.kr/en
CIP	June 22, 2022	1.5 GW	https://cop.dk/spink/
KFWind	June 2, 2022	1.2 GW	https://www.offshorewind.biz/2022/06/02/korea-floating-wind-partners-with-east-west-power
GIG	Aug 11, 2021	1.5 GW	https://www.greeninvestmentgroup.com/en/news/2021/gig-and-totalenergies-obain-ebl-for-koreas-first-floating-offshore-wind-farm.html
Shell	Mar 15, 2022	1.3 GW	https://www.offshorewind.biz/2022/03/15/shell-making-further-floating-offshore-wind-moves-in-south-korea/

A metocean analysis was performed for Ulsan, including observations and models. Appendix C presents the report with all normal and extreme analyses alongside wind-wave correlation analysis. An overview of data used in the analysis and summary tables of the results are presented in this section.

Table 15 summarizes the data obtained on the site, which is 30 km away from the city of Ulsan. One set of measurement data from Korea Meteorological Administration and two sets of reanalysis data from ECMWF and NASA are used.

Table 15. Data Obtained for Ulsan

Information	Ulsan Buoy	ERA-5	MERRA-2
Type	Measurement	Reanalysis	Reanalysis
Obtain height	5 m	100 m	50 m
Data interval	1 hour	1 hour	1 hour
Dataset	Wind speed, Wind directions	Wind speed, Wind directions	Wind speed, Wind directions
Data period	7 years (2016~2022)	13 years (2010~2022)	43 years (1980~2022)

The extreme wind statistics analysis is based on a hub height of 100 m, and the Gumbel method is applied (Table 16).

Table 16. Metocean Data for Ulsan; Analysis of Extreme Wind Statistics

Gumbel Parameter	Ulsan Buoy	ERA-5	MERRA-2
Scale parameter (β)	1.802	3.540	3.511
Mode parameter (μ)	19.798	25.259	22.528
Return Period	**Extreme Wind Speed**		
5 years	33.41 m/s	32.11 m/s	31.51 m/s
10 years	35.41 m/s	34.90 m/s	34.49 m/s
30 years	38.45 m/s	39.11 m/s	39.00 m/s
50 years	39.83 m/s	41.04 m/s	41.06 m/s
100 years	41.70 m/s	43.63 m/s	43.84 m/s
500 years	46.02 m/s	49.63 m/s	50.26 m/s

Wind-wave combined analysis was also performed. To ensure the most accurate correlation with the real sea state conditions, six different equations have been identified through regression analysis; these are presented in Appendix C. The metocean data of Ulsan is summarized in Table 17.

Table 17. Metocean Data for Different Wind Speeds (Ws) for Ulsan

	Items	Unit	Ws 1m/s	Ws 2m/s	Ws 3m/s	Ws 4m/s	Ws 5m/s	Ws 6m/s	Ws 7m/s	Ws 8m/s
Wave	Direction from true North	deg	180, 190	170, 180, 190	170, 190	180	190	180	40	0
	Significant wave height (H_s)	m	0.82	0.78	0.80	0.76	0.80	0.82	0.89	1.23
	Spectral peak period (T_p)	deg	6.23	6.20	6.22	6.19	6.22	6.23	6.20	6.55
	Maximum wave height	m	5.5	6.9	7.7	7	7.1	6	7.4	8.1
Tide	Highest design water level	m	0.33							
	Lowest design water level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10 min at hub	m/s	1	2	3	4	5	6	7	8
	Direction from true North	deg	130, 210	80	90	70	80	60	60	210
	Exponent for wind profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	Unit	Ws 9m/s	Ws 10m/s	Ws 11m/s	Ws 12m/s	Ws 13m/s	Ws 14m/s	Ws 15m/s	Ws 16m/s
Wave	Direction from true North	deg	0	0	0	0	0	10	0	0
	Significant wave height (H_s)	m	1.68	2.13	2.58	3.03	3.48	3.93	4.38	4.83
	Spectral peak period (T_p)	deg	6.90	7.24	7.59	7.94	8.28	8.63	8.98	9.32
	Maximum wave height	m	5.9	6.9	7	6.9	8.9	7.2	8.3	7.8

Tide	Highest design water level	m	0.33							
	Lowest design water level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10 min at hub	m/s	9	10	11	12	13	14	15	16
	Direction from true North	deg	220	230	220	230	230	230	230	230
	Exponent for wind profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	**Unit**	**Ws 17m/s**	**Ws 18m/s**	**Ws 19m/s**	**Ws 20m/s**	**Ws 21m/s**	**Ws 22m/s**	**Ws 23m/s**	**Ws 24m/s**
Wave	Direction from true North	deg	0	0	0	0	350	0	0	350
	Significant wave (H_s)	m	5.28	5.73	6.18	6.63	7.08	7.53	7.98	8.43
	Spectral peak period (T_p)	deg	9.67	10.02	10.36	10.71	11.06	11.40	11.75	12.10
	Maximum wave height	m	8.3	8.8	8	8.3	8.5	10.5	10.1	11.8
Tide	Highest design water level	m	0.33							
	Lowest design water level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10 min at hub	m/s	17	18	19	20	21	22	23	24

	Direction from true North	deg	320	230	320	50	30, 250	330	30	40
	Exponent for wind profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	**Unit**	**Ws 25m/s**	**Ws 26m/s**	**50-yr**	**100-yr**	**500-yr**
Wave	Direction from true North	deg	10	0	0	0	-
	Significant wave height (H_s)	m	8.88	9.33	11.117	11.959	13.905
	Spectral peak period (T_p)	deg	12.44	12.79	14.171	14.820	16.320
	Maximum wave height	m	9.5	10.4	17.859	19.189	22.263
Tide	Highest design water level	m	0.33		0.7	0.7	-
	Lowest design water level	m	0		- 0.7	- 0.7	-
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)				
		Medium	0.13 (m/s) / 26 (deg)				
		Bottom	0.07 (m/s) / 26 (deg)				
	Extreme current	Surface	1.63 (m/s) / 12 (deg)				
		Medium	0.61 (m/s) / 12 (deg)				
		Bottom	0.34 (m/s) / 12 (deg)				
	10 min at hub	m/s	25	26	39.83	41.70	46.02
	1 hour at hub	m/s	-	-	37.84	39.62	43.72
	Direction from true North	deg	40	40	60, 230, 320	60, 230, 320	60, 230, 320
	Exponent for wind profile	-	0.14	0.14	0.11	0.11	0.11

4.4.4 Moneypoint Offshore One

Gavin and Doherty Geosolutions (GDG) were responsible for the delivery of a pre-FEED metocean study close to the proposed floating offshore wind farm development, Moneypoint Offshore One. This study stands as a deliverable for the Integrated Design of Floating Wind Arrays Ireland (IDEA-IRL) project funded by the Sustainable Energy Authority of Ireland. This deliverable is aligned with the scope of this report.

Moneypoint Offshore Wind Farm is a proposed floating offshore wind farm development located in Ireland, owned by ESB. ESB is Ireland's foremost energy company and the largest supplier of renewable energy in Ireland. If this project is developed, it will be delivered in two phases. The first phase, Moneypoint Offshore One, is located 16 kilometers (km) off the Clare/Kerry Coast. The expected capacity from the first phase is estimated to be 400 megawatts (MW) and will likely cover 70 km^2. The second phase is proposed to be located 20 km west of the first phase, taking the total project capacity to between 1 GW and 1.5 GW. The second phase will likely cover 180 km^2.

The ECMWF ERA5 climate reanalysis model was identified as the best model to provide numerical datasets for wind and wave variables in this location. ERA5 is the fifth-generation atmospheric reanalysis model produced by Copernicus Climate Change Service at the ECMWF and is based on the 2016 version of the integrated forecasting system. It produces data from 1950 to the present. Its outputs include atmospheric, ocean wave, and land surface data. The reanalysis combines model data with observations from across the world into a globally complete and consistent dataset. The horizontal resolution of the model is 0.25° x 0.25° (atmosphere variables) and 0.5° x 0.5° (ocean wave variables). Parameters of interest for this study are displayed in Table 18. Data from the closest grid point to the site were downloaded and analyzed. A detailed description of the model and each parameter can be found on the ECMWF website [14].

Table 18. Wind and Wave Variables Obtained From the ERA5 Model for Moneypoint Offshore One

ERA5 Code	Parameter	Metocean Discipline	Units	Time Frame	Temporal Resolution (hours)	Data Point
hmax	Maximum individual wave height	Wave	m	1979–2022	1	-10.5°, 52.5°
pp1d	Peak wave period	Wave	s	1979–2022	1	-10.5°, 52.5°
swh	Significant wave height of combined wind waves and swell	Wave	m	1979–2022	1	-10.5°, 52.5°
mwd	Mean wave direction	Wave	degrees	1979–2022	1	-10.5°, 52.5°
u10	10-m u-component of wind	Wind	m/s	1979–2022	1	-10.25°, 52.5°
v10	10-m v-component of wind	Wind	m/s	1979–2022	1	-10.25°, 52.5°
u100	10-m u-component of wind	Wind	m/s	1979–2022	1	-10.25°, 52.5°

ERA5 Code	Parameter	Metocean Discipline	Units	Time Frame	Temporal Resolution (hours)	Data Point
v100	10-m v-component of wind	Wind	m/s	1979–2022	1	-10.25°, 52.5°

Due to the lack of availability of measured water level and tidal current data for the site of interest, modeled data from the Irish Marine Institute Northeast Atlantic (NEATL) model was acquired and analyzed. This model is an implementation of the Regional Ocean Modeling System for a domain covering the Irish coastal and oceanic waters held by the Irish Marine Institute [23]. It is a hindcast and forecast 3D physics model with a curvilinear grid. The grid size is 1,200 x 750 x 40 km with a variable data resolution from 1.2 to 2 km. It should be noted that the Northeast Atlantic model is not specifically validated using in situ datasets for this site; therefore, currents should be interpreted with caution until in situ measured data are collected. Data from the model grid point closest to the center of the site were downloaded and used (−10.2625°, 52.5125°) (Table 19).

Table 19. Parameters Used From the Northeast Atlantic Model for Moneypoint Offshore One

Parameter	Units	Time Frame	Temporal Resolution (hours)
Surface elevation	m	2012–2017	3
		2017–2022	1
Bottom-water u component	m/s	2012–2017	3
		2017–2022	1
Bottom-water v component	m/s	2012–2017	3
		2017–2022	1
Mid-water u component	m/s	2012–2017	3
		2017–2022	1
Mid-water v component	m/s	2012–2017	3
		2017–2022	1
Surface-water u component	m/s	2012–2017	3
		2017–2022	1
Surface-water v component	m/s	2012–2017	3
		2017–2022	1

Using these datasets, normal, extreme, and severe metocean conditions were assessed. Operability statistics such as wind-wave persistence were also generated. A summary of parameters most relevant to design are presented in Table 20 to Table 22. The full report is available in Appendix D. The results presented can only be considered as a pre-FEED study and are meant to serve as input for preliminary design.

Table 20. Summary of Metocean Conditions Relevant for Pre-FEED Design Close to Moneypoint Offshore One

Variable	Value
High still water level (50-year) (mMSL – meters above mean sea level)	4.06
High still water level (1-year) (mMSL)	2.76
Highest astronomical tide (HAT) (mMSL)	2.14
Lowest astronomical tide (LAT) (mMSL)	-2.25
Low still water level (1-year) (mMSL)	-2.73
Low still water level (50-year) (mMSL)	-2.94
Bottom current speed (m/s) (normal conditions)	Mean: 0.09 Max: 0.32 P25: 0.06 P50: 0.08 P75: 0.11
Bottom current speed (m/s) (1-year)	0.23
Bottom current speed (m/s) (50-year)	0.36
Mid current speed (m/s) (normal conditions)	Mean: 0.14 Max: 0.54 P25: 0.07 P50: 0.13 P75: 0.19
Mid current speed (m/s) (1-year)	0.44
Mid current speed (m/s) (50-year)	0.58
Surface current speed (m/s) (normal conditions)	Mean: 0.20 Max: 1.08 P25: 0.11 P50: 0.18 P75: 0.27
Surface current speed (m/s) (1-year)	0.67
Surface current speed (m/s) (50-year)	1.10
Wind speed (150 m above sea level) (m/s) mean	10.1
Wind speed (150 m above sea level) (m/s) max	41.3
Wind speed (150 m above sea level) (m/s) P95	18.9
Wind direction (150 m above sea level) (°) mean	245.4
Wind speed (10 m above sea level) – Weibull parameters	A = 8.7; k = 2.28
Wind speed (150 m above sea level) – Weibull parameters	A = 11.4; k = 2.19
Extreme 10-min wind speed (150 m above sea level) (m/s) (1-year)	27.4

Variable	Value
Extreme 10-min wind speed (150 m above sea level) (m/s) (50-year)	44.2
Extreme 10-min wind speed (150 m above sea level) (m/s) (100-year)	46.7
Normal sea state	See relevant report section
Extreme sea state (ESS) – significant wave height (1-year) (m)	6.0
ESS – peak wave period (1-year) (s)	9.7 ≤ 12.4
ESS – individual maximum wave height (1-year) (m)	11.2
ESS – period of maximum wave height (1-year) (s)	8.7 ≤ 11.2
ESS – significant wave height (50-year) (m)	14.0
ESS – peak wave period (50-year) (s)	14.7 ≤ 19.0
ESS – individual maximum wave height (50-year) (m)	26.0
ESS – period of maximum wave height (50-year) (s)	13.3 ≤ 17.1
Severe sea state	See relevant report section

Table 21. Normal Sea State: Lumped Scatter Diagram of Moneypoint Offshore One

V_{hub} (m/s)	H_s (m)	T_p (s)	Wave Direction (°)	Wind Direction (°)	Frequency of Occurrence (%)
2	1.01	9.00	281.25	303.75	0.25
4	1.03	8.47	281.25	303.75	0.46
6	1.50	9.99	281.25	292.50	0.64
8	1.50	9.02	281.25	225.00	0.67
10	2.00	9.99	270.00	247.50	0.58
12	2.50	10.00	270.00	236.25	0.33
14	2.01	6.46	270.00	236.25	0.26
16	3.00	8.49	270.00	213.75	0.19
18	4.02	11.99	270.00	213.75	0.11
20	4.98	11.02	258.75	236.25	0.08
22	5.00	11.02	270.00	202.50	0.04
24	6.50	12.04	270.00	270.00	0.02
26	8.03	13.53	258.75	270.00	0.01
28	9.45	14.52	258.75	247.50	0.01
30	8.04	12.14	270.00	247.50	0.00
32	9.76	13.69	270.00	258.75	0.01

V_{hub} (m/s)	H_s (m)	T_p (s)	Wave Direction (°)	Wind Direction (°)	Frequency of Occurrence (%)
34	11.03	14.38	247.50	258.75	0.00
36	10.18	13.46	270.00	281.25	0.00
42	6.41	11.82	247.50	270.00	0.00

Table 22. Severe Sea State Within Cut-in and Cut-Out Wind Speeds, Computed From the Inverse First-Order Reliability Method, for Moneypoint Offshore One

ID	V_{hub} (150 m)	H_s	T_p	T_p min	T_p max
0	1	6.99	14.23	11.54	17.36
1	2	7.88	14.73	12.22	17.61
2	3	8.41	15.02	12.62	17.76
3	4	8.82	15.25	12.92	17.87
4	5	9.18	15.43	13.17	17.97
5	6	9.51	15.60	13.40	18.06
6	7	9.79	15.74	13.60	18.13
7	8	10.04	15.87	13.77	18.20
8	9	10.25	15.97	13.90	18.25
9	10	10.41	16.05	14.01	18.29
10	11	10.53	16.11	14.09	18.33
11	12	10.63	16.15	14.16	18.35
12	13	10.70	16.19	14.21	18.37
13	14	10.77	16.22	14.25	18.39
14	15	10.86	16.26	14.31	18.41
15	16	10.97	16.32	14.38	18.44
16	17	11.12	16.39	14.47	18.48
17	18	11.31	16.48	14.60	18.53
18	19	11.55	16.59	14.75	18.59
19	20	11.84	16.72	14.93	18.67
20	21	12.18	16.87	15.14	18.76
21	22	12.56	17.05	15.37	18.86
22	23	12.98	17.23	15.62	18.97
23	24	13.43	17.43	15.88	19.09
24	25	13.92	17.63	16.16	19.21
25	26	14.41	17.84	16.43	19.34

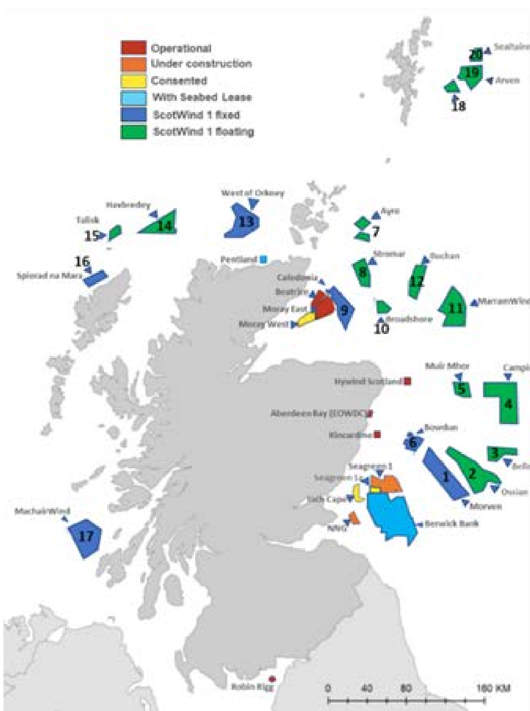
ID	V_{hub} (150 m)	H_s	T_p	T_p min	T_p max
26	27	14.92	18.05	16.71	19.48
27	28	15.43	18.26	16.98	19.61
28	29	15.92	18.46	17.24	19.74
29	30	16.39	18.64	17.48	19.87

4.4.5 Havbredey

DHI A/S delivered a preliminary metocean study close to the Havbredey floating offshore wind farm project. This is a deliverable of the IDEA project funded by the Energy Technology and Demonstration Program of the Danish Energy Agency and is aligned with the scope of work defined in this report.

The preliminary metocean study used existing datasets to establish normal and extreme metocean conditions. Analyses of the normal (operational) conditions and extreme conditions were performed at one location close to the lease area representing the Havbredey floating offshore wind farm, originally called the N2 area in the ScotWind leasing round.

Figure 11 shows the location of all sites awarded within the ScotWind lease round [24]. Site 14, awarded to Northland Power, represents the currently named Havbredey floating offshore wind farm project, with a planned installed capacity of 1.5 GW.



ScotWind Round

SITE	DEVELOPERS	CAPACITY
1	BP and EnBW	2,907MW
2	SSE Renewables, CIP and Marubeni	3,610MW
3	Falck Renewables and BlueFloat Energy	1,200MW
4	ScottishPower Renewables and Shell	2,000MW
5	Vattenfall and Fred Olsen Renewables	798MW
6	Thistle Wind Partners	1,008MW
7	Thistle Wind Partners	1,008MW
8	Falck Renewables, Orsted and BlueFloat Energy	1,000MW
9	Ocean Winds	2,000MW
10	Falck Renewables and BlueFloat Energy	900MW
11	ScottishPower Renewables and Shell	3,000MW
12	Floating Energy Allyance	960MW
13	RIDG, Corio Generation and TotalEnergies	2,000MW
14	Northland Power	1,500MW
15	Magnora Offshore Wind	495MW
16	Northland Power	840MW
17	ScottishPower Renewables	2,000MW
18	Ocean Winds	500MW
19	Mainstream RP and Ocean Winds	1,800MW
20	ESB Asset Management	500MW

Total = 30,026MW
Floating Wind = 19,271MW (64%)

Figure 11. ScotWind lease areas with awarded developers and planned installed capacity

DHI provided 20 years (Jan. 1, 2001–Dec. 31, 2021) of time series hindcast data and analyses of normal and extreme conditions of wind, water levels, currents, and waves for one location close to the Havbredey project site. Figure 12 shows the analysis location (N2, 58.84328°, -5.58093°) used for this study with the water depth used from DHI's three-dimensional hydrodynamic model.

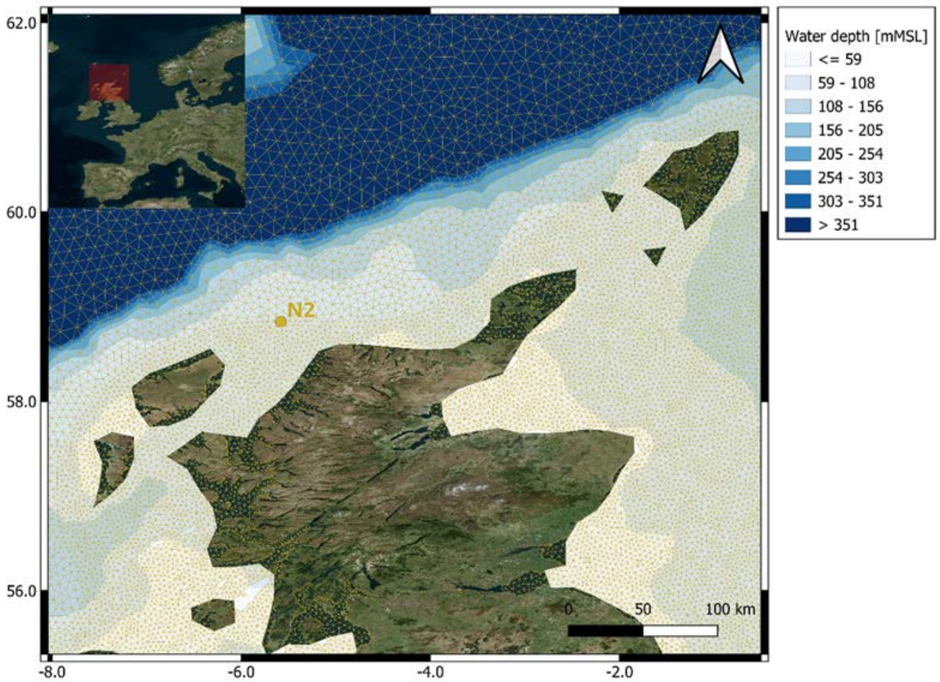


Figure 12. Analysis location (N2) used to represent the Havbredey project with the mesh and bathymetry of DHI's hydrodynamic UK and North Sea model.

The long-term normal and extreme metocean conditions had been established based on high-resolution numerical modeling for a period of 20 years from 2001 to 2021 (inclusive). Climate Forecast System Reanalysis (CFSR) winds were used to establish normal conditions. Waves were extracted from DHI's global spectral wave model forced with CFSR (SW_{CFSR}).

Since this pre-FEED study relates to a floating offshore wind farm, the water levels and currents are extracted from DHI's three-dimensional hydrodynamic model available for the UK and North Sea (UKNS) region (HD_{UKNS}). Hence, the data delivery can also include time-resolved current profiles.

The present study is suitable for a preliminary (pre-FEED) assessment of the metocean conditions at the site. Additional analyses might be required for a FEED study. Moreover, for detailed design, local metocean measurements and a bathymetry survey would be required for establishing higher-resolution models and more representative and validated conditions.

The preliminary extreme omnidirectional values resulting from DHI's analyses at the Havbredey project site are summarized in Table 23. Hourly winds from CFSR represent 2-hour measurements, and hourly waves from SW_{CFSR} represent 3-hour averaged measurements.

Appendix E consists of a report with the delivered analyses of normal and extreme conditions for the Havbredey floating offshore wind farm.

Table 23. Summary of Extreme Conditions at Havbredey Site

Extreme Values (Omnidirectional)	**Return Period (year)**		
Variable	**1**	**50**	**100**
Wind speed (WS) at 10 mMSL, 2-hour, WS_{10} (m/s)	27.0	36.4	38.0
Wind speed at 150 mMSL, 2-hour, WS_{150} (m/s)	39.4	53.1	55.6
High water level (HWL) (mMSL)	2.3	2.7	2.8
Low water level (LWL) (mMSL)	-2.2	-2.5	-2.5
Current speed (CS), total, depth-averaged (m/s)	0.8	1.1	1.1
Significant wave height (H_{m0}) total, 3-hour (m)	10.8	15.2	15.9
Wave period (T_p) (s), associated with H_{m0} (m)	16.0	19.3	19.6
Maximum significant wave height (H_{max}) (m)	19.5	27.9	29.3
Maximum wave period (TH_{max}) (s), associated with H_{max} (m)	11.4	21.1	22.8
Maximum crest height (C_{max}) (m)	12.6	18.2	19.2

4.4.6 Fukushima

The Fukushima Floating Offshore Wind Farm Demonstration project (Fukushima FORWARD) was the world's first floating offshore wind project. It started in 2011 in Japan, and the first wind turbine (2-MW semisubmersible) was operational in November 2013. The wind farm consisted of 2-MW, 5-MW and 7-MW floating wind turbines and one floating substation.

The site was located 20 km off the coast of Fukushima prefecture in Japan where the water depth is around 120 m (Figure 13). For more details, see the Fukushima Offshore Wind Consortium webpage (http://www.fukushima-forward.jp/english).

The Fukushima floating offshore wind farm was removed in 2021.

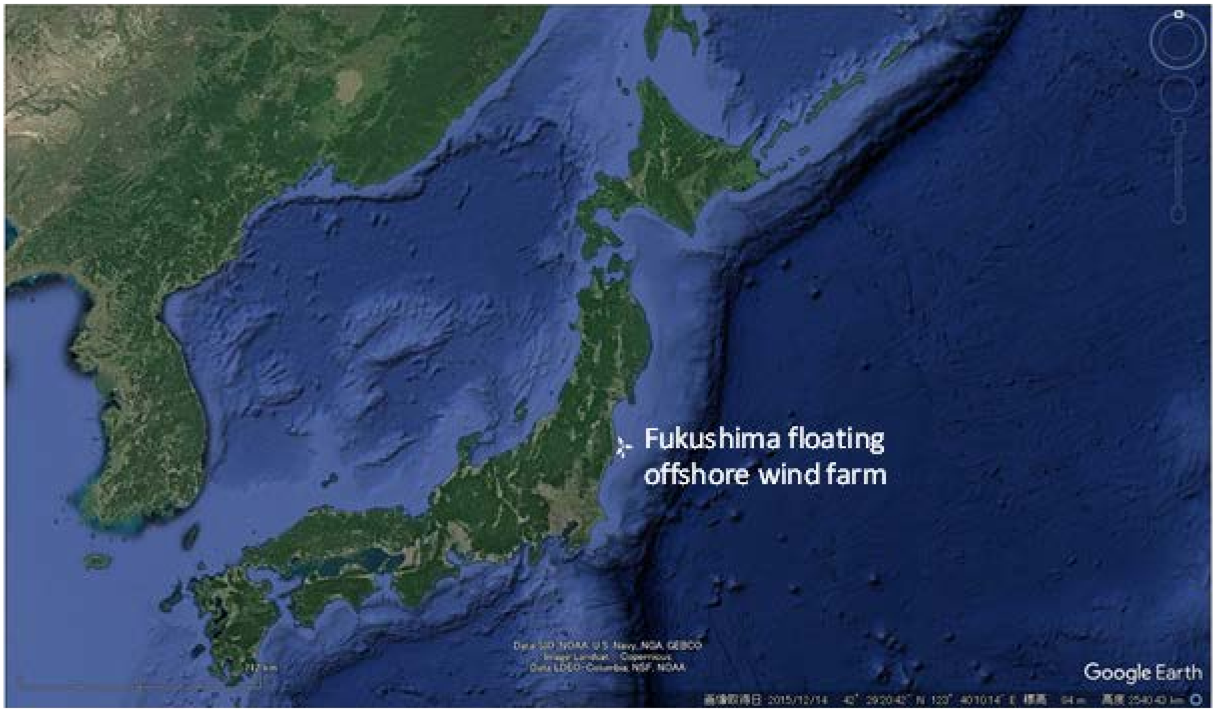


Figure 13. Location of Fukushima floating offshore wind farm

Metocean conditions used for the designs of the turbine and platform are summarized in Table 24 and Table 25. The calculation methods and more detailed information can be found in Ishihara et al. [25] and in Appendix F. Note that these wind conditions were calculated at 60 m above sea level. While publicly available information used for the actual design is limited, measurement campaigns of wind, wave, and sea current were conducted during the project (see Yamaguchi et al. [26]). Some of those numeric text data are also available in the consortium webpage (http://www.fukushima-forward.jp/english).

Table 24. Metocean Conditions Used for Wind Turbine and Platform Design in Fukushima

C.D.L: Chart Datum Level. H.H.W.L: Highest High Water Level (may be used as 50-year return period). H.W.L: High Water Level (may be used as 1-year return period). M.S.L: Mean Sea Level. NA: not available in public document.

General Information			
Number of turbines	3 (plus one floating substation)		
Rated power	2 MW (Fukushima Mirai)	5 MW (Fukushima Hamakaze)	7 MW (Fukushima Shimpu)
Hub height (above sea level)	65 m	86 m	105 m
Platform type	Compact semisubmersible	Advanced spar	V-shape semisubmersible
Mooring type/No. moorings	Chain catenary/6	Chain catenary/6	Chain catenary/8
Distance to shore	Approx. 20 km		
Water depth	Approx. 120 m		

Wind Condition (at 60 m above sea level)		
Extreme condition	50-year return period	48.3 m/s
	1-year return period	32.5 m/s
	Wind shear exponent	0.11
Normal condition	Annual average wind speed	N/A
	Weibull parameters (given by combined model)	Non-typhoon condition: k = 1.73, C = 8.06 Typhoon condition: k = 1.99, C = 15.27 Weight function: N/A
	Wind shear exponent	0.14
	Turbulence intensity	IEC Category C (I_{ref} = 0.12)
Water Level Condition		
Normal condition	Mean sea level	Chart datum level (CDL) + 0.84 m
	High water level	CDL + 1.44 m
Extreme condition	Highest high-water level	CDL + 2.77 m
Wave Condition		
Normal condition	Significant wave height	See Table 25
	Significant wave period	
Extreme condition	Significant wave height	11.71 m
	Significant wave period	13.0 s
Sea current condition		
Extreme condition	50-year return period	1.5 m/s
	1-year return period	1.0 m/s
Normal condition	Annual average current speed	0.1 m/s
Other condition		
Tsunami condition	Water level	3.2 m
	Horizontal velocity	0.87 m/s

Table 25. Wave Height, H_0, and Wave Period T_0, for Fukushima as a Function of Wind Speed at 10 m (U_{10})

U_{10} (m/s)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34
H_0 (m)	1.45	1.44	1.41	1.57	1.96	2.46	3.03	3.64	4.27	4.92	5.59	6.27	6.96	7.66	8.36	9.07	9.78
T_0 (s)	7.75	6.99	6.16	5.89	6.14	6.58	7.08	7.58	8.07	8.54	8.98	9.41	9.82	10.21	10.59	10.95	11.29

4.4.7 Utsira Nord and Sørlige Nordsjø II

The sites Utsira Nord and Sørlige Nordsjø II were subject to a metocean analysis published by Cheynet, Li, and Jiang [27] using NORA3 modeled data. Figure 14 shows a map with the location of these twos reference sites inside the Norwegian economic zone.

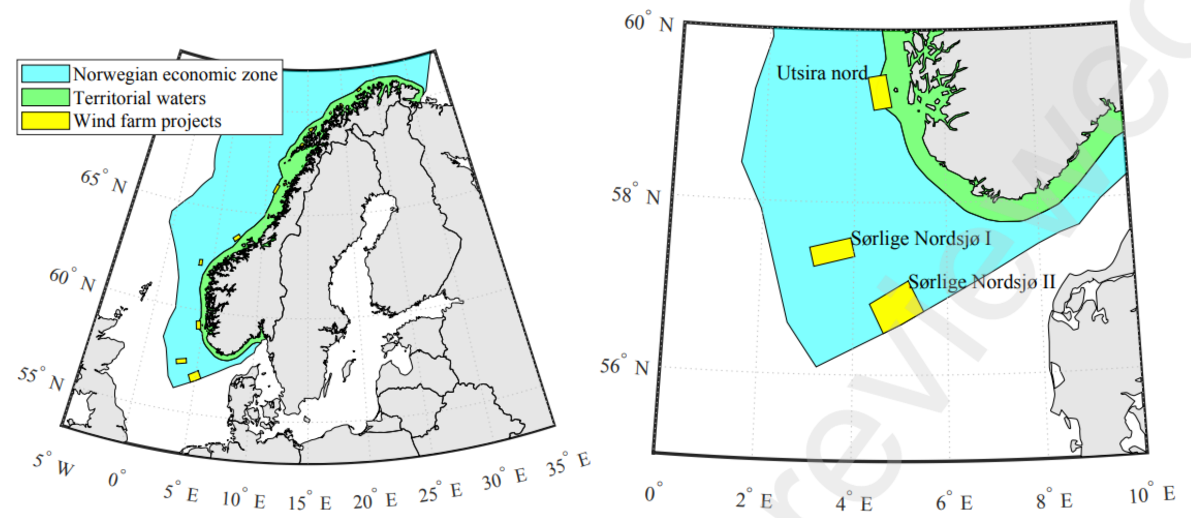


Figure 14. (Left) Areas opened for wind farm deployment in the Norwegian economic zone. (Right) Close-up of Utsira Nord and Sørlige Nordsjø II.

The analyses presented in the publication [27] estimate extreme values for significant wave height and hub height wind speed at 150 m MSL for 1, 10, 50, and 100-year return periods. The results for Utsira Nord and Sørlige Nordsjø II are shown in Table 26 and Table 27, respectively. Further results for Utsira Nord are presented in Appendix G and for Sørlige Nordsjø II in Appendix K.

Table 26. Extreme Value Analysis at Utsira Nord

The values in brackets represent the minimum and maximum values from all grid points.

Return Period (year)	Significant Wave Height (m)	Wind Speed at 150-m Hub Height (m/s)
1	9.6 [9.3, 9.8]	31.0 [30.4, 31.2]
10	12.8 [12.7, 13.0]	34.7 [34.4, 35.3]
50	14.4 [14.3, 14.5]	37.5 [37.0, 38.5]
100	14.9 [14.9, 15.1]	38.7 [38.0, 39.8]

Table 27. Extreme Value Analysis at Sørlige Nordsjø II

The values in brackets represent the minimum and maximum values from all grid points.

Return Period (year)	Significant Wave Height (m)	Wind Speed at 150-m Hub Height (m/s)
1	8.7 [8.4, 8.9]	30.5 [30.3, 30.9]
10	11.3 [10.8, 11.7]	37.6 [37.5, 39.6]
50	12.7 [12.1, 13.2]	43.0 [42.6, 46.2]
100	13.2 [12.6, 13.8]	45.3 [44.8, 48.9]

4.4.8 Gulf of Maine

The Gulf of Maine reference site is intended to be representative of conditions at the Maine Research Array location, where the first multi-unit deployment of floating wind turbines is expected to take place in the region [28]. The location of NDBC station 44005 (43.2°, -69.127°), with a depth of 177 m, was chosen as the reference location. All other data sources were chosen based on the distance to this location and the data coverage of respective stations. The content of this section is based on NREL's reference site conditions datasets for floating wind arrays in the United States [22].

Data for the reference site conditions come from the NOW-23 dataset, and measurement data come from metocean buoys operated by the NDBC. The wind data (from the NOW-23 dataset) were interpolated directly at the target location. Wave data were taken primarily from NDBC buoy station 44005 (43.2°, -69.127°) due to its proximity to the Gulf of Maine floating offshore wind research array (15 nm). To fill data gaps, including more than half of missing wave direction data, data from NBDC station 44098 were substituted when needed. Current data come from NDBC station 4403, the nearest available station with long enough current measurements. Figure 15 shows the data source locations, and Table 28 lists their details. Measurements from 2000 onward were used for a consistent time duration. More details are given in Appendix H.

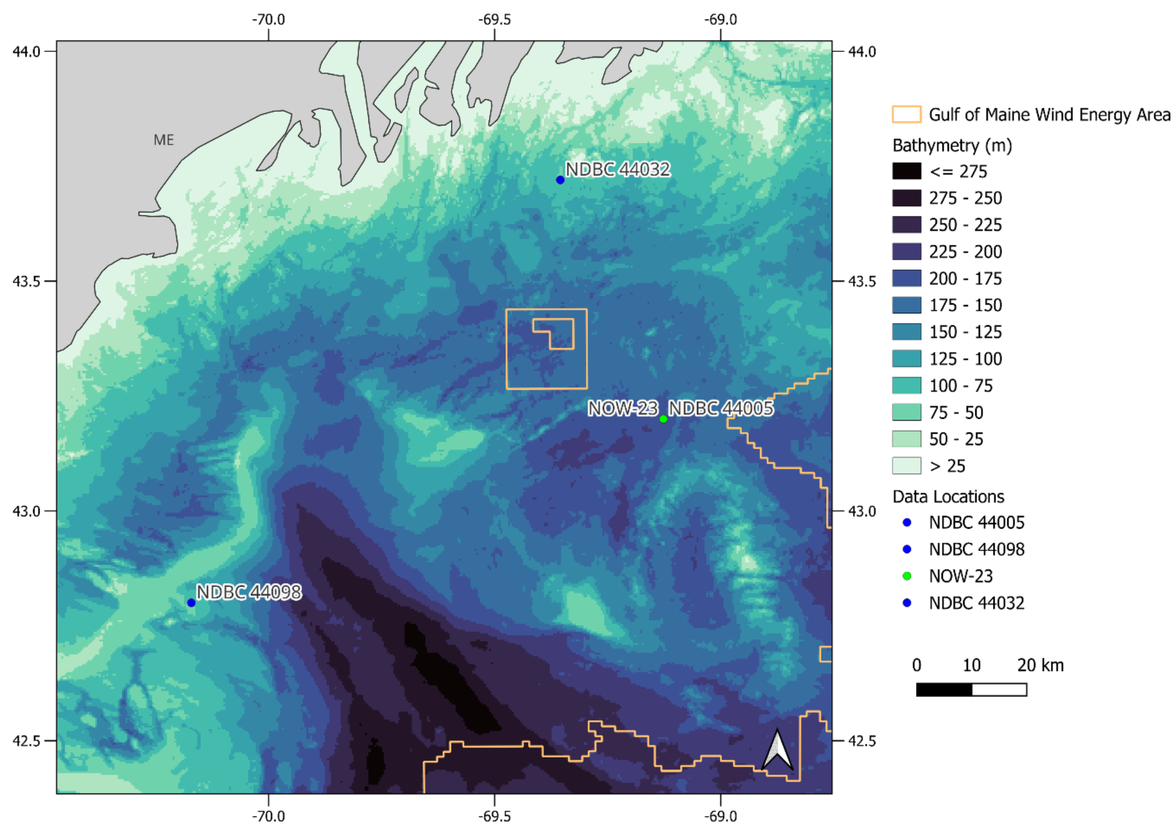


Figure 15. Gulf of Maine metocean data sources

Table 28. Gulf of Maine Locations of Data Sources and Covered Years per Data Type

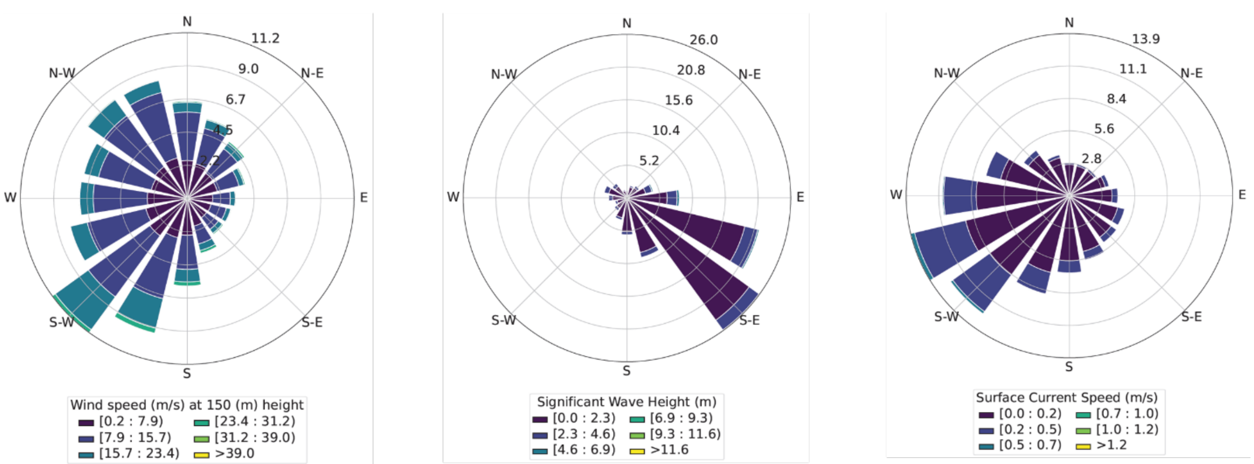
Data Type	Data Sources	Latitude (deg)	Longitude (deg)	Water Depth (m)	Distance to Shore (nm)	Start Year	End Year
Wave/ metocean (primary)	NBDC station 44005	43.2	-69.127	176.8	78	1978	2022
Wave/ metocean (secondary)	NBDC station 44098	42.8	-70.171	80	22	2008	2022
Wind	NOW-23	43.2	-69.127	176.8	78	2000	2020
Current	NDBC station 44032 (E01*)	43.72	-69.355	100	10	2001	2022

The metocean analysis uses data from 2000 to 2020 to have a consistent time span.

**Current data come from UMOOS buoy E01: current data link.*

Three time spans were excluded from the current time series due to data quality concerns: 2016-01-12 to 2016-03-03, 2017-01-01 to 2017-09-01, 2019-10-01 to 2020-01-01.

The speed and directional distributions of wind, waves, and current data are shown in a wind rose format in Figure 16. For waves, significant wave height is plotted in place of wind or current speed.



(a) (b) (c)

Figure 16. Gulf of Maine (a) wind, (b) wave, and (b) current roses

Extreme wind, wave, and current parameters for return periods ranging from 1 year to 500 years are shown in Table 29. The mean directions of the peaks used for the extrapolation are 339° for wind, 302° for waves, and 264° for currents.

Table 29. Extreme Metocean Parameters for Gulf of Maine

Return Period (years)	Wind Speed (m/s)	Significant Wave Height (m)	Peak Wave Period (s)	Current Speed (m/s)
1	33.39	7.07	12.17	0.71
5	37.01	9.2	13.87	0.88
10	38.25	10.04	14.49	0.94
50	40.59	11.86	15.75	1.11
100	41.41	12.59	16.23	1.18
500	42.96	14.19	17.23	1.34

Conditional values of wave height, wave period, and current speed for wind speed bins of every 2 m/s, are given in Appendix H, as are the parameters for 100 fatigue bins generated with a maximum dissimilarity algorithm.

4.4.9 Geomundo

A detailed analysis was performed for the Geomundo site, including observations and models. The dataset is not public; for details of usage, reach out to the contacts listed in Appendix I.

4.4.10 Sud de la Bretagne

Analysis presented here represents the South Brittany location, which is west of the Sud de la Bretagne site, specifically located at -4.59250688553°, 46.8014068604°. According to GEBCO, the water depth at this site is 150 m. Wind and wave analysis at the South Brittany site was carried out using modeled hindcast datasets. This study is provided in full in Appendix J, a summary of which is provided in this section.

Mapping the wind resource and conducting wind power analysis and offshore site assessments requires high-quality data over various time and spatial scales. Due to the limited and sparse nature of ocean observations, obtaining high-resolution wind resource data for specific regions is crucial. Here, we use a downscaling dataset derived from ERA5, known as NORA3. NORA3 employs the HARMONIE-AROME model instead of WRF, offering hourly wind and wave data within a 3×3 km horizontal grid [29,30]. This dataset covers Northern Europe, the Baltic Sea, North Sea, Norwegian Sea, and parts of the Barents Sea, providing complete coverage of the South Brittany area (Figure 17).

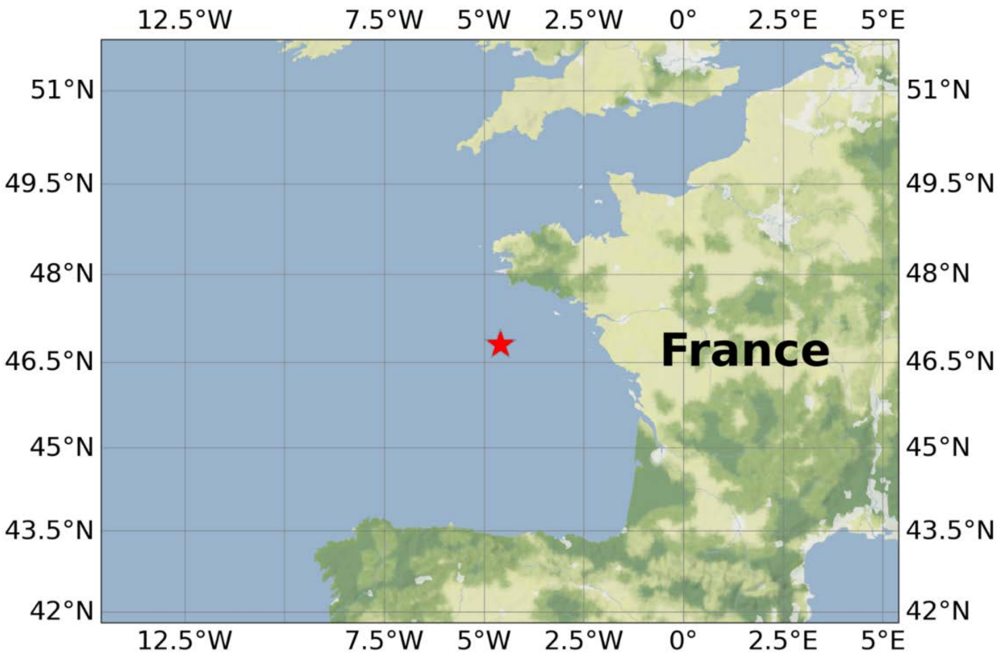


Figure 17. The geographical location of South Brittany (from Hai Bui)

Wind data, containing wind speed and direction, are accessible at various elevations (i.e., Table 30): 10.0 m, 20.0 m, 50.0 m, 100.0 m, 250.0 m, 500.0 m, and 750.0 m. Additionally, the wave dataset provides a comprehensive array of wave parameters, including significant wave height (H_s), wave peak period (T_p), wave mean direction, and several others.

Table 30. Two netCDF Files, One for Wind Data at Different Heights and One for Surface Wind and Wave Data

File name	Details
wam.sbrit.1993-2019.nc	Wind speed (ff) and direction at surface (dd), significant wave height (H_s), peak wave period (T_p), mean wave direction (thq)
nora3.sbrit.1988-2021.nc	Wind speed at 7 different heights.

Wind roses at 10 m and 100 m above sea level are presented in Figure 18.

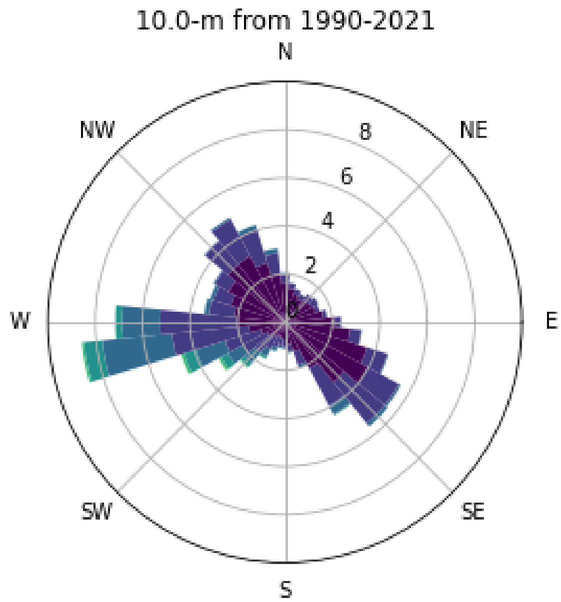


Figure 18. Wind direction at heights of 10 m and 100 m from 1990 to 2021 at the Sud de la Bretagne site.

Figure 19 displays the 50-year and 1-year environmental contours for the South Brittney study sites in the southern north region, utilizing 30 years of NORA3 hindcast data. These contours can be used to estimate extreme sea state conditions.

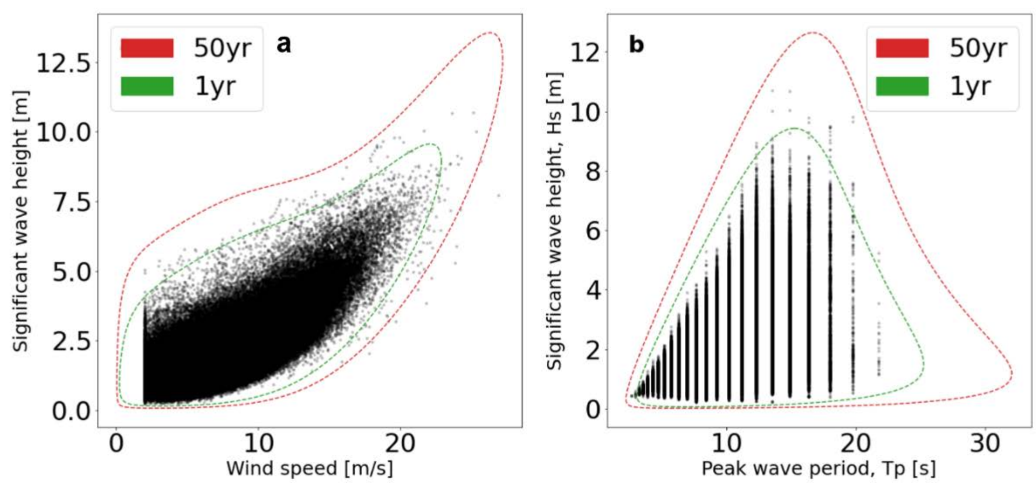


Figure 19. Tentative scatter plots of (a) wind speed at 10-m height and significant wave height overlaid with the joint probabilistic model results, i.e., 50-year (red curve) and 1-year (green curve) environmental contours. (b) 50-year and 1-year contours for wave peak period and significant wave height using the inverse first-order reliability method. This figure can vary significantly based on the geographical location as we investigated in FINO1 met-mast data.

4.5 Turbulence Intensity Across All Reference Sites

Turbulence intensity (TI) is calculated with a new approach that includes large-scale turbulence, wave conditions, and stability effect. As the offshore turbines increase in size (15+ MW, and approximately 400 m tall), it is questionable to continue using a typical boundary layer turbulence model, such as the Kaimal model, for the frequency range from the spectral gap region to the inertial subrange. We use the full-scale turbulence model [31] to include the large-scale, 2D contribution to the turbulence calculation. This effect is important at heights higher than about 50 m and is more significant at higher elevations. The result is that it naturally introduces the decreasing dependence of TI with wind speed for wind speed lower than 10 m/s, in agreement with published measurements. We also include the wave age dependence into the calculation of roughness length using the algorithms from Fan et al. [32], in which water depth is also considered. The wave age is calculated using the ERA5 data. We use the surface heat flux, temperature, and friction velocity from the ERA5 data to calculate the Obukhov length, and we add the stability effect to TI following the Monin-Obukhov similarity theory.

Figure 20 shows two maps that give an overview of mean TI results at 10 m and 100 m across the globe. The calculation of TI for the 11 reference sites is done at the selected hub height of 150 mMSL (meters above mean sea level) for 12 directional sectors and 21 wind speed bins from 0 to 42 m/s with bins of 2 m/s. As requested, the calculation of TI is done for the height of 150 m. The results for each site are stored in the database in ASCII files with name "TI-150m-IEA-XXXX," where "XXXX" is the location ID.

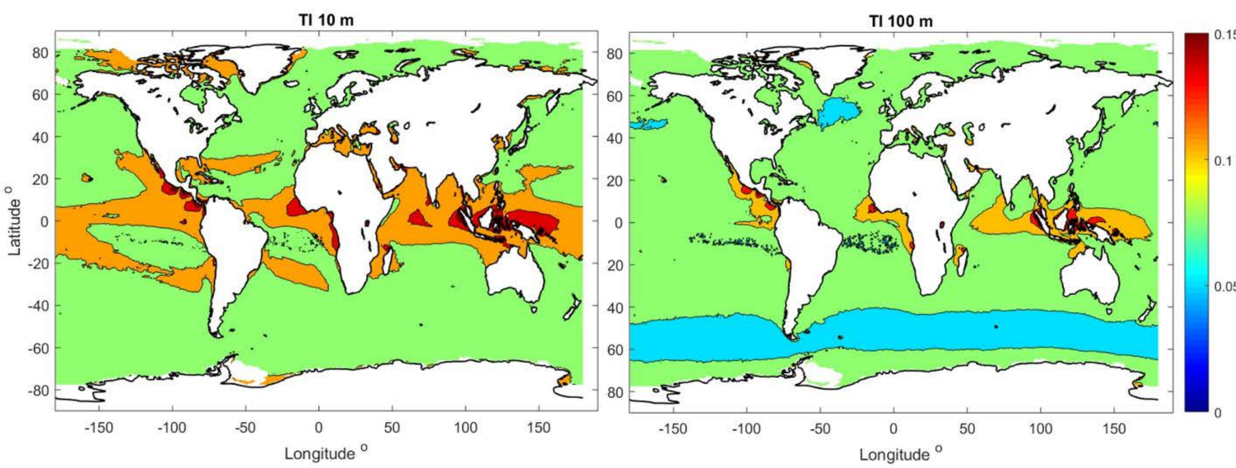


Figure 20. Global map with mean TI for 10 m and 100 m

4.6 Marine Growth Along the Mesopelagic Zone

Marine growth is an important environmental parameter for the design of offshore infrastructure and is required by industry standards as a design parameter. For floating wind farms, water depths greater than 200 m are usually considered; hence, a deeper study on biodiversity in the mesopelagic zone is needed.

The mesopelagic zone, also known as the twilight zone, represents a critical transition layer in the ocean where the interplay between depth and light creates a complex environment. Situated between approximately 200 to 1,000 m below the ocean surface, this realm experiences diminishing sunlight as depth increases.

DHI performed an extensive literature review on this topic and correlated the state of the art with current requirements of industry standards, specifically DNV-ST-0437. Results of this study are presented in Appendix M. Table 31 shows the marine growth estimation for three selected reference sites. Furthermore, for density estimates, we recommended following DNV-ST-0437 and considering a value of 1,325 kg/m^2.

Table 31. Marine Growth Estimation for Three Selected Reference Sites Based on DNV-ST-0437

ID	Name	Latitude (deg)	Longitude (deg)	Water Depth (m)	Marine Growth Thickness Expectations
US0W	Humboldt	40.928	-124.708	-707	~200 mm (less may be expected)
NO44	Utsira Nord	59.276	4.541	-273	2–40-m depth: 60 mm >40-m depth: 30 mm
NO66	Sørlige Nordsjø II	56.78	4.92	-60	2–40-m depth: 100 mm >40-m depth: 50 mm

5 Seabed Conditions

5.1 Introduction

Floating offshore wind farm development is controlled by multiple factors, and the ground condition is considered one of the most important. It is this factor that can dictate which anchoring technique is most suitable.

The objective of this technical note is to provide general information about the geotechnical parameters and to establish a baseline for the geotechnical parameters and stratigraphy that may be encountered on the sites.

These requirements and parameters are indicative only, and a detailed and site-specific study shall be performed in the early stages of the project to produce a detailed design. The analysis done in this study is a synthetic case study based on a simplified methodology and does not include any in situ data.

5.2 Ground Conditions

5.2.1 Available Resources

It is important to note that currently there are no institutions, such as the European Commission through the Eurocodes, regulating wind farm construction. However, different standards, guidelines, and recommended practices exist, and are generally followed by industry [33].

Section 7.3.1 of DNV standard ST-0126 – Support structures for wind turbines (2021) [34] provides the following information:

- **7.3.1.1** The soil investigations shall provide all necessary soil data for a detailed geotechnical design. The soil investigations may be divided into geological studies, geophysical surveys and geotechnical soil investigations.
- **7.3.1.3** For multiple foundations, such as in a wind farm, the soil stratigraphy and range of soil strength properties shall be assessed per foundation location.
- **7.3.1.4** Soil investigations should be carried out before the design. However, in the scenario when no soil investigations are available yet when the foundation is designed, conservative assumptions shall be made for the soil properties. These shall be confirmed by soil investigations before the start of construction.
- **7.3.1.5** Soil investigations shall provide relevant information about the ground to a depth below which possible existence of weak formations will not influence the safety or performance of the wind turbine support structure.

Section 7.3.1.6 of the standard states that soil investigation should normally comprise the following types of investigations:

- Site geological survey
- Topography survey of the soil surface
- In situ testing, for example, by cone penetration tests or down-the-hole standard penetration test, pressuremeter tests, and dilatometer tests

- Soil and rock sampling with subsequent static laboratory testing.

They may also comprise, if useful in special circumstances or required by local authorities:

- Geophysical investigations for correlation with borings and in situ testing
- Shear wave velocity measurements for assessment of maximum shear modulus
- Cyclic laboratory testing.

The DNV-ST-0126 standard is supported by local British standards—BS 5930:1999+A2:2010 [35] and BS 8004.2015 [36]—which provide relevant information about practice for site investigation and practice for foundations, but none of them is tailored for surveys of the seabed and seabed foundations for the offshore windfarm industry. BS EN ISO: 19901-4:2016 [37] provides details about geotechnical and foundation design for the oil and gas industry.

In 2023 BOEM prepared an updated version of the "Guidelines for Providing Geophysical, Geotechnical, and Geohazard Information Pursuant to 30 CFR Part 585" [38]. That document should not be taken as a rule or other legal regulation; however, it provides some additional information about requirements and good practices for geophysical and geological surveys. The following list provides example information:

- Example data should be collected 10 m beyond penetration depth with recommended resolution of 0.3 m in the top 10 m of sediment.
- Adequate in situ testing, boring, or sampling should demonstrate the feasibility of foundation or anchor locations; samples should be collected at 1,000-m intervals along the proposed cable route.
- A "sufficient" number of boreholes should be made (depending on the site conditions).

Based on geological, geotechnical, and geophysical standards and experiences from other, similar industries [39,40] as well as latest guides; the following actions should be taken across the site (but scope should not be limited to these actions):

- The geological study should be the first study to be done, as it can provide information about the presence of faults on the site and the type of bedrock present.
- The geophysical study is relatively easy to conduct and can cover a wide area of the site. It provides information about the actual seabed level and can help estimate the type of soil present.
- Finally, it can be beneficial to carry out the geotechnical surveys last, as the geological and geophysical campaign can be used to inform the planning of the geotechnical campaign. This survey is also the most important because it provides ground material that is used in lab testing. To reach the depth needed at the bottom of the ocean, not every technique is suitable, as some can destroy and remold the ground content; therefore, robust survey planning is key to produce high-quality datasets.

5.2.2 Constitutive Model

To recreate the projects numerically for the design, it is important to choose the correct constitutive model. There are many different constitutive models, each with different required geotechnical parameters. Some are more suited for rocks and others for clays, for example. For design, it is recommended to adopt a software package that uses the finite-element method.

The most commonly used model is the linear and elastic perfectly plastic law with a rupture criterion of Mohr-Coulomb type. This model is characterized by two failure parameters: the cohesion, c, and the friction angle, φ, an isotropic linear elasticity of Hooke (υ, E), a yield surface, and a plastic potential. The main drawback of this behavior law is that the loading and unloading modules are equal, which does not accurately represent the soil response.

Therefore, another model could be considered, such as the hardening soil model. This model is a nonlinear isotropic model with two independent plasticity mechanisms with hardening, which allow the consideration of plastic strains on the soil. Thus, this model uses the same parameters as the Mohr-Coulomb model (c, φ, υ) but also includes the dilatation angle, ψ, and the different stiffness parameter (secant stiffness, E_{50}, tangent stiffness, E_{oed}, reference stiffness, E_{ref}).

For detailed design, this information and more is needed to represent the soil of the site studied. Other parameters needed at the detailed design stage include plasticity index, liquid limit, plastic limit, elastic shear modulus, secant stiffness, tangent stiffness, reference stiffness, and bearing capacity factors. To model the site as realistic as possible, it is highly important that the in situ test and laboratory testing are carried out attentively in order to reduce the incertitude on the data produced.

In this study, the parameters to design the soil according to the Mohr-Coulomb law are provided.

5.2.3 Geotechnical Testing

The standard penetration test is an in situ test that produces an N-value. This value represents the number of blows of a standardized sampler driven into the soil for standardized distance. With this number, it is possible to estimate the shear strength of the clays and the relative density of the sand.

The (Piezo) cone penetration test ((P)CPT) is an in situ test that gives data on the variations in the vertical soil profile. It consists of inserting a cone into the soil at a constant speed. The test gives data on the soil bearing capacity. With this, it is possible to find correlations between that value and the friction angle and undrained shear strength. At least one CPT per anchor is recommended, and an additional two CPTs along the cable route are recommended [41].

The borehole coring is the only method to extract soil samples from the site to allow for laboratory testing. At least one borehole coring should be done in each anchor, and an additional two borehole corings should be done along the cable route.

A wide variety of laboratory testing can be done to determine the geotechnical parameters of the soil and the rock. The particle size distribution test gives information about the sand, silt, and clay content and should be done first. According to the result, if the soil has high clay content, an Atterberg limit test should be carried out. If there are rocks, a uniaxial compressive load test is to be considered. The laboratory testing can also consist of triaxial testing, oedometer testing or chemical testing, for example.

5.3 Geotechnical Parameters

5.3.1 Synthetic Cases

In the same region, significant spatial variability in soil characteristics can be observed, including variations in strength parameters and geotechnical properties as well as differences in stratigraphy. The vertical and horizontal variability of the soil is an important factor to consider. In this study, it is assumed that no horizontal variability is present in the soil—the soil is homogeneous and considered isotropic. The given parameters are only for a synthetic preliminary study.

Three scenarios are presented. The scenarios do not represent a real situation. For the preliminary design, it would be wise to use the scenario that best corresponds to the real strata determined in the geology study.

It is important to acknowledge that the values provided in Sections 5.3.1.1 to 5.3.1.4 serve as illustrative examples of potential parameters and may differ from the actual values encountered at a specific site.

5.3.1.1 Scenario 1

In this scenario, the soil is composed of sand with bedrock beneath. Two variations of this scenario were considered. In Scenario 1a, loose sand overlays shallow bedrock (Table 32), and in Scenario 1b, dense sand overlays deep bedrock (Table 33).

Table 32. Seabed Conditions Scenario 1a – Ground Parameters

Soil	Depth of Top of Strata (m below ground level)	Bulk Density (kN/m^3)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Loose sand	0	16	10^{-4}	-	30	5	0.30
Shallow bedrock	10	20	10^{-8}	10,000	30	50	0.35

Table 33. Seabed Conditions Scenario 1b – Ground Parameters

Soil	Depth of Top of Strata (m below ground level)	Bulk Density (kN/m^3)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Dense sand	0	18	10^{-5}	-	38	40	0.30
Deep bedrock	70	24	10^{-9}	15,000	35	200	0.25

5.3.1.2 Scenario 2

In this scenario, clay overlays the bedrock, and two variations are considered. In Scenario 2a, soft clay overlays shallow bedrock (Table 34). In Scenario 2b, very firm clay overlays deep bedrock (Table 35).

Table 34. Seabed Conditions Scenario 2a – Ground Parameters

Soil	Depth of Top of Strata (mbgl)	Bulk Density (kN/m³)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Soft clay	0	14	10^{-7}	20	-	2	0.25
Shallow bedrock	10	20	10^{-8}	10,000	30	50	0.35

Table 35. Seabed Conditions Scenario 2b – Ground Parameters

Soil	Depth of Top of Strata (mbgl)	Bulk Density (kN/m³)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Very firm clay	0	20	10^{-8}	250	-	15	0.30
Deep bedrock	70	24	10^{-9}	15,000	35	200	0.25

5.3.1.3 Scenario 3

This scenario considers that the bedrock was not present in the soil investigation, and it is assumed that the bedrock is deep enough to not interact with the foundation. The sand and the clay overlay each other. Two variations are considered: Scenario 3a considers soft clay overlaying dense sand (Table 36); Scenario 3b considers loose sand overlaying very firm clay (Table 37).

Table 36. Seabed Conditions Scenario 3a – Ground Parameters

Soil	Depth of Top of Strata (mbgl)	Bulk Density (kN/m³)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Soft clay	0	14	10^{-7}	20	-	2	0.25
Dense sand	0	18	10^{-5}	-	38	40	0.30

Table 37. Seabed Conditions Scenario 3b – Ground Parameters

Soil	Depth of Top of Strata (mbgl)	Bulk Density (kN/m³)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Loose sand	0	16	10^{-4}	-	30	5	0.30
Very firm clay	0	20	10^{-8}	250	-	15	0.30

5.3.1.4 Consideration

The other parameters that could be used for the design are described in Table 38.

Table 38. Seabed Conditions – Additional Ground Parameters

Soil	Cone Resistance (MPa)	Unconfined Compressive Strength (MPa)	Point Load Index (MPa)	Liquidity Limit (%)	Plasticity Index (%)
Loose sand	2	-	-	-	-
Dense sand	15	-	-	-	-
Soft clay	0.5	-	-	70	30
Very firm clay	2	-	-	35	20
Shallow bedrock	-	10	0.1	-	-
Deep bedrock	-	50	0.4	-	-

5.4 Conclusion

This section presents a summary of the main ground parameters needed for design (Table 39–Table 40). Note that the parameters presented in this document are based on simplified methodology and do not include real in situ data.

The ground conditions and the geotechnical parameters associated with each soil are important data that can better explain the behavior of the foundation under different loads. A soil investigation program must be performed in the early stages of a floating offshore wind project.

Table 39. Seabed Conditions – Ground Parameter Summary

Soil	Depth of Top of Strata (mbgl)	Bulk Density (kN/m^3)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
Loose sand	0	16	10^{-4}	-	30	5	0.30
Dense sand	0	18	10^{-5}	-	38	40	0.30
Soft clay	0	14	10^{-7}	20	-	2	0.25
Very firm clay	0	20	10^{-8}	250	-	15	0.30
Shallow bedrock	10	20	10^{-8}	10,000	30	50	0.35
Deep bedrock	70	24	10^{-9}	15,000	35	200	0.25

Table 40. Seabed Conditions – Additional Ground Parameters

Soil	Cone Resistance (MPa)	Unconfined Compressive Strength (MPa)	Point Load index (MPa)	Liquidity Limit %	Plasticity Index %
Loose sand	2	-	-	-	-
Dense sand	15	-	-	-	-
Soft clay	0.5	-	-	70	30
Very firm clay	2	-	-	35	20
Shallow bedrock	-	10	0.1	-	-
Deep bedrock	-	50	0.4	-	-

6 Coastal Infrastructure Requirements

6.1 Introduction

Ports play a key role in all development phases involved in a floating offshore wind farm project because they link land-based activities and marine operations. The objective of this technical note is to provide general information about the main requirements that a port should comply with to provide satisfactory service during floating offshore wind farm construction.

Note that the port requirements presented in this document are based on existing available information and will be reviewed as more commercial-scale floating offshore projects are developed and more detailed information becomes available.

6.2 Key Assumptions

6.2.1 Types of Floating Foundations

Port site requirements are dependent on the floating foundation typology, which determines the necessities related to manufacturer, assembly, and staging port facilities. The main floater typologies are presented in Figure 21.

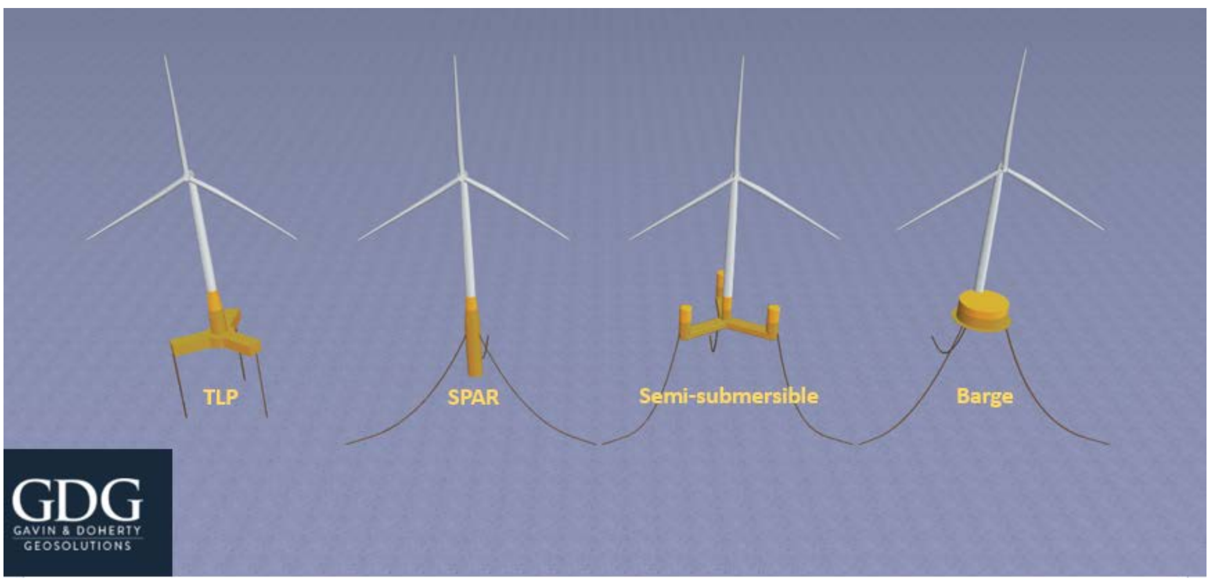


Figure 21. Typical floating foundation types.

Figure from GDG. TLP = tension-leg platform.

- **Tension-leg platform:** These are smaller and lighter floating foundations associated with a higher buoyancy force, which requires fully tensioned anchoring mooring lines to guarantee stability. Tension-leg platforms have a shallow draught and experience high vertical loads on the mooring lines and anchor due to high buoyancy.
- **Spar or buoy spar:** Cylinder structures that are stabilized by keeping the center of gravity below the center of buoyancy using a ballast made of one or various heavy materials. It is the substructure with the largest draught (70–90 m), which makes the

structure less responsive to wind, waves, and currents. The foundation is fixed to the seabed using catenary, semi-taut, or taut mooring lines.

- **Semisubmersible foundations:** Semisubmersible platforms have a hull with columns connected to each other with bracings. This floater stability is provided by a combination of buoyancy (waterplane area) and ballast. The most common steel designs use three columns, one of which supports the turbine either in the center or in a corner. Semisubmersible prototypes have been developed to evaluate the possibility of accommodating several turbines with one platform. The substructure is anchored to the seabed by using catenary, semi-taut, or taut moorings.
- **Barge:** A barge foundation consists of a steel or concrete hull that provides stability through its buoyancy (waterplane area). These foundations have a low draught, making them suitable for shallow waters if required. The structure is fixed to the seabed by using catenary, semi-taut, or taut moorings.

Floating foundations are usually manufactured and assembled onshore, then later towed to the integration port for the installation of the wind turbines. It should be highlighted that the installation of wind turbines on spar floaters might be performed offshore (as for the fixed foundations) due to the draft requirements for these specific foundations.

Steel semisubmersible floaters are currently the most popular solution for planned commercial developments; however, the optimal technology is still undecided. Therefore, unless a site has extensive prior experience with a specific solution, any port development should be performed considering different floating foundation solutions for flexibility to future market demands. Note that even though port infrastructure is to some extent similar for concrete and steel solutions, the requirements for concrete manufacturing facilities are slightly more demanding in terms of bearing capacity at berth. This potentially makes it more feasible to convert concrete facilities into steel assembly ports if required [42].

6.2.2 Indicative Floating Foundation Parameters

Table 41 presents indicative dimensions for floating substructures used with 17-MW and 20-MW wind turbine generators (WTGs). Note that these parameters are defined based on the existing literature [43] and subject to change depending on the selected design solution.

Table 41. Indicative Floating Substructure Parameters

WTG Size	Floater Length (m)	Floater Width (m)	Floater Draft Excluding WTG (m) – Before Integration	Floater Draft Including WTG (m) – After Integration	Operational Draft (m)
17 MW	90	90	11.5	13.5	22.5
20 MW	100	100	15.0	15.0	25.0

6.2.3 Key Vessels for Construction, Installation, and Operations and Maintenance

The vessel categories used in the construction of a typical floating offshore wind farm are presented in Table 42. The aim is to derive the dimensions for the requirements of the ports, but not to represent the full range of vessels required for the installation of the floating wind farm. For more information on floating offshore wind farm construction activities and required vessels, Cooperman et al. described typical construction and installation activities including vessels required for floating offshore wind projects in California [44].

Table 42. Typical Vessels Used in Floating Offshore Wind Farm Construction

Activities	Activities Description	Vessel Type	Vessel Details (m)
Component Transfer Vessel(1)(2) **(Refer to Appendix L)**	Import of WTG components to the staging port and transport of mooring equipment to installation site or to an intermediate staging port. These vessels can be equipped with heavy-lift cranes that can be used for offloading operations; however, in some occasions they consist of open deck cargo ships that require cranes on deck or the use of Self-Propelled Modular Transporters modules ("ro-ro operations").	Heavy-lift vessels (HLVs), general cargo vessels, barges or coasters	Length Overall (LOA): 100–204 Beam: 15–43 Draft: 5.25–13 *e.g., Star Lysefjord, Zhi Xian Zhi Xing, SAL 171, etc.*
Floaters Transport(1)	Transport of modular substructure elements or fully assembled substructures to either assembly or staging ports. Given the significant submerged draft, fully assembled substructures may need to be floated-off in deep water and towed either into the staging port or to wet storage facilities.	Semi-submersible HLVs	LOA: 134–275 Beam: 36–68 Draft: 9–11 *e.g., BOKA Vanguard, COSCO 68 - Xin Guang Huz, SAL MV Sun Rise, etc.*
Anchor Handling	Used for towing fully assembled units from deeper water into staging ports and for towing fully assembled units from the staging port to the installation site. Vessels also used for the installation of mooring equipment for floaters.	Anchor Handling Tug Supply Vessel (AHTS)	LOA: 95 Beam: 25 Draft: 7–9 *e.g., AHTS Maersk Mariner*

Activities	Activities Description	Vessel Type	Vessel Details (m)
Long-Distance Towing	Alternative and most cost-effective solution for long-distance towing activities in comparison with AHTS.	Oceangoing Tugs	LOA: 75–90 Beam: 18–20 Draft: 7–9 *e.g., BOKA Summit, ALP Keeper*
Offshore Construction & Support Activities	May be used instead of the AHTS for anchor and mooring installation, plus the power cable installation.	Offshore Construction Vessel with dynamic positioning (DP2/3) system.	LOA: 157 Beam: 27 Draft: 8.5 *e.g., Normand Vision*
Towing at Port[(3)]	Used during approaching and departure maneuver of the component transfer vessels to guarantee complete control of the vessel. *Note that tug requirements are generally required by port authorities depending on vessel type and size.*	Tug vessel	LOA: up to 40 Beam: up to 14 Draft: up to 6
Cable Laying	Floating wind turbines require dynamic cables to support export in addition to the typical buried cables associated with fixed-bottom installations. It is anticipated that cables will be transferred directly to the installation site, and as such, there is no requirement for the staging port to accommodate these types of vessels.	Cable Laying Vessel (CLV)	LOA: 133 Beam: 24 Draft: 6.7 *e.g., Seven Pacific*
Operations & Maintenance	Used for maintenance activities during the operational phase of the project.	Service Operations Vessel (SOV) & Crew Transfer Vessel (CTV)	SOV LOA: up to 100 Beam: up to 14 Draft: up to 6 CTV LOA: up to 26 Beam: up to 10.5 Draft: up to 3

Notes:

1) Main vessel parameters are defined by a range of values due to the variability of vessel sizes within this vessel typology. Refer to Appendix L for the list of vessels utilized in component transfer activities and used as a reference in this analysis.

2) As a conservative approach, only general cargo vessels and HLVs have been considered for the definition of the vessel details considered for the transfer of components, as they are associated with larger dimensions in general.
3) Tug vessel parameters are dependent on tug availability in the port site(s) considered during the construction of the floating offshore wind farm.

6.3 Distance to Floating Offshore Wind Farm

6.3.1 Floater Manufacturing Port

There are no specific requirements with respect to the distance between the floater manufacturing port and the integration port or the offshore wind farm site. The location for the construction of the floating foundations will be defined based on the availability of laydown area at port/shipyards, the local supply chain, and the existence of a local qualified workforce.

6.3.2 Integration Port

Proximity between the offshore wind farm and the port facilities used for assembling and marshalling activities is critical to optimize transit times during construction and fleet costs. Also, it should be noted that transport and installation operations are mainly driven by available weather windows, which are most accurate within 72 hours [42]. Hence, it is desirable that towing and installation operations are performed within an operating window no longer than 72 hours.

According to available literature as well as GDG experience in offshore wind projects, a distance of 150 nm between the offshore wind farm location and the installation site is recommended. Considering a tow speed of 3–5 knots, tow operations would take between 30 and 50 hours.

A recommended distance of 150 nm for transport and installation activities is indicative only, and larger distances might be required depending on the existing port infrastructure near the project site. For example, the 2.3-MW Hywind demonstration device (spar foundation) was towed 250 nm to the final installation location, and the WindFloat demonstration device was installed 225 nm from the assembly port [45].

6.3.3 Operation and Maintenance Ports

The prevailing practice within the fixed-bottom alternatives sector advocates for establishing a permanent operations and maintenance (O&M) base, with crew transfer vessels berthed at a port close to the wind farm. However, in the case of offshore wind farms, which are designed to be deployed in substantial water depths, often at considerable distances from shore, and in areas characterized by challenging environmental conditions, the use of a solution based on crew transfer vessels might not be an efficient alternative due their restrictive working limits (with a typical maximum workable wave height of 1.5 m). Instead, specialized offshore vessels are increasingly preferred for their suitability to such demanding operational contexts.

It is expected that developers would opt for an SOV-based O&M strategy. Under this scenario, technicians will be based at the wind farm during a specific number of days without needing to visit the O&M port during that period. Therefore, in this case the distance between the O&M port and the offshore wind farm is not a key limit to consider.

6.4 Navigation Requirements

Ports used in the different activities involved in the offshore wind farm construction shall guarantee the availability of navigation areas suitable to accommodate the design fleet expected in the offshore wind farm project. These navigation areas are referred to as:

- Access channel
- Turning basin
- Waiting anchorage areas.

All navigation routes within the port shall be supplied with aid-to-navigation devices compliant with International Association of Marine Aids to Navigation and Lighthouse Authorities requirements.

The indicative navigation area requirements are defined based on PIANC 121 "Harbour Approach Channels - Design Guidelines" considering a single lane channel and moderate environmental conditions. PIANC guidelines offer indicative recommendations for determining the dimensions of navigation areas; however, it is advisable to conduct navigation simulations to verify the necessary navigation areas and tug requirements, taking into account specific local conditions. Depending on the project's characteristics, these simulations may lead to optimization of the navigation requirements initially estimated using PIANC guidelines.

Within an existing port, the port authority typically establishes the maximum allowable beam, draft, and overall length for vessels transiting the access and departure routes. If the vessels planned in the design fleet exceed these dimensions, the project developer should demonstrate that navigation safety will not be compromised and should seek permission from the port authorities to use such vessels. Note that vessels used only sporadically throughout the duration of the project could be subject to special handling or arrangements.

6.4.1 Access Channel

The access routes are mainly defined by the channel width and water depth, as discussed in further detail below.

Channel width is usually calculated in terms of the largest beam expected at port, and it depends on several factors such as ship maneuverability, vessel speed, environmental conditions, and existing aid-to-navigation devices. According to PIANC 121 guidelines [46], the required channel width should be between 4 and 5 times the vessel beam.

Ship-related factors are the most important in the definition of the required water depth for safe navigation. Based on PIANC 121 guidelines, an under-keel clearance of 10% of the vessel draft would be sufficient in sheltered areas (e.g., at berth or within the port basin), whereas an under-keel clearance of 20%–30% would be recommended for areas exposed to moderate swell.

6.4.2 Turning Basin

The turning basin is the area where vessels are often assisted by tugs to their berths and may be turned beforehand. In an early project stage, the minimum nominal diameter of the turning basin should be 2 times the vessel length overall (LOA) in case of tug assistance, or 3 times LOA in a scenario without tugs.

6.4.3 Anchorage Areas

Anchorage areas are defined by the zones where vessels drop anchor either awaiting entry into port or to undertake cargo handling, passenger transfer, or other cargo operations associated with the port.

As per PIANC 121 guidelines, the anchorage area size is defined by the sum of the anchor chain length (≈5 times water depth), an anchor dragging of 30 m, and the ship LOA. In terms of water depth, a minimum under-keel clearance of 10% is recommended.

6.4.4 Summary of Vessel Navigation Requirements

Table 43 provides navigation requirements in terms of minimum and maximum recommended values. Table 44 summarizes the recommended vessel navigation requirements.

As a conservative scenario, the navigation requirements are determined by considering vessel details associated with the anticipated fleet that will operate within the port, depending on the activities taking place. In cases where the same port accommodates various types of vessels, the minimum design parameters are set as the upper bounds of the lower ranges, while the maximum parameters are defined as the upper ranges. This ensures that the design parameters encompass the variability of the fleet without excluding any vessel type.

Table 43. Maximum and Minimum Design Parameters for Vessel Navigation Requirements

Port Facilities	Assumptions	Minimum Design Parameters (m)	Maximum Design Parameters (m)
Floaters Production and/or Transport Port	Navigation requirements driven by small component transfer vessels and floaters transport vessels (refer to Table 42)	LOA: 134 (1) Beam: 36 (2) Draft: 9 (3)	LOA: 275 (1) Beam: 68 (2) Draft: 11 (3)
Integration Port	Navigation requirements driven by component transfer vessels and floaters transport vessels (refer to Table 42)	LOA: 134 (4) Beam: 36 (5) Draft: 9 (6)	LOA: 275 (4) Beam: 68 (5) Draft: 13 (6)
O&M Port	Navigation requirements driven by SOVs (refer to Table 42)	LOA: 100 Beam: 20 Draft: 6.5	

Notes:

(1) Values defined based on the lower and upper LOA range for floaters transport vessels expected in the port facilities. These values cover the small component transfer vessels assumed to use the floater production port.

(2) Values estimated based on the beam range for floaters transport vessels expected in the port facilities. These values cover the small component transfer vessels assumed to use the floater production port.

(3) Values estimated based on the draft range for floaters transport vessels expected in the port facilities. These values cover the small component transfer vessels assumed to use the floater production port.

(4) Values defined based on the lower and upper LOA range for floaters transport vessels expected in the port facilities. These values cover the range of component transfer vessels expected in the integration port.

(5) Values defined based on the lower and upper beam range for floaters transport vessels expected in the port facilities. These values cover the range of component transfer vessels expected in the integration port.

(6) Values defined based on the lower draft range defined for floaters transport vessels and on the upper draft range for component transfer vessels expected in the integration port, covering the whole design fleet expected in the port facilities.

Table 44. Summary of Recommended Vessel Navigation Requirements

Port Facilities	Channel Width (m) (1) *4.5 x Beam*		Channel Water Depth (m) (2) *1.25 x Draft*		Turning Basin Diameter (3) *2 x LOA*		Water Depth at Sheltered Locations (4) *1.1 x Draft*	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
Floaters Transport	≈160	≈310	11.25	13.75	270	550	10.00	12.1
Integration Port	≈160	≈310	11.25	16.25	270	550	10.00	14.30
O&M	90		8.10		200		7.15	

Notes:
(1) Channel width considering 4.5 times the vessel beam.
(2) Channel water depth estimated considering an under-keel clearance of 25% as recommended by PIANC for areas affected by swell waves (conservative scenario).
(3) Turning basin diameter estimated considering tug support (2 x LOA).
(4) Assuming an under-keel clearance of 10% as recommended by PIANC for protected waters.
(5) Values have been rounded to the nearest five.

6.4.5 Space Requirements for Floaters Transport and Integration

When vessels are towing a floating substructure alone or a substructure including the turbine, the estimated navigation requirements for the vessels may not be sufficient to ensure safety during the transportation of the substructure. Therefore, it is essential to always review that the available navigation spaces have the capacity to accommodate not only the design fleet by itself but also the vessels transporting the floater.

In the transportation of a floating substructure via towing with a vessel, the navigation requirements will be determined by the greater of the space requirements between the vessel navigation and the dimensions of the floating substructure.

The floater space requirements in integration and manufacturing facilities are dependent on the floater dimensions. Based on the indicative parameters presented in Table 41, the following space requirements are suggested for these facilities (Table 45).

Table 45. Indicative Space Requirements for Floaters Transport and Integration

WTG Size	Integration Port (Floater + WTG)		Manufacturing Port (Floater)		Float-On and Float-Off Maneuvers
	Water Depth at Berth and Navigation Areas (m) *Floater and WTG draft + 1.5 m*	Channel Width (m)	Water Depth at Berth and Navigation Areas (m) *Floater draft + 1.5 m*	Channel Width (m)	Min Water Depth (m) *(See Note 1)*
17 MW	15.0	230	8.5	230	25–27
20 MW	16.5	260	8.5	260	25–27

Notes:

(1) The draft required for float-on and float-off maneuvers is estimated based on several factors, including the depth of the semisubmersible HLV hull (14.5–15.5 m), the draft of the floater (8.5 m), an under-keel clearance of 1.5 m, and the utilization of deck supports to accommodate the floater onboard.

(2) Space requirements defined for the integration and the manufacturing facilities based on the available literature [43].

6.5 Quay Wall Berth Requirements

6.5.1 Water Depth at Berth Pocket

The existing depth at the berth must ensure that the vessel can be securely moored during both high and low tides. In terms of remaining at berth, a water depth equivalent to 10% of the vessel's maximum draft is recommended, with a minimum under-keel clearance of 1 m. If the berth is used for storing floaters, a minimum water depth of 8.5 m is recommended, while 15–16 m are suggested for assembly activities of WTGs and floaters (refer to Table 45).

6.5.2 Quay Wall Length

Assuming a continuous berth line and the vessel moored alongside, the required quay wall length will be defined by the mooring layout defined for this vessel.

As per BS 6349-4 "Code of practice for design of fendering and mooring systems," the typical mooring arrangement for continuous quay lines consists of mooring lines issuing at the extremities of the ship with a horizontal angle of 45° with respect the berthing line (refer to stern line and head line in Figure 22) in combination with breast lines and spring lines with a horizontal angle of 90° and 10°, respectively.

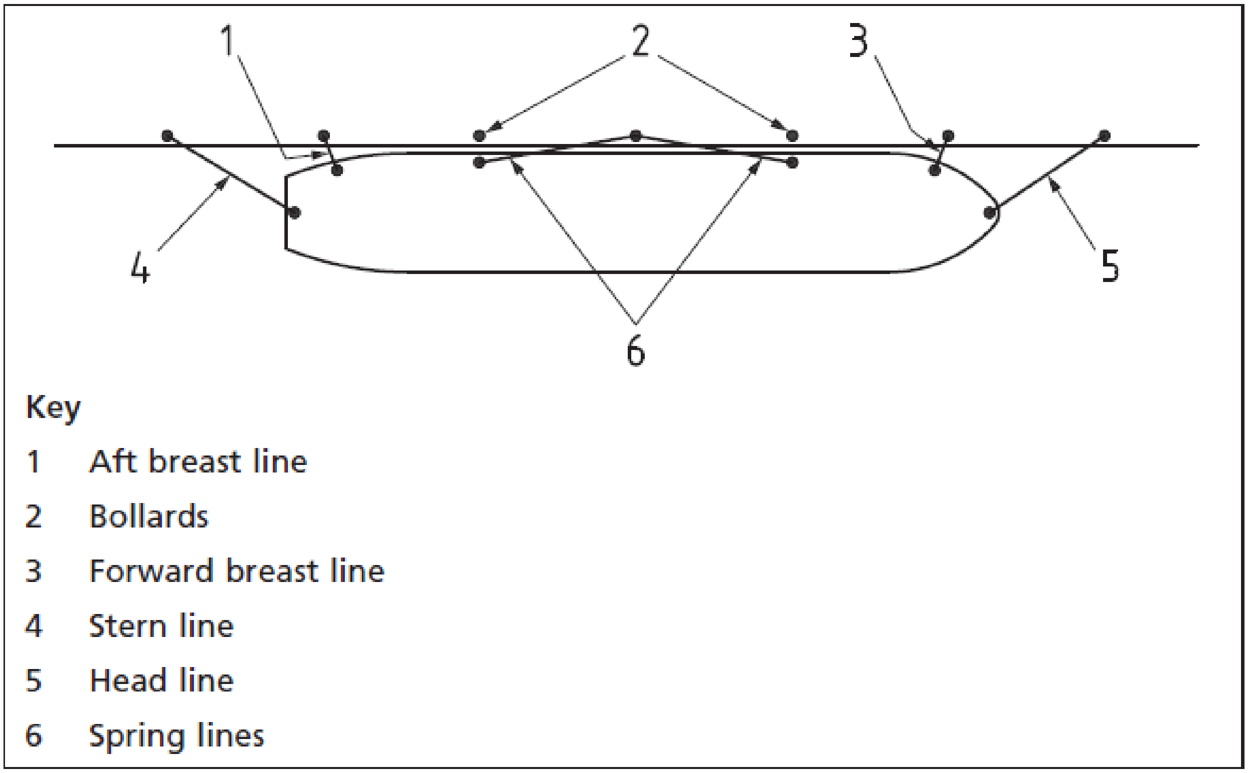


Figure 22. **Typical mooring pattern for continuous quay (Source: BS 6349-4)**

As shown in Figure 23, the required quay wall length is therefore defined by the sum of the vessel LOA and the required quay wall length to accommodate the stern and head lines (“x” in Figure 23). Note that this value is indicative and can be refined through the completion of a “geometrical combability assessment” and a “mooring analysis” undertaken as part of initial project development.

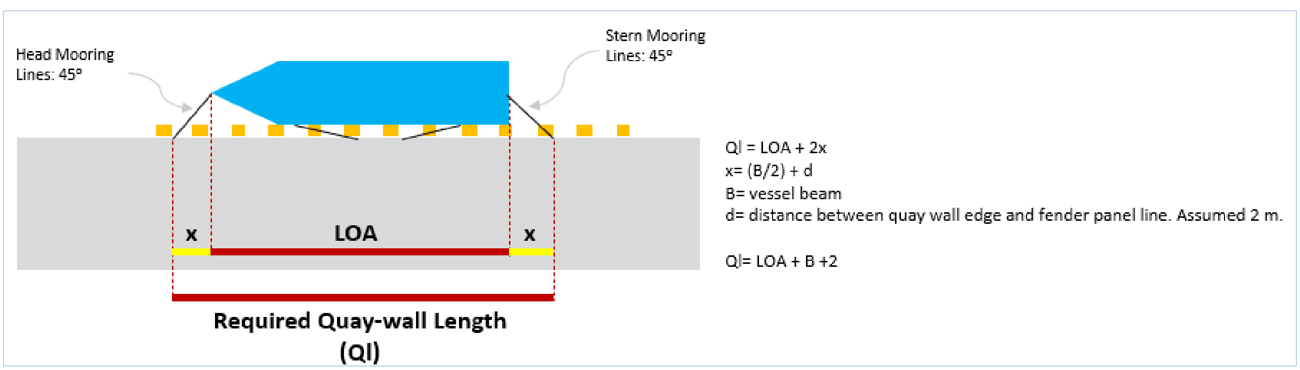


Figure 23. **Estimation of required quay wall length by main vessel categories**

Table 46 presents the minimum and the maximum quay wall length required by a component transfer vessel and a floaters transport vessel. Port facilities used for floating offshore wind farm construction might accommodate various vessels simultaneously; therefore, the total quay wall length required will be a combination of the length estimated for each vessel category.

Table 46. Quay Wall Length Requirements Depending on Vessel Category

Vessel Category	Vessel Details (1)	Required Quay Wall Length (m)	
		Min	Max
Component Transfer Vessel	LOA: 100–204 m Beam: 15–43 m	120	240
Floaters Transport Vessel	LOA: 134–275 Beam: 36–68	170	345

Notes:

(1) Note that the maximum LOA does not have to be associated with the maximum vessel beam. Refer to Appendix L for further details about the vessel data considered in this assessment.

(2) Values have been rounded to the nearest five.

In a floating offshore wind project, quay length requirements at port will depend on various parameters such as:

- Activities undertaken at port: floaters manufacturing, WTG component import, assembly of wind turbine on substructure, etc.
- Logistics philosophy: simultaneous with activities, design fleet, number of import berths, floaters launch methodology, onshore layout, etc.

As a preliminary approach, the required quay wall length has been estimated for two different scenarios presented below:

- **Integration port**: facility located a reduced distance from the wind farm used to install the wind turbine on the floater. This port will also include a dedicated quay wall section for the import of WTG components as well as a dedicated onshore area for their storage.
- **Floater manufacturing port**: facilities where floaters are manufactured and assembled before being transported to the integration port. This port is not required to be in the wind farm vicinity, and its location usually depends on factors such as local supply chain, local experience in similar projects, or Oil & Gas, existence of shipyards or dry docks at port, etc. It is assumed that this port will also include an import berth for materials, which will be transported in small general cargo vessels. Note that quay wall length requirements for manufacturing ports could be optimized with the importation of material to site by railway or road.

Table 47 presents the quay wall length requirements estimated for the integration port and for the floater manufacturing port.

Table 47. Quay Wall Length Requirements for Port Facilities

Port Facilities	Assumptions	Required Total Quay Wall Length (m)	
		Min	Max
Integration Port	**Minimum scenario:** - One berth dedicated to import of WTGs components: required quay wall length of 240 m as shown in Table 46 (1) - One berth dedicated to receiving floaters and to integration activities: required quay wall length of 170 m as shown in Table 46 - An additional separation between dedicated berths of 20 m (area for tug assistance, safe maneuvers, etc.) **Maximum scenario:** - One berth dedicated to import of WTG components: required quay wall length of 240 m as shown in Table 46 (1) - One berth dedicated to receiving floaters and to integration activities: required quay wall length of 345 m as shown in Table 46 - An additional separation between dedicated berths of 20 m (area for tug assistance, safe maneuvers, etc.)	≈430	≈605
Floater Manufacturing Port	**Minimum scenario:** - One berth dedicated to import of materials: required quay wall length of 120 m as shown in Table 46 (2) - One berth dedicated to launch floaters: required quay wall length of 170 m as shown in Table 46 - An additional separation between dedicated berths of 20 m (area for tug assistance, safe maneuvers, etc.) **Maximum scenario:** - One berth dedicated to import of materials: required quay wall length of 120 m as shown in Table 46 (2) - One berth dedicated to launch floaters: required quay wall length of 345 m as shown in Table 46 - An additional separation between dedicated berths of 20 m (area for tug assistance, safe maneuvers, etc.)	≈310	≈485

Notes:

(1) Considering the turbine sizes used in offshore wind, the quay wall length estimated for the import of WTGs is always estimated considering the upper bound vessel contemplated in the reference fleet shown in Table 42.

(2) Import of materials at floater manufacturing port is assumed to be performed by small general cargo vessels. Note that quay wall length requirements for manufacturing ports could be optimized with the importation of material to site by railway or road.

(3) Values have been rounded to the nearest five.

6.6 Storage Areas

The construction of a floating offshore wind farm would require onshore laydown areas as well as wet storage areas in sheltered waters for the floating foundations storage.

Storage area requirements are highly dependent on the wind farm capacity, turbine size, project logistics philosophy, and floater typology. The values provided in this document (Table 48) are reference values obtained from an analysis of existing literature [42,43,47–49] relating to floating offshore wind farm construction and are subject to modification after the completion of more site-specific assessments required to be performed within a floating offshore wind farm project.

Table 48. Storage Area Requirements

Port Facilities	Activity	Required Laydown Area (*Ha*)	
		Min	Max
Integration Port (1)	Storage of 15–20-MW WTG components, assembly on substructure	6	25
Floater Manufacturing Port	Floaters manufacturing and assembly (steel or concrete)	20	40
Wet Storage	Mooring of assembled floaters at integration port and/or floater manufacturing port	4	70
O&M Activities	Continuous service to the offshore wind farm during operations	1	4

Notes:

(1) The landside area requirements exclude storage of cable storages and mooring equipment.

6.7 Bearing Capacity

Bearing capacity requirements defined for the quayside and for the laydown areas are considered the same for the Integration Port and for the Floater Manufacturing Port as shown in Table 49.

Table 49. Bearing Capacity Requirements.

Port Area	Required Laydown Area (*Ha*)	
	Min	Max
Quayside	20 (1)	50
Laydown Area	10	20

Notes:

(1) Lower values might be accepted for assembly of steel floaters.

6.8 Other Requirements

It is important that project developers agree with port authorities that selected port facilities will have the capacity to comply with the project requirements, contributing to a successful project completion. Apart from the requirements presented in previous sections, it is important to guarantee that the selected port will be in a good position to provide as a minimum:

- Exclusive use of berth(s) (if possible)
- Tug support and pilotage services when required (24/7 service)—two or three tugs might be required for vessel approaching/departure and towing operations
- Cranage equipment compliant with the logistics project requirements (24/7 service)
- Qualified mooring services (24/7 service)
- Port utilities such as power connections in the quay wall, lighting in port facilities, security camera systems in the quay wall and laydown areas, communication system, etc.
- Maritime equipment in good condition and compliant with project design fleet (e.g., mooring bollards, fenders, ship-to-shore gangway, etc.)
- Suitable access routes (a combination of road and train infrastructure might be beneficial for import activities).

6.9 Summary Table

This section presents a summary of the main port requirements defined for the integration port, the floater fabrication port, and for O&Ms activities (Table 50–Table 52). Note that port requirements presented in this document are based on the existing available information and shall be reviewed as more floating offshore projects are developed at a commercial scale and more detailed information becomes available.

A port site screening shall be performed in the early stages of a floating offshore wind project based on project-specific parameters such as project location, WTG size, floater typology, transport and installation philosophy, etc.

Reference vessel particulars for HVLs and general cargo vessels are provided in Appendix L.

Table 50. Port Requirements for the Integration Port

Parameter	Min	Max
Distance to Offshore Wind Farm (nm)	-	150
Channel Width (m)	230 (1)	310 (2)
Channel Depth (m) (1)	15	16.5
Air Draft (m)	Unrestricted	Unrestricted
Turning Basin Diameter (m)	270 (2)	550 (2)
Water Depth at Berth (m) (1)	15	16.5
Quay Wall Length (m)	≈430	≈600
Laydown Area (Ha)	6	25
Wet Storage Area in Sheltered Waters (Ha)	4	70
Bearing Capacity at Quayside (t/m^2)	20	50
Bearing Capacity at Laydown Area (t/m^2)	10	20

Notes:
(1) Driven by the space requirements recommended for floating foundations (refer to Table 45).

(2) Driven by the design fleet navigation requirements (refer to Table 44)

Table 51. Port Requirements for the Floater Manufacturing Port

Parameter	Min	Max
Distance to Offshore Wind Farm	Unrestricted	Unrestricted
Channel Width (m)	230 (1)	310 (2)
Channel Depth (m)	11.25 (2)	13.75 (2)
Air Draft (m)	50	Unrestricted
Turning Basin Diameter (m)	270 (2)	550 (2)
Water Depth at Berth (m)	10 (2)	12.1 (2)
Quay Wall Length (m)	≈310	≈485
Laydown Area (Ha)	20	40
Wet Storage Area in Sheltered Waters (Ha)	4	70
Bearing Capacity at Quayside (t/m^2)	20	50
Bearing Capacity at Laydown Area (t/m^2)	10	20

Notes:

(1) Driven by the space requirements recommended for floating foundations (refer to Table 45).

(2) Driven by the design fleet navigation requirements (refer to Table 44

Table 52. Port Requirements for O&Ms Port.

Parameter	Min	Max
Distance to Offshore Wind Farm	Unrestricted	Unrestricted
Channel Width (m)	-	90
Channel Depth (m)	-	8.1
Air Draft (m)	50	Unrestricted
Turning Basin Diameter (m)	-	200
Water Depth at Berth (m)	-	7.1
Laydown Area (Ha)	1	4

Notes:

(1) Navigation requirements estimated a SOV up to 100-m LOA, 14-m beam, and 6-m draft. The minimum values will depend on the lower bound vessel considered in the SOV fleet.

7 Environmental Impact

Floating wind arrays as technical installations impact the environment. This environmental impact is recognized now and politically acknowledged. The Ostend Declaration [50] signed in April 2023 by nine European countries, for example, states: "We will take all relevant and appropriate steps to advance the balanced coexistence of renewables deployment, biodiversity and environmental protection, as well as to contribute to healthy and robust marine ecosystems."

However, one major challenge is the lack of standardized practices to evaluate environmental impact. Universal criteria and limits of demographic and cumulative impacts on species have not been established. Moreover, environmental impact is highly site-specific, and its determination requires expert knowledge. Suitable techniques for monitoring, data collection, simulation, and analysis must be further developed and integrated in regulatory frameworks. This includes environmental responses during all phases of a wind array life cycle, from pre-construction to post-decommissioning. Valuation methods to define trade-offs between environmental, social, and techno-economic aspects are necessary for sustainably developing offshore wind [51]. It could also be beneficial to exchange information about environmental risks with other maritime industries.

The following are planning and design considerations that can determine a floating array's environmental impact:

- **Marine spatial planning** considers the proximity to sensitive habitats of birds and marine species by the definition of exclusion zones that constrain the available areas. Examples of relevant constraining areas are fish spawning grounds, feeding grounds and reefs, and overlaps with migration routes of larvae, fish, and marine mammals. Above water, relevant factors include existing seabird and migrating bird distribution, the distance to closest colonies, and the vulnerability of regional species. These factors depend on the specific location and require local judgement.
- **Structural design choices** like the type of material used and the shape of structures (linking to amount of material) affect the sourcing of materials and the extraction and production methods. The material also impacts the extent and consequences of pollution during operation, decommissioning, end-of-life, and waste treatment, leading to the overall carbon footprint and environmental impact of the value chain on biodiversity and land use.

  Impacts during operation: Depending on the species, the disturbance can result in displacement and/or attraction by the wind farm. Above water, birds and bats are at risk of colliding with wind turbines [52]. Below water, both fish and marine mammals are at risk of secondary entanglement in ghost gear from fishing activities that gets entangled at mooring lines [53–55]. Acoustic emissions from operating offshore wind turbines impact fish and other animals [56,57]. The noise associated with thrumming lines and the electromagnetic fields around cables can impact fish, marine mammals, and other animals. Moreover, biofouling will occur and influence fish. Anchors and catenary mooring lines laying on the seafloor influence the substrate conditions and benthic ecosystems. The energy extraction creates wake effects and can change the ocean mixing. Larger wind arrays affect the local wind conditions for several kilometers. There are concerns about the impact of wind-wave effects on upwelling. Moreover, design choices affect also O&M activities, which again can have an environmental impact. Examples of design choices include the use of reliable components and predictive maintenance, which can reduce the total amount of material needed and the risk of pollution caused by failures.

Design measures to mitigate the negative environmental impact include:

- Avoiding long mooring lines and cables to prevent entanglement
- Painting the tower or one blade to create visual obstacles to prevent bird collisions [57]
- Installing monitoring systems for mooring lines to detect entanglement
- Installing monitoring systems that allow active adjustment of the operation such as turbine shutdown or altered rotor speed to avoid bird and bat collisions
- Using nature-inclusive design options to create a positive impact, for example, artificial reefs and cod hotels [58].

In summary, the environmental impact of floating wind arrays is highly site-specific, and suitable monitoring and evaluation methods are still lacking. Therefore, this report assumes that marine spatial planning ensures that a site with the least expected negative impact on the environment (as a trade-off for social and techno-economic aspects) is selected for the floating wind array. Moreover, structural design choices of single elements in the array, including life cycle considerations of materials, are excluded because IEA Task 49 builds on existing components. The mooring line and cable lengths are the only design parameter identified here with immediate environmental impact. Other design options that mitigate a potentially negative environmental impact involve installing add-ons like additional monitoring equipment. Therefore, the reference sites for the design of floating wind arrays do not include building blocks or parameter sets for the class of environmental impact. We acknowledge, however, that criteria for the environmental impact should be considered in future reference sites and should possibly be based on future consenting processes and regulations.

8 Social Impact

The installation and operation of floating wind arrays also has social-technical dimensions. These are site-specific like the environmental impacts and require careful evaluation and judgment to ensure that the technical installations do not readily supersede the interests of other stakeholders.

Coexistence is a keyword in this context, and it means to respect and maintain the interests and rights of other sea users, including nonhuman species. Within this report, nonhuman species are addressed in the previous section on environmental impact. The remainder of this section will focus on human stakeholders.

The following are planning and design considerations that can determine a floating array's social impact:

- **Marine spatial planning** contemplates the opening of sea areas for wind energy with interests from other stakeholders. There are obvious exclusion zones (marine protected areas, military zones, shipping routes), but it is also important to consider the local communities and their ecological knowledge. It is difficult to establish guidelines for selecting trade-offs to balance different interests when selecting sites for floating wind arrays.
- **Structural design choices** can affect fisheries that are active in the same area. Anchoring systems and cables provide a risk of entanglement for fishing gear. Thus, the length, curvature, and strength of mooring lines have a potentially large impact on fishing activities. Due to the potential interference of the mooring design with other sea users, increased spacing between wind turbines could be beneficial for co-use cases. The impact of component design and materials on humans is present throughout the life cycle, affecting human rights, working conditions, and health and safety. This socioeconomic dimension has employment and value-added ripple effects in other industries. The choice of material affects the ability to provide local content, e.g., substructures made from concrete instead of steel. Using local content could help fulfil requirements in consenting and route-to-market processes.
- **Impacts during operation** like changed wind patterns, acoustic noise, and visual impacts can affect local interests after installation. The social issue of who owns and has the right to "harvest" the wind is a significant consideration. Social impacts related to noise and view are expected to increase the closer the floating wind array is to the shore. Depending on the characteristics of the area (e.g., level of tourism, port/beach community, historical site) and related demographics of its community (e.g., employment rates in tourism or at ports), operational impacts can greatly affect the local economy.

Design measures to alleviate a potentially negative impact on other stakeholders include:

- Real-time marking of mooring lines (especially the location of anchors) for safety considerations in co-use cases of the marine space.
- Long-term stakeholder engagement with the goal of moving from community acceptance to involvement. If the community is not continuously involved throughout the process, the initially positive attitude of affected communities often decays over time. Hybrid models between developer-led and community-led projects have experienced success.

> Monitoring is a prerequisite to effectively assess the socioeconomic impact and develop strategies for good practices of stakeholder engagement and coexistence [59].

In summary, the social impact assessment of floating wind arrays is challenging. To quantify the social impact, valuation methods are needed to balance techno-economic, environmental, and social parameters. Besides the selection of the overall offshore energy technology and the selection of the site, there are few examples for specific structural design choices that have a direct socioeconomic impact. For example, more use cases and knowledge about coexistence in the marine area are required to define quantitative criteria that allow for qualified decisions. Currently, potential impacts must be carefully considered in collaboration with stakeholders and local communities to ensure that wind energy is developed in a sustainable and equitable manner. Therefore, the reference sites for the design of floating wind arrays do not include building blocks or parameter sets for the class of socioeconomic impact. We acknowledge, however, that criteria for social impact should be considered in future reference sites and possibly be based on future consenting processes and regulations.

9 Permissions and Regulations

The permissions and regulations for the development of offshore wind power depend on country-specific considerations. An assessment of key process steps for project implementation showed large variation between European countries [60]. Despite the experiences from land-based wind development and the increasing number of completed offshore wind projects, the administrative assessment and permission processes are still under development. Process-related issues, conflicts concerning the wind resource as public good, third-party issues, and grid issues have been identified as relevant key barriers challenging offshore wind developers. This applies to both fixed-bottom and floating wind turbines.

National authorities and the European Union are working on updated permission processes to accelerate the green energy transition. In Norway, for example, the regulatory framework for the use of renewable offshore energy, including wind [61], is under development. In the European Union, an amendment to the renewable energy directive [62] has recently been approved by the European Parliament [63]. Moreover, in her State of the Union Address on 13 September 2023, European Commission President Ursula von der Leyen announced the European Wind Power package to accelerate permission procedures and improve the auction systems across the EU [64]. On 24 October 2023, The European Commission released the European Wind Power Action Plan, which outlines acceleration of deployment and improved auction design as two of the six main pillars [65].

In summary, permissions and regulations for offshore wind power projects are highly country-specific and currently under development. This applies to fixed-bottom offshore wind and even more to floating wind, which is still an immature technology. Specific conditions for the techno-economic design as targeted by IEA Wind Task 49 Reference Sites are not directly addressed in these regulations. Given this lack of clear regulations for offshore wind even in single countries, a general categorization of permissions and regulations relevant for the techno-economic design of floating wind arrays is not applicable. Therefore, the reference sites for the design of floating wind arrays do not include building blocks or parameter sets for the class of permissions and regulations.

10 Summary and Conclusion

A building block concept was developed for the synthesis of reference sites for the design of floating wind arrays. The building blocks include three classes of site conditions: metocean conditions, seabed conditions, and coastal infrastructure. The eleven blocks for the metocean conditions represent the international global floating wind deployment pipeline. Metocean data for 69 sites was included in the analysis categorizing wind and sea states into mild, lower-moderate, upper-moderate, and severe conditions. Based on this categorization, the eleven representative sites with available data are selected. For the seabed conditions, three blocks with two sub-scenarios each are defined, representing different combinations of soil conditions. The class of coastal infrastructure includes three blocks with different ports, namely integration port, floater manufacturing port, and an O&M port.

The building blocks for the IEA Wind Task 49 Reference Sites focus on parameters for the techno-economic design of floating wind arrays. Although identified as relevant, no building blocks are provided for social impacts, environmental impacts, or regulations and permissions due to a lack of knowledge and data. However, the building block concept provides the flexibility to extend the reference sites when relevant knowledge and quantifiable data become available for these categories.

The supporting datasets are published and available as open-source [1]. The characteristics of the reference sites will be used to inform the design of the reference floating wind arrays in Work Package 2 of IEA Wind Task 49.

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Appendix A. Hannibal Preliminary Metocean Study

Authors: Davide Airoldi (RSE, Italy); Roberto Naldi (RSE, Italy)

A.1 Wind

Both wind speed datasets at 10-m and 150-m hub height are extrapolated from AEOLIAN (https://atlanteeolico.rse-web.it/), the new Italian wind atlas developed by RSE by means of a novel approach combining Weather Research and Forecasting (WRF) based numerical weather modeling with the Analog Ensemble (AnEn) statistical technique. Datasets cover a period of 30 years, from 1990 to 2019 [19].

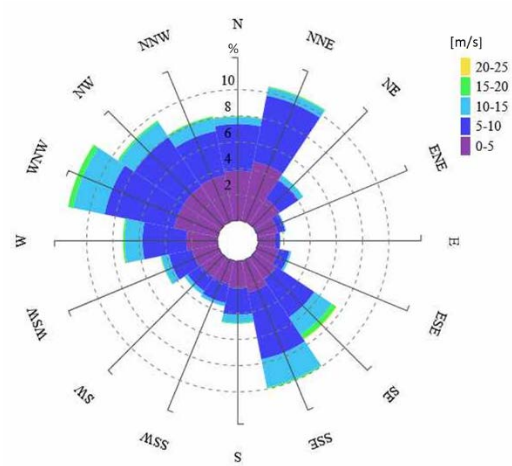


Figure A-1. Wind rose at 10 m hub height

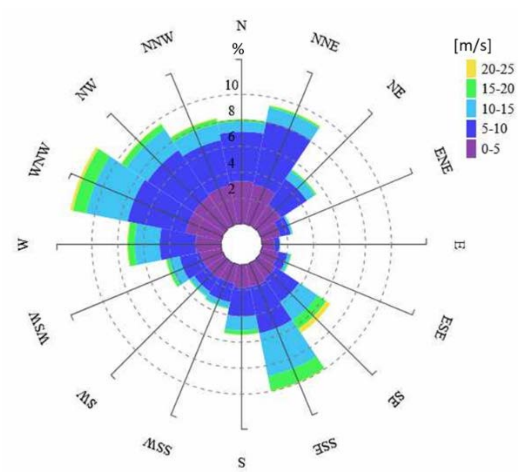


Figure A-2. Wind rose at 150-m hub height

Annual/monthly minimum, mean and maximum values are shown in the following tables.

Table A-1. Annual Minimum, Mean, and Maximum Value for Each Year at 10-m Hub Height

Year	Min Value (m/s)	Mean Value (m/s)	Max Value (m/s)
1990	0.40	6.12	19.02
1991	0.50	6.22	27.93
1992	0.63	6.11	21.56
1993	0.56	6.25	21.19
1994	0.44	6.32	21.61
1995	0.42	6.46	19.12
1996	0.63	7.03	19.81
1997	0.58	6.15	20.17
1998	0.57	6.32	21.10
1999	0.54	6.45	19.43
2000	0.59	6.37	20.59
2001	0.49	6.46	21.25
2002	0.44	6.42	20.23
2003	0.40	6.28	21.91
2004	0.54	6.36	23.62
2005	0.50	6.34	20.53
2006	0.40	6.09	20.15
2007	0.55	6.22	20.02
2008	0.53	6.31	24.79
2009	0.49	6.41	20.93
2010	0.63	6.88	19.62
2011	0.51	6.06	21.71
2012	0.62	6.45	20.46
2013	0.64	6.47	23.66
2014	0.49	6.39	20.59
2015	0.09	6.20	20.10
2016	0.08	6.43	22.65
2017	0.05	6.20	23.09
2018	0.03	6.28	22.05
2019	0.12	6.71	25.08

Table A-2. Annual Minimum, Mean, and Maximum Value for Each Year at 150-m Hub Height

Year	Min value (m/s)	Mean value (m/s)	Max value (m/s)
1990	1.13	7.23	25.60
1991	1.12	7.34	35.29
1992	1.26	7.25	27.18
1993	1.21	7.50	27.39
1994	1.11	7.57	27.30
1995	1.10	7.72	25.70
1996	1.14	8.40	26.68
1997	1.12	7.30	27.24
1998	1.29	7.52	27.62
1999	1.26	7.73	27.39
2000	1.09	7.60	27.89
2001	1.08	7.68	28.07
2002	1.34	7.76	29.21
2003	1.10	7.50	25.97
2004	1.14	7.54	29.16
2005	1.12	7.52	25.27
2006	1.27	7.31	25.34
2007	1.18	7.39	26.30
2008	1.33	7.50	28.39
2009	1.34	7.65	28.85
2010	1.14	8.29	25.93
2011	1.26	7.14	27.13
2012	1.06	7.70	26.68
2013	1.10	7.79	31.39
2014	1.26	7.61	26.78
2015	0.12	7.30	26.64
2016	0.09	7.72	28.00
2017	0.12	7.28	30.64
2018	0.07	7.50	30.35
2019	0.06	8.03	34.32

Table A-3. Monthly Minimum, Mean, and Maximum Value at 10-m Hub Height

Month	Min value (m/s)	Mean value (m/s)	Max value (m/s)
January	0.14	7.33	23.62
February	0.12	7.38	21.98
March	0.13	7.19	23.66
April	0.03	6.68	25.08
May	0.21	5.69	23.09
June	0.05	5.03	19.18
July	0.13	4.94	16.90
August	0.08	4.90	21.91
September	0.13	5.81	24.79
October	0.08	6.37	20.02
November	0.12	7.37	27.93
December	0.25	7.69	23.67

Table A-4. Monthly Minimum, Mean, and Maximum Value at 150-m Hub Height

Month	Min value (m/s)	Mean value (m/s)	Max value (m/s)
January	0.26	8.59	29.16
February	0.12	8.69	29.02
March	0.15	8.73	31.39
April	0.12	8.33	34.32
May	0.12	7.29	30.64
June	0.13	6.27	26.03
July	0.14	5.81	20.56
August	0.07	5.57	18.78
September	0.20	6.68	28.19
October	0.06	7.43	27.24
November	0.13	8.64	35.29
December	0.09	9.02	29.08

An extreme value analysis has been conducted on the dataset at 10-m hub height using the "generalized extreme value" methodology with "block maxima" approach (1-year temporal window). Values for 150 m have been calculated with the Frøya equation.

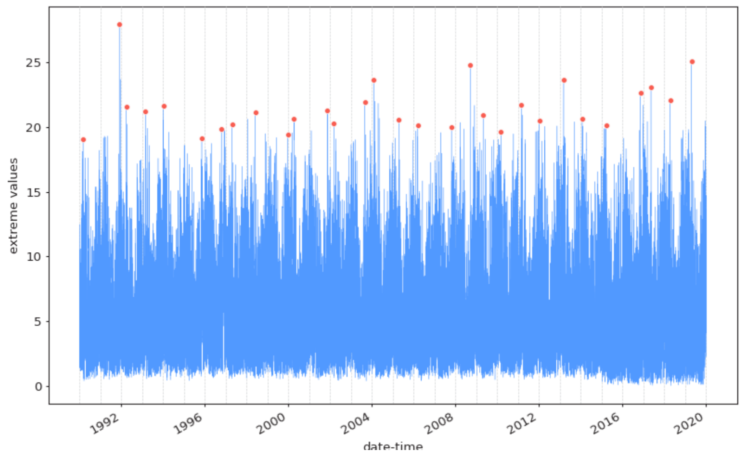


Figure A-3. Peak values for each year of 10-m dataset

Table A-5. Return Values for Wind Speed

Return Period (years)	Wind Speed at 10 m (m/s)	Wind Speed at 150 m (m/s)
5	24.58	33.12
10	26.06	35.11
20	27.70	37.31
50	30.19	40.66
100	32.37	43.61
500	38.74	52.18

A.2 Wave

For wave characteristics the DICCA MeteOcean Re-Analysis[1] has been used [66]. The wave dataset covers a period of 41 years, from 1979 to 2020.

[1] http://www3.dicca.unige.it/meteocean/hindcast.html

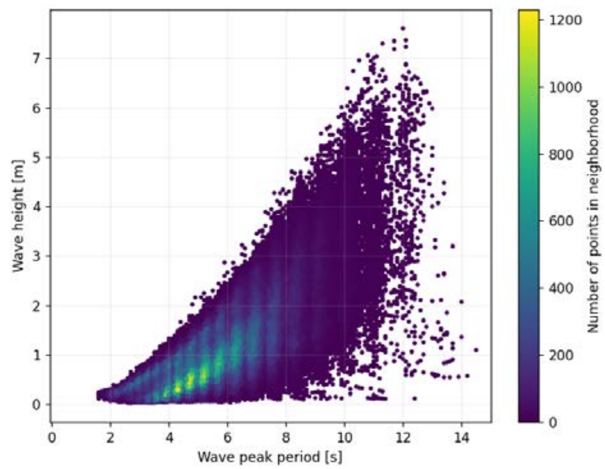


Figure A-4. Density scatter plot for wave dataset

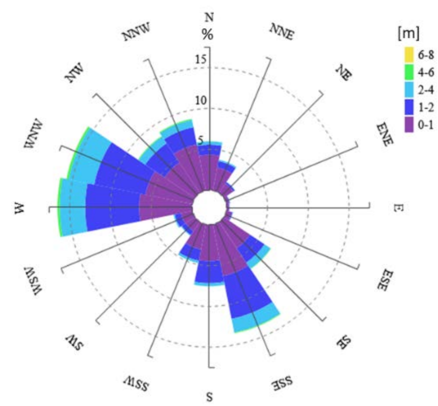


Figure A-5. Wave rose based on significant wave height classification

Also in this case, due to the availability of a long period of data, the block maxima approach and generalized extreme value have been conducted as analysis on extreme events.

Table A-6. Return Values for Wave

Return Period (years)	Wave Height (m)	Minimum Peak Period (s)	Maximum Peak Period (s)
5	6.67	9.16	11.80
10	7.17	9.49	12.22
20	7.65	9.80	12.63
50	8.30	10.21	13.16
100	8.81	10.52	13.55
500	10.04	11.23	14.47

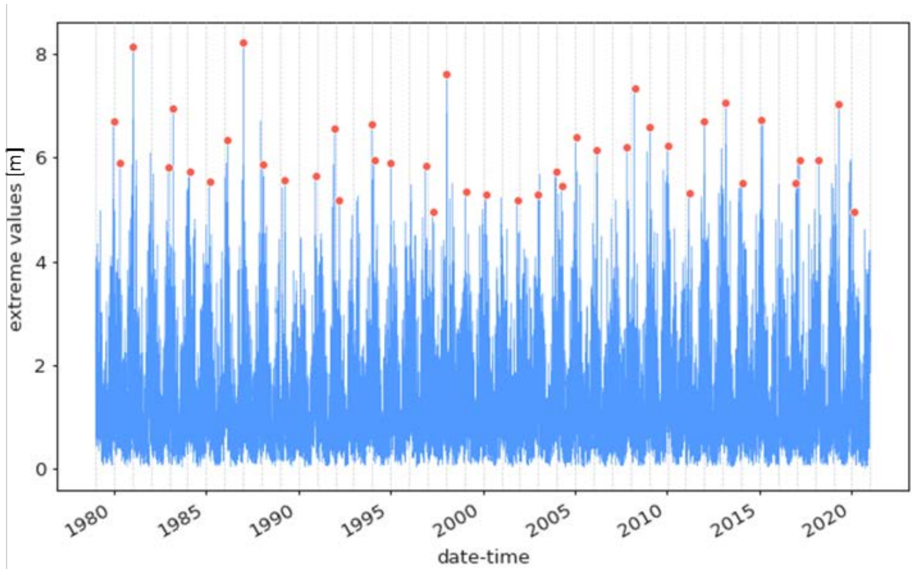


Figure A-6. Peak values of significant wave height

A.3 Wind-Wave Correlation

The relationship between waves and wind is shown in the next table and figure.

Table A-7. Lumped Scatter Diagram

Wind Speed (m/s)	Mean Wave Peak Period (s)	Mean Wave Height (m)	Occurrence (%)
2	5.31	0.58	13.54
4	5.36	0.68	25.87
6	5.67	0.94	23.81
8	6.21	1.35	15.97
10	6.70	1.78	10.23
12	7.30	2.30	5.82
14	7.91	2.86	2.73
16	8.55	3.49	1.02
18	9.13	4.12	0.33
20	9.18	4.51	0.09
22	9.57	5.18	0.02
24	9.30	4.89	0.01
26	9.20	4.27	0.00
28	7.80	2.47	0.00

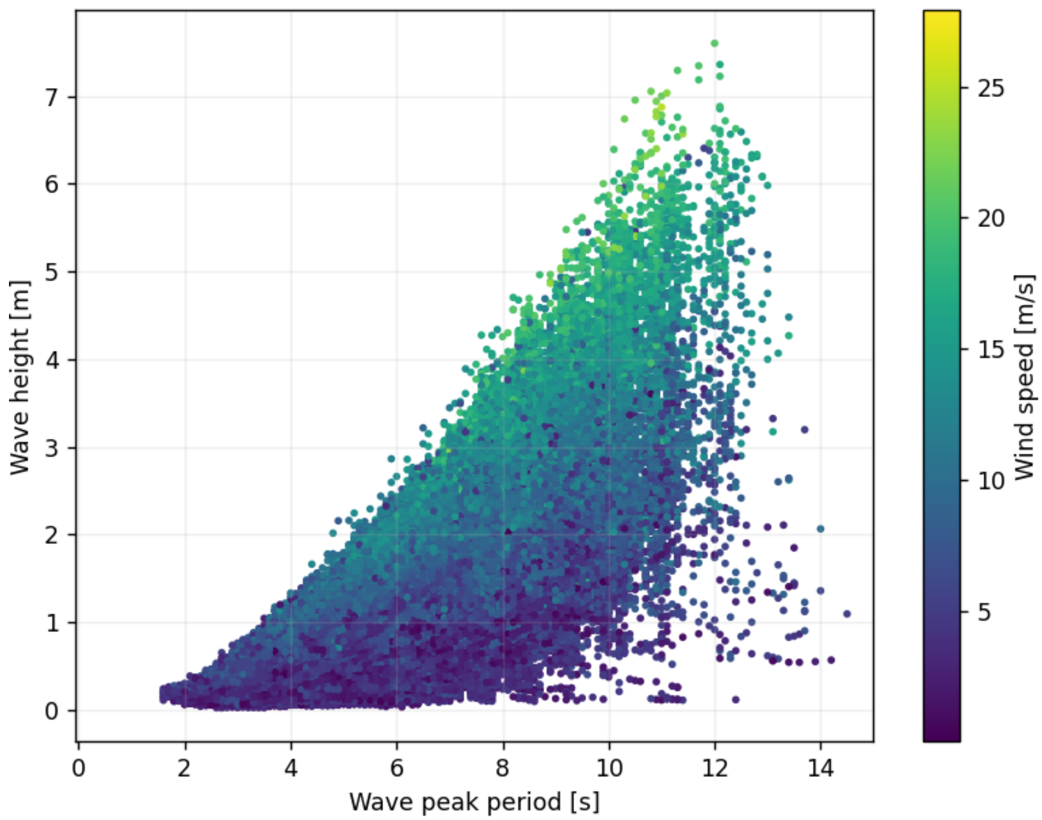


Figure A-7. Scatter diagram with H_s, T_p, and V_{hub} at 10-m parameters

Appendix B. Humboldt Preliminary Metocean Study

Authors: Michael Biglu (NREL, United States); Matthew Hall (NREL, United States); Ericka Lozon (NREL, United States)

The Humboldt reference site is based on conditions representative of the Humboldt Bay lease areas, OCS-P0561 and OCS-P0562, awarded by BOEM in 2023. The water depths of the leased areas range from 550 m to 1,300 m. The target location (40.928°, -124.708°) is the centroid of the western lease area because it is located further offshore (25 nm to shore) and in deeper waters (800 m) than the adjacent lease area. This can lead to slightly higher loads and is therefore considered representative for both lease areas. More information is available in [22] and the dataset is available on the NREL Data Catalog (https://data.nrel.gov/submissions/241).

The data sources are as follows:

- Wind data: 2023 National Offshore Wind dataset (NOW-23) is the latest wind resource dataset for offshore regions in the United States [67,68]. It was made using the Weather Research and Forecasting Model (WRF) for distinct regions of the United States, with an initial horizontal grid spacing (before refinement) of 6 km and 61 vertical levels.
- Wave data: Measurements from National Data Bouy Center (NDBC) buoys [69].
- Current data: Measurements from the Integrated Ocean Observing System (IOOS), which is a network of high-frequency radar systems (HFRNet), operated by the Scripps Institution of Oceanography [70].

The wind data (from the NOW-23 dataset) were interpolated directly at this location. All other data sources were chosen based on their proximity to this location and the data coverage of respective stations. Figure B-1 shows the data source locations, and the details are listed in Table B-1. The measurement data were only used from 2000 onward, although station 46022 covers a much longer period. This was done to have similar time periods for the extrapolation compared to other parameters and thus achieve a comparable level of accuracy.

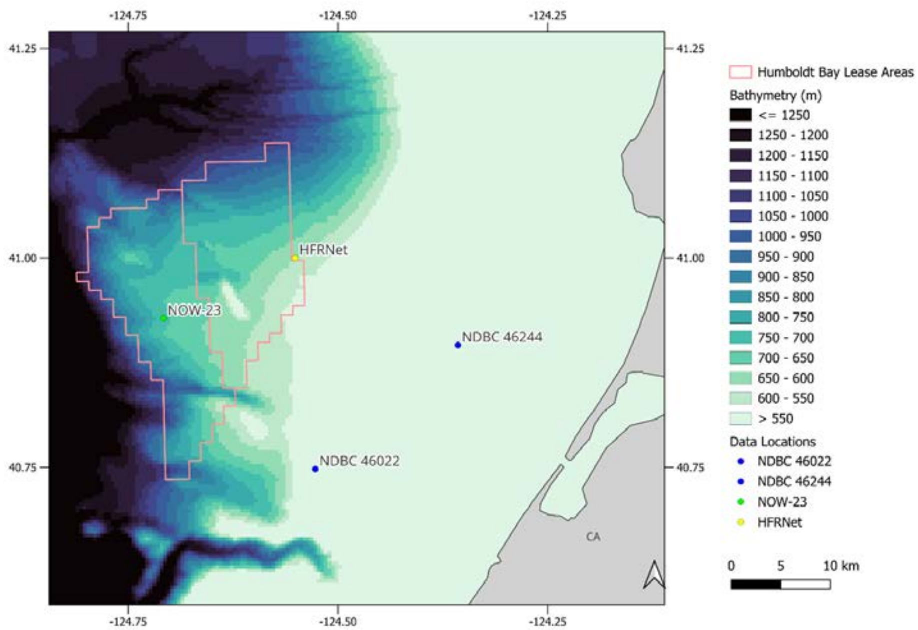


Figure B-1. Humboldt Bay metocean data sources

Table B-1. Humboldt Bay Locations of Data Sources and Covered Years per Data Type

The metocean analysis uses data from 2000 to 2020 to have a consistent time span

Data type	Data sources	Latitude (deg)	Longitude (deg)	Water depth (m)	Distance to shore (nm)	Start year	End year
Wave/ metocean (primary)	NDBC station 46022	40.748	-124.527	419	12	1982	2022
Wave/ metocean (secondary)	NDBC station 46244	40.896	-124.357	110	8	2010	2022
Wind	NOW-23	40.928	-124.708	800	25	2000	2022
Current	HFRNet	41	-124.551	600	20	2012	2023

NDBC station 46022 (12.5 nm distance to target location) was used as the primary source for wave and wind at buoy level data. The station is moored at water depth of 419 m and 12 nm off Humboldt Bay. NDBC station 46244 (110-m water depth, 8 nm to shore) was used to fill wave data gaps of station 46022, especially for wave directions, because only about 9 years of directional wave data were available from station 46022. The distance between these stations is 12 nm.

The closest available high-frequency radar current measurements grid point location was found at the boundary of the eastern lease area, at 8.5 nm off the target location, which provides 13 years of almost continuous ocean current measurements. NDBC station 46022 provided 2 years of discontinuous current measurements only, so the radar measurement is better choice for the present application.

Analysis of extreme values for wind speeds was done by computing the monthly maxima of each time series and then fitting a generalized extreme value distribution to those maxima. Extreme values can then be read off the distribution. For wave and current speed, due to the larger presence of suspect data, daily or sub-daily peaks were instead computed, then fit using a Weibull distribution, which gave more consistent results. For conditional extreme values, the wave and current time series were filtered based on wind speed bins of 2 m/s before doing the monthly maxima. Unconditional and conditional extreme values of wave height, wave period, and current speed, for wind speed bins of every 2 m/s, are given in Table B-2.

Table B-2. Conditional Extreme Metocean Values for Humboldt Bay

Wind speed (m/s)	Wind Dir. (deg)	Wave Dir. (deg)	Significant Wave Height (m)						Peak Wave Period (s)						Curr. Dir. (deg)	Current Speed (m/s)					
			Return Period (years)						*Return Period (years)*							*Return Period (years)*					
			1	*5*	*10*	*50*	*100*	*500*	*1*	*5*	*10*	*50*	*100*	*500*		*1*	*5*	*10*	*50*	*100*	*500*
All	339	302	8.5	9.8	10.4	11.8	12.4	13.7	16.8	18.1	18.6	19.8	20.3	21.4	264	0.92	1.09	1.15	1.28	1.33	1.44
0-2	287	295	5.4	6.9	7.6	9.1	9.8	11.4	13.4	15.2	15.9	17.4	18.1	19.5	278	0.27	0.65	0.73	0.88	0.93	1.04
2-4	301	294	6.4	8.2	8.9	10.8	11.6	13.6	14.6	16.5	17.2	18.9	19.7	21.3	269	0.55	0.81	0.89	1.06	1.12	1.25
4-6	318	296	6.8	8.4	9.1	10.8	11.6	13.3	15.0	16.7	17.4	19.0	19.6	21.0	261	0.60	0.83	0.90	1.04	1.09	1.19
6-8	330	297	7.1	8.9	9.7	11.6	12.5	14.4	15.3	17.2	18.0	19.7	20.4	21.9	264	0.63	0.86	0.93	1.08	1.13	1.24
8-10	334	300	7.0	8.6	9.3	11.0	11.8	13.5	15.2	16.9	17.6	19.2	19.8	21.2	267	0.67	0.89	0.95	1.06	1.10	1.18
10-12	340	304	6.7	8.3	9.0	10.5	11.2	12.8	15.0	16.6	17.2	18.7	19.3	20.6	259	0.70	0.89	0.94	1.03	1.06	1.12
12-14	342	309	6.4	7.6	8.1	9.3	9.8	10.9	14.6	15.9	16.4	17.6	18.0	19.0	263	0.70	0.89	0.95	1.06	1.09	1.17
14-16	345	312	6.2	7.3	7.7	8.7	9.2	10.1	14.3	15.5	16.0	17.0	17.5	18.3	261	0.64	0.87	0.94	1.07	1.12	1.22
16-18	346	310	6.1	7.1	7.5	8.4	8.7	9.6	14.2	15.3	15.8	16.7	17.0	17.8	257	0.58	0.84	0.90	1.03	1.08	1.17
18-20	346	309	6.0	7.0	7.4	8.2	8.6	9.3	14.2	15.2	15.7	16.5	16.9	17.6	257	0.51	0.83	0.90	1.03	1.07	1.15
20-22	348	309	6.0	7.1	7.6	8.6	9.0	10.0	14.1	15.4	15.8	16.9	17.3	18.3	272	0.62	0.85	0.91	0.96	0.97	0.98
22-24	350	308	5.9	7.1	7.5	8.6	9.1	10.1	14.1	15.3	15.8	16.9	17.4	18.3	271	0.52	0.73	0.86	0.97	0.98	0.99
24-26	167	294	6.0	7.3	7.9	9.3	9.9	11.4	14.1	15.6	16.2	17.6	18.2	19.4	329	0.34	0.62	0.75	0.90	0.95	1.03
26-28	166	267	5.6	7.0	7.5	8.7	9.2	10.3	13.6	15.2	15.8	17.0	17.5	18.5	91	0.3	0.58	0.71	0.9	0.95	1.05

A maximum dissimilarity algorithm was used to generate 100 clusters of the hourly metocean data points, representing 100 fatigue bins that can be used for fatigue loads analysis. The parameters of these bins are provided in Table B-3.

Table B-3. Metocean Joint Probability Fatigue Clusters for Humboldt Bay

			Cluster Centroid						Cluster Standard Deviation				
Bin number	Number of data points	Cluster probability	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
1	9291	0.072158	354	11.2	334	1.93	7.4	0.059	4.6	1.8	5.4	0.41	0.9
2	8528	0.066232	356	13.4	333	2.86	8.9	0.057	4.7	1.8	7.9	0.47	0.9
3	7551	0.058644	354	9.8	312	1.49	7.8	0.063	5.5	2.0	4.7	0.43	1.2
4	4735	0.036774	352	12.5	295	2.44	11.2	0.057	5.4	2.0	6.3	0.56	1.4
5	4727	0.036712	1	7.1	287	2.01	13.1	0.071	4.8	2.1	5.6	0.58	1.0
6	4646	0.036083	357	8.4	319	2.47	11.5	0.063	6.6	2.1	5.1	0.57	1.1
7	4485	0.034832	351	4.9	325	1.44	8.4	0.088	7.8	1.8	5.4	0.49	1.1
8	3935	0.030561	340	4.7	292	1.73	11.2	0.088	5.2	2.1	6.5	0.58	1.3
9	3713	0.028837	356	8.0	284	1.29	9.4	0.071	5.7	2.1	5.1	0.43	1.3
10	3367	0.026149	351	19.4	332	3.53	8.9	0.055	3.8	2.2	9.1	0.69	1.1
11	3312	0.025722	15	4.4	298	1.53	10.5	0.088	5.2	1.8	6.8	0.55	1.4
12	2380	0.018484	358	7.3	294	3.82	14.1	0.071	6.7	2.6	7.5	0.66	1.4
13	2213	0.017187	357	8.1	353	1.82	7.9	0.063	7.2	2.4	5.0	0.56	1.2
14	2087	0.016208	215	4.1	324	1.52	8.7	0.088	8.8	2.1	7.2	0.46	1.1
15	1908	0.014818	178	4.0	300	1.83	11.4	0.138	6.5	2.0	6.0	0.60	1.3
16	1776	0.013793	354	13.8	329	3.92	12.6	0.057	5.5	2.5	7.3	0.73	1.4
17	1744	0.013545	307	3.5	286	1.96	12.1	0.138	5.9	1.9	7.0	0.65	1.6
18	1734	0.013467	211	5.2	282	1.47	9.9	0.088	5.8	2.3	6.7	0.52	1.4
19	1722	0.013374	178	15.3	287	2.11	11.4	0.056	5.2	1.9	6.1	0.67	1.1
20	1607	0.012481	194	9.8	277	2.20	12.3	0.063	5.7	1.7	5.9	0.65	1.1
21	1597	0.012403	237	3.6	292	2.03	11.8	0.138	5.9	1.9	7.2	0.68	1.3
22	1594	0.012380	34	3.4	287	2.51	13.4	0.138	6.3	1.8	8.4	0.89	1.3
23	1566	0.012162	352	16.6	295	3.78	13.6	0.055	5.6	2.6	6.1	0.73	1.8
24	1552	0.012053	297	3.1	317	1.55	9.0	0.138	9.0	1.7	8.8	0.51	1.3
25	1503	0.011673	184	8.9	328	1.67	8.6	0.063	6.6	2.8	6.5	0.52	1.3
26	1442	0.011199	14	5.6	290	2.27	16.7	0.088	6.4	2.4	6.5	0.72	1.6
27	1431	0.011114	346	6.0	289	1.87	16.4	0.071	6.2	2.8	5.7	0.62	1.6
28	1424	0.011059	201	4.5	285	1.91	14.2	0.088	6.7	2.2	5.7	0.59	1.2
29	1393	0.010819	356	7.1	245	1.09	15.2	0.071	6.6	2.7	5.9	0.41	1.6
30	1350	0.010485	314	8.9	309	3.15	11.8	0.063	7.0	2.6	8.8	0.66	1.3
31	1341	0.010415	182	12.4	293	2.40	14.6	0.057	5.6	2.1	6.8	0.67	1.2
32	1286	0.009988	183	9.1	295	1.39	8.8	0.063	7.0	2.7	5.7	0.47	1.4
33	1252	0.009724	173	18.4	293	3.28	14.1	0.055	6.0	2.0	6.5	0.64	1.5
34	1250	0.009708	166	10.5	295	2.32	12.1	0.059	6.8	2.0	6.4	0.64	1.1
35	1233	0.009576	47	3.2	319	1.72	9.5	0.138	9.4	1.8	7.6	0.65	1.6
36	1228	0.009537	178	5.0	268	1.59	11.0	0.088	6.2	2.2	6.0	0.63	1.5
37	1211	0.009405	272	3.8	281	1.68	10.2	0.138	7.3	2.2	7.1	0.63	1.7
38	1157	0.008986	138	3.2	282	1.73	12.5	0.138	7.6	1.9	7.2	0.71	1.7
39	1154	0.008962	178	15.4	264	3.47	13.2	0.056	6.4	2.2	5.8	0.71	1.4

Bin number	Number of data points	Cluster probability	Cluster Centroid: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Cluster Standard Deviation: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
40	1139	0.008846	203	6.9	292	3.48	12.8	0.071	6.0	2.3	6.7	0.57	1.2
41	1071	0.008318	179	13.8	259	1.94	8.8	0.057	5.6	2.4	6.4	0.55	1.5
42	1064	0.008263	169	4.7	291	3.87	14.4	0.088	7.1	2.2	7.9	0.79	1.5
43	994	0.007720	358	10.6	317	2.88	16.1	0.059	6.0	2.4	7.5	0.75	1.7
44	934	0.007254	359	5.9	252	1.43	9.8	0.088	9.5	2.6	8.7	0.61	1.6
45	933	0.007246	181	13.6	285	4.36	16.3	0.057	6.2	2.7	7.9	0.72	1.6
46	913	0.007091	317	4.4	295	3.98	14.2	0.088	7.0	2.1	7.7	0.76	1.6
47	867	0.006733	355	7.5	212	1.08	15.4	0.071	5.8	2.5	5.5	0.31	1.5
48	847	0.006578	258	6.3	319	2.84	11.6	0.071	7.8	3.1	7.3	0.75	1.5
49	800	0.006213	125	3.2	317	1.67	9.4	0.138	9.9	2.1	7.9	0.52	1.5
50	762	0.005918	79	2.4	291	2.16	14.1	0.138	7.1	1.4	8.2	0.87	1.9
51	762	0.005918	225	12.7	286	3.76	12.3	0.057	7.1	2.7	9.0	0.74	1.5
52	751	0.005833	271	4.2	294	3.18	14.6	0.088	6.6	2.5	7.2	0.80	1.5
53	737	0.005724	167	16.5	201	2.27	7.0	0.055	7.1	2.4	8.2	0.52	1.3
54	729	0.005662	172	23.4	275	4.39	14.3	0.054	6.5	2.8	7.7	0.79	1.8
55	706	0.005483	183	8.1	292	2.18	18.4	0.063	8.2	3.6	8.0	0.75	1.5
56	634	0.004924	112	3.0	297	3.28	13.1	0.138	7.9	1.8	9.2	0.85	1.6
57	615	0.004776	212	9.8	250	2.48	9.6	0.063	7.9	2.8	8.0	0.82	1.5
58	608	0.004722	170	21.1	271	2.98	10.1	0.055	5.9	2.6	7.6	0.60	1.6
59	605	0.004699	273	8.7	279	3.98	12.3	0.063	7.6	3.1	8.7	0.73	1.4
60	605	0.004699	202	5.9	320	2.32	13.4	0.088	7.9	2.8	5.4	0.69	1.5
61	601	0.004668	62	2.4	270	1.49	10.7	0.138	9.5	1.3	9.1	0.61	1.6
62	585	0.004543	169	21.8	204	2.99	7.8	0.055	6.4	2.0	7.4	0.55	1.0
63	552	0.004287	162	9.8	266	4.11	14.1	0.063	8.2	2.6	7.4	0.85	1.4
64	548	0.004256	180	15.4	328	2.89	10.0	0.056	7.1	2.6	8.6	0.68	1.8
65	526	0.004085	167	11.8	239	2.13	10.3	0.059	7.5	2.3	6.8	0.74	1.4
66	523	0.004062	219	5.5	286	4.50	15.4	0.088	7.6	2.5	8.6	0.77	1.5
67	485	0.003767	186	7.8	243	1.36	15.0	0.071	8.1	3.5	6.7	0.61	1.3
68	484	0.003759	135	10.0	288	2.46	15.9	0.063	7.4	3.6	7.6	0.74	2.0
69	434	0.003371	306	11.4	316	5.50	14.1	0.059	9.2	3.0	9.6	0.76	1.5
70	428	0.003324	355	6.6	340	2.09	13.8	0.071	8.0	2.6	7.7	0.81	1.4
71	406	0.003153	241	4.0	285	2.10	16.8	0.138	9.5	2.5	8.6	0.69	1.8
72	382	0.002967	187	17.4	229	3.28	10.3	0.055	8.1	2.4	7.4	0.70	1.4
73	354	0.002749	251	9.7	298	5.44	15.2	0.063	8.0	3.2	9.0	0.80	1.4
74	351	0.002726	224	3.7	218	0.96	14.9	0.138	9.1	2.0	11.1	0.30	1.6
75	341	0.002648	189	12.3	208	1.54	5.8	0.057	7.7	3.1	8.8	0.47	1.4
76	340	0.002641	168	21.9	238	3.87	10.8	0.055	6.8	2.6	5.8	0.70	1.5
77	285	0.002213	305	3.7	235	1.23	14.1	0.138	9.5	2.3	7.9	0.58	2.1
78	279	0.002167	24	3.2	218	0.95	15.1	0.138	8.1	1.5	9.2	0.37	1.7
79	275	0.002136	247	5.6	242	1.74	8.6	0.088	11.0	3.0	10.4	0.75	1.5

Bin number	Number of data points	Cluster probability	Cluster Centroid: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Cluster Standard Deviation: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
80	242	0.001879	175	6.4	207	1.04	15.1	0.071	8.9	3.8	6.9	0.29	1.7
81	240	0.001864	169	27.3	194	4.11	8.6	0.054	5.8	2.6	7.3	0.75	1.1
82	230	0.001786	326	4.0	317	2.42	17.2	0.088	8.9	2.0	9.1	0.83	2.3
83	204	0.001584	138	6.8	230	1.93	9.4	0.071	9.3	3.6	9.5	0.70	1.6
84	185	0.001437	171	27.8	245	5.25	11.7	0.054	6.5	2.8	10.4	1.14	1.9
85	169	0.001313	359	7.5	177	1.07	14.3	0.071	6.9	2.7	7.5	0.34	1.8
86	167	0.001297	204	13.8	274	6.88	16.4	0.057	11.0	3.8	10.2	0.92	1.6
87	137	0.001064	101	2.5	240	1.28	14.1	0.138	11.3	1.7	8.5	0.61	2.0
88	122	0.000947	320	3.1	190	0.95	14.8	0.138	11.5	1.7	10.2	0.28	1.8
89	86	0.000668	358	8.2	147	1.05	16.5	0.063	7.8	2.5	10.3	0.30	1.8
90	65	0.000505	351	6.6	72	0.99	15.5	0.071	13.9	2.7	12.1	0.30	2.0
91	58	0.000450	193	8.5	157	1.15	16.5	0.063	11.2	4.2	10.9	0.39	2.1
92	40	0.000311	166	5.6	344	2.32	17.5	0.088	12.6	4.2	10.2	1.00	1.9
93	38	0.000295	101	2.3	189	0.95	15.0	0.138	11.7	1.7	9.5	0.35	2.0
94	34	0.000264	274	14.4	310	8.71	16.3	0.056	15.0	4.3	8.0	0.93	1.5
95	29	0.000225	359	9.9	13	2.55	20.2	0.063	4.7	3.5	12.4	0.83	2.3
96	17	0.000132	219	4.7	33	1.09	13.2	0.088	13.8	1.8	9.5	0.28	3.4
97	8	0.000062	169	18.9	176	4.13	17.5	0.055	7.0	4.7	18.7	0.93	2.3
98	5	0.000039	184	9.7	67	1.73	19.1	0.063	9.3	4.5	11.6	0.59	1.2
99	3	0.000023	138	4.0	68	1.01	13.6	0.138	7.5	0.7	8.6	0.05	1.1
100	1	0.000008	166	28.0	95	4.26	17.4	0.054	0.0	0.0	0.0	0.00	0.0

Appendix C. Ulsan Preliminary Metocean Study

Authors: Young-Jae Yu (UlsanLab, South Korea); Yong-Yook Kim (IAE, South Korea); Miho Park (IAE, South Korea)

Currently in South Korea, floating offshore wind farms with a total capacity of 9.5 GW to about 11 GW are planned in Ulsan. The five international consortia in Table C-1 are leading the development plan.

Table C-1. Overview of Development Plan for Floating Offshore Wind Farms in Ulsan, South Korea

Floating Offshore Wind Farm Business Plan		Date	Total 9.5 GW (Total 11.5 GW)	Source
5 International consortia	Equinor	Dec. 7, 2022	4 GW (6 GW)	https://www.equinor.co.kr/en
	CIP	June 22, 2022	1.5 GW	https://cop.dk/spink/
	Korea Floating Wind (KFWind)	June 2, 2022	1.2 GW	https://www.offshorewind.biz/2022/06/02/korea-floating-wind-partners-with-east-west-power
	GIG, TotalEnergies	Aug. 11, 2021	1.5 GW	https://www.greeninvestmentgroup.com/en/news/2021/gig-and-totalenergies-obain-ebl-for-koreas-first-floating-offshore-wind-farm.html
	Shell	March 15, 2022	1.3 GW	https://www.offshorewind.biz/2022/03/15/shell-making-further-floating-offshore-wind-moves-in-south-korea/

C.1 Available Dataset

Table C-2 summarizes the data obtained on the site, which is 30 km away from the city of Ulsan. One set of measurement data from Korea Meteorological Administration and two sets of reanalysis data from ECMWF and NASA are utilized.

Table C-2. Data Obtained for Ulsan

Information	Ulsan Buoy	ERA-5	MERRA-2
Type	Measurement	Reanalysis	Reanalysis
Obtain height	5 m	100 m	50 m
Data interval	1 hour	1 hour	1 hour
Dataset	Wind speed, Wind directions	Wind speed, Wind directions	Wind speed, Wind directions
Data period	7 years (2016–2022)	13 years (2010–2022)	43 years (1980–2022)

C.2 Normal Wind Analysis

To select the most accurate profile for the extrapolation of the wind speed at different heights, the two profiles have been checked and compared to each other.

The power law profile:

$$V(z) = V(z_r)\left(\frac{z}{z_r}\right)^{\alpha}$$

The logarithmic profile:

$$V(z) = V(z_r)\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)}$$

With

$V(z)$: wind speed at height z [m/s]

z : height above the still water level [m]

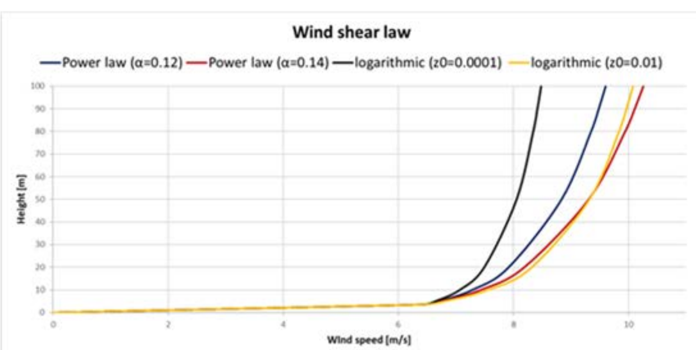
z_r : reference height above the still water level [m]

z_0 : roughness parameter [m]

α : power law exponent [-]

The standard IEC 61400-3-2 [71] recommends for normal wind conditions, $\alpha = 0.14$. The project Lifes50+ uses $\alpha = 0.14$ and $z_0 = 0.0002$ [5].

Figure C-1 shows the wind shear comparing power law profile and logarithmic profile for different parameters. Based on this, a conservative normal wind profile is extracted.

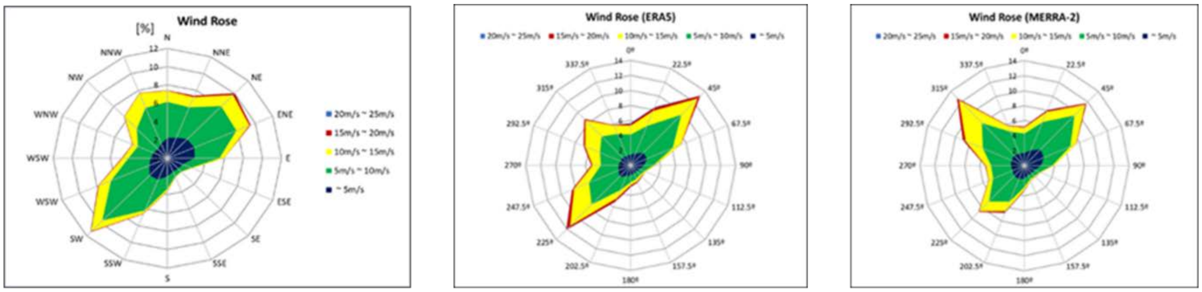


Conservative

Normal Wind Profile	
Height [m]	Speed [m/s]
4.30	6.44
5.00	6.58
10.00	7.25
20.00	7.99
50.00	9.08
90.00	9.86
100.00	10.00

Figure C-1. Comparison of wind shear and result of normal wind profile

The wind roses in Figure C-2 illustrate the wind speed distribution for the different datasets included in this analysis.



Wind rose of Ulsan buoy at 4.3 m height

Wind rose of ERA-5 at 50 m height

Wind rose of MERRA-2 at 100 m height

Figure C-2. Wind roses of each dataset

C.3 Extreme Wind Analysis

The analysis of extreme wind statistics is based on the hub height of 100 m and the Gumbel method is applied which calculates the probability density function (PDF) as

$$f(x) = exp\left\{-exp\left[\frac{-(x-\mu)}{\beta}\right]\right\} \cdot exp\left[\frac{-(x-\mu)}{\beta}\right] \cdot \frac{1}{\beta}$$

and the cumulative probability distribution function (CPF) as

$$F(x) = exp\left\{-exp\left[\frac{-(x-\mu)}{\beta}\right]\right\}$$

With extreme value x, scale parameter β, mode parameter μ and return period R.

The return period R corresponds to the probability that an event will be exceeded, and thus, the extreme values can be calculated as

$$x = \mu - \beta \cdot \ln\left[-\ln\left(1 - \frac{1}{R}\right)\right]$$

Table C-3. Extreme Wind Statistics Analysis Result Using the Gumbel Method

Gumbel Parameter	**Ulsan Buoy**	**ERA-5**	**MERRA-2**
Scale parameter (β)	1.802	3.540	3.511
Mode parameter (μ)	19.798	25.259	22.528
Return Period	**Extreme Wind Speed**		
5 years	33.41 m/s	32.11 m/s	31.51 m/s
10 years	35.41 m/s	34.90 m/s	34.49 m/s
30 years	38.45 m/s	39.11 m/s	39.00 m/s
50 years	39.83 m/s	41.04 m/s	41.06 m/s
100 years	41.70 m/s	43.63 m/s	43.84 m/s
500 years	46.02 m/s	49.63 m/s	50.26 m/s

C.4 Combined Wind-Wave Analysis

To ensure the most accurate correlation with the real sea state conditions, six different equations have been identified through regression analysis (Figure C-3).

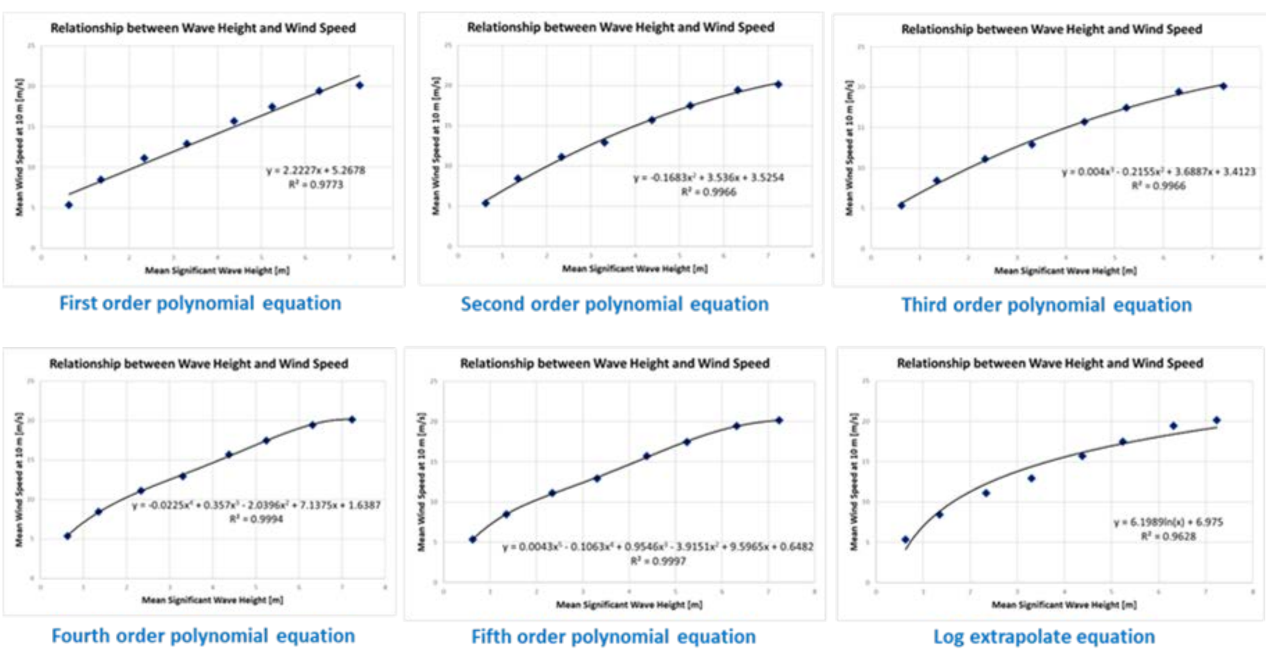


Figure C- 3. Regression analysis for relationship between wind speed and wave height

The figure below shows the relation of the mean wind direction and the wave direction for the misalignment and multi-direction analysis.

[%]		Wind Direction [º]																
		0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	Total
Wave Direction [º]	0	10.67	15.80	18.09	14.66	11.16	9.18	7.76	10.96	15.05	24.81	35.41	28.98	15.85	7.49	8.33	10.62	17.45
	22.5	16.70	12.61	11.55	13.51	9.52	9.59	7.39	7.65	7.63	8.23	9.07	6.90	5.62	6.69	9.74	14.15	10.43
	45	15.37	10.32	9.75	10.74	9.52	11.37	11.83	7.30	4.41	4.89	3.54	3.37	5.78	6.29	13.72	15.59	8.97
	67.5	8.96	7.07	5.25	4.63	4.46	4.66	5.73	4.70	2.69	2.21	1.82	1.79	3.22	6.09	11.88	12.00	5.45
	90	6.03	4.57	3.41	2.52	1.64	2.05	2.03	1.57	2.26	1.01	1.00	0.94	2.89	6.39	9.12	7.33	3.48
	112.5	4.16	3.35	2.23	1.45	1.97	1.92	2.03	0.70	0.75	1.73	1.20	1.14	3.47	6.39	8.21	5.38	2.87
	135	5.66	4.31	2.62	1.40	2.30	2.60	2.59	2.26	3.12	2.33	1.89	2.18	4.46	8.99	6.92	5.33	3.53
	157.5	5.18	6.65	4.19	3.10	3.94	4.52	3.70	5.22	5.05	5.96	4.53	6.25	11.23	9.89	6.92	6.51	5.61
	180	5.87	6.70	6.15	4.79	8.40	10.82	12.75	13.04	11.18	10.85	8.24	8.24	10.32	10.89	5.57	4.72	7.74
	202.5	3.63	3.99	5.60	5.95	7.49	8.49	10.91	9.22	12.37	9.42	3.98	2.98	4.95	4.60	3.12	1.44	5.32
	225	2.24	2.34	4.74	6.44	5.65	6.03	5.73	12.52	4.95	3.22	4.02	4.57	5.12	4.70	2.08	1.79	4.26
	247.5	1.81	2.87	2.94	5.16	5.06	5.07	4.81	3.65	3.33	2.39	2.92	6.50	6.11	3.60	1.47	2.10	3.58
	270	2.08	2.55	3.76	4.92	5.84	4.66	3.70	4.87	3.66	2.86	1.55	2.53	2.31	1.80	1.53	1.69	2.97
	292.5	1.87	3.94	4.46	5.16	4.86	4.25	5.36	5.22	5.81	2.86	2.51	2.83	2.81	3.10	2.14	2.21	3.49
	315	3.47	5.05	5.01	6.07	7.49	5.89	6.28	4.87	6.99	5.37	4.81	5.86	5.53	5.09	3.00	2.67	5.06
	337.5	6.30	7.87	10.26	9.50	10.70	8.90	7.39	6.26	10.75	11.87	13.53	14.94	10.32	7.99	6.25	6.46	9.79
	Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Figure C-4. Distribution of wind direction and wave direction

The metocean data of Ulsan is summarized in Table C-4.

Table C-4. Metocean Data for Ulsan

	Items	Unit	Ws 1m/s	Ws 2m/s	Ws 3m/s	Ws 4m/s	Ws 5m/s	Ws 6m/s	Ws 7m/s	Ws 8m/s
Wave	Direction from TN	deg	180, 190	170, 180, 190	170, 190	180	190	180	40	0
	Significant Wave (Hs)	m	0.82	0.78	0.80	0.76	0.80	0.82	0.89	1.23
	Spectral Peak Period (Tp)	deg	6.23	6.20	6.22	6.19	6.22	6.23	6.20	6.55
	Maximum Wave Height	m	5.5	6.9	7.7	7	7.1	6	7.4	8.1
Tide	Highest Design Water Level	m	0.33							
	Lowest Design Water Level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							

	Items	Unit	Ws 1m/s	Ws 2m/s	Ws 3m/s	Ws 4m/s	Ws 5m/s	Ws 6m/s	Ws 7m/s	Ws 8m/s
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10min at hub	m/s	1	2	3	4	5	6	7	8
	Direction from TN	deg	130, 210	80	90	70	80	60	60	210
	Exponent for Wind Profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	Unit	Ws 9m/s	Ws 10m/s	Ws 11m/s	Ws 12m/s	Ws 13m/s	Ws 14m/s	Ws 15m/s	Ws 16m/s
Wave	Direction from TN	deg	0	0	0	0	0	10	0	0
	Significant Wave (Hs)	m	1.68	2.13	2.58	3.03	3.48	3.93	4.38	4.83
	Spectral Peak Period (Tp)	deg	6.90	7.24	7.59	7.94	8.28	8.63	8.98	9.32
	Maximum Wave Height	m	5.9	6.9	7	6.9	8.9	7.2	8.3	7.8
Tide	Highest Design Water Level	m	0.33							
	Lowest Design Water Level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10min at hub	m/s	9	10	11	12	13	14	15	16
	Direction from TN	deg	220	230	220	230	230	230	230	230
	Exponent for Wind Profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	Unit	Ws 17m/s	Ws 18m/s	Ws 19m/s	Ws 20m/s	Ws 21m/s	Ws 22m/s	Ws 23m/s	Ws 24m/s
Wave	Direction from TN	deg	0	0	0	0	350	0	0	350
	Significant Wave (Hs)	m	5.28	5.73	6.18	6.63	7.08	7.53	7.98	8.43
	Spectral Peak Period (Tp)	deg	9.67	10.02	10.36	10.71	11.06	11.40	11.75	12.10
	Maximum Wave Height	m	8.3	8.8	8	8.3	8.5	10.5	10.1	11.8
Tide	Highest Design Water Level	m	0.33							
	Lowest Design Water Level	m	0							
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)							
		Medium	0.13 (m/s) / 26 (deg)							
		Bottom	0.07 (m/s) / 26 (deg)							
	Extreme current	Surface	1.63 (m/s) / 12 (deg)							
		Medium	0.61 (m/s) / 12 (deg)							
		Bottom	0.34 (m/s) / 12 (deg)							
Wind	10min at hub	m/s	17	18	19	20	21	22	23	24
	Direction from TN	deg	320	230	320	50	30, 250	330	30	40
	Exponent for Wind Profile	-	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14

	Items	Unit	Ws 25m/s	Ws 26m/s	50-yr	100-yr	500-yr
Wave	Direction from TN	deg	10	0	0	0	-
	Significant Wave (Hs)	m	8.88	9.33	11.117	11.959	13.905
	Spectral Peak	deg	12.44	12.79	14.171	14.820	16.320

	Period (Tp)						
	Maximum Wave Height	m	9.5	10.4	17.859	19.189	22.263
Tide	Highest Design Water Level	m	0.33		0.7	0.7	-
	Lowest Design Water Level	m	0		- 0.7	- 0.7	-
Current	Normal current	Surface	0.37 (m/s) / 26 (deg)				
		Medium	0.13 (m/s) / 26 (deg)				
		Bottom	0.07 (m/s) / 26 (deg)				
	Extreme current	Surface	1.63 (m/s) / 12 (deg)				
		Medium	0.61 (m/s) / 12 (deg)				
		Bottom	0.34 (m/s) / 12 (deg)				
	10min at hub	m/s	25	26	39.83	41.70	46.02
	1hour at hub	m/s	-	-	37.84	39.62	43.72
	Direction from TN	deg	40	40	60, 230, 320	60, 230, 320	60, 230, 320
	Exponent for Wind Profile	-	0.14	0.14	0.11	0.11	0.11

Appendix D. Moneypoint Offshore One Preliminary Metocean Study

This appendix is available in the following report:

Creane, S. (2024). IDEA-IRL report. Reference site technical report A: Reference site 1 preliminary metocean site conditions assessment. https://www.marei.ie/wp-content/uploads/2024/02/IDEA-IRL_WP1-D1A_Reference-Site1.pdf

Appendix E. Havbredey Preliminary Metocean Study

This appendix is available in the following report:

de Paiva, H. S. W. R., & Santos, P. (2023). Havbredey Preliminary Metocean Study (0.1). DHI Report. https://doi.org/10.5281/zenodo.12731737

Appendix F. Fukushima Preliminary Metocean Study

Author: Jun Tanemoto (Shimizu Corporation, Japan)

Fukushima Floating Offshore Wind Farm Demonstration project (Fukushima FORWARD) was the world's first floating offshore wind project. It started in 2011 in Japan, and operation of the first wind turbine (2 MW semisubmersible) was started in November 2013. The wind farm consisted of 2-MW, 5-MW and 7-MW floating wind turbines and one floating substation.

The site was located 20 km off the coast of Fukushima prefecture in Japan in a water depth of around 120 m. The location and turbine layout of the wind farm are shown in Figure F-1 and Figure F-2. For more details, see Fukushima Offshore Wind Consortium Web Page.[2]

The Fukushima floating offshore wind farm was removed in 2021.

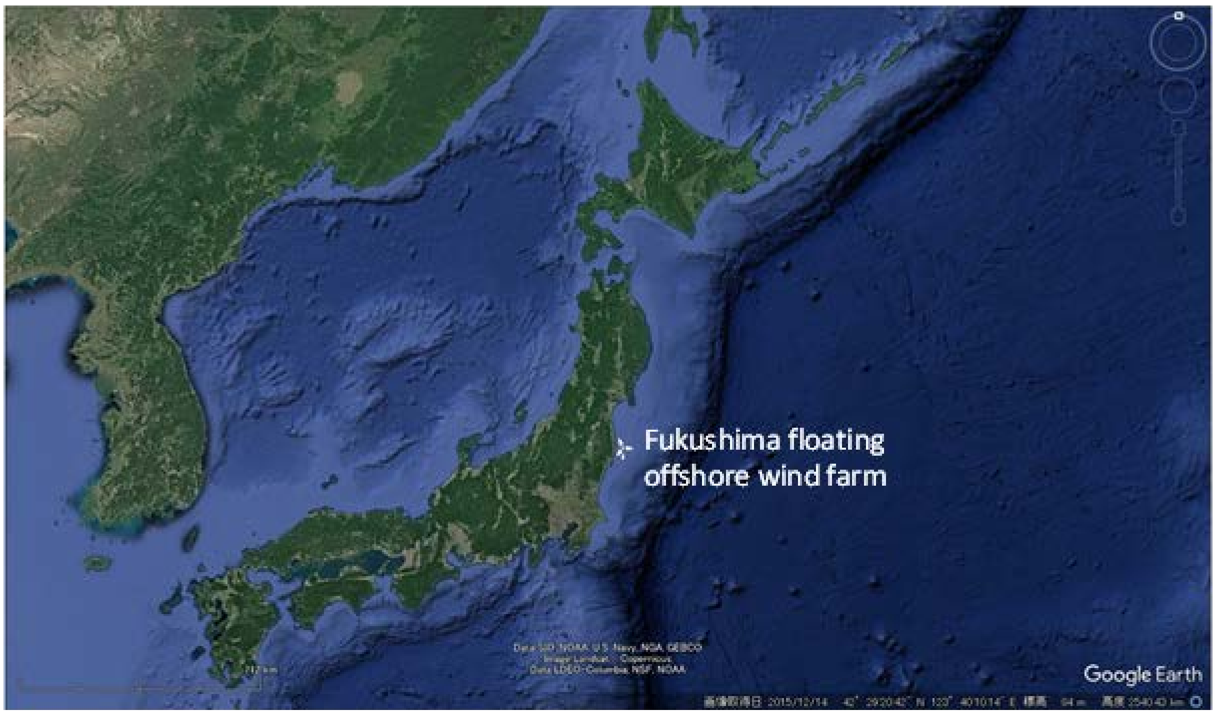


Figure F-1. Location of Fukushima floating offshore wind farm

[2] https://www.fukushima-forward.jp/english/index.html

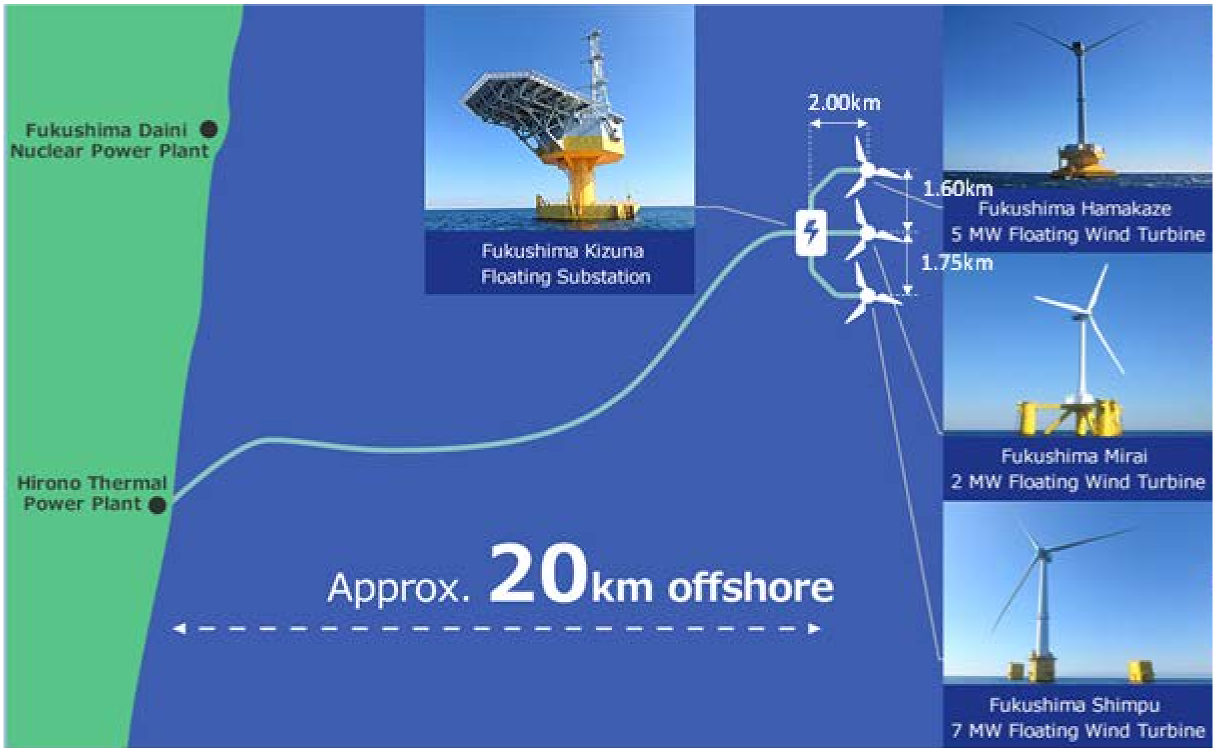


Figure F-2. Turbine layout of Fukushima floating offshore wind farm[3]

Metocean conditions used for the turbine and platform designs are summarized in Table F-1. The calculation method and more detailed information can be found in Ishihara et al. [25]. Note that these wind conditions were calculated at 60 m above sea level. Although publicly available information used for the actual design is limited, measurement campaigns of wind, wave, and sea currents had been conducted during the project (see Yamaguchi et al. [26]). Figures for representative metocean conditions are shown in Figure F-2. Some of those numeric text data are also available in the consortium webpage.[4]

[3] https://www.shimz.co.jp/en/topics/sustainability/item01/
[4] Fukushima Offshore Wind Consortium Web page: http://www.fukushima-forward.jp/english/index.html, accessed on 3rd July, 2023.

Table F-1. Metocean Conditions Used for Wind Turbine and Platform Design in Fukushima

CDL: Chart Datum Level. H.H.W.L: Highest High Water Level (may be used as 50-year return period). H.W.L: High Water Level (may be used as 1-year return period). M.S.L: Mean Sea Level. NA: not available in public document.

General Information			
Num. of turbine	3 (plus one floating substation)		
Rated Power	2 MW (Fukushima Mirai)	5 MW (Fukushima Hamakaze)	7 MW (Fukushima Shimpu)
Hub height (above sea level)	65 m	86 m	105 m
Platform Type	Compact semi-sub	Advanced spar	V-shape semi-sub
Mooring Type / Num. of Moorings	Chain catenary/6	Chain catenary/6	Chain catenary/8
Distance to shore	Approx. 20 km		
Water depth	Approx. 120 m		
Wind Condition (at 60 m above sea level)			
Extreme Condition	50-year return period		48.3 m/s
	1-year return period		32.5 m/s
	Wind shear exponent		0.11
Normal Condition	Annual average wind speed		NA
	Weibull parameters (given by combined model)		Non-Typhoon condition: k=1.73, C=8.06 Typhoon condition: k=1.99, C=15.27 Weight function: NA
	Wind shear exponent		0.14
	Turbulence intensity		IEC Category C (I_{ref}=0.12)
Water Level Condition			
Normal condition	M.S.L.		Chart datum level (CDL) + 0.84 m
	H.W.L.		CDL + 1.44 m
Extreme condition	H.H.W.L.		CDL + 2.77 m
Wave Condition			
Normal condition	Significant wave height		See Table F-2
	Significant wave period		
Extreme condition	Significant wave height		11.71 m
	Significant wave period		13.0 m
Sea Current Condition			

Extreme condition	50-year return period	1.5 m/s
	1-year return period	1.0 m/s
Normal condition	Annual average current speed	0.1 m/s
Other Condition		
Tsunami condition	Water level	3.2 m
	Horizontal velocity	0.87 m/s

Table F-2. Wave Height (H_0) and Wave Period (T_0) for Fukushima as a function of wind speed at 10-m height (U_{10})

U_{10} (m/s)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34
H_0 (m)	1.45	1.44	1.41	1.57	1.96	2.46	3.03	3.64	4.27	4.92	5.59	6.27	6.96	7.66	8.36	9.07	9.78
T_0 (s)	7.75	6.99	6.16	5.89	6.14	6.58	7.08	7.58	8.07	8.54	8.98	9.41	9.82	10.21	10.59	10.95	11.29

The wave height H_0 and wave period T_0 are calculated as

$$H_0 = \alpha H_{0,SMB} + (1-\alpha) H_{0,\mathrm{swell}}$$

$$T_0 = \alpha T_{0,SMB} + (1-\alpha) T_{0,\mathrm{swell}}$$

where,

$$H_{0,SMB} = \frac{0.3U_{10}^2}{g}\left[1 - \left(1 + 0.004\sqrt[2]{235000gU_{10}^{-2}}\right)^{-2}\right]$$

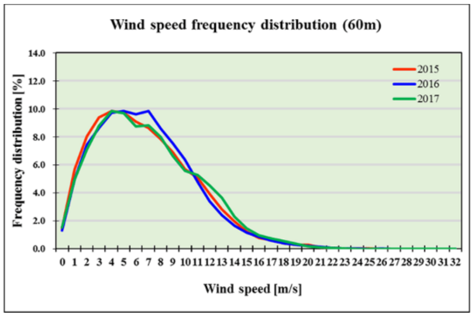
$$T_{0,SMB} = \frac{1.37 \cdot 2\pi U_{10}}{g}\left[1 - \left(1 + 0.008\sqrt[3]{235000gU_{10}^{-2}}\right)^{-5}\right]$$

$$H_{0,\mathrm{swell}} = 1.31 + (2.46 - 1.31)U_{10}/12$$

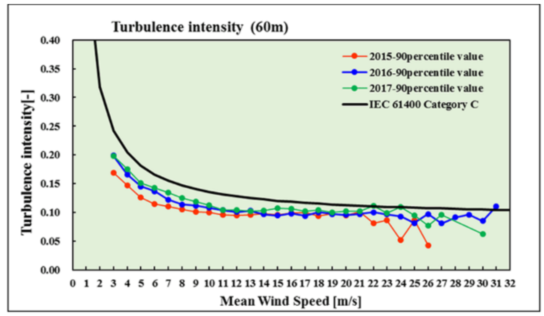
$$T_{0,\mathrm{swell}} = 8$$

$$\alpha = \max(0.4\tan^{-1}(0.34U_{10} - 1.88) + 0.39, 0)$$

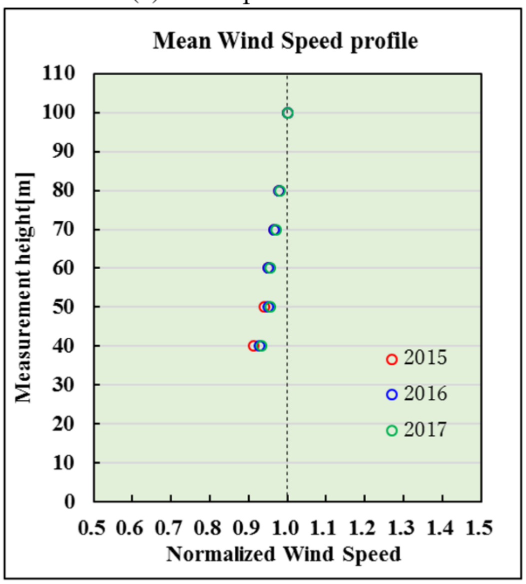
Figure F-3 summarizes the metocean data obtained in measurement campaigns during the Fukushima Floating Offshore Wind Farm Demonstration project.



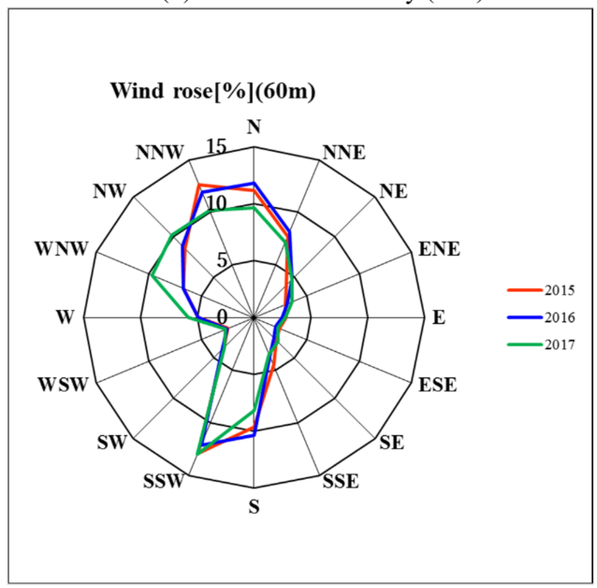
(a) Wind speed direction



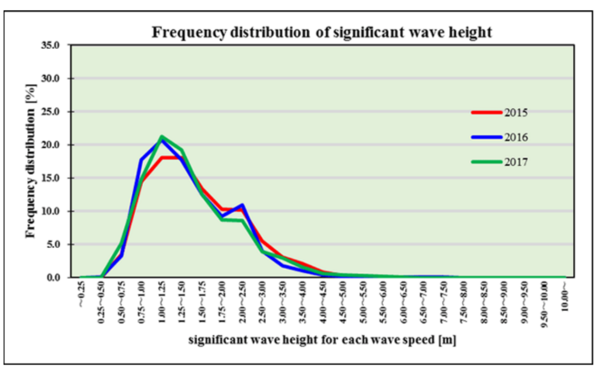
(b) Turbulence intensity (P90)



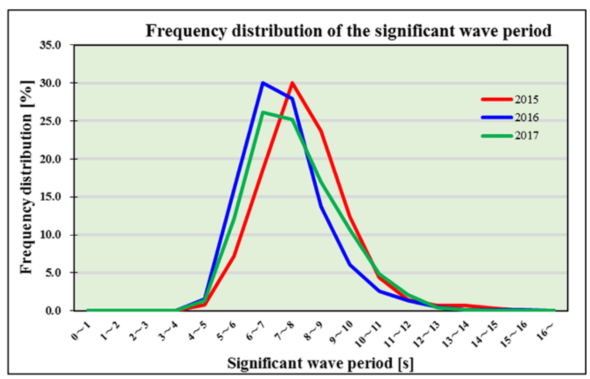
(c) Wind shear



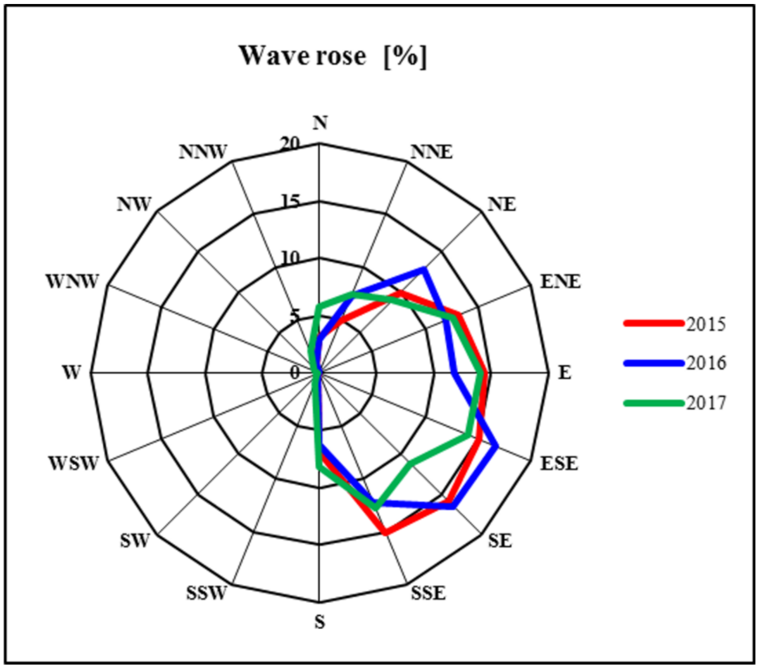
(d) Wind direction distribution



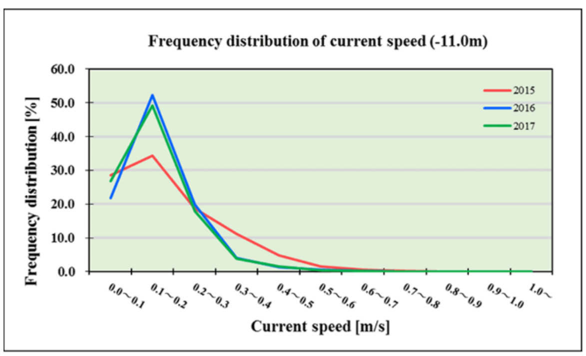
(e) Wave height distribution



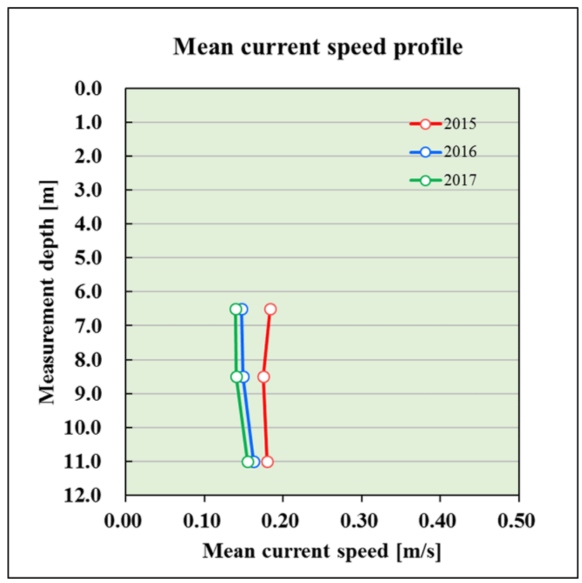
(f) Wave period distribution



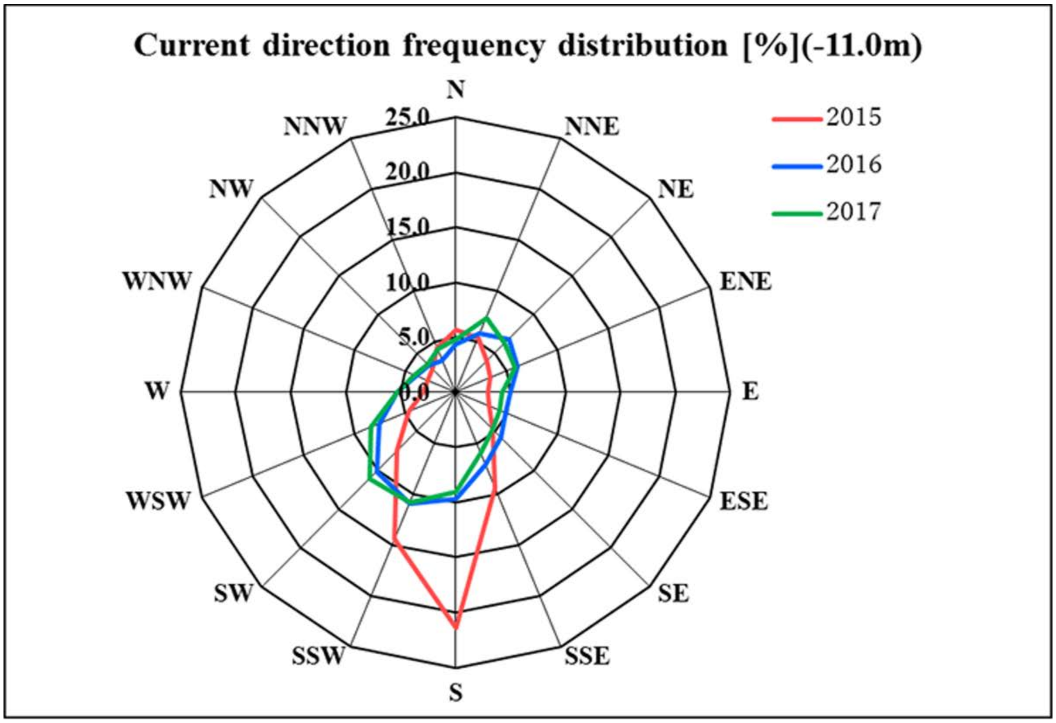
(g) Wave direction distribution



(h) Current speed distribution



(i) Current speed profile



(j) Current direction distribution

Figure F-3. Metocean data obtained in measurement campaigns during project in Fukushima[5]

[5] http://www.fukushima-forward.jp/english/deta/index.html

Appendix G. Utsira Nord Preliminary Metocean Study

Authors: Lin Li (University of Stavanger, Norway); Etienne Cheynet (University of Bergen, Norway); Lars Frøyd (4Subsea, Norway)

G.1 Description of Site

Two areas within the Norwegian economic zone, namely Utsira Nord and Sørlige Nordsjø II, were opened for license applications for the development of offshore wind farms in 2020. Figure G-1 shows a map with the location of the two sites. The reference site Utsira Nord lies about 22 km off the Norwegian coast, covering 1,010 km^2. In 2022, the Norwegian government proposed a total installed capacity of 1.5 GW for Utsira Nord. The bathymetric water depth ranges between 185 m and 280 m.

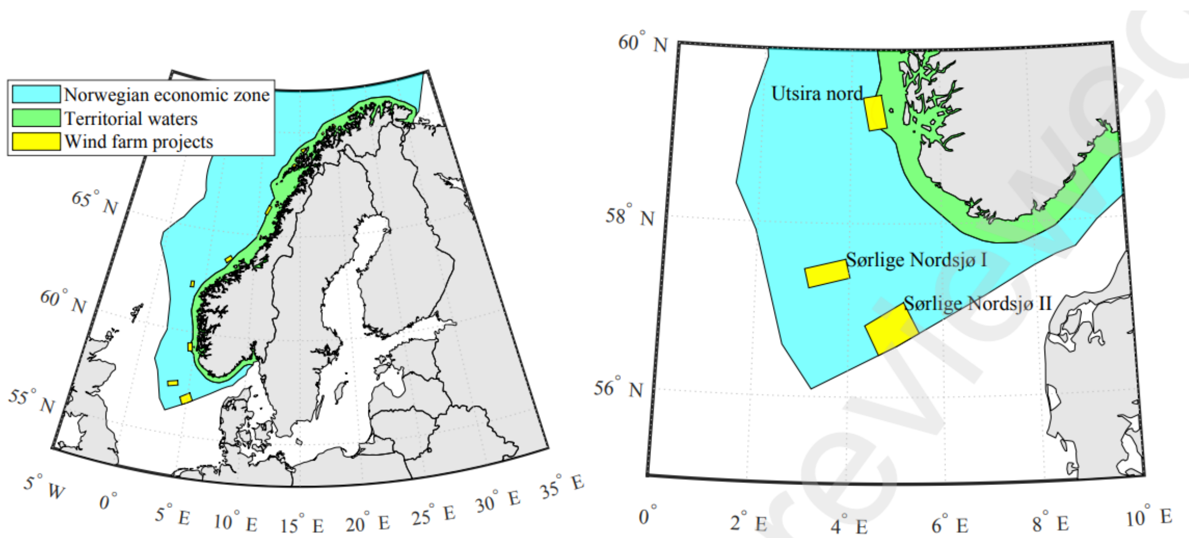


Figure G-1. (Left) Areas opened for wind farm deployment in the Norwegian economic zone. (Right) Close-up of Utsira Nord.

G.2 Description of Wind and Wave Hindcast Database

The metocean conditions generated by NORA3 database (the 3-km Norwegian Reanalysis) [72] has been used. NORA3 is a dynamical downscaling of the ERA5 reanalysis, produced with the non-hydrostatic regional numerical weather prediction model HARMONIE-AROME. Since 2021, NORA3 has been publicly available at https://thredds.met.no/thredds/projects/nora3.html. The database offers wind data at a horizontal spatial resolution of 3 km and a temporal resolution of 1 h, using a hybrid sigma-pressure coordinate system. NORA3 has also been applied to refine wave condition modeling in the North Sea, the Norwegian Sea, and the Barents Sea, within the WINDSURFER project. This initiative resulted in an additional dataset, available at https://thredds.met.no/thredds/projects/windsurfer.html, detailing wave conditions with a temporal resolution of 1 h and a spatial resolution of 3 km.

Wind and wave data from 1982 to 2022 at Utsira Nord were downloaded. The original data were interpolated into a new grid with domain boundaries match the Utsira Nord site, with a maximum element size of roughly 3 km. This configuration led to 317 grid points in Utsira Nord. The detailed coordinates of the grid points are shown in Figure G-2.

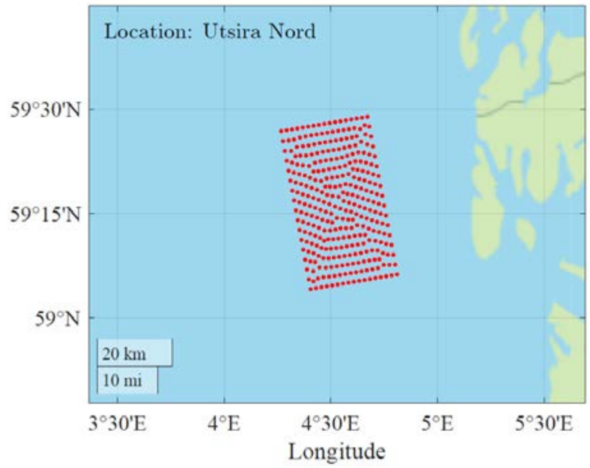


Figure G-2. Coordinates of the 317 grid points at Utsira Nord where the wind and wave data are available

G.3 Wind and Wave Statistics

Since the reference site covers a large area, the spatially averaged wind and wave data of the whole area were analyzed. However, the data at individual grid points are available and can be used to assess the spatial heterogeneity of the metocean data. Figure G-3 presents the polar histograms of the mean wind speed at 150-m height, H_s and T_p at the reference site using spatially averaged hourly data.

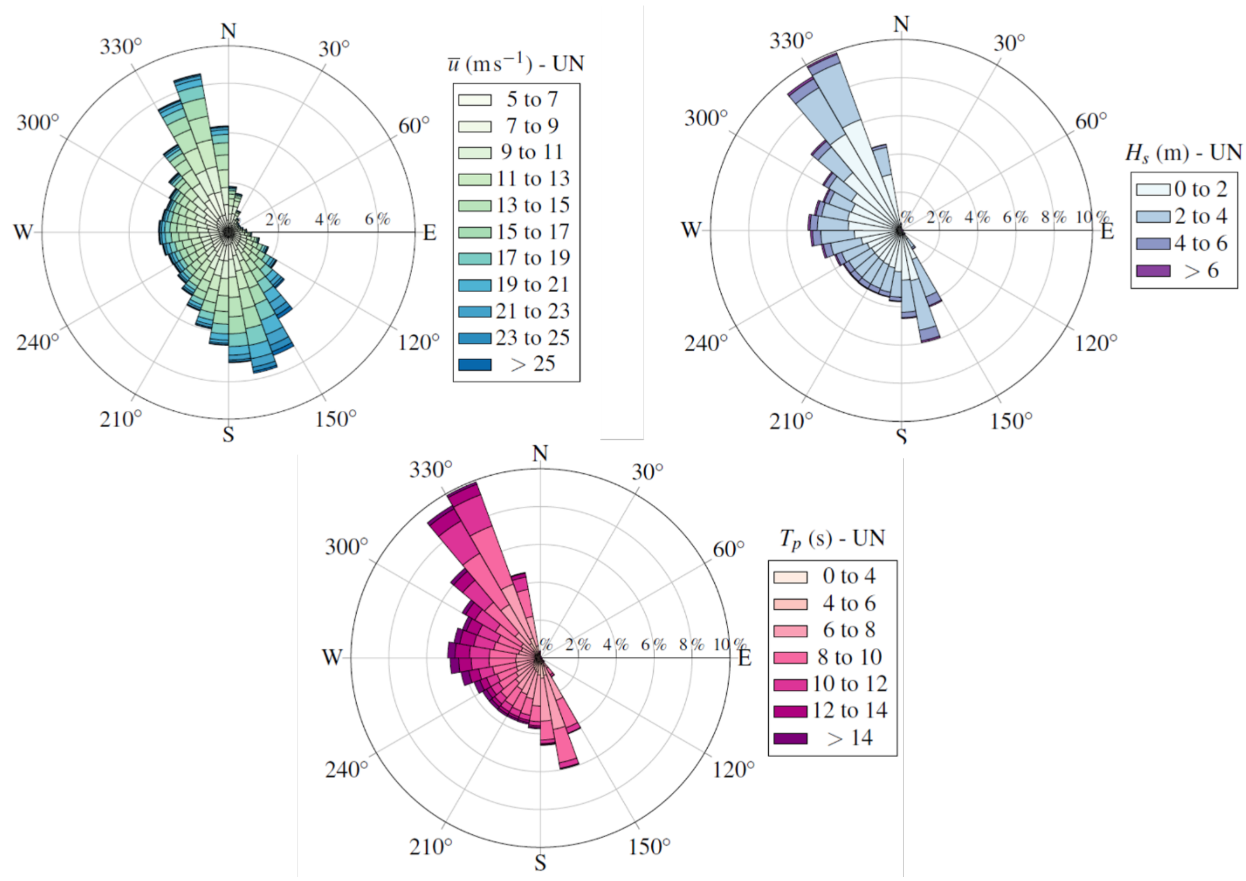


Figure G-3. Polar histograms of the mean wind speed at 150-m height, significant wave height (H_s), and spectral peak period (T_p) at Utsira Nord

The extreme values for mean wind speed at 150-m height and significant wave heights are estimated using block maxima approach. Given that 41 years of data are available, annual maxima are used. Table G-1 presents the mean, minimum, and maximum values of the extremes from all grid points at the reference site.

Table G-1. Extreme Mean Wind Speed at 150-m Height and H_s Corresponding to Return Periods of 1 Year, 10 Years, 50 Years, and 100 Years

The values in brackets present the minimum and maximum values from all grid points.

Return Period (years)	Significant Wave Height (m)	Wind Speed at Hub Height (150 m) (m/s)
1	9.6 [9.3, 9.8]	31.0 [30.4, 31.2]
10	12.8 [12.7, 13.0]	34.7 [34.4, 35.3]
50	14.4 [14.3, 14.5]	37.5 [37.0, 38.5]
100	[14.9, 15.1]	38.7 [38.0, 39.8]

G.4 Joint Distribution of Waves and Wind

The joint distribution of significant wave height (H_s) and spectral peak period (T_p) for the total sea, and mean wind speed at 150-m hub height ($\bar{u}_{hub}$) has been established using spatially averaged data for Utsira Nord. Here, it should be noted that the joint distribution is modeled based on metocean data with a 3-hour temporal resolution instead of hourly data.

When establishing the joint distribution, the conditional modeling approach is applied. Detailed procedures can refer to Li et al. [73]. H_s is considered as the main parameter here. Thus, the joint distribution consists of a marginal distribution of H_s, $f_{H_s}(h)$, a conditional distribution of $\bar{u}_{hub}$ given H_s, $f_{\bar{u}_{hub}|H_s}(u|h)$, and a conditional distribution of T_p given H_s, $f_{T_p|H_s}(t|h)$. The joint distribution is formulated as

$$f_{H_s,\bar{u}_{hub},T_p}(h,u,t) = f_{H_s}(h)\, f_{\bar{u}_{hub}|H_s}(u|h)\, f_{T_p|H_s}(t|h)$$

The marginal distribution for H_s is fitted to the hybrid LonoWe distribution. The conditional distribution of $\bar{u}_{hub}$ given H_s follows the two-parameter Weibull distribution. For the conditional distribution of T_p given H_s, the data follow a lognormal distribution. The distribution functions and the fitted parameters are presented in Table G-2.

Table G-2. Distribution Models and Parameters for the Joint Distribution of Significant Wave Height (Hs), Spectral Peak Period (Tp), and Mean Wind Speed at 150-m Hub Height $\bar{u}_{hub}$ for Utsira Nord Using Spatially Averaged 3-Hour Data

Distribution Model	Parameter	Value
Marginal distribution of Hs $f_{H_s}(h) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_{HM} h} \exp\left[-\frac{1}{2}\left(\frac{ln(h) - \mu_{HM}}{\sigma_{HM}}\right)^2\right], & h \le h_0 \\ \frac{\alpha_{HM}}{\beta_{HM}}\left(\frac{h}{\beta_{HM}}\right)^{\alpha_{HM}-1} \exp\left[-\left(\frac{h}{\beta_{HM}}\right)^{\alpha_{HM}}\right], & h > h_0 \end{cases}.$	h_0	4.6
	μ_{HM}	0.569
	σ_{HM}	0.574
	α_{HM}	1.207
	β_{HM}	1.882
Conditional distribution of $\bar{u}_{hub}$ for given H_s $f_{\bar{u}_{hub}\|H_s}(u\|h) = \frac{\alpha_{UC}}{\beta_{UC}}\left(\frac{u}{\beta_{UC}}\right)^{\alpha_{UC}-1} \exp\left[-\left(\frac{u}{\beta_{UC}}\right)^{\alpha_{UC}}\right]$ $\alpha_{UC} = a_1 + a_2 \cdot h^{a_3}$ $\beta_{UC} = b_1 + b_2 \cdot h^{b_3}$	a_1	1.613
	a_2	0.468
	a_3	1.257
	b_1	0.461
	b_2	7.778
	b_3	0.573
Conditional distribution of T_p for given H_s $f_{T_p\|H_s}(t\|h) = \frac{1}{\sqrt{2\pi}\sigma_{TC} t} \exp\left[-\frac{1}{2}\left(\frac{ln(t) - \mu_{TC}}{\sigma_{TC}}\right)^2\right]$ $\mu_{TC} = c_1 + c_2 \cdot h^{c_3}$ $\sigma_{TC}^2 = d_1 + d_2 \cdot \exp(d_3 h)$	c_1	1.768
	c_2	0.276
	c_3	0.489
	d_1	0.002
	d_2	0.119
	d_3	-0.354

From the joint distribution, contour surfaces of H_s, $\bar{u}_{hub}$, and T_p and contour lines can be generated. Figure G-4 presents the contour lines of H_s and T_p for varying $\bar{u}_{hub}$ corresponding to a return period of 50 years.

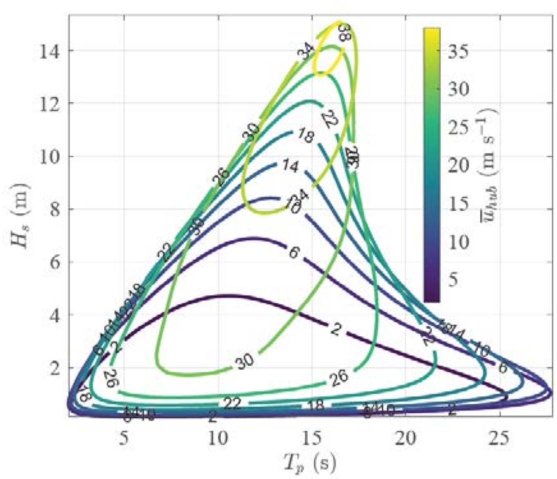


Figure G-4. Environmental contour lines of H_s and T_p for varying $\bar{u}_{hub}$ with a return period of 50 years based on the fitted parameters in Table G-2 for Utsira Nord

G.5 Description of Site and the Coastal Physics Simulation Hindcast Database

The Utsira Nord development zone is located in an area dominated by a costal, predominantly north-bound, current, as illustrated in Figure G-5.

The coastal physics data are taken from the NorKyst-800 hindcast model which includes salinity, temperature, and currents along the Norwegian Coast on 1-hour temporal and 800-m spatial resolution with up to 35 vertical layers (depending on depth). The current model includes the eight major primary harmonic constituents (M2, S2, N2, K1, K2, O1, P1, Q1) of diurnal and semidiurnal frequencies, and atmospheric forcing through surface fields from AROME-MetCoOP.[6]

The NorKyst-800 dataset is publicly available from the Norwegian Meteorological Institute.[7]

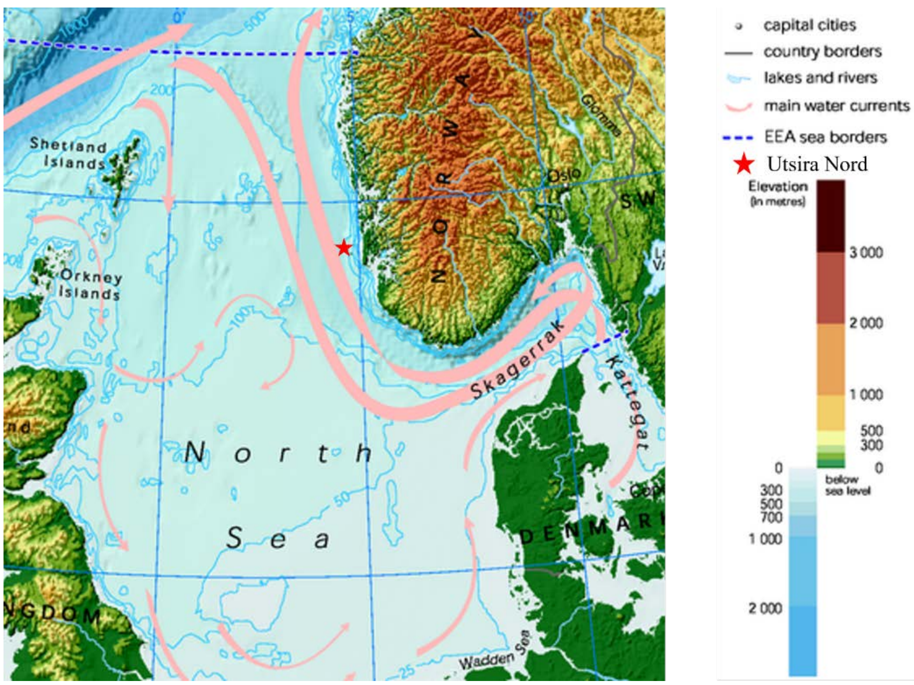


Figure G-5. North Sea physiography (Source: European Env. Agency)[8]

At the time of writing, the dataset spans from February 2017 to September 2023 (approximately 6.5 years with some missing data). The dataset is continually appended with new data.

G.6 Current Statistics

Key omnidirectional current statistics throughout the water column are summarized in Table G-3.

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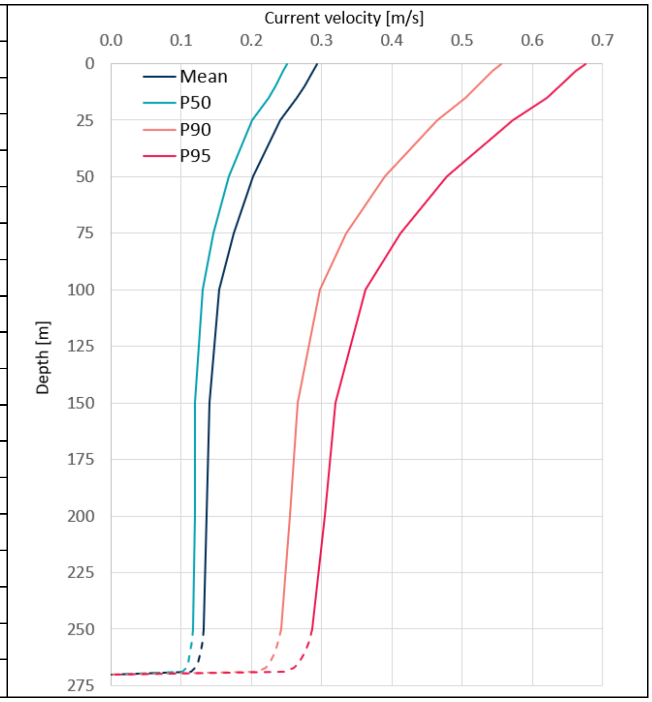
[6] https://ocean.met.no/models
[7] https://thredds.met.no/thredds/catalog/fou-hi/norkyst800m-1h/catalog.html
[8] https://www.eea.europa.eu/ds_resolveuid/FF266A0B-23F8-420C-886D-33D7AB733E73

Table G-3. Omnidirectional Current Profile Statistics at Utsira Nord

Depth [m]*	Current speed [m/s]			
	Mean	P_{50}	P_{90}	P_{95}
0	0.29	0.25	0.56	0.68
3	0.29	0.25	0.54	0.66
10	0.28	0.23	0.52	0.64
15	0.26	0.22	0.50	0.62
25	0.24	0.20	0.47	0.57
50	0.20	0.17	0.39	0.48
75	0.17	0.15	0.34	0.41
100	0.15	0.13	0.30	0.36
150	0.14	0.12	0.27	0.32
200	0.14	0.12	0.25	0.30
250	0.13	0.12	0.24	0.29
255	0.13	0.12	0.24	0.28
260	0.13	0.11	0.23	0.28
265	0.12	0.11	0.23	0.27
267	0.12	0.11	0.22	0.26
269	0.11	0.10	0.21	0.25
270	0.00	0.00	0.00	0.00



* Extrapolated to assumed seabed (270 m, red color) based on power law profile

Directional probability distributions (current roses) are provided for 11 different water depths from surface to near seabed, corresponding to the depths in the NorKyst-800 dataset.

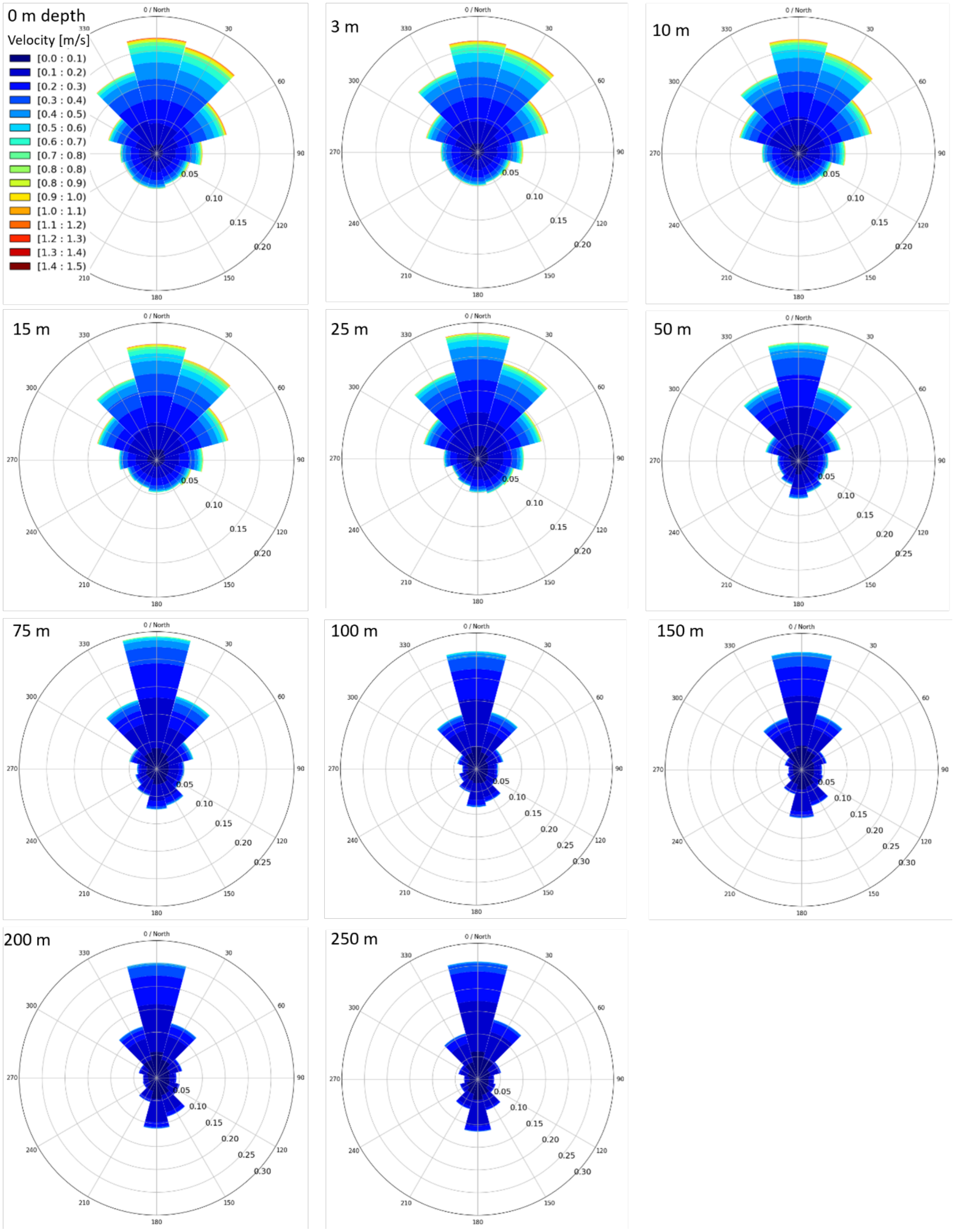


Figure G-6. Current roses (going toward) for a range of discrete water depths at Utsira Nord

G.7 Current Extremes

Current extremes have been estimated based on a peak-over-threshold approach using the maximum likelihood estimator method. Two different extreme value distributions (truncated Gumbel [Gompertz] and General Pareto) have been used at different water depths depending on the achieved model fit. The threshold x has been selected as $x = \mu + n\sigma$ with $3 < n < 4$. Declustering has been used to ensure independent peaks, with a minimum separation of 24 hours between peaks.

An example is shown below for current velocity at 3-m depth, comparing Gompertz and Generalized Pareto distribution (GPD).

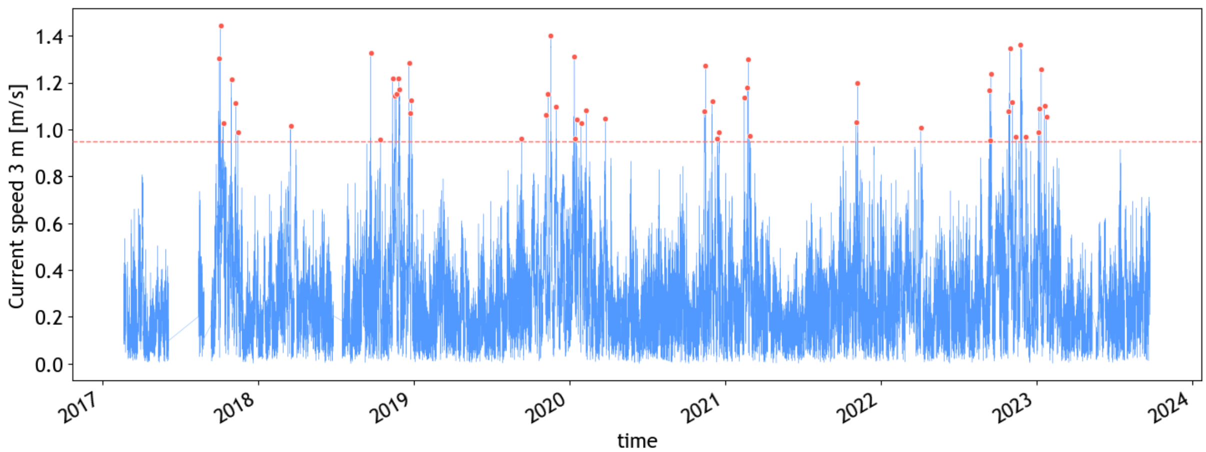


Figure G-7. Full time series of current velocity at 3-m depth with peak-over-threshold shown

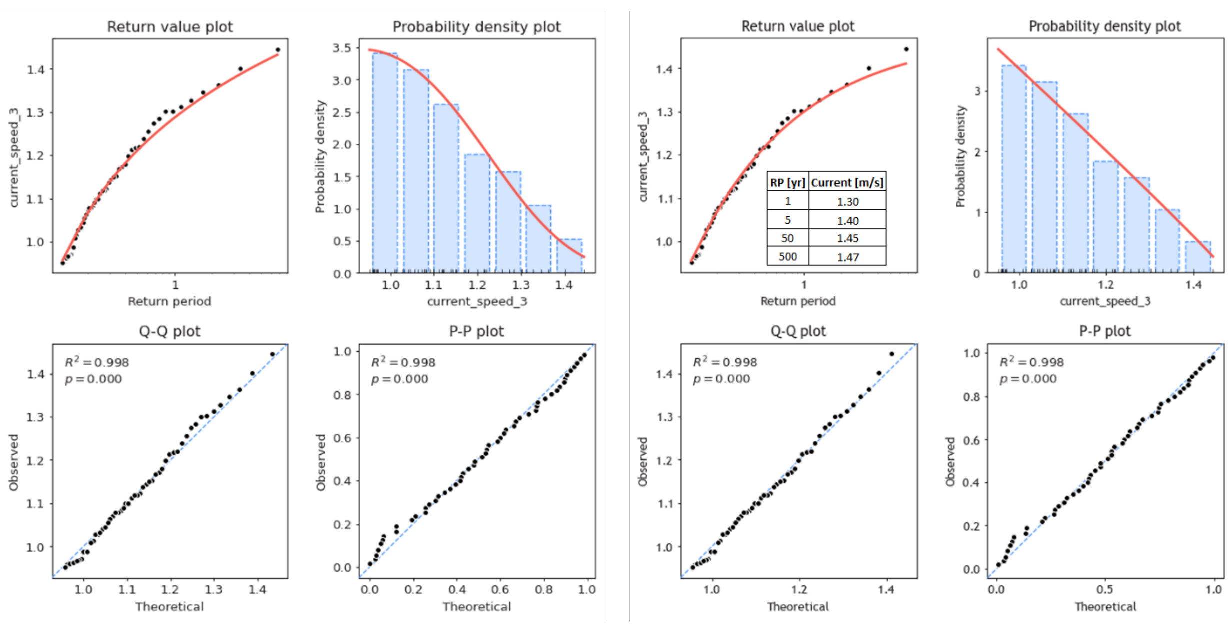


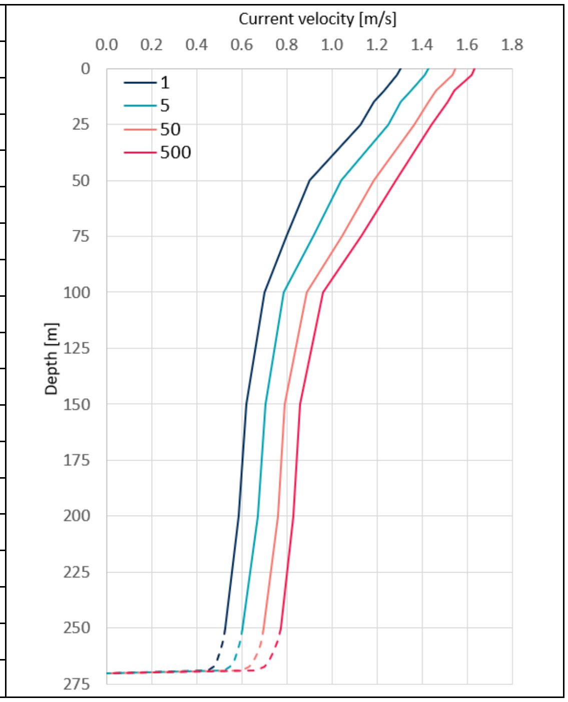
Figure G-8. Extreme value distribution fit at 3-m depth, comparing model fit and distributions

The GPD is most used with peak-over-threshold extreme value methods, but the Gompertz distribution has been included here as it was demonstrated to achieve a good fit. The Gompertz distribution was found to better match the tail of the observed distribution and resulted in more conservative extreme value estimates for higher return periods. Thus, the Gompertz distribution has been used where a good fit has been possible to achieve, with the GPD as a fallback solution for a few water depths.

The resulting omnidirectional current extremes are shown in Table G-4. It should be highlighted that the current hindcast time series is less than 7 years long, such that extreme value estimates for return periods 50 years and above must be considered uncertain. It must also be stressed that current hindcast models are considered to be significantly less accurate than wind and wave hindcast models.

Table G-4. Omnidirectional Current Extremes at Utsira Nord

Depth [m]*	Current speed [m/s] at return period [years]					
	1	**5**	**10**	**50**	**100**	**500**
0	1.30	1.43	1.47	1.55	1.58	1.63
3	1.29	1.41	1.46	1.53	1.56	1.62
10	1.23	1.35	1.39	1.47	1.49	1.55
15	1.19	1.31	1.35	1.43	1.46	1.52
25	1.13	1.25	1.29	1.36	1.39	1.44
50	0.90	1.04	1.09	1.18	1.22	1.28
75	0.80	0.92	0.96	1.05	1.08	1.13
100	0.70	0.79	0.82	0.89	0.91	0.96
150	0.62	0.70	0.73	0.79	0.81	0.86
200	0.58	0.67	0.70	0.76	0.78	0.83
250	0.52	0.60	0.63	0.70	0.72	0.77
255	0.52	0.60	0.63	0.69	0.71	0.76
260	0.51	0.58	0.61	0.67	0.70	0.75
265	0.49	0.56	0.59	0.65	0.67	0.72
267	0.48	0.55	0.58	0.63	0.66	0.70
269	0.45	0.52	0.55	0.60	0.62	0.66
270	0.00	0.00	0.00	0.00	0.00	0.00



* Extrapolated to assumed seabed (270 m, red color) based on power law profile

G.8 Temperature and Salinity

Temperature and salinity statistics at Utsira Nord are shown in Figure G-9.

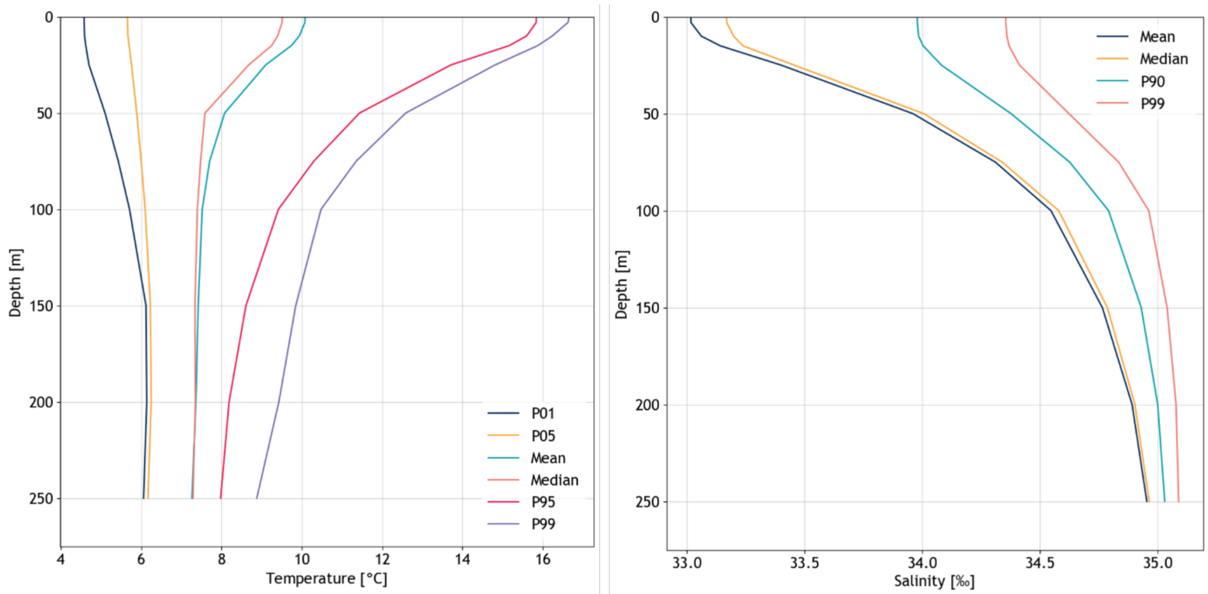


Figure G-9. Temperature and salinity statistics throughout water column

Appendix H. Gulf of Maine Preliminary Metocean Study

Authors: Michael Biglu (NREL, United States); Matthew Hall (NREL, United States); Ericka Lozon (NREL, United States)

The Gulf of Maine reference site is intended to be representative of conditions at the Maine Research Array (MERA) location, where the first multi-unit deployment of floating wind turbines is expected to take place in the region. For well over 10 years there have been efforts to establish a floating offshore wind demonstration projects, with a current focus on developing an array for research purposes [28]. The Gulf of Maine is known for its unique geographical location and for having two major ocean streams flowing into the gulf. The northern Labrador Current brings cold water, and the Gulf Stream transports warm water into the Gulf of Maine [74]. In addition to this, the adjacent Bay of Fundy in the northeast is known for the highest tides in the world [75] with corresponding strong currents.

The location of NDBC station 44005 (43.2°, -69.127°), with a depth of 177 m, was chosen as the reference location. All other data sources were chosen based on the distance to this location and the data coverage of respective stations. More information is available in [22] and the dataset is available on the NREL Data Catalog (https://data.nrel.gov/submissions/241).

The data sources are as follows:

- Wind data: 2023 National Offshore Wind dataset (NOW-23) is the latest wind resource dataset for offshore regions in the United States [67,68]. It was made using the Weather Research and Forecasting Model (WRF) for distinct regions of the United States, with an initial horizontal grid spacing (before refinement) of 6 km and 61 vertical levels.
- Wave data: Measurements from National Data Bouy Center (NDBC) buoy station 44005 (43.2°, -69.127°) were used as a primary source for wave and wind data at buoy level, due to its proximity to the Gulf of Maine floating offshore wind research array (15 nm) and data availability [69]. The station is moored at a water depth of 176.8 m and is 43 nm off the coast. NBDC station 44098 was used to fill wave data gaps of station 44005, especially because 44005 provides approximately 5 years of directional wave measurements between 2016 and 2022 only. Station 44098 is located in a depth of 80 m and is 40 nm offshore, 51 nm away from 44005.
- Current: NDBC Station 44032 was used for current data; the station is moored at a water depth of 100 m and is located 10 nm off the coast. This station is operated and maintained as part of the University of Maine Ocean Observing System and provides up to 22 years of current measurements [76].

The wind data (from the NOW-23 dataset) were interpolated directly at the target location. All other data sources were chosen based on their proximity to this location and the data coverage of respective stations. Figure H-1 shows the data source locations. Table H-1 summarizes basic information of used data source, providing the location, depth at these locations, distance to shore as well as the number of years covered per data source. The measurement data were only used from 2000 onwards, although station 44005 covers a much longer period. This was done to have similar time periods for the extrapolation compared to other parameters and thus achieve a comparable level of accuracy.

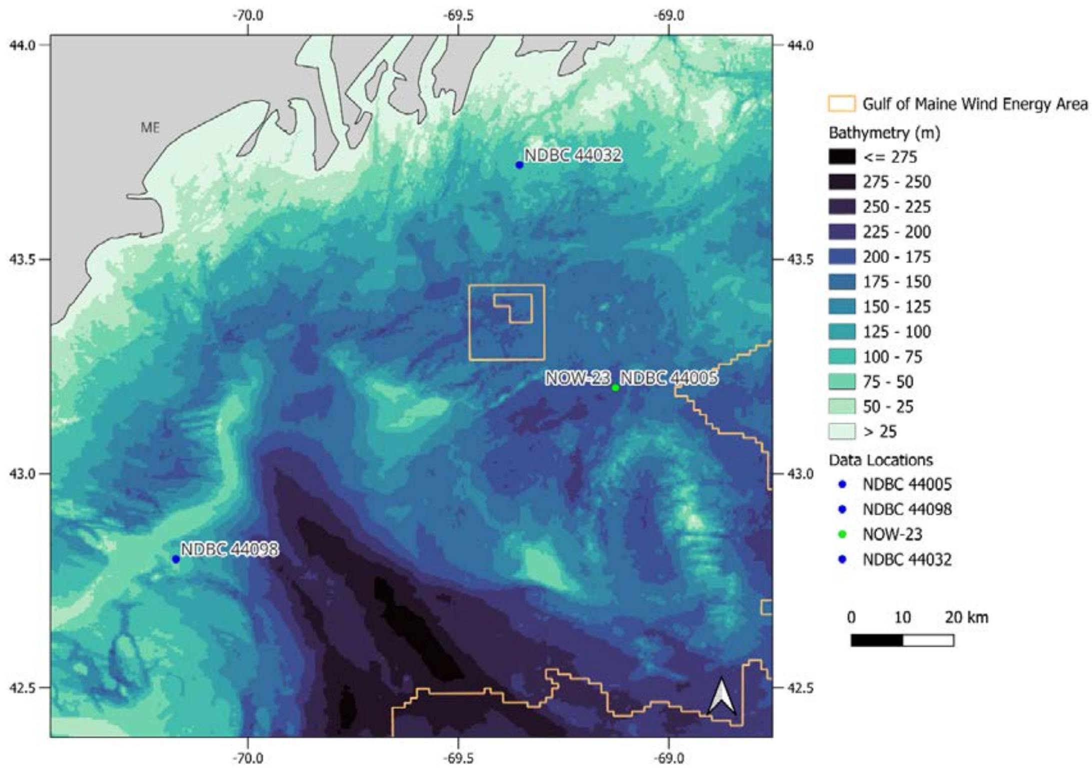


Figure H-1. Gulf of Maine metocean data sources

Table H-1. Gulf of Maine Locations of Data Sources and Covered Years per Data Type

Data type	Data sources	Latitude (deg)	Longitude (deg)	Water depth (m)	Distance to shore (nm)	Start year	End year
Wave/ metocean (primary)	NBDC station 44005	43.2	-69.127	176.8	43	1978	2022
Wave/ metocean (secondary)	NBDC station 44098	42.8	-70.171	80	22	2008	2022
Wind	NOW-23	43.2	-69.127	176.8	43	2000	2020
Current	NDBC station 44032 (E01*)	43.72	-69.355	100	10	2001	2022

The metocean analysis uses data from 2000 to 2020 to have a consistent time span

**Current data comes from UMOOS buoy E01: current data link*

Three time spans were excluded from the current time series due to data quality concerns: 2016-01-12 to 2016-03-03, 2017-01-01 to 2017-09-01, 2019-10-01 to 2020-01-01.

An analysis of extreme values was done by computing the monthly maxima of each time series and then fitting a generalized extreme value distribution to those maxima. Extreme values can then be read off the distribution. For conditional extreme values, the wave and current time series were filtered based on wind speed bins of 2 m/s before doing the monthly maxima. Unconditional and conditional extreme values of wave height, wave period, and current speed, for wind speed bins of every 2 m/s, are given in Table H-2.

Table H-2. Conditional Extreme Metocean Values for Gulf of Maine

Wind speed (m/s)	Wind Dir. (deg)	Wave Dir. (deg)	Significant Wave Height (m) Return Period (years)						Peak Wave Period (s) Return Period (years)						Curr. Dir. (deg)	Current Speed (m/s) Return Period (years)					
			1	*5*	*10*	*50*	*100*	*500*	*1*	*5*	*10*	*50*	*100*	*500*		*1*	*5*	*10*	*50*	*100*	*500*
All	253	134	7.1	9.2	10.0	11.9	12.6	14.2	12.2	13.9	14.5	15.8	16.2	17.2	224	0.71	0.88	0.94	1.11	1.18	1.34
0-2	141	118	2.6	3.4	3.8	4.5	4.8	5.5	7.4	8.5	8.9	9.7	10.0	10.7	225	0.52	0.65	0.70	0.80	0.84	0.92
2-4	240	116	3.2	4.1	4.5	5.3	5.6	6.4	8.2	9.3	9.7	10.5	10.9	11.6	228	0.56	0.66	0.70	0.76	0.79	0.83
4-6	286	120	3.6	4.6	4.9	5.8	6.1	6.9	8.7	9.8	10.2	11.0	11.3	12.0	224	0.60	0.69	0.73	0.79	0.81	0.85
6-8	284	118	4.0	5.2	5.6	6.6	7.0	7.9	9.2	10.4	10.8	11.8	12.1	12.8	227	0.59	0.67	0.70	0.75	0.76	0.79
8-10	284	117	4.3	5.4	5.8	6.7	7.0	7.8	9.5	10.6	11.0	11.8	12.1	12.8	224	0.62	0.74	0.78	0.88	0.91	0.98
10-12	289	115	4.6	5.7	6.2	7.1	7.4	8.1	9.8	11.0	11.4	12.2	12.5	13.1	224	0.62	0.74	0.79	0.88	0.91	0.98
12-14	269	116	4.7	5.6	5.9	6.5	6.7	7.1	9.9	10.8	11.1	11.6	11.8	12.1	224	0.61	0.74	0.79	0.90	0.94	1.03
14-16	267	122	5.1	6.2	6.6	7.4	7.7	8.3	10.3	11.4	11.8	12.5	12.7	13.2	222	0.57	0.66	0.69	0.74	0.75	0.78
16-18	245	117	5.1	6.1	6.4	6.9	7.1	7.5	10.3	11.3	11.5	12.1	12.2	12.5	232	0.60	0.76	0.83	0.98	1.03	1.16
18-20	241	109	5.4	6.4	6.7	7.3	7.5	7.8	10.6	11.6	11.9	12.4	12.5	12.8	226	0.54	0.67	0.72	0.83	0.87	0.95
20-22	231	109	5.8	7.1	7.6	8.4	8.7	9.2	11.0	12.2	12.6	13.2	13.5	13.9	236	0.53	0.70	0.77	0.91	0.97	1.11
22-24	218	101	6.1	7.4	7.9	8.7	9.0	9.5	11.3	12.5	12.8	13.5	13.7	14.1	229	0.47	0.59	0.63	0.72	0.75	0.81
24-26	183	101	6.3	7.3	7.6	8.0	8.2	8.4	11.5	12.3	12.6	13.0	13.1	13.3	241	0.44	0.59	0.66	0.80	0.86	0.99
26-28	181	93	6.9	7.9	8.2	8.7	8.8	9.0	12.0	12.9	13.1	13.5	13.6	13.7	237	0.43	0.62	0.70	0.90	0.99	1.20

A maximum dissimilarity algorithm was used to generate 100 clusters of the hourly metocean data points, representing 100 fatigue bins that can be used for fatigue loads analysis. The parameters of these bins are provided in Table H-3.

Table H-3. Metocean Joint Probability Fatigue Clusters for Gulf of Maine

			Cluster Centroid						Cluster Standard Deviation				
Bin number	Number of data points	Cluster probability	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
1	2956	0.034218	229	6.5	136	0.83	7.7	0.070	5.7	2.5	5.5	0.34	1.4
2	2366	0.027388	195	8.3	140	0.88	7.8	0.062	6.0	2.7	6.8	0.38	1.4
3	2282	0.026416	270	7.8	137	0.87	6.4	0.070	6.8	2.9	7.8	0.34	1.4
4	2238	0.025906	227	14.7	146	1.17	6.3	0.055	6.9	2.5	5.2	0.40	1.3
5	2026	0.023452	261	5.6	120	0.99	9.8	0.087	5.9	2.5	6.3	0.48	1.6
6	2005	0.023209	168	4.6	128	0.79	7.9	0.087	6.8	2.2	7.0	0.33	1.4
7	1791	0.020732	312	11.9	277	1.52	5.3	0.058	6.8	2.5	7.7	0.46	0.8
8	1788	0.020697	299	6.9	137	1.08	9.1	0.070	6.0	2.8	7.5	0.53	1.5
9	1745	0.020200	323	5.6	127	0.83	6.7	0.087	7.4	2.6	8.3	0.32	1.6
10	1662	0.019239	207	15.3	178	1.25	5.1	0.055	6.0	2.2	6.1	0.42	1.0
11	1662	0.019239	216	5.1	110	0.83	7.5	0.087	7.3	2.1	7.3	0.36	1.7
12	1660	0.019216	124	4.6	119	0.97	9.3	0.087	6.2	2.4	7.7	0.51	1.7
13	1606	0.018591	319	17.3	302	2.47	6.3	0.055	6.5	2.5	7.2	0.57	0.8
14	1597	0.018486	327	8.6	299	1.17	4.7	0.062	9.0	2.5	7.7	0.35	0.7

Bin number	Number of data points	Cluster probability	Cluster Centroid: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Cluster Standard Deviation: Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
15	1589	0.018394	1	6.3	111	1.18	10.8	0.070	6.0	2.6	6.7	0.57	1.6
16	1555	0.018000	14	5.8	136	0.88	8.0	0.087	7.1	2.8	5.5	0.41	1.4
17	1525	0.017653	45	5.3	119	1.02	9.6	0.087	6.0	2.4	6.9	0.46	1.7
18	1522	0.017618	341	10.8	139	1.01	7.5	0.058	8.0	2.8	8.0	0.45	1.5
19	1480	0.017132	180	15.4	149	1.29	5.6	0.055	6.9	2.8	7.0	0.51	1.3
20	1427	0.016518	219	11.6	113	1.02	10.5	0.058	6.9	2.6	6.7	0.45	1.4
21	1397	0.016171	242	10.0	223	1.16	4.8	0.058	8.8	2.5	7.2	0.48	1.0
22	1392	0.016113	231	15.1	205	1.62	5.5	0.055	6.6	2.1	6.2	0.62	1.0
23	1353	0.015662	323	5.8	110	1.17	11.0	0.087	5.6	2.5	7.4	0.62	1.7
24	1351	0.015639	89	5.2	124	0.92	7.0	0.087	6.9	2.4	6.9	0.42	1.6
25	1293	0.014967	336	13.6	315	1.78	5.4	0.056	7.5	2.0	6.6	0.45	0.7
26	1256	0.014539	271	14.7	137	2.18	9.3	0.055	7.8	2.7	6.7	0.82	2.0
27	1251	0.014481	188	8.7	182	0.88	4.7	0.062	8.3	2.6	9.8	0.34	1.4
28	1225	0.014180	64	8.0	75	1.20	5.6	0.070	6.2	2.5	8.2	0.43	1.3
29	1221	0.014134	137	9.6	139	1.07	5.6	0.062	8.2	2.8	8.4	0.42	1.6
30	1198	0.013868	237	9.6	183	0.92	4.8	0.062	8.1	2.5	6.6	0.32	1.0
31	1176	0.013613	206	22.6	162	2.00	6.4	0.054	7.4	2.6	6.3	0.59	0.9
32	1170	0.013544	278	12.8	255	1.78	5.6	0.056	7.0	2.4	6.1	0.49	0.9
33	1157	0.013393	226	20.1	183	1.83	6.0	0.054	6.3	2.1	7.1	0.65	1.0
34	1133	0.013115	225	12.8	113	1.06	5.9	0.056	7.8	2.6	7.6	0.45	1.5
35	1091	0.012629	175	5.5	108	0.95	11.1	0.087	8.0	2.4	6.1	0.45	1.5
36	1058	0.012247	68	6.5	150	0.96	7.9	0.070	7.8	3.0	8.5	0.49	1.8
37	1057	0.012235	344	9.7	338	1.26	4.8	0.062	8.8	2.7	6.8	0.40	0.8
38	1019	0.011796	35	9.1	38	1.21	5.0	0.062	7.6	2.8	6.3	0.44	1.0
39	983	0.011379	232	6.0	106	0.97	12.4	0.070	7.9	2.6	8.4	0.51	1.8
40	970	0.011228	19	7.5	109	1.00	5.9	0.070	8.5	3.0	7.0	0.43	1.4
41	943	0.010916	181	10.8	108	1.15	7.9	0.058	6.9	2.5	6.3	0.46	1.8
42	914	0.010580	277	7.5	273	1.06	4.6	0.070	8.0	2.2	9.0	0.35	0.8
43	910	0.010534	356	12.4	17	1.66	5.5	0.056	8.3	1.9	7.0	0.46	0.9
44	889	0.010291	277	12.2	105	1.56	8.8	0.056	8.4	2.7	7.7	0.74	2.0
45	882	0.010210	50	13.9	65	2.22	6.7	0.056	8.4	2.1	8.1	0.52	1.1
46	872	0.010094	106	13.4	110	1.95	6.5	0.056	7.9	2.6	8.1	0.58	1.4
47	849	0.009828	293	11.1	223	1.57	5.8	0.058	8.4	2.8	6.8	0.56	1.2
48	842	0.009747	25	10.3	107	2.53	11.4	0.058	8.0	2.6	7.6	0.89	1.7
49	838	0.009700	289	5.1	99	1.16	10.8	0.087	6.2	2.4	8.5	0.68	2.1
50	782	0.009052	203	18.3	120	1.99	8.8	0.054	8.0	2.5	8.5	0.78	1.7
51	770	0.008913	106	7.0	81	1.06	5.4	0.070	7.2	2.6	8.6	0.44	1.3
52	758	0.008774	266	15.2	186	1.75	6.4	0.055	7.2	2.7	8.0	0.71	1.3
53	746	0.008635	82	5.9	111	1.29	11.7	0.087	8.0	2.8	7.9	0.78	1.8
54	736	0.008520	297	18.2	272	2.97	7.1	0.054	7.7	2.8	5.9	0.66	1.0

			Cluster Centroid							Cluster Standard Deviation				
Bin number	Number of data points	Cluster probability	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
55	716	0.008288	333	12.6	128	1.99	11.8	0.056	8.9	2.7	8.0	0.82	1.7
56	703	0.008138	1	9.9	67	1.55	6.2	0.062	6.8	2.8	7.7	0.58	1.2
57	697	0.008068	9	7.3	11	0.96	4.5	0.070	7.3	2.3	8.0	0.30	0.9
58	667	0.007721	146	18.2	129	2.08	7.1	0.054	7.2	2.8	9.5	0.64	1.6
59	631	0.007304	59	13.7	122	2.36	8.6	0.056	7.5	2.7	10.0	0.77	1.6
60	618	0.007154	330	11.1	86	1.77	9.2	0.058	7.1	2.6	8.4	0.75	1.9
61	585	0.006772	27	6.5	69	1.19	7.0	0.070	6.5	2.6	7.5	0.52	1.9
62	554	0.006413	195	6.2	136	1.04	12.7	0.070	9.3	2.9	8.9	0.51	1.8
63	554	0.006413	171	27.1	145	3.41	8.1	0.054	7.8	3.2	10.2	0.95	1.2
64	541	0.006262	319	7.7	196	0.97	5.7	0.070	10.4	3.2	10.5	0.38	1.5
65	523	0.006054	284	18.7	230	3.08	7.3	0.054	9.7	2.8	7.7	0.81	1.0
66	522	0.006043	255	6.2	162	1.01	8.8	0.070	8.7	2.7	8.4	0.44	1.7
67	508	0.005880	47	19.9	74	3.75	8.5	0.054	7.9	2.6	7.9	0.73	0.9
68	499	0.005776	7	16.4	80	3.19	8.7	0.055	7.9	2.4	8.3	0.63	1.6
69	490	0.005672	328	6.4	45	0.98	5.5	0.070	9.0	3.0	10.0	0.41	1.6
70	480	0.005556	133	5.2	169	0.84	8.4	0.087	10.1	2.6	8.3	0.46	2.0
71	430	0.004978	232	10.3	125	2.84	10.8	0.058	8.3	2.9	8.7	0.90	1.6
72	430	0.004978	359	18.3	15	2.78	6.7	0.054	8.7	2.1	9.2	0.60	0.9
73	343	0.003970	215	14.1	151	1.83	11.3	0.055	9.3	2.4	7.8	0.87	1.6
74	338	0.003913	163	5.0	79	0.87	5.7	0.087	9.6	2.6	9.5	0.46	1.5
75	309	0.003577	35	6.9	180	0.84	6.6	0.070	11.0	3.2	10.8	0.33	1.7
76	308	0.003565	12	22.3	60	4.20	8.6	0.054	7.8	2.7	8.9	0.74	1.2
77	307	0.003554	98	17.7	120	3.43	8.6	0.055	7.1	2.7	8.7	0.86	1.5
78	305	0.003531	169	11.4	107	3.24	11.7	0.058	10.7	3.7	8.8	1.12	1.4
79	304	0.003519	228	21.2	144	3.83	10.0	0.054	10.2	3.1	10.0	0.93	1.6
80	272	0.003149	43	19.2	103	5.20	12.7	0.054	9.3	3.3	7.2	0.83	1.9
81	262	0.003033	6	7.0	162	1.18	11.3	0.070	10.0	3.0	9.3	0.50	1.9
82	236	0.002732	121	24.0	117	4.07	8.9	0.054	8.7	3.1	7.9	0.92	1.4
83	166	0.001922	112	13.9	63	2.11	6.6	0.056	11.9	3.0	7.3	0.68	1.2
84	135	0.001563	288	8.5	292	1.37	8.1	0.062	8.3	3.1	10.1	0.70	2.1
85	129	0.001493	260	4.5	36	0.96	5.8	0.087	13.2	2.9	13.3	0.66	1.8
86	128	0.001482	90	26.9	98	6.03	10.5	0.054	9.4	3.8	7.4	0.80	1.1
87	123	0.001424	330	9.4	300	1.27	9.5	0.062	8.4	3.1	10.1	0.43	1.5
88	123	0.001424	34	28.1	73	6.52	11.0	0.053	10.3	2.9	7.9	1.06	1.4
89	109	0.001262	341	24.7	337	4.18	7.7	0.054	7.8	3.4	11.8	0.83	1.0
90	98	0.001134	223	5.6	296	0.75	4.3	0.087	12.6	2.9	13.3	0.38	1.2
91	70	0.000810	68	6.1	357	1.00	5.3	0.070	10.3	3.1	15.0	0.54	2.3
92	63	0.000729	127	7.3	15	1.22	5.6	0.070	13.1	4.6	11.5	0.64	1.4
93	57	0.000660	234	8.1	224	0.86	10.2	0.062	8.7	2.2	10.6	0.43	1.3
94	37	0.000428	315	23.5	125	2.87	10.5	0.054	10.5	3.5	9.8	0.95	2.9

Bin number	Number of data points	Cluster probability	Cluster Centroid Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)	TI	Cluster Standard Deviation Wind Dir. (deg)	Wind Speed (m/s)	Wave Dir. (deg)	Wave Height (m)	Wave Period (s)
95	30	0.000347	166	10.2	88	0.72	15.9	0.058	11.7	4.0	16.6	0.22	1.8
96	14	0.000162	141	7.1	231	0.65	8.9	0.070	6.0	3.4	14.6	0.26	5.0
97	6	0.000069	181	8.2	280	0.58	16.9	0.062	12.6	4.0	18.3	0.11	1.9
98	2	0.000023	180	35.7	360	6.01	9.5	0.054	0.0	1.6	0.0	0.12	0.5
99	1	0.000012	340	8.6	78	0.32	25.0	0.062	0.0	0.0	0.0	0.00	0.0
100	1	0.000012	286	2.4	188	0.29	25.0	0.136	0.0	0.0	0.0	0.00	0.0

Appendix I. Geomundo Preliminary Metocean Study

Authors: Yong-Yook Kim (IAE, South Korea); Miho Park (IAE, South Korea)

The data for this site is not public. Questions about data access should be addressed to the authors above.

Appendix J. Sud de la Bretagne Preliminary Metocean Study

Author: Mostafa Bakhoday-Paskyabi (University of Bergen)

Mapping the wind resource and conducting wind power analysis and offshore site assessments require high-quality data over various time and spatial scales. Due to the limited and sparse nature of ocean observations, obtaining high-resolution wind resource data for specific regions is crucial. However, there are some wind resource datasets suitable for wind energy applications, such as the New European Wind Atlas (NEWA)[9] and the Global Wind Atlas (GWA).[10] They are dynamic downscaling of the ECMWF's ERA5 reanalysis product based on the Weather Research and Forecasting model (WRF). NEWA covers European countries and some surrounding offshore areas, and GWA provides global onshore and near-coastal coverage. However, to conduct a comprehensive wind resource assessment for the southern North Sea area, specifically to cover the South Britney site, we require a high-resolution dataset that covers this specific region.

Here, we utilize a downscaling dataset derived from ERA5, known as NORA3. NORA3 employs the HARMONIE-AROME model instead of WRF, offering hourly wind and wave data within a 3×3-km horizontal grid [29,30]. This dataset covers Northern Europe, the Baltic Sea, North Sea, Norwegian Sea, and parts of the Barents Sea, providing complete coverage of the South Brittaney area (see Figure J-1).

Analysis presented here represents a location west of the Sud de la Bretagne site, specifically located at -4.59250688553°, 46.8014068604°. According to GEBCO, the water depth at this site is 150 m (see Figure J-1). Note that we use the coordinates of the HIPERWIND “South Brittany” site, which differs from the “Sud de la Bretagne” site specified in the French State’s commercial tender, located in shallower waters (80–100 m).[11] Nevertheless, the concept behind the HIPERWIND EU project for the South Brittany site aimed to recreate Atlantic wave and sea-state conditions near a viable commercial area while maintaining a water depth like the original University of Maine design (200 m). However, achieving a depth of 200 m was unfeasible due to the bathymetry, which gradually increases from 100 m to 150 m offshore Brittany before abruptly dropping to depths exceeding 1,000 m. As a result, we aimed for a more practical depth of 150 m.

[9] https://map.neweuropeanwindatlas.eu/
[10] https://globalwindatlas.info/en
[11] https://www.hiperwind.eu/

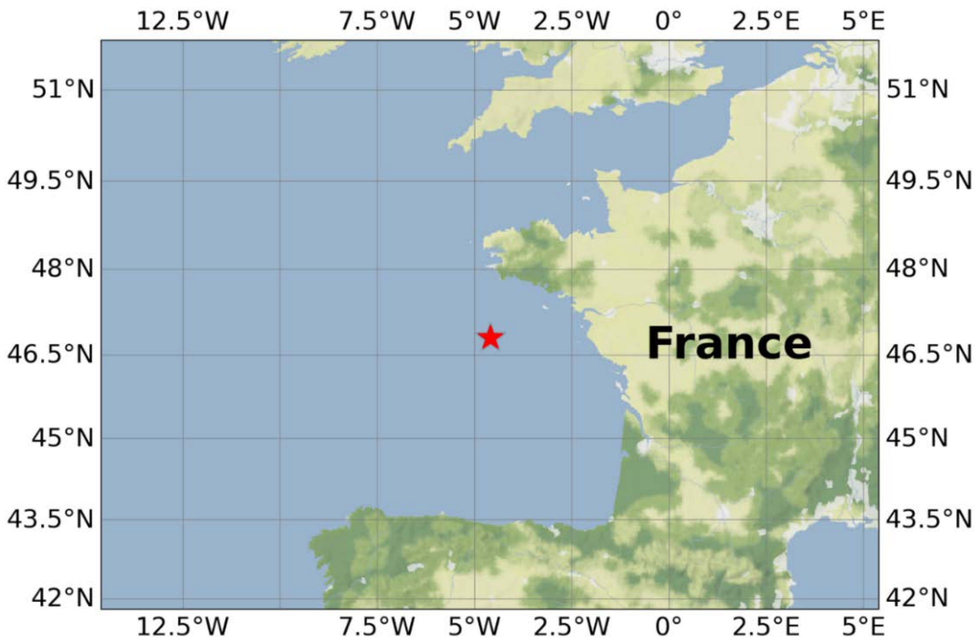


Figure J-1. The geographical location of South Brittany (from Hai Bui)

Wind data, containing wind speed and direction, is accessible at various elevations (Table J-1): 10.0 m, 20.0 m, 50.0 m, 100.0 m, 250.0 m, 500.0 m, and 750.0 m. Additionally, the wave dataset provides a comprehensive array of wave parameters, including significant wave height (H_s), wave peak period (T_p), wave mean direction (thq), and several others.

Table J-1. Two netCDF Files, One for Wind Data at Different Heights and One for Surface Wind and Wave Data

wam.sbrit.1993-2019.nc	Wind speed (ff) and direction at surface (dd), significant wave height (H_s), peak wave period (T_p), mean wave direction (thq)
nora3.sbrit.1988-2021.nc	Wind speed at 7 different heights.

In Figure J-2, we generated 50-year and 1-year environmental contours for the South Brittany study sites in the southern North Sea region, using NORA3 hindcast data. These contours were constructed using the established inverse first-order reliability method. The NORA3 data span is around 30 years, allowing for long-term analysis of wind and wave parameters. The contour lines in Figure J-2, demonstrate different levels of probability of encountering specific combinations of wave height and wind speed. These contours can be used to estimate extreme wave conditions or design criteria for structures, or to assess the risk of wave-induced damage on offshore constructions. There is significant variability among the contributions of wind speed and significant wave height. Notably, the highest modeled wave height maximum occurs consistently along the 50-year contour in all datasets. It is important to highlight that a more in-depth analysis is necessary to determine how contours can effectively incorporate both the dependency between significant wave height and wave period, as well as how to adequately address sea states with the highest H_s in a meaningful way.

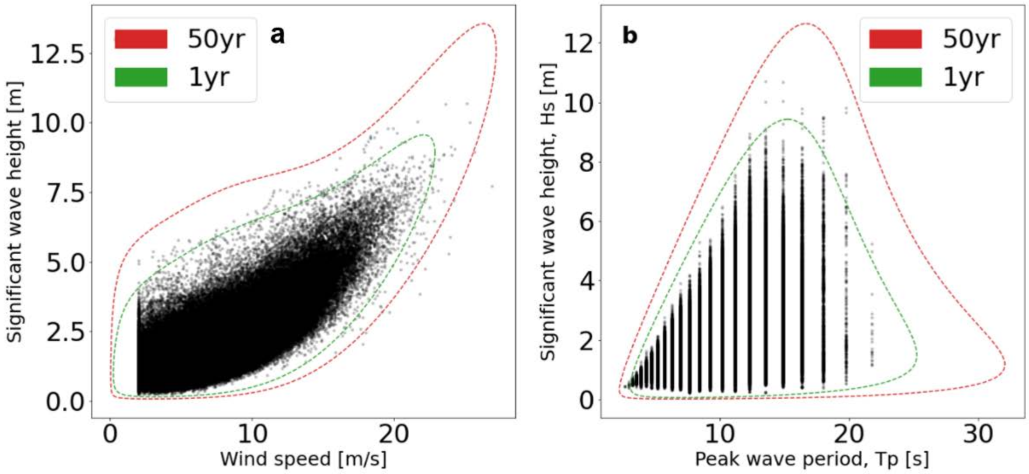


Figure J-2. Tentative scatter plots of (a) wind speed at 10-m height and significant wave height overlaid with the joint probabilistic model results, i.e., 50-year (red curve) and 1-year (green curve) environmental contours. (b) 50-year and 1-year contours for wave peak period and significant wave height using the inverse first-order reliability method. This figure can vary significantly based on the geographical location as we investigated in FINO1 met-mast data.

J.1 Wave

Figure J-2a shows a visual representation of the hourly NORA3 significant wave height distribution for the offshore South Brittany site, with the added overlay of the 3-parameter Weibull distribution, fitted to the H_s-histogram. Figure J-2b demonstrates the wave rose for the South Brittany site. Compared to Figure J-3a, the primary wave direction shown in the wave rose is relatively like the dominant wind direction. This alignment could be influenced by various factors, such as swell waves or the coastal geography, contributing to a complex wave climate.

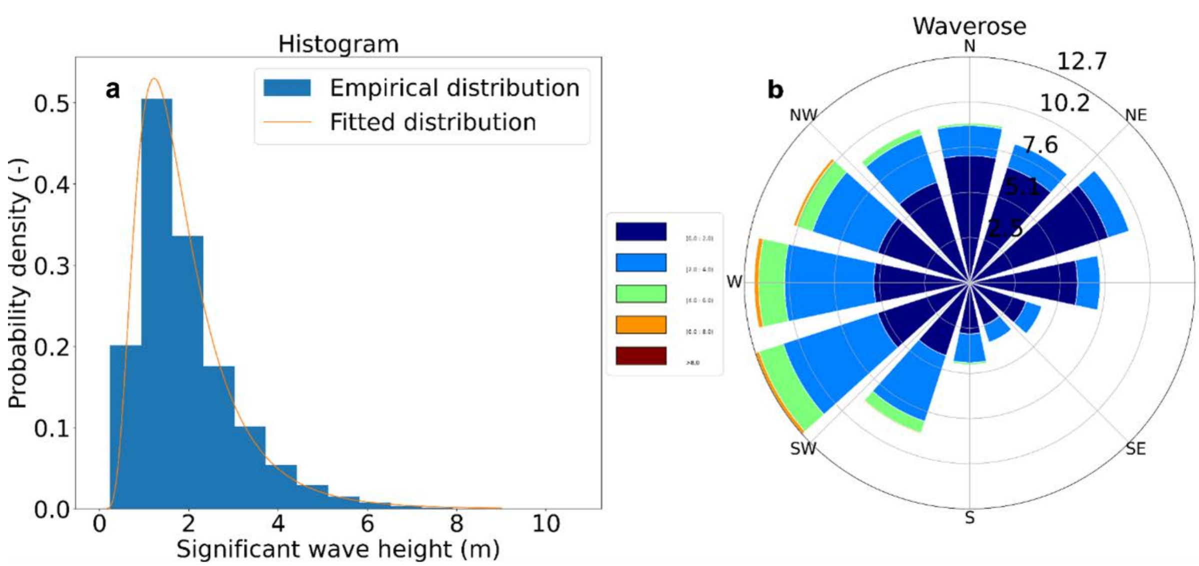


Figure J-3. (a) Histogram of significant wave height spanning 1993 to 2019 overlaid with the empirical distribution curve; (b) wave rose

J.2 Wind

Wind patterns exhibit variations on both seasonal/monthly and diurnal (daily) scales. Figure J-4 depicts these variations specific to the South Brittany site's geographical location for wind data at 100-m height. Notably, the South Brittany area shows strong winds from March to June due to temperature differences between land and sea. Conversely, between September and November (specifically during the winter), wind patterns can undergo shifts attributed to the cold air from the Arctic region (leading to northerly or northeasterly winds) and alterations in atmospheric pressure systems (prevailing wind direction during winter is typically from the west or southwest). This might be due to the movement of low-pressure systems and other systems, often associated with stormy weather, across the North Atlantic Ocean toward Western Europe.

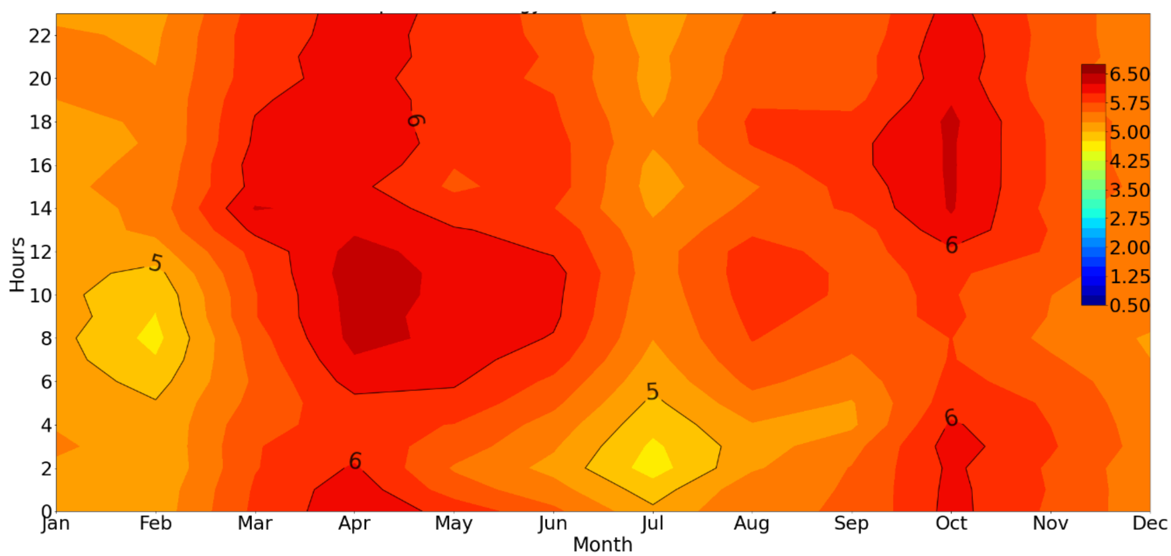


Figure J-4. Wind climatology at 100-m height between 1990 and 2020 at the geographical location of the South Brittany offshore wind site

We generated wind roses at two different heights at this location to enhance our understanding of the wind climate (Figure J-5). These wind roses include data for both 10-m and 100-m wind speeds and wind directions.

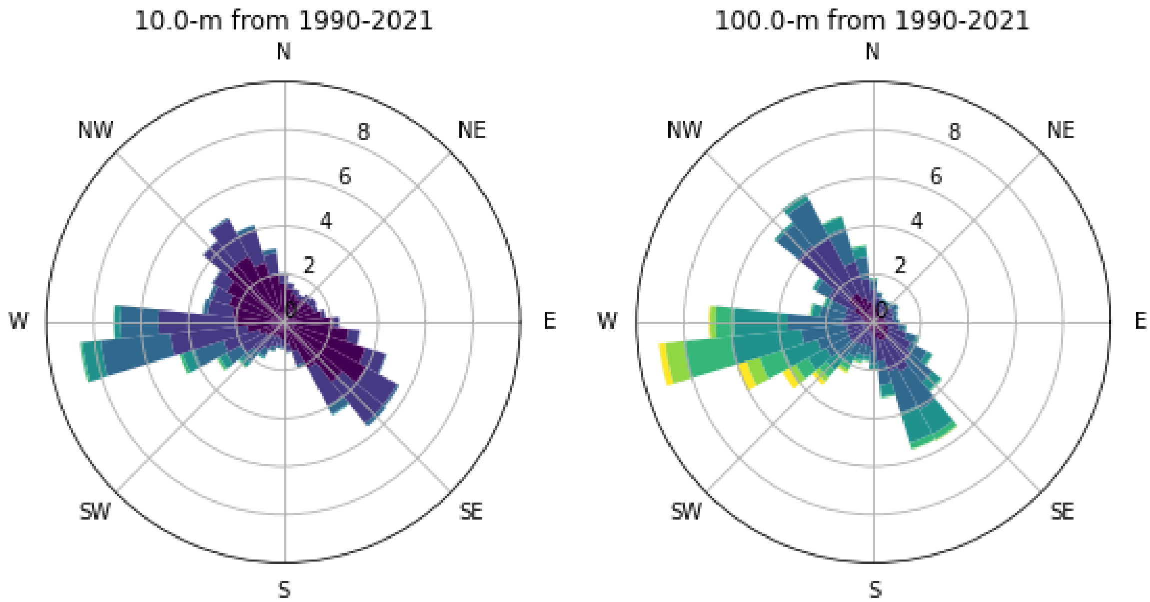


Figure J-5. Wind direction at heights of 10 m and 100 m from 1990 to 2021

Appendix K. Sørlige Nordsjø II Preliminary Metocean Study

Authors: Lin Li (University of Stavanger, Norway); Etienne Cheynet (University of Bergen, Norway); Lars Frøyd (4Subsea, Norway)

K.1 Description of Site

The reference site Sørlige Nordsjø II (SN2) lies about 140 km off the Norwegian coast, covering 2,591 km^2. In 2022, the Norwegian government proposed a total installed capacity of 3 GW for SN2. The bathymetric water depth ranges between 53 m and 70 m, compatible with both floating and fixed-bottom offshore wind turbines. The location of the reference site is shown in Figure 14 in Section 4.4.7.

The metocean conditions generated by NORA3 database (the 3-km Norwegian Reanalysis) has been used for SN2. For a detailed description of NORA3, refer to Appendix G. Wind and wave data from 1982 to 2022 at SN2 were downloaded. The original data were interpolated into a new grid with domain boundaries to match the site and a maximum element size of roughly 3 km. This configuration led to 753 grid points in SN2. The detailed coordinates of the grid points are shown in Figure K-1. The wind and wave data used in the analyses are available on Zenodo (https://doi.org/10.5281/zenodo.7057407).

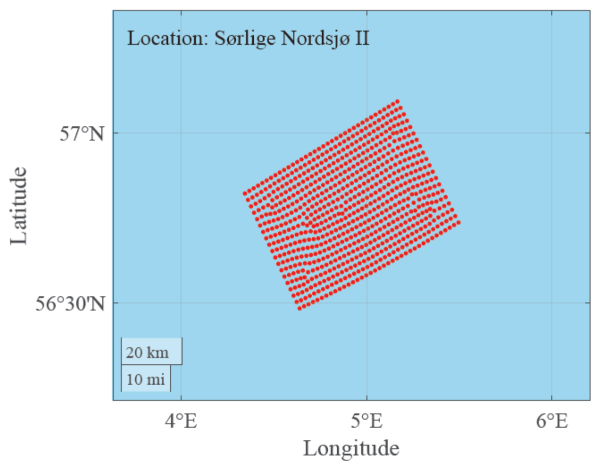


Figure K-1. Coordinates of the 753 grid points at SN2 where the wind and wave data are available

K.2 Wind and Wave Statistics

Since the reference site covers a large area, the spatially averaged wind and wave data of the whole area were analyzed. However, the data at individual grid points are available and can be used to assess the spatial heterogeneity of the metocean data. Figure K-2 presents the polar histograms of the mean wind speed at 150-m height and H_s and T_p at the reference site using spatially averaged hourly data.

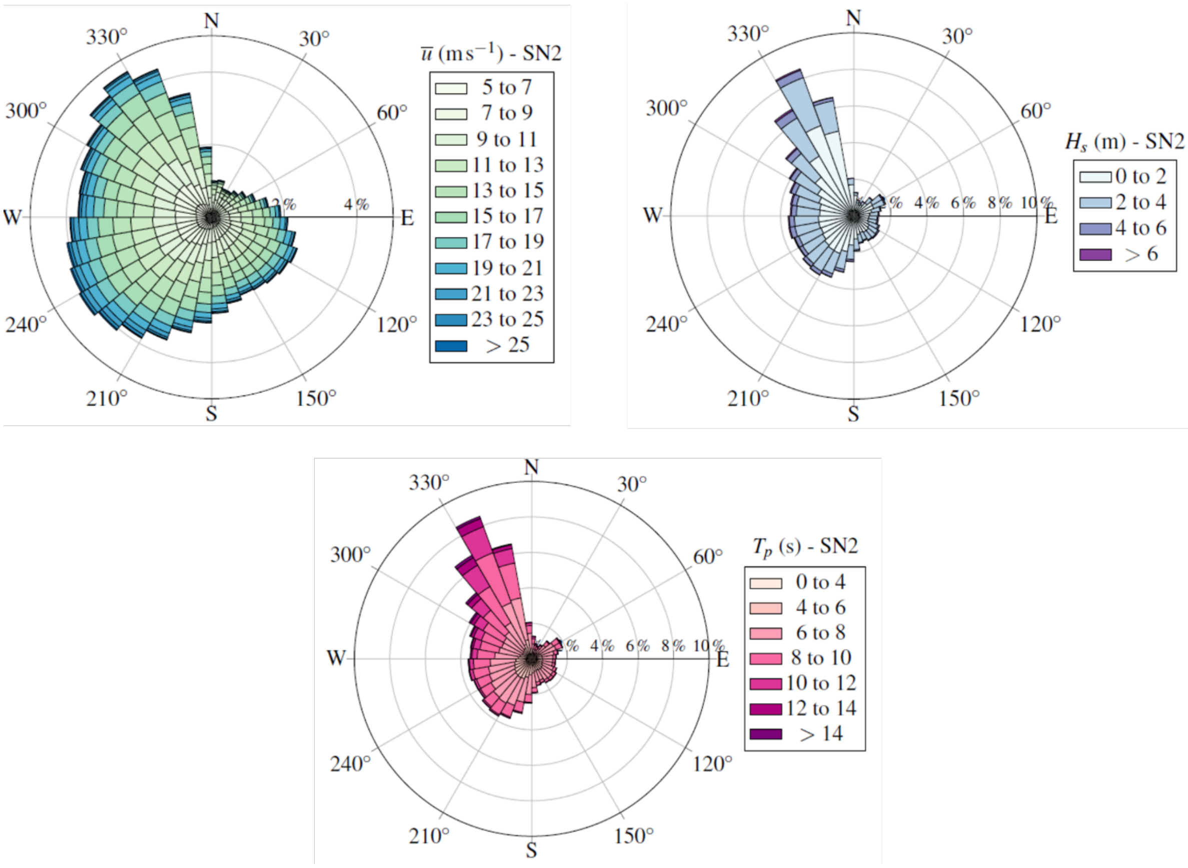


Figure K-2. Polar histograms of the mean wind speed at 150-m height, significant wave height (H_s) and spectral peak period (T_p) at SN2

The extreme values for mean wind speed at 150-m height and significant wave heights are estimated using the block maxima approach. Given that 41 years of data are available, annual maxima are used. Table K-1 presents the mean, minimum, and maximum values of the extremes from all grid points at the reference site.

Table K-1. Extreme Mean Wind Speed at 150-m Height and Significant Wave Height Corresponding to Various Return Periods at SN2

The values in brackets present the minimum and maximum values from all grid points.

Return Period (years)	Significant Wave Height (m)	Wind Speed at Hub Height (150 m) (m/s)
1	8.7 [8.4, 8.9]	30.5 [30.3, 30.9]
10	11.3 [10.8, 11.7]	37.6 [37.5, 39.6]
50	12.7 [12.1, 13.2]	43.0 [42.6, 46.2]
100	13.2 [12.6, 13.8]	45.3 [44.8, 48.9]

K.3 Joint Distribution of Waves and Wind

The joint distribution of significant wave height (H_s) and spectral peak period (T_p) for the total sea, and the mean wind speed at 150-m hub height ($\overline{u}_{hub}$) have been established using spatially averaged data for SN2. Here, it should be noted that the joint distribution is modeled based on metocean data with a 3-hour temporal resolution instead of hourly data.

When establishing the joint distribution, the conditional modeling approach is applied. H_s is considered as the main parameter here. Thus, the joint distribution consists of a marginal distribution of H_s, $f_{H_s}(h)$, a conditional distribution of $\bar{u}_{hub}$ given H_s, $f_{\bar{u}_{hub}|H_s}(u|h)$, and a conditional distribution of T_p given H_s, $f_{T_p|H_s}(t|h)$. The joint distribution is formulated as

$$f_{H_s,\bar{u}_{hub},T_p}(h,u,t) = f_{H_s}(h)\, f_{\bar{u}_{hub}|H_s}(u|h)\, f_{T_p|H_s}(t|h).$$

The marginal distribution for H_s is fitted to the hybrid LonoWe distribution. The conditional distribution of $\bar{u}_{hub}$ given H_s follows the two-parameter Weibull distribution. For the conditional distribution of T_p given H_s, the data follow a Lognormal distribution: The distributions functions and the fitted parameters are presented in Table K-2.

Table K-2. Distribution Models and Parameters for the Joint Distribution of Significant Wave Height, Spectral Peak Period, and Mean Wind Speed at 150-m Hub Height for SN2 Using Spatially Averaged 3-hour Data

Distribution Model	Parameter	Value
Marginal distribution of Hs $f_{H_s}(h) = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma_{HM} h} \exp\left[-\frac{1}{2}\left(\frac{ln(h)-\mu_{HM}}{\sigma_{HM}}\right)^2\right], & h \le h_0 \\ \frac{\alpha_{HM}}{\beta_{HM}}\left(\frac{h}{\beta_{HM}}\right)^{\alpha_{HM}-1} \exp\left[-\left(\frac{h}{\beta_{HM}}\right)^{\alpha_{HM}}\right], & h > h_0 \end{cases}.$	h_0	4.0
	μ_{HM}	0.520
	σ_{HM}	0.568
	α_{HM}	1.252
	β_{HM}	1.783
Conditional distribution of $\bar{u}_{hub}$ for given H_s $f_{\bar{u}_{hub}\|H_s}(u\|h) = \frac{\alpha_{UC}}{\beta_{UC}}\left(\frac{u}{\beta_{UC}}\right)^{\alpha_{UC}-1} \exp\left[-\left(\frac{u}{\beta_{UC}}\right)^{\alpha_{UC}}\right]$ $\alpha_{UC} = a_1 + \frac{a_2}{a_3 + \exp(-h)}$ $\beta_{UC} = b_1 + b_2 \cdot h^{b_3}$	a_1	1.984
	a_2	0.264
	a_3	0.042
	b_1	3.972
	b_2	4.976
	b_3	0.770
Conditional distribution of T_p for given H_s $f_{T_p\|H_s}(t\|h) = \frac{1}{\sqrt{2\pi}\sigma_{TC} t} \exp\left[-\frac{1}{2}\left(\frac{ln(t)-\mu_{TC}}{\sigma_{TC}}\right)^2\right]$ $\mu_{TC} = c_1 + c_2 \cdot h^{c_3}$ $\sigma_{TC}^2 = d_1 + d_2 \cdot \exp(d_3 h)$	c_1	0.826
	c_2	1.0
	c_3	0.258
	d_1	0.002
	d_2	0.135
	d_3	-0.512

From the joint distribution, contour surfaces of H_s, $\bar{u}_{hub}$, and T_p and contour lines can be generated. Figure K-3 presents the contour lines of H_s and T_p for varying $\bar{u}_{hub}$ corresponding to a return period of 50 years.

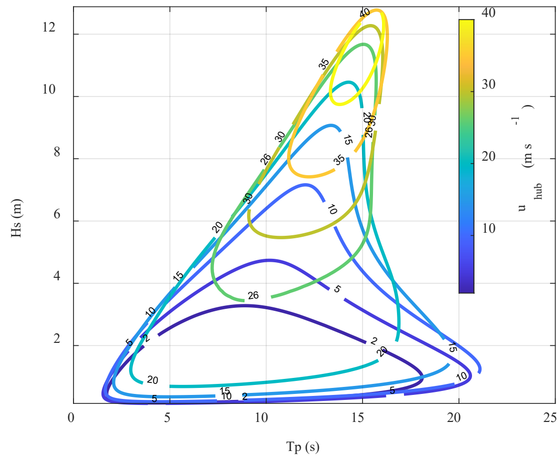


Figure K-3. Environmental contour lines of H_s and T_p for varying $\bar{u}_{hub}$ with a return period of 50 years based on the fitted parameters in Table K-2 for SN2

K.4 Description of Site and the Coastal Physics Simulation Hindcast Database

The SN2 development zone is located in a shallow area in the central North Sea away from the main ocean currents, as illustrated in Figure K-4.

The coastal physics data is taken from the NorKyst-800 hindcast model, which includes salinity, temperature, and currents along the Norwegian Coast at 1-hour temporal and 800-m spatial resolution with up to 35 vertical layers (depending on depth). The current model includes the eight major primary harmonic constituents (M2, S2, N2, K1, K2, O1, P1, Q1) of diurnal and semidiurnal frequencies, and atmospheric forcing through surface fields from AROME-MetCoOP12.

The NorKyst-800 dataset is publicly available from the Norwegian Meteorological Institute.[13]

[12] https://ocean.met.no/models
[13] https://thredds.met.no/thredds/catalog/fou-hi/norkyst800m-1h/catalog.html

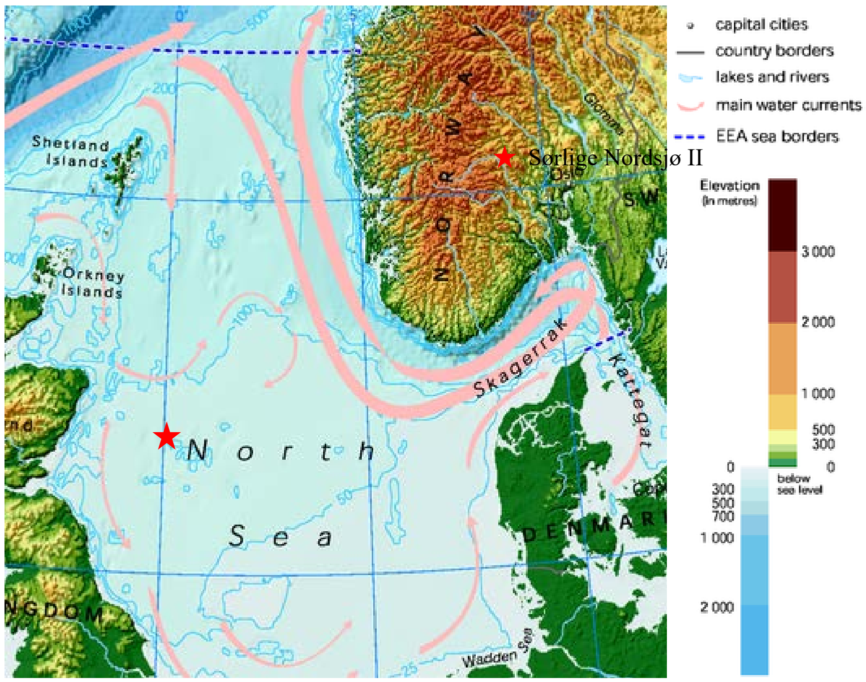


Figure K-4. North Sea physiography (Source: European Env. Agency (EEA)[14]

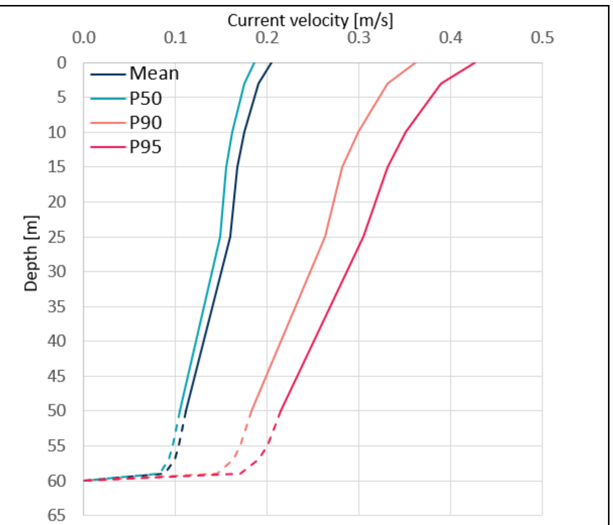
At the time of writing, the dataset spans February 2017 to January 2027 (approximately 7 years with some missing data). The dataset is continually appended with new data.

K.5 Current Statistics

Key omnidirectional current statistics throughout the water column are summarized in Table K-3.

Table K-3. Omnidirectional Current Profile Statistics at SN2

Depth [m]*	Current speed [m/s]			
	Mean	P_{50}	P_{90}	P_{95}
0	0.21	0.19	0.36	0.43
3	0.19	0.18	0.33	0.39
10	0.17	0.16	0.30	0.35
15	0.17	0.16	0.28	0.33
25	0.16	0.15	0.26	0.31
50	0.11	0.10	0.18	0.21
55	0.10	0.10	0.17	0.20
57	0.10	0.09	0.16	0.19
59	0.09	0.08	0.15	0.17
60	0.00	0.00	0.00	0.00



* Extrapolated to assumed seabed (60 m, red color) based on power law profile

[14] https://www.eea.europa.eu/ds_resolveuid/FF266A0B-23F8-420C-886D-33D7AB733E73

Directional probability distributions (current roses) are provided for 11 different water depths from surface to near seabed, corresponding to the depths in the NorKyst-800 dataset.

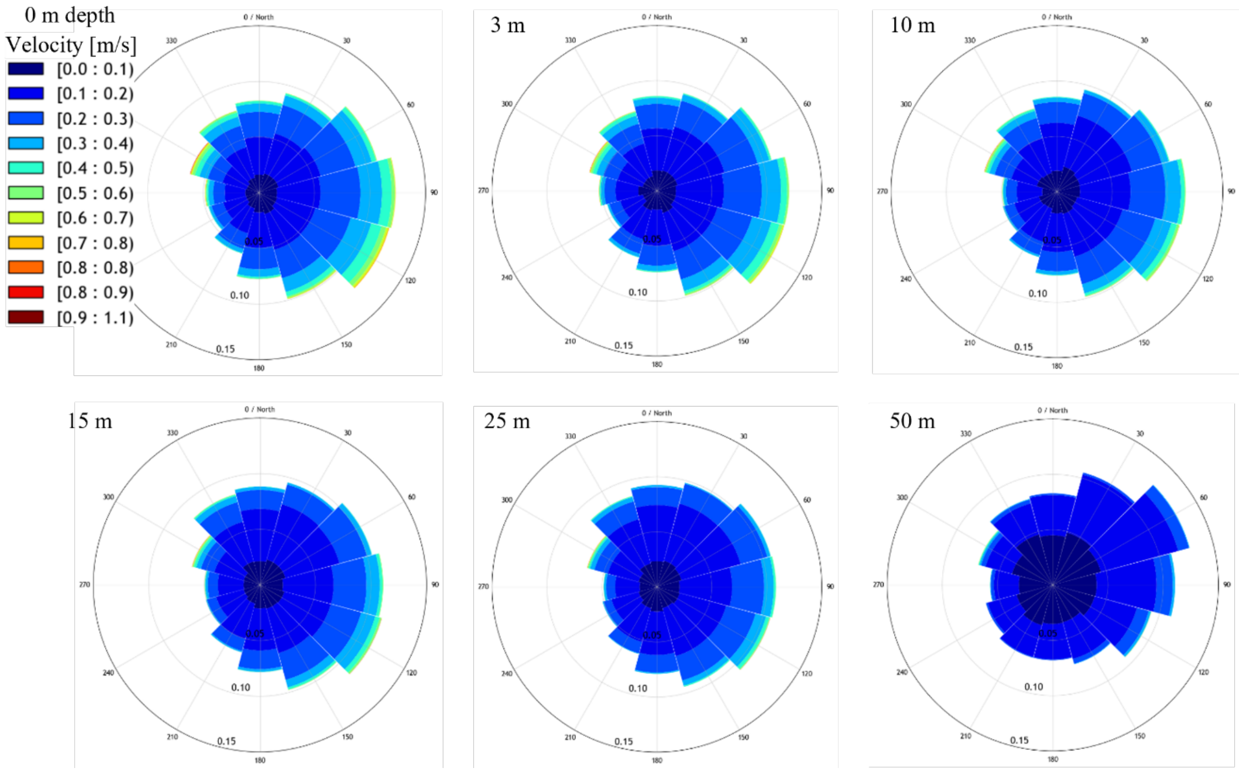


Figure K-5. Current roses (going toward) for a range of discrete water depths at SN2

By comparison with the wind rose shown above, and due to the lack of a characteristic bidirectional tidal current signature, the current seems to be predominantly wind-driven. Current extremes have been estimated based on a peak-over-threshold approach using the maximum likelihood estimator method. Two different extreme value distributions (exponential and general Pareto) have been evaluated and compared for different water depths in terms of the achieved model fit. The threshold x has been selected as $x = \mu + n\sigma$ with $3 < n < 4$. Declustering has been used to ensure independent peaks, with a minimum separation of 24 hours between peaks.

An example is shown in Figure K-6 for current velocity at 3-m depth, comparing exponential and Generalized Pareto Distribution (GPD).

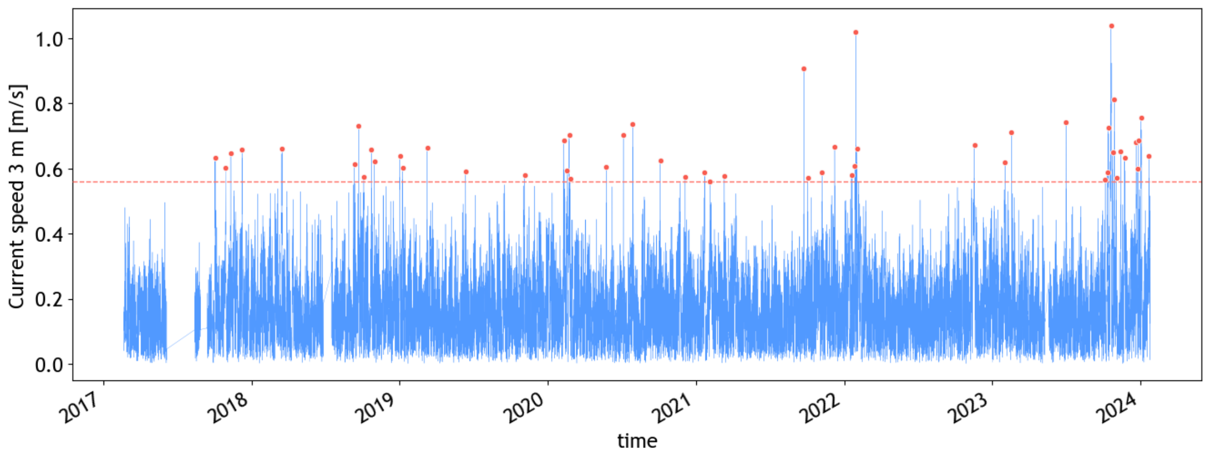


Figure K-6. Full time series of current velocity at 3-m depth with peak-over-threshold shown

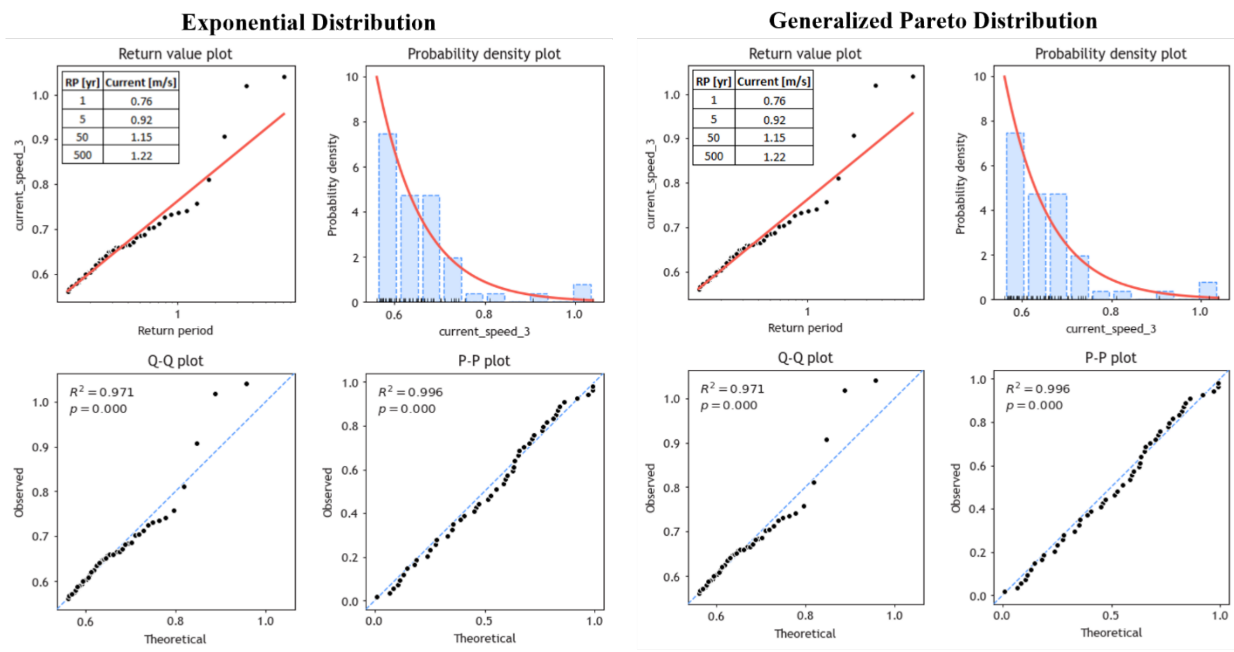


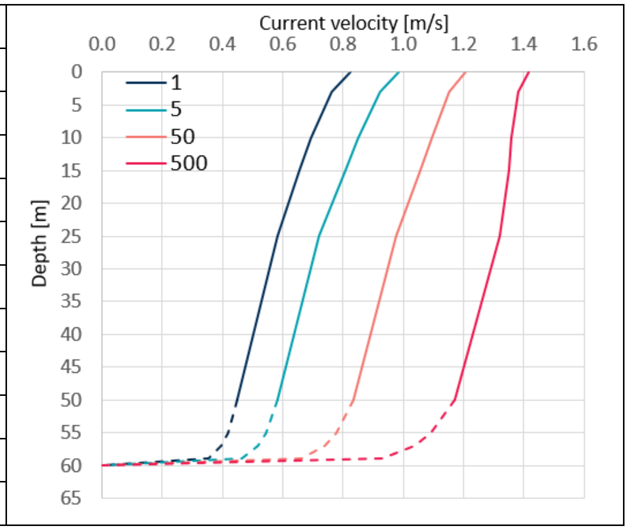
Figure K-7. Extreme value distribution fit at 3-m depth, comparing model fit and distributions

The GPD is most used with peak-over-threshold extreme value methods, but the exponential distribution is also sometimes considered suitable. The model fit of the two models were found to be similar, and none of the two models achieved a particularly good fit of the tail of the distribution. Following common practice for peak-over-threshold extreme value analysis, the GPD results were selected and reported.

The resulting omnidirectional current extremes are shown in Table K-4. It should be highlighted that the current hindcast time series is only 7 years long, such that extreme value estimates for return periods 50 years and above must be considered uncertain. It must also be stressed that current hindcast models are considered to be significantly less accurate than wind and wave hindcast models.

Table K-4. Omnidirectional Current Extremes at SN2

Depth [m]*	Current speed [m/s] at return period [years]					
	1	5	10	50	100	500
0	0.82	0.98	1.05	1.21	1.27	1.42
3	0.76	0.92	0.99	1.15	1.22	1.38
10	0.69	0.85	0.92	1.09	1.17	1.36
15	0.66	0.81	0.88	1.06	1.14	1.35
25	0.58	0.72	0.79	0.98	1.07	1.32
50	0.45	0.58	0.65	0.83	0.92	1.17
55	0.42	0.54	0.61	0.78	0.86	1.09
57	0.40	0.52	0.58	0.74	0.82	1.04
59	0.35	0.46	0.52	0.66	0.73	0.93
60	0.00	0.00	0.00	0.00	0.00	0.00



* Extrapolated to assumed seabed (60 m, red color) based on power law profile

K.6 Temperature and Salinity

Temperature and salinity statistics at SN2 are shown in Figure K-8.

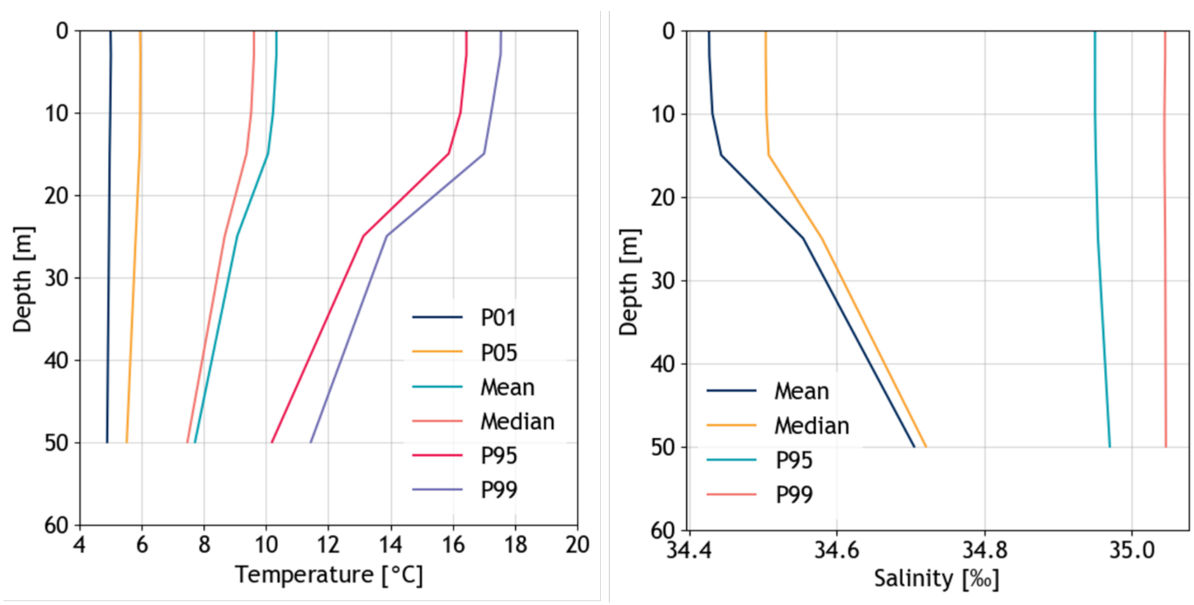


Figure K-8. (Left) Temperature and (Right) salinity statistics throughout the water column

Appendix L. Reference Vessel Details for HLVs and General Cargo Vessels

Vessel Name	LOA (m)	Beam (m)	Draft (m)	Deadweight Tonnage (tons)
STAR LYSEFJORD	204.4	32.26	12.7	
62K Type	201.8	32.36	13.3	61,800
ZHI YUAN KOU	195.2	41.5	8.8	38,000
A- Class Vessels	193.9	28.2	11.2	31,000
MPV CLIO	192.9	27.8		
MPV URANIA	192.9	27.8		
TIAN FU	190	28.5	11	
Tian Type	189.99	28.5	11	38,100
Da Type III	179.57	28	9.2	28,000
W - Class Vessels	179.5	28	10.8	32,387
Song Type 2	179.5	27.2	10.2	27,000
BIG ROLL - MC CLASS	173	42	6.5	20,675
MC-Class	173	42	6.5	20,675
Happy P-Type	168.68	25.43	9.5	20,100
Da Type II	166.5	27.4	10.1	28,450
OCEAN GLOBE	166.15	22.9	9.8	
171	166.15	22.9	9.8	19,100
MV UHL PARTNER	166	22.9	9.5	
800	166	22.9	9.5	19,100
BIG ROLL BERING/BEAUFORT	162.8	42	6.5	
COMBI DOCK I	162.3	25.4	6.6	
Combi Dock Type	162.3	25.4	6.6	10,500
183	160.6	27.91	9.01	12,501
ZHI XIAN ZHI XING	160	43	6.8	
G-Class Vessels	159.99	27.4	9.8	25,734
176	159.8	24.34	9	12,000
Happy D-type	156.93	25.6	10.32	17,518

Vessel Name	LOA (m)	Beam (m)	Draft (m)	Deadweight Tonnage (tons)
Happy S-type	155.97	29	9.5	19,000
Happy Sky	154.8	26.5	9.5	17,775
BBC Amber	153.44	23.2	11.95	
CY-Class	152.64	40	5.52	15,630
K3000	152.6	27.4	8.65	14,000
161B	151.67	21.02	7.85	8,900
161A	151.67	21.02	7.85	9,370
161	151.67	20.65	7.85	9,544
ST Class	151.5	25.4	5.67	
MV UHL FAITH	150	25.9	8.3	
F900	149.99	25.6	8.3	16,729
SERVANT	147	22.8	8.1	12,301
STELLAR MAESTRO	146.25	20.2		
BIG ROLL - BISCAY	146	28	5.25	12,285
Happy Buccaneer	145.89	28.3	8.24	13,740
FWN RAPIDE	145.63	18.25		
J1800	144.1	26.7	8.1	13,017
S Class	142	24	5.67	
160	139.99	21.5	8.2	12,346
Happy R-Type	138	22.88	9.5	15,634
INDUSTRIAL RUBY	134.52	21.84		
116	133	23	7.8	10,000
VECTIS PROGRESS	123.96	17		10,234
INDUSTRIAL EMMA	122.45	18.4	7.15	7,700
AURORA	119.98	15		
BOTHNIA	119.98	15		
CHARGER	119.8	20	7.72	8,034
CHALLENGER	119.8	20	7.72	8,034
INDUSTRIAL CHARGER	119.8	20	7.72	8,034

Vessel Name	LOA (m)	Beam (m)	Draft (m)	Deadweight Tonnage (tons)
INDUSTRIAL CHALLENGER	119.8	20	7.72	8,034
INDUSTRIAL HOBART	118.55	15.2	7.05	7,778
FWN MOMENTUM	116.26	17.8		
MERCHANT	116.26	17.8		
H800	110.49	20.85	7.7	7,051
INDUSTRIAL COLOR	99.99	20.5	8.3	8,400
INDUSTRIAL CONFIDENCE	99.99	20.5	8.3	8,400
INDUSTRIAL CONSTANT	99.99	20.5	8.3	8,400
INDUSTRIAL COURAGE	99.99	20.5	8.3	8,400
ACE	99.92	17	7.28	6,265
AMA	99.92	17	7.28	6,265
INDUSTRIAL AIM	99.92	17	7.28	6,265

Appendix M. Marine Growth Along the Mesopelagic Zone

This appendix is available in the following report:

Devantier, C. B., Wong, X. H., & Schrameyer, V. (2024). Marine growth along the mesopelagic zone (1.0). DHI Technical Report. https://doi.org/10.5281/zenodo.12731585