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IEA Wind Task 49: Reference Site Conditions for Floating Wind Arrays

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IEA Wind Task 49: Reference Site Conditions for Floating Wind Arrays

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Abstract. The commercial-scale deployment of floating offshore wind (FOW) projects is expected to take place in a diverse range of sites that may differ significantly from existing fixed-bottom projects. FOW farms are particularly sensitive to the water depth, and the meteorological and oceanographic (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 FOW 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. This study represents the outputs of work package 1 of International Energy Agency Wind Task 49, which focuses on the integrated design of floating wind arrays. The primary goal of this study is to establish the type of parameters and constraints required to characterize FOW array reference sites; provide a realistic and publicly available set of reference site conditions to the FOW community as a baseline set of data for individual research projects; identify and categorize any critical gaps in the existing data or methodologies required to define reference site characteristics; and inform and support the design of reference FOW arrays. A building block concept was developed for synthesizing reference sites for the design of FOW arrays. The building blocks include three classes of site

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conditions focusing on the techno-economic design of FOW projects: metocean conditions, seabed conditions, and coastal infrastructure. All reference site data produced and collected in this study are publicly available.

1. Introduction
The International Energy Agency (IEA) predicts an annual increase in global wind energy of 390 GW until 2030, and 350 GW to 2050 to meet the net-zero emission target by 2050 [1,2]. Offshore wind will play an important role in reaching those levels. In 2020, the annual increase in offshore wind capacity was 5 GW. According to the IEA, this annual increase will reach 80 GW in 2030 and 70 GW in 2050. While fixed-bottom wind energy currently dominates offshore wind technology, the IEA net-zero scenario estimates that floating offshore wind (FOW) will provide a major contribution from 2030 [2].

Research and development have focused mainly on single FOW turbines, particularly on the design of the floating platform and its mooring and anchoring systems [3]. Such single FOW structures were tested in pilot projects like Equinor's Hywind Demo in Norway [4]. However, FOW on a larger scale implies installing arrays of wind turbines moored in proximity to each other on the seafloor and using the same electrical infrastructure to export the power. The optimal design and operation of such FOW arrays require a system perspective starting from the early planning phase.

The ambition of the IEA Wind Task 49 work package "Reference Sites for Floating Wind Arrays" is to provide a realistic and publicly available set of reference site conditions to the floating wind community as a baseline set of data for individual research projects. Such open reference sites for FOW arrays will increase the comparability of research and development work on the design of FOW arrays and thus accelerate the maturation of floating wind technology.

This paper highlights the main results of this study. Section 2 outlines the building-block methodology used to generate reference sites. Section 3 elaborates on three components of the building blocks, which are metocean conditions, seabed conditions, and coastal infrastructure. The full report and supporting datasets are published and available as open source [5,6].

2. Methods

2.1. Building block concept
This study provides reference sites for the techno-economic design of FOW farms, utilising a concept with building blocks to synthesize purpose-built site representations. The authors identified six classes with relevant factors for FOW farms, namely metocean conditions, seabed conditions, coastal infrastructure, environmental impact, social impact, and permissions and regulations. The first three describe key parameters for the FOW farm design while the latter three classes are important for the site selection but less relevant in the techno-economic design.

The metocean conditions are key to estimating 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, currents, and joint probability of two or more variables. This includes values for both typical operation and extreme events, allowing the evaluation of 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 that foremost the soil type and strength, but also the slope and roughness of the seabed, influence the design of the mooring system. On an extreme site, seismic hazards could dictate the floating array design.

The coastal infrastructure is another important factor, determining 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 this context but also involves the existing maritime workforce. As part of the coastal infrastructure, the power grid capacity determines if a wind energy project can be connected to the regional grid without further expansion.

The environmental impact, during both the short and long term, cannot be neglected when developing wind energy projects. Offshore wind energy deployment means disturbing natural maritime habitats with technical installations, foreign materials, noise, light, and traffic. The intensity of these impacts on the local environment are highly dependent on the regional marine flora and fauna [7].

The socioeconomic impact is important for the sustainable development of wind energy, as well as the support and acceptance of the local communities and larger society. Technical and social challenges should be solved in an interdisciplinary approach to successfully mitigate climate change [8]. Although local communities are less affected by visual and noise impacts from FOW arrays due to the typically larger distance from shore, their interests and concerns should be considered throughout the whole 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 significant attention. The European Union and many of its member states, for example, seek to accelerate permissions to reach the zero greenhouse gas emissions target by 2050. Floating wind is in the early stages of technology development and regulations unifying the procedures are yet to be established.

In each of the three classes with influencing design factors, building blocks are used to describe the characteristic properties and their spread. Figure 1 summarizes these building blocks. For the metocean conditions, a database representing the global pipeline of FOW projects is generated. The wind conditions and sea-state (wave) conditions at each site in the generated pipeline are separated and assessed to understand the range of conditions expected. From this initial set of data, the metocean representative sites are reduced to 11 real sites that represent different areas of the characterized pipeline. For the seabed conditions building block, recommendations are provided on site-specific data required for detailed design, but a set of "synthetic cases" are outlined providing the different parameters required for design under each defined case or soil condition. For instance, seabed scenario 1a considers loose sand and shallow bedrock. This is the most reasonable approach since, depending on the soil conditions, they may favor or disfavor a specific type of anchor. The analysis done is a synthetic case study that is based on a simplified methodology and does not include any in situ data. These requirements are indicative only, and a detailed site-specific study should be performed in the early stages of a project to produce a detailed design. The objective of the coastal infrastructure building block is to provide information about the main requirements that a port should comply with to provide a satisfactory service during the FOW farm construction. In this work, three types of ports are considered.

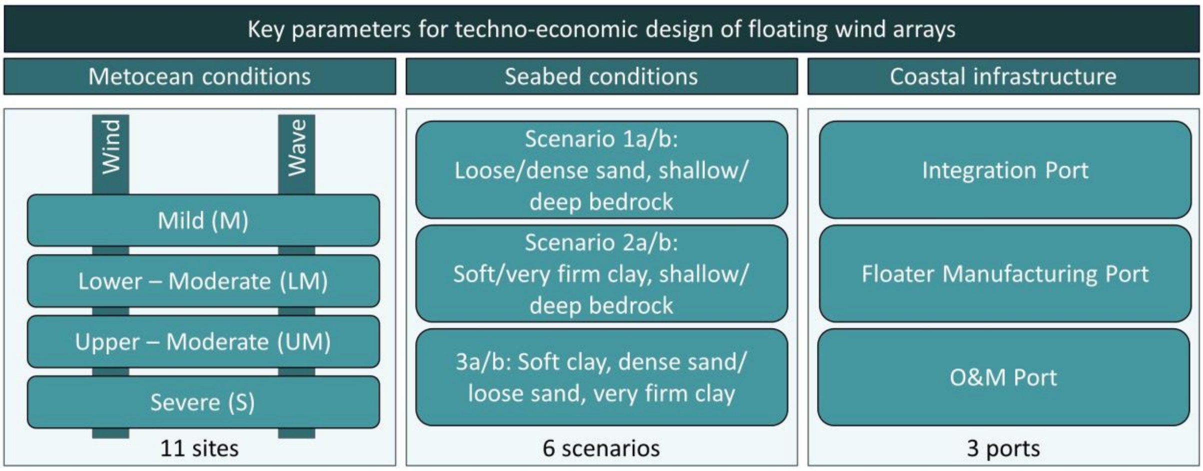

Figure 1. Building block concept for synthesizing reference sites for techno-economic design of floating wind arrays. Note: O&M = operations and maintenance

3. Results

3.1. Metocean conditions

3.1.1. Floating array pipeline To deliver a set of fully defined reference sites characteristic of the international global FOW deployment pipeline, a database of existing and proposed locations for floating arrays was first constructed. The 4C offshore map [9] of FOW projects provided a base for this database. This map identifies a total of 581 FOW farms organized into the following development statuses: concept/early planning, consent application submitted, consent authorized, development zone, fully commissioned, partial generation/under construction, preconstruction, and under construction. Using expert knowledge from our consortium 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 (Figure 2).

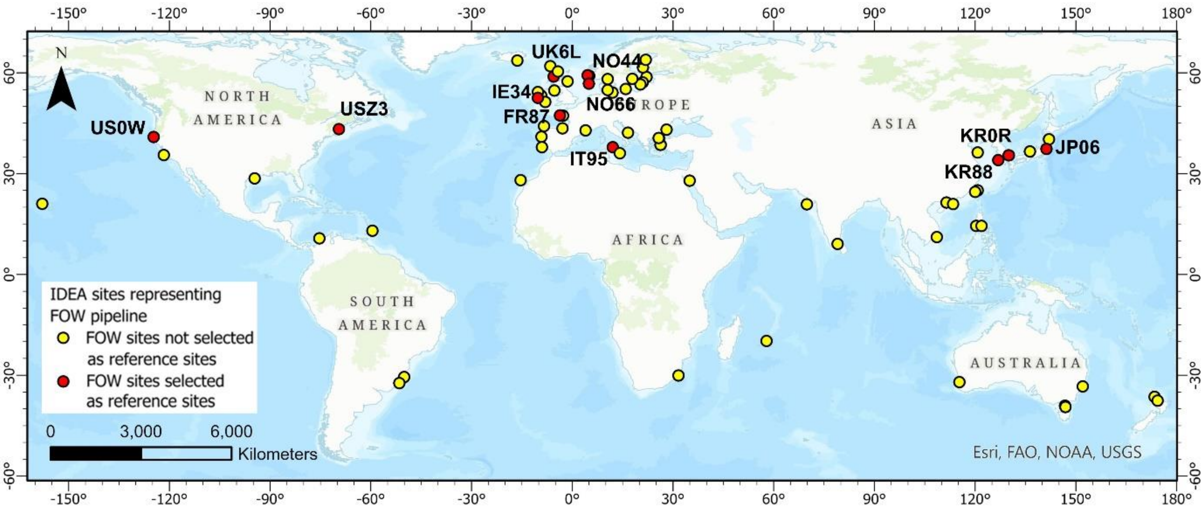

Figure 2. Location of the FOW projects selected by the Integrated Design of Floating wind Arrays project to characterize the global FOW pipeline, alongside 11 sites further selected as reference sites. Sites are labeled according to the 4C Offshore database [9].

3.1.2. Classification of metocean conditions For these 69 representative sites, the European Centre for Medium Range Weather Forecasts 5 Reanalysis (ERA-5) dataset [10] was used to identify several "severity" categories that could be utilized to describe the metocean conditions characterizing the global pipeline. At the closest grid point to each site, the following parameters were extracted at a 1-hour temporal resolution from 1979 to 2020: significant wave height (H_s), individual maximum wave height (H_{max}), peak wave period (T_p), mean wave direction, and u- and v-velocity components of wind at 10 m and 100 m above sea level [10].

Extreme value analysis was carried out for H_s and wind speed on each dataset to understand the range of conditions across the database [6]. The raw ERA-5 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. A generalized extreme value model in association with the block maxima method [11] was chosen to calculate the extreme values for wave height and wind speed at each location. The predicted extreme 1-hour wind speeds at 10 m above sea level were converted to 10-minute extreme wind speeds using the Froya wind speed profile according to DNV-RP-C205 [12]. These were then extrapolated to hub height (150 m) using the power law [13] with the shear exponent value 0.11 as recommended by International Electrotechnical Commission 61400-3-1 [13] for extreme conditions. The resulting 50-year return values for significant wave height and 10-minute averaged wind speeds at hub height are presented in Figure 3 and Figure 4 [6]. The raw time series and 50-year return values at each location are publicly available [5]. The threshold water depth between fixed and floating wind is considered as 60 m in this study [6]. Therefore, the 69 sites were then reduced to 49 representative sites.

Considering the pipeline of international FOW projects, based on calculated 50-year extreme wind and wave values, several severity categories are defined in Table 1 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 FOW projects. The selected representative sites are outlined in Table 2 and Figure 2. Note that JP06 (Fukushima) was not included in the analysis presented in Figure 3 and Figure 4.

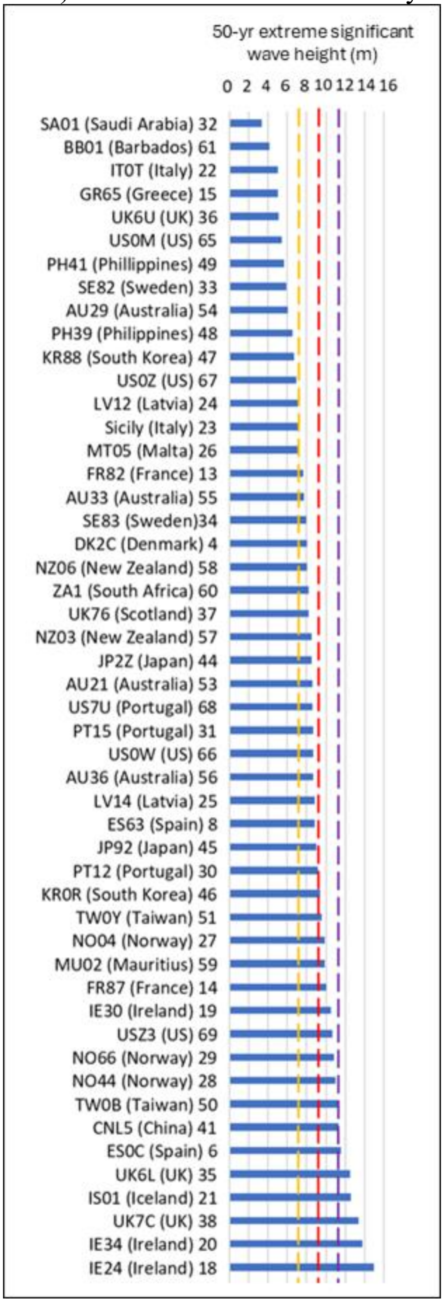

Figure 3. Calculated 50-year return values of H_s for each of the 49 selected FOW sites in the global pipeline. FOW site label refers to "[4C Offshore Map code [9]] [(Country)] [data

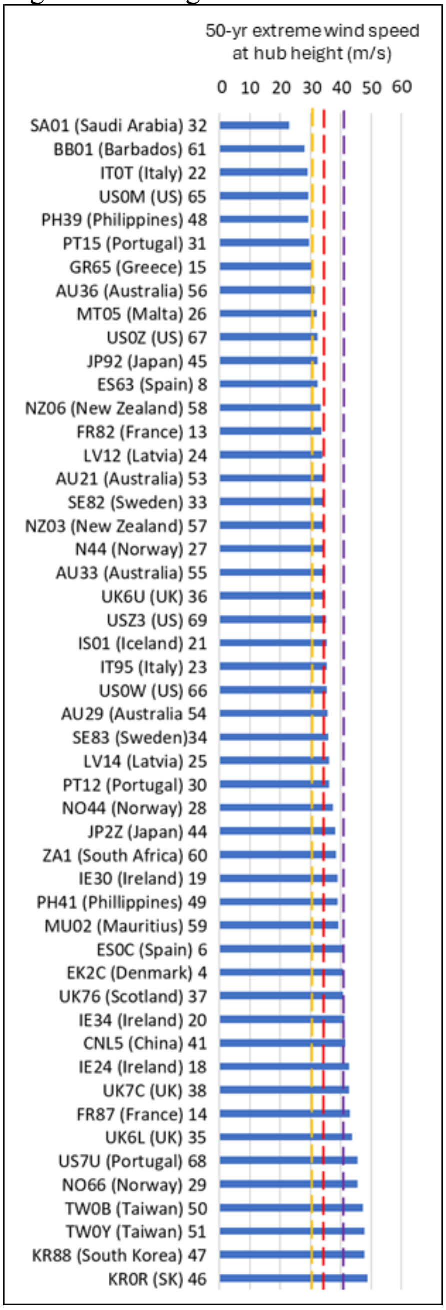

Figure 4. Calculated 50-year return values of 10-min wind speeds at hub height (150 m above sea level) for each of the 49 selected FOW sites in the global pipeline. FOW site label refers to

analysis key number [6]].” Dashed lines indicate severity categories: below yellow (< 7.5 m) = mild; between yellow and red (> 7.5 and < 9 m) = lower moderate; between red and purple (> 9 and < 11 m) = upper moderate; above purple (> 11 m) = severe.

“[4C Offshore Map code [9]] [(Country)] [data analysis key number [6]].” Dashed lines indicate severity categories: below yellow (< 33 m/s) = mild; between yellow and red (33 < 36 m/s) = lower moderate; between red and purple (> 36 and < 42 m/s) = upper moderate; above purple (> 42 m/s) = severe.

Table 1. Wind and wave severity categories, based on 50-year return values.

Severity	Wind Threshold (m/s)	Wave Threshold (m)
Mild (M)	< 33	< 7.5
Lower Moderate (LM)	> 33 and < 36	> 7.5 and < 9
Upper Moderate (UM)	> 36 and < 42	> 9 and < 11
Severe (S)	> 42	> 11

Table 2. Selected sites that represent different parts of the global pipeline and where site-specific analysis is available within the consortium.

Name	Latitude (deg) [9]	Longitude (deg) [9]	Water Depth (m) (GEBCO) [14]	Distance From Shore (km) [5]	Severity (Wind)	Severity (Wave)
IT95 (Hannibal)	37.84	12.07	-353	35	LM	M
US0W (Humboldt Bay)	40.93	-124.71	-707	43.8	LM	LM
KR0R (Ulsan)	35.45	129.95	-188	32	S	UM
IE34 (Moneypoint Offshore One)	52.52	-10.28	-102	23.4	UM	S
UK6L (Havbredey)	58.86	-5.54	-91	41.6	S	S
JP06 (Fukushima)	37.31	141.25	-90	19.4	S	S
NO44 (Utsira Nord)	59.28	4.54	-273	42.4	UM	UM
USZ3 (Gulf of Maine)	43.25	-69.50	-148	138	LM	UM
KR88 (Geomundo)	34.04	126.90	-70	47	S	UM
FR87 (Sud de la Bretagne II)	47.33	-3.66	-94	30.7	S	UM
NO66 (Sørlige Nordsjø II)	56.78	4.92	-60	180	S	UM

3.1.3. Environmental conditions required for floating offshore wind farm design Through working group discussions, the relevant standards and guidelines for defining environmental conditions for FOW design and operation were reviewed and compiled [11–13,15–20]. The minimum parameters and level of analysis required for pre-Front End Engineering Design level design basis were subsequently determined. These included normal and extreme conditions for wind, water levels, currents, waves, but also information regarding turbulence intensity, joint probability distributions, and marine growth. These parameters are summarized in Section 4.3 of the WP1 IEA Wind Task Report [6]. Each reference site was analysed using the minimum parameters defined. Different input datasets and methods were used for each site yet an alignment with listed standards and guidelines was maintained. Due to the differences in methods that appear in some analyses, the resulting conditions, particularly on extreme conditions, should be treated as site-specific and solely for the purpose of preliminary design. Time-

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series information for each representative site along with site condition assessment results are provided as open source [5].

3.2. Seabed conditions

3.2.1. Ground conditions To date, there are currently no institutions, such as the European Commission through Eurocodes, regulating wind farm construction. Yet, different standards, guidelines, and recommended practices exist that are generally followed by industry [21–29]. According to DNV-ST-0126 [22], soil investigations should provide all necessary soil data for a detailed geotechnical design. The soil investigations can be divided into geological studies, geophysical surveys, and geotechnical investigations [21,29–31]. For multiple foundations, such as in a wind farm, the soil stratigraphy and range of soil strength properties should be assessed per foundation location. In situ testing includes but is not limited to the standard penetration test, cone penetration test, pressiometer test, and dilatometer test. Soil and rock sampling should also be conducted along with a wide variety of laboratory testing to determine the geotechnical parameters [22]. Soil investigations should be carried out before the design. However, when no soil investigations are available at the time of foundation design, conservative assumptions can be made for the soil properties. These should be confirmed by soil investigations before starting construction.

3.2.2. Constitutive model To recreate the project numerically for the design, it is important to choose the correct constitutive model [21]. Many different constitutive models exist, each suited for different soil types and with different geotechnical parameters needed. For design, it is recommended to adopt a software package that utilises the finite element method. The most-used model is the linear and elastic perfectly plastic law with a rupture criterion of Mohr-Coulomb type. This model is characterised by two failure parameters: the cohesion, c, and friction angle, φ, an isotropic linear elasticity of Hooke (υ, E), a yield surface, and a plastic potential. The main drawback of this behaviour law is that the loading and unloading modules are equal, which does not accurately represent the soil response.

Another model that should be considered is the Hardening soil model. This model is a non-linear isotropic model with two independent plasticity mechanisms with hardening, which allow for 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 realistically as possible, it is highly important that the in situ test and laboratory testing are carried out attentively to reduce the incertitude on the data provided. In this study, the parameters to design the soil according to the Mohr-Coulomb law are provided.

3.2.3. Geotechnical parameters – synthetic cases In the same region, significant spatial variability in soil characteristics can be observed, including variations in stratigraphy, strength parameters, and geotechnical properties. It is important to consider the vertical and horizontal variability of the soil. In the three synthetic scenarios presented in Table 3, it is assumed that no horizontal variability is present in the soil, as the soil is homogeneous and considered isotropic. These are illustrative examples for a preliminary study and do not include any in situ data. For a preliminary design, it is recommended to use the scenario that best corresponds with the real strata determined in the geology study. Additional ground parameters that can be used in design are presented in Table 4. For detailed design, a detailed and site-specific geological and geotechnical survey should be performed early in the project.

Table 3. Ground parameters for the three synthetic scenarios (1 [a & b], 2 [a & b], and 3 [a & b]).

Scenario	Soil	Depth of Top of the Strata (mbgl)	Bulk Density (kN/m^3)	Permeability (m/s)	Undrained Shear Strength (kPa)	Friction Angle (°)	Elastic Modulus (MPa)	Poisson Ratio
1a	Loose sand	0	16	10^{-4}	-	30	5	0.30
	Shallow bedrock	10	20	10^{-8}	10,000	30	50	0.35
1b	Dense sand	0	18	10^{-5}	-	38	40	0.30
	Deep bedrock	70	24	10^{-9}	15,000	35	200	0.25
2a	Soft clay	0	14	10^{-7}	20	-	2	0.25
	Shallow bedrock	10	20	10^{-8}	10,000	30	50	0.35
2b	Very firm clay	0	20	10^{-8}	250	-	15	0.30
	Deep bedrock	70	24	10^{-9}	15,000	35	200	0.25
3a	Soft clay	0	14	10^{-7}	20	-	2	0.25
	Dense sand	0	18	10^{-5}	-	38	40	0.30
3b	Loose sand	0	16	10^{-4}	-	30	5	0.30
	Very firm clay	0	20	10^{-8}	250	-	15	0.30

Table 4. 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	-	-

3.3. Coastal infrastructure

3.3.1. Type of floating foundations Port site requirements depend on the floating foundation typology [6], which will determine the necessities in relation to manufacturer, assembly, and staging port facilities. Floating foundations are usually manufactured and assembled onshore, to be 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 [32]. Steel semi-submersible floaters are the most popular solution for planned commercial developments; however, the optimal technology is still undecided. Therefore, any port development should be performed considering different floating foundation solutions to be flexible enough to meet 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 [32].

3.3.2. Key vessels for construction and installation The typical vessel categories used in the construction of a typical FOW farm are wind turbine installation vessels, heavy lift vessels, anchor handling tug supply vessels and cable laying vessels. Other important vessels for the offshore wind farm installation activities are offshore construction and support vessels, service operation vessels and crew transfer vessel to name a few. A list of these vessels used as a reference in this analysis is outlined in the IEA Wind Task 49 WP1 report [6]. Typical construction and installation activities including vessels required for FOW are described in the Representative Project Envelope for Floating Offshore Wind Energy in California [33].

3.3.3. Port requirements Considering the variations of floater types in the market and vessel requirements, this section provides an overview and a set of reference values of the requirements that a port should comply with to be considered for the construction of an FOW farm. Three port types are considered: integration port, floater manufacturing port, and operations and maintenance (O&M) ports (Table 5) [6]. These requirements are indicative only and an existing port that is not initially compliant with all of them might be a feasible solution as real necessities are very site-specific. This assessment is mainly focused on the distance from the FOW farm, navigation requirements, quay length, storage areas, and port services in general. The port requirements presented in this study are based on the available information and should be reviewed as more FOW projects are developed at the commercial scale and more detailed information becomes available.

Table 5. Port requirements for the integration port. *U: Unrestricted.

Parameter	Integration Port		Floater Manufacturing		O&M	
	Min	Max	Min	Max	Min	Max
Distance to Offshore Wind Farm (nautical miles)	-	150	U*	U	U	U
Channel Width (m)	230	310	230	310	-	90
Channel Depth (m)	15	16.5	11.25	13.75	-	8.1
Air Draft (m)	U	U	50	U	50	U
Turning Basin Diameter (m)	270	550	270	550	-	200
Water Depth at Berth (m)	15	16.5	10	12.1	-	7.1
Quay Wall Length (m)	≈430	≈600	≈310	≈485	1	4
Laydown Area (Ha)	6	25	20	40	-	-
Wet Storage Area in Sheltered Waters (Ha)	4	70	4	70	-	-
Bearing Capacity at Quayside (t/m^2)	20	50	20	50	-	-
Bearing Capacity at Laydown Area (t/m^2)	10	20	10	20	-	-

Ports utilised in the different activities involved in the floating offshore wind farm construction can 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 the access channel, turning basin, and waiting anchorage areas. Table 5 summarizes navigation requirements in terms of minimum and maximum recommended values. As a conservative scenario, the navigation requirements are determined by considering the vessels' particulars 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, whereas the maximum parameters are defined as the upper ranges. This approach ensures that the design parameters encompass the variability of the fleet without excluding any vessel type. When vessels are towing a floating substructure alone or a substructure including the wind 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 not only have the capacity to accommodate the design fleet by itself but also the vessels transporting the floater. When transporting 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 depend on the floater dimensions.

Assuming a continuous berth line and vessel moored alongside, the required quay wall length is defined by the mooring layout defined for this vessel. As per BS 6349-4:1994 [34] 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 to the berthing line in combination with breast lines and spring lines with a horizontal angle of 90° and 10°, respectively. The quay wall length is therefore defined by the sum of the vessel length overall and the required quay wall length to accommodate the stern and head lines. In a FOW project, quay length requirements at port will depend on various parameters, such as activities undertaken at the port (e.g. floaters manufacturing, wind turbine generator's component import), and logistics and philosophy (e.g. number of import berths, floaters launch methodology, onshore layout). As a preliminary approach, the minimum and maximum quay wall length required by a CTV and FTV are considered, and the quay wall length requirements are estimated for the integration port and floater manufacturing port [6] (Table 5).

The construction of a FOW farm would require 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 paper are reference values obtained from an analysis of existing literature [32,35–39] relating to FOW farm construction and are subject to modification after the completion of more site-specific assessments required to be performed within a FOW project [6]. Additionally, bearing capacity requirements defined for the quayside and laydown areas are considered the same for the integration port and floater manufacturing port (Table 5).

4. Summary and conclusions

This paper presents a methodology with results for the identification and characterisation of the relevant parameters for floating offshore wind siting and design load cases. Project sites across all the main markets currently being considered for this technology are covered, with 11 sites being selected for further analysis. A building-block concept was developed for synthesizing 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 blocks for the metocean conditions are based on metocean data from 11 real sites and divided into wind and sea states. These states are categorized into mild, lower-moderate, upper-moderate, and severe conditions. 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 the 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 the social impact, the environmental impact, 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 in the future. 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 and are available for use in other projects.

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